Geology and Geomorphology of Jenolan Caves and the Surrounding Region

DAVID F. BRANAGAN[1], JOHN PICKETT[2] AND IAN G. PERCIVAL[3]

[1]Honorary Associate, School of Geosciences, University of Sydney, NSW 2006 (dbranaga@usyd.edu.au);
[2]Honorary Associate, Geological Survey of NSW, WB Clarke Geoscience Centre, Londonderry NSW 2753 (picketj@bigpond.net.au);
[3]Geological Survey of NSW, WB Clarke Geoscience Centre, Londonderry NSW 2753 (ian.percival@trade.nsw.gov.au)

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Detailed mapping by university students and staff since the 1980s has significantly elucidated previously poorly known stratigraphic and structural relationships in the Jenolan Caves region. Apart from andesite of ?Ordovician age, rocks west of the caves probably correlate with the lower Silurian Campbells Group. That succession is faulted against the Silurian (mid Wenlockian) Jenolan Caves Limestone, in which caves developed during several episodes from the late Palaeozoic. Immediately east of Jenolan Caves, siliciclastic sedimentary and volcaniclastic rocks with interbedded silicic lavas constitute the newly defined Inspiration Point Formation, correlated with the upper Silurian to Lower Devonian Mount Fairy Group. Several prominent marker units are recognised, including limestone previously correlated with the main Jenolan limestone belt. Extensive strike-slip and thrust faulting disrupts the sequence, but in general the entire Silurian succession youngs to the east, so that beds apparently steeply-dipping westerly are actually overturned. Further east, Upper Devonian Lambie Group siliciclastics unconformably overlie the Inspiration Point Formation and both are overlain unconformably by lower Permian conglomeratic facies. Carboniferous intrusions include the Hellgate Granite with associated felsite dykes. The regional geomorphology probably evolved from late Carboniferous–early Permian time, with 'steps' in the deep valleys indicating episodic periods of valley formation, possibly including Permian glaciation.

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INTRODUCTION

Jenolan Caves, located 182 km west of Sydney by road (Fig. 1), are Australia's best known and most spectacular limestone caves. Early geological studies concentrated on the narrow belt of limestone and mapping of the cave system it encloses, whereas more recent scientific research has emphasized the speleogenesis of the caves and their antiquity. In comparison, the regional geology surrounding the Jenolan karst area has been relatively neglected, largely due to its rugged terrain and structural complexity. Thus the geological context in which Jenolan Caves formed, that is so crucial to an understanding of how the cave system evolved, has taken a long time to unravel, and indeed still requires

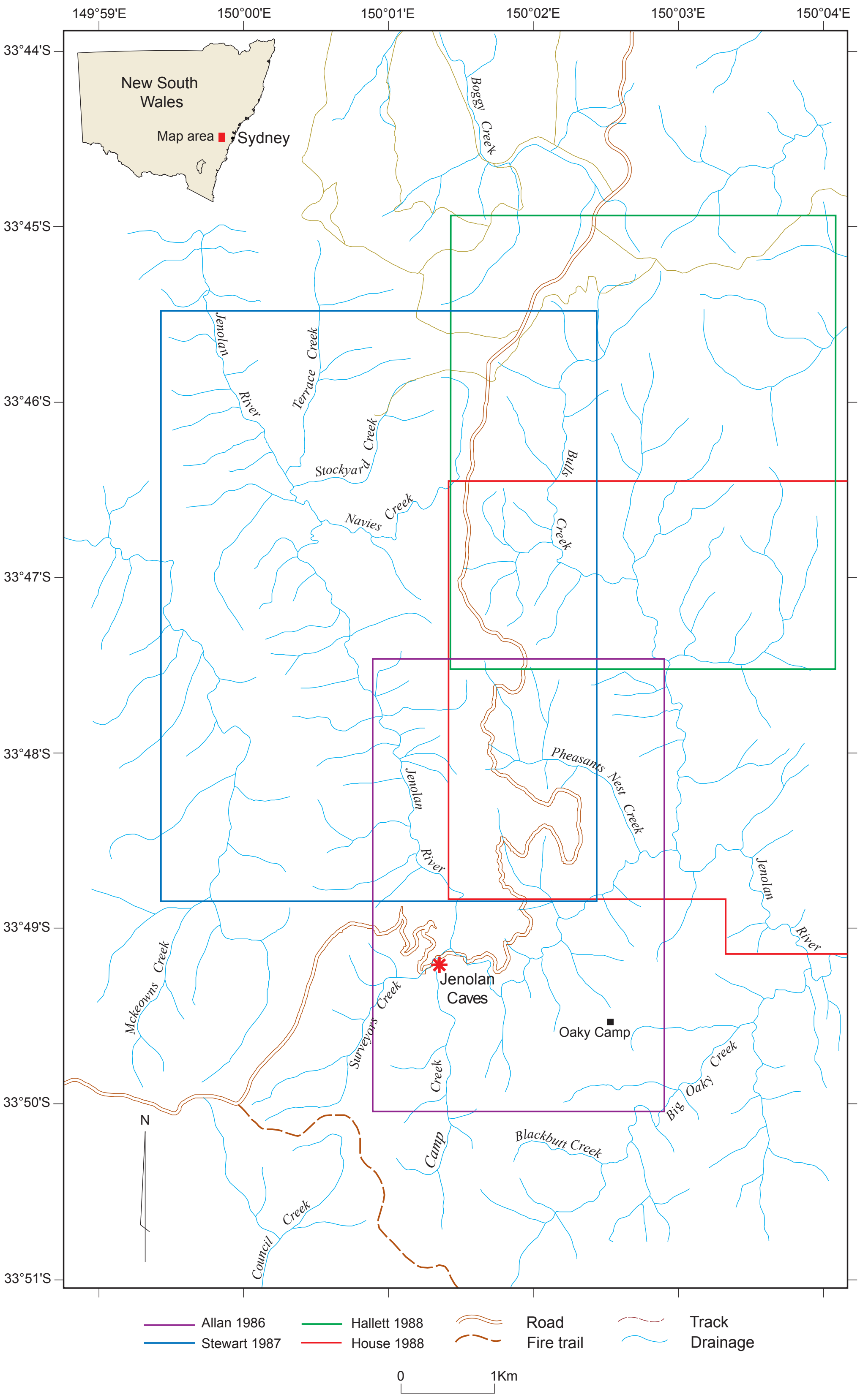

Fig. 1. The Jenolan Caves region, showing the main access road and natural drainage pattern; inset map shows location within the state of New South Wales. Also plotted are the outlines of student thesis maps reproduced as Fig. 5 (Allan 1986, in purple), Fig. 6 (Stewart 1987, in blue), Fig. 7 (Hallett 1988, in green) and Fig. 8 (House 1988, in red).

further study. Geological mapping by students and staff (mainly at the University of Sydney) over the past thirty years, notably during the 1980s, has greatly improved knowledge of rock types, their distribution and relationships in the vicinity of Jenolan, but this work has remained largely inaccessible in unpublished theses and field compilations. The results presented here are primarily based on detailed field mapping (at a scale of 1:10,000) and accompanying reports by Allan (1986), Stewart (1987), Hallett (1988) and House (1988) (Figs 1, 5, 6, 7, 8), supplemented with mapping over the same period by D.F. Branagan and K.J. Mills (all of the University of Sydney), with additional thesis mapping by Doughty (1994). Unpublished studies by Stanley (1925), Chand (1963), Pratt (1965), McClean (1983), and E. Holland (former Jenolan Manager) have also been taken into consideration. Other geological investigations of the area remain unpublished, although in preparation of this paper we have had the benefit of discussion with various workers (particularly Ian Cooper) who have mapped the Jenolan Caves Limestone and nearby strata in considerable detail.

PREVIOUS WORK

The earliest geological observations of a scientific nature on the Jenolan Caves area were made by staff of the Geological Survey of New South Wales (Fig. 2), including Wilkinson (1884) and Young (1884) (vide Havard 1933). Fossils in the limestone attracted the attention of Government Palaeontologist Robert Etheridge Jr (1892) who described a pentameride brachiopod and first assigned a late Silurian age to these rocks. Initial usage of the name ‘Jenolan Cave Limestone’ can be attributed to Etheridge (1894) but the terminology was not formalized for another 77 years.

T.W.E. David (1894) (Fig. 2) concurred with the late Silurian age of the limestone, also assigning that age to the strata to the east that he later described (David 1897a) as consisting of “several hundred feet of dark indurated shales, greenish-grey argillites, reddish-purple shale and coarse volcanic conglomerates with large lumps of *Favosites*, *Heliolites*, etc.”. David (1897b) further postulated that “the felsite dykes east of the limestone had assimilated much lime in their passage through the limestone”, and suggested that the conglomerates exposed on the Jenolan road 6 miles (9.7 km) from the caves were Upper Devonian. Extrapolating from his work on similar rocks at Tamworth of Devonian age, David surmised that the cherty radiolarian-bearing rocks cropping out west of the limestone belt at Jenolan were younger than the limestone, for which he indicated a westerly dip, and that their cherty nature was the result of contact metamorphism by intruding dykes. Consequently he revised his opinion of the age of the “Cave Limestone” to Early or Middle Devonian, younger than the limestones at Yass. However, David and Pittman (1899), in a further examination of the radiolarian-bearing cherty sediments, expressed uncertainty as to whether the limestone was Silurian or Devonian.

Curran (1899) (Fig. 2) discussed some aspects of the Jenolan geology, placing the eastern succession of sedimentary rocks in the Silurian, intruded by diorites, quartz- and felspar- porphyries, and included a photo of one of the cuttings on the road down to the caves.

The matter rested there until Morrison (1912), carrying out a reconnaissance trip to complete the proposed Geological Map of New South Wales (published 1914), placed the limestone in the Silurian, together with the adjacent rocks including ‘slates, radiolarian cherts, claystones … and contemporary lavas’, and assigned a post-Devonian age to the intrusive porphyries and felsite dykes observed by David. Morrison (Fig. 2) noted the unconformable nature of the junction between the Devonian sandstones and quartzites [Lambian rocks] and the ‘Upper Marine’ Permian beds, and the occasional occurrence of the younger strata abutting the Devonian rocks, but several hundred feet below the Devonian outcrops.

Süssmilch and Stone (1915), following brief statements by Süssmilch (1911, 1913), presented the results of a study of the caves region undertaken over a number of years. Their paper remained the standard explanation of the geology until at least the 1960s**.** The study by Süssmilch and Stone (Fig. 2), based on the outcrops along the Mount Victoria road (almost to Inspiration Point), and the first few bends (Two Mile Hill) of the Tarana road, the Six-Foot track and the Jenolan River, recognised the essential lithological variations. They dismissed David’s contention that the cherts occurring west of the limestone were formed by contact metamorphism and determined that they did not dip conformably with the limestone, but were probably brought into contact by overthrusting. Süssmilch and Stone (1915) suggested that the cherts (‘Jenolan radiolarian cherts’) and associated dark claystones were of Ordovician age. They recognised the ‘Cave limestone’ and the geographically distinct (but then vaguely located) east-dipping ‘eastern limestone’, which appeared to be unfossiliferous, believing that the separated limestones belonged to a single ‘bed’ on opposite sides of a large anticline.

Fig. 2. A selection of geologists who have made significant contributions (discussed in the text) to the investigation or mapping of the Jenolan Caves region, spanning more than a century from 1884 to 1988. The final four photographs are those of students from the University of Sydney whose B.Sc. (Honours) thesis maps were used in the compilation of this paper. Some of the historic photographs are sourced from Johns (1976) and Middleton (1991); others are from the image library of the NSW Department of Resources and Energy. Top row (L to R): C.S. Wilkinson (NSW Geological Surveyor-in-charge 1875-1891), T.W.E. David (University of Sydney), E.F. Pittman (NSW Government Geologist 1891-1916), Rev. J.M. Curran. Middle row, left image: officers of the NSW Department of Mines c.1893 (clockwise from top left L.F. Harper*, R. Etheridge Jr (Palaeontologist), O. Trickett (Inspector of Caves), M. Morrison (Assistant Geological Surveyor); right image: C.A. Süssmilch (seated) and W.G. Stone, both of the Department of Geology, Mineralogy and Mining, Sydney Technical College; Bottom row (L to R): J.E. Carne (NSW Government Geologist 1916-1920), G.A.V. Stanley (graduate of the University of Sydney 1925), T. Allan (B.Sc. Hons 1986, S.U.), W. Stewart (B.Sc. Hons 1987, S.U.), M. Hallett (B.Sc. Hons 1988, S.U.), M. House (B.Sc. Hons 1988, S.U.). *note that L.F. Harper was engaged on geological investigations in areas other than Jenolan Caves.

Süssmilch and Stone grouped all the variably-coloured, thin-bedded, highly-jointed rocks, east of the 'Cave limestone', as Silurian slates underlying the limestone. The unit identified by them as a rhyolite-porphyry, cropping out close to the Grand Arch, was an important marker for their structural interpretation of an anticline, as it was located again west of the eastern limestone. Other igneous bodies were identified as intrusive. These included the andesite occurring west of the 'Cave limestone', and quartz porphyrites and felsites to the east.

The stratigraphic order set down by Süssmilch and Stone (1915), in addition to their interpretation of the geomorphic history, subsequently became entrenched in the literature of Jenolan. Influenced by Andrews' (1911) concept of the Kosciusko Uplift, said to have occurred at the end of the Pliocene, they thought that the age of formation of the cave system could only be less than 500,000 years.

The regional geological interpretation of Süssmilch and Stone (1915) was accepted by Carne and Jones (1919), who outlined more accurately the outcrop of the limestone, showing it extending for some distance both north and south of the tourist caves. Of particular interest on their map is the marking of two pods of limestone approximately 400 m westerly of the almost continuous main belt at its northernmost extent, close to McKeowns Creek, suggesting a possible offsetting by faulting**.** However, mapping of these bodies was clearly affected by the inadequate base maps available to these earlier workers, as more recent mapping shows that despite poor outcrop, the limestone does in fact swing westerly away from the creek, by flexure, and encloses these two pods. Carne and Jones also located the eastern limestone more accurately than was shown on earlier maps (e.g. Süssmilch and Stone 1915).

Süssmilch (1923) expanded a little on his previous work, with a revised cross-section, and provided a geological history beginning with a deep-sea environment in which the radiolarian cherts were deposited, shallowing to a warm sea in which the eastern sediments were deposited, followed by clear, shallow seas in which lime-secreting organisms built up a mass of limestone (but not a reefal body). The succession was thought to have been folded at the close of the Devonian or during the early Carboniferous.

G.A.V. Stanley (Fig. 2) carried out considerable mapping for an Honours thesis at the University of Sydney in 1925, but this work was never published, so the results were ignored for many years. He thought the western succession was probably Devonian with a gradational boundary against the limestone. Though pointing out the considerable differences between the main and eastern limestones, Stanley still regarded them as stratigraphically equivalent, interpreting the eastern body as closer to the sediment source, while the main body he surmised to be of reefal origin. He thus accepted the large anticlinal structure suggested by Süssmilch and Stone (1915), but believed it was complicated by cross faults and strike -slip faulting. Stanley regarded all the igneous bodies east of the main limestone as sills. Perhaps Stanley's major achievement was the preparation of the first, surprisingly accurate, contour map of the Jenolan region, using compass and tape, Abney level and aneroid.

Geological interpretation of the Jenolan region remained untouched for the next 40 years, until a new round of university student studies took place in the mid-1960s, with work by Chand (1963), Gulson (1963) and Pratt (1965). However, stratigraphic relationships and actual geological ages remained uncertain and there was certainly some confusion introduced by the incorrect assignment of bedding to structures in the limestone and other units. Chand's 1963 work, extending a considerable distance east from the limestone belt beyond Black Range, was the most painstaking, including the collection of nearly 900 rock specimens from widespread documented localities.

Branagan and Packham (1967) were the first to recognise the overturning of the sequence east of the limestone belt, and Packham (1969) revised the stratigraphic relations, with the western units being oldest, followed by the limestone and the younger eastern beds.

Pickett (1969, 1970, 1981, 1982) provided much of the modern palaeontological data available on the limestone. His early reports identified macrofossils submitted by C. Mitchell and L. Chalker who remapped the limestone (Chalker 1971). Additional fossils, predominantly corals, stromatoporoids and algae, were identified for that paper by J. Byrnes. The age of the Jenolan Caves Limestone was given as Ludlovian (late Silurian). Conodonts diagnostic of Silurian biostratigraphic zones, however, proved elusive, despite 20 samples being processed from throughout the extent of the western limestone belt (Pickett 1981). Talent et al. (1975, 2003:198), citing unpublished work by P.D. Molloy, mentioned the presence of conodonts referable to the *Ozarkodina crispa* Zone (of latest Ludlow age: Strusz 2007) from the upper well-bedded part of the main limestone belt. Unfortunately these specimens were not illustrated. Strata underlying the Jenolan Caves Limestone were assigned to 'equivalents of the Campbells Formation' (now Group) of late Silurian (Ludlow) age by Talent et al. (1975: fig. 1, column 23).

Lishmund et al. (1986) presented a generalized map of the limestone occurrences in the vicinity of Jenolan and the immediately surrounding geology, modified from mapping by Chand (1963), Gulson (1963), Pratt (1965) and Chalker (1971). Lishmund et al. (1986) also thought that the sedimentary rocks west of (underlying) the main limestone belt might be Silurian, based on lithological similarity to potential regional equivalents, notably the Kildrummie Formation.

Subsequent detailed mapping by Allan (1986), Stewart (1987), Hallett (1988) and House (1988), which has remained largely unpublished till now (Figs 5-8), forms the basis of our current understanding of the geology of the Jenolan region, and is fully discussed below. Osborne and Branagan (1985) indicated a likely karstification age at least as old as Permian for the development of the caves, and subsequently (Osborne and Branagan 1988) included a brief description of the Jenolan karst in an overall review of karst in New South Wales. Detailed studies of the Jenolan Caves Limestone, concentrating on its karstification history, have been published by Osborne (1991, 1993, 1994, 1995, 1999), Osborne et al. (2006) and Cooper (1990, 1993). For a project directed to developing tourism at Jenolan, Branagan (in Hunt 1994) compiled a geological map based largely on the detailed Honours thesis mapping undertaken between 1986 and 1988 mentioned above. Branagan et al. (1996) summarized the results from this mapping together with that of Doughty (1994).

Apart from the maps by Süssmilch and Stone (1915), Carne and Jones (1919), Chalker (1971) and Lishmund et al. (1986), other generalised maps of the boundary of the limestone to have been published include those of Trickett (1925), Shannon (1976), and Kelly and Knight (1993), the latter which also shows adjacent geology, based on unpublished thesis mapping by Allan and Stewart. Osborne (1999) in illustrating the limestone belt used mapping by Shannon (in Welch 1976), but attributed it to Welch.

STRATIGRAPHY

Despite the rather formidable topography, some excellent road and creek exposures can be measured in the Jenolan area, providing the key to much of the understanding of the stratigraphy presented in this paper (Figs 3, 4). The road exposures were the basis of the mapping by Süssmilch and Stone (1915), although some sections of the roads have since been relocated. Allan (1986) mapped the Inspiration Point road section in great detail, providing the basis for our revised interpretation of the rock succession east of the Jenolan Caves Limestone. In Figures 5-8 depicting the detailed geology as mapped by Allan (1986), Stewart (1987), Hallett (1988) and House (1988), we retain the informal stratigraphic nomenclature of their studies, but on the compilation map (Fig. 4) the formal stratigraphic terminology as described below is employed. It should be noted that there are some differences apparent between the compilation map (Fig. 4) and those of the student theses (Figs 5, 6, 7 and 8). These differences are due to additional field observations by Branagan and K.J. Mills and consequent reinterpretation. The main stratigraphic sections presented (Figs 5-8) are Five Mile Hill to Jenolan Caves, Navies Creek, Bulls Creek (with Pheasants Nest Creek), and the Jenolan-Kanangra Road (Two Mile Hill section). These sections reveal unequivocally that this stratigraphic sequence is overturned (with but few exceptions) — the succession younging to the east. Numerous strike (and thrust) faults in the area separate the rocks into distinct lithostratigraphic and structural domains but because of the paucity of fossils so far found, the relative age of these domains cannot be stated with certainty. However, reinterpretation of the scant palaeontological evidence provides the basis for revised correlations of rock units west and east of the main limestone belt, as well as reassessment of the age of the Jenolan Caves Limestone.

A. Lower Palaeozoic rocks west of the main Jenolan Caves Limestone belt

As indicated above, these rocks, with a few exceptions, have generally been regarded as older than the limestone and probably of Ordovician (or alternatively Silurian) age. Pratt (1965) informally referred to these beds as the 'Oberon Hill Chert', including the andesitic volcanic unit exposed behind Caves House (and in the Lower Car Park), which he thought belonged within the 'Jaunter Tuff' of Shiels (1959). Pratt noted closely-spaced concentric folds within the chert sequence. Doughty (1994) followed Pratt (1965) to some extent, informally naming the succession of shales, siltstones, sandstones, cherts and andesite, west of and underlying the limestone in the vicinity of Jenolan, as the 'Oberon Hill Formation'. Doughty commented on the general lack of chert where he examined the unit as the basis for the modification of the name, and gave its minimum thickness as between 1200 and 1500 m. The succession continues north from the tourist area, beyond Dillons Creek (the first main stream northerly from the Jenolan-Oberon Hill road, draining from Oberon Hill and joining McKeowns Creek opposite South Mammoth Bluff),

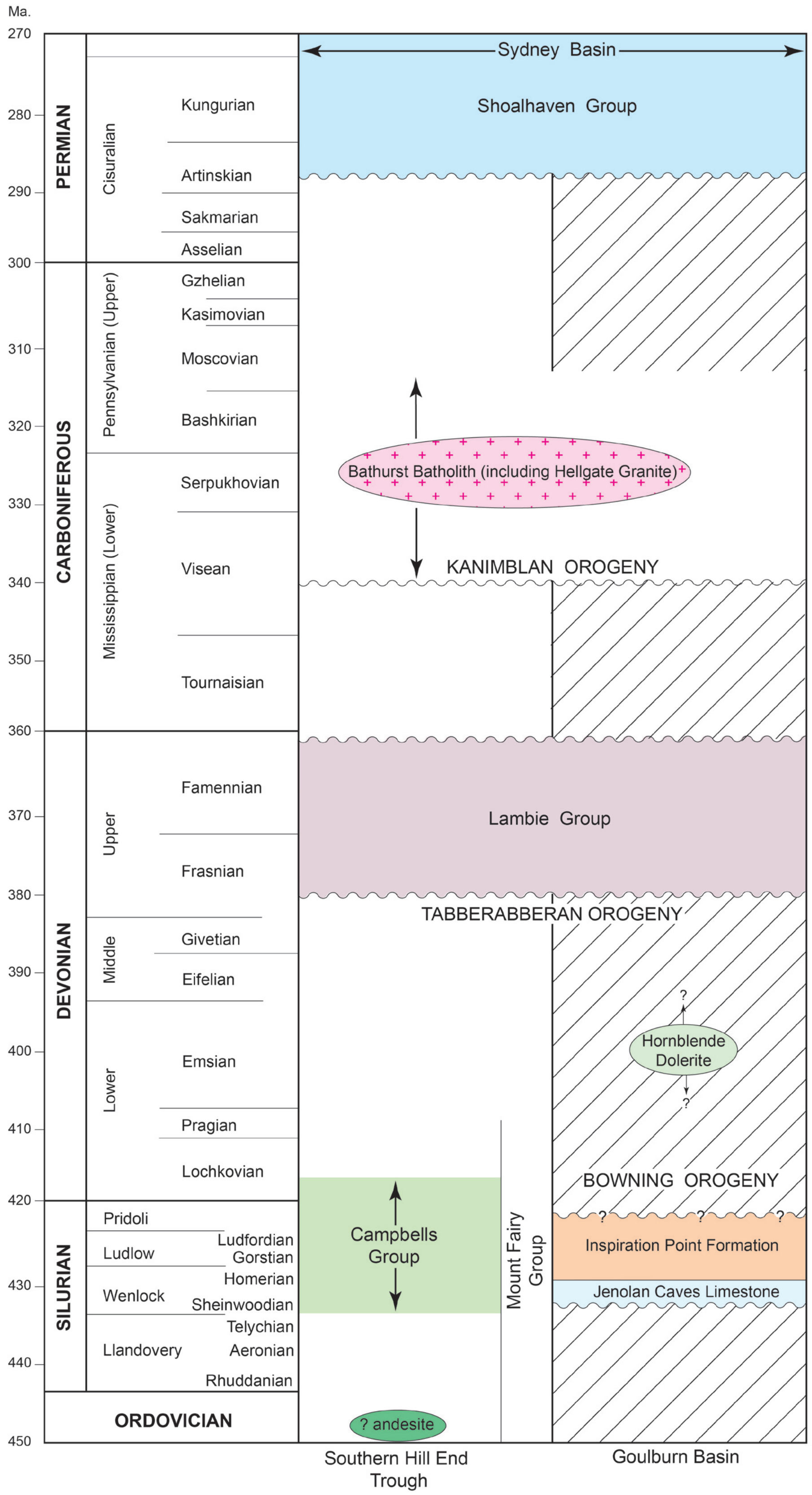

Fig. 3. Palaeozoic stratigraphy and intrusion history of the Jenolan Caves region; cross-hatched areas represent intervals of non-deposition and/or erosion (see text for discussion). Timescale from Gradstein et al. (2012).

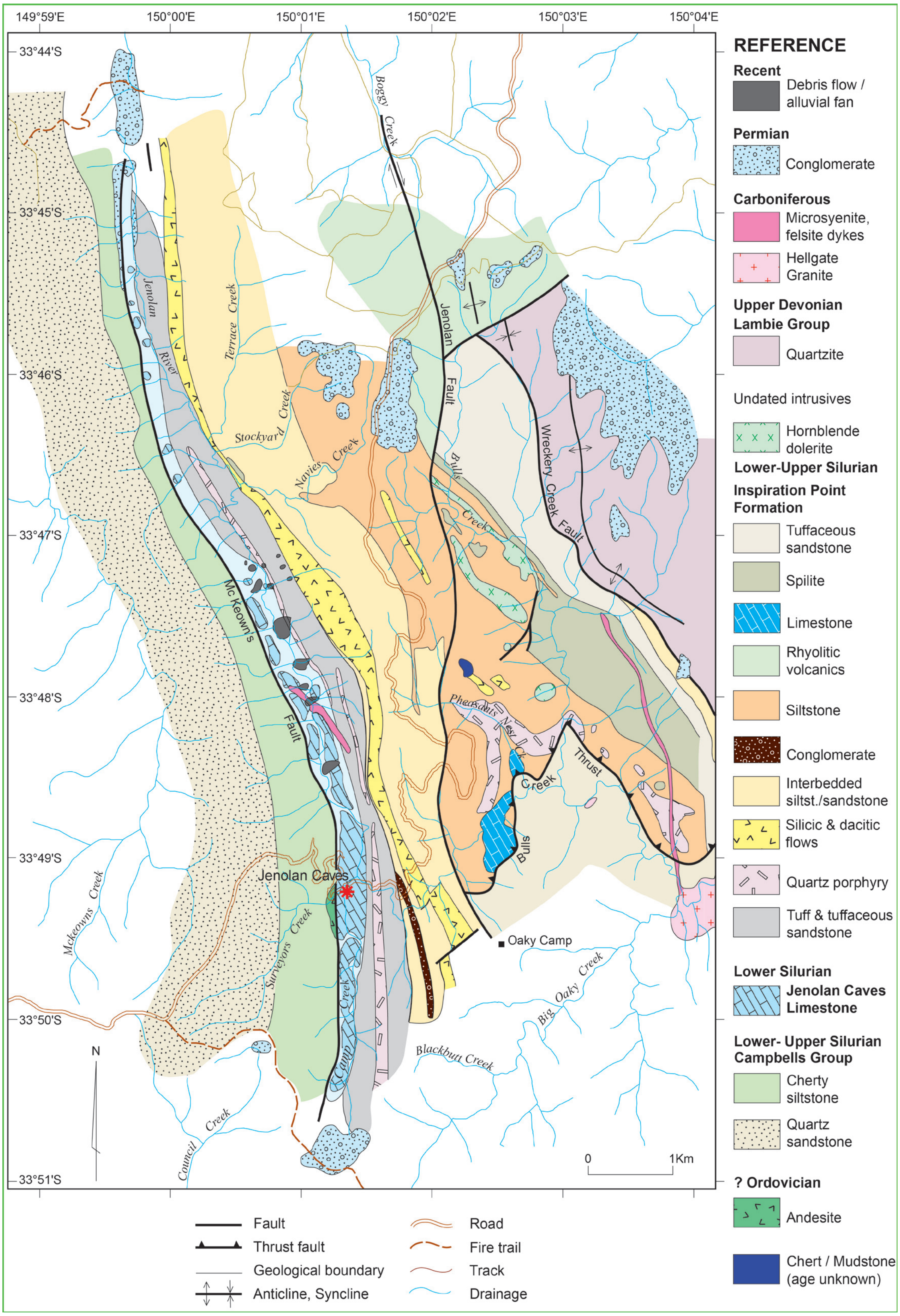

Fig. 4. Geological map of the Jenolan Caves region, compiled by D.F. Branagan and K.J. Mills, based on B.Sc. Honours thesis mapping especially as shown in Figs 5-8, and personal observations. Note that there are minor inconsistencies between this map (which shows the formal stratigraphic nomenclature adopted in this paper) and those of the students.

where Stewart (1987) mapped a sequence more than 500 m thick that he informally named the 'Western Jenolan Beds'**.**

1. ?Ordovician andesite

The andesite (informally referred to as 'Caves House andesite' on some maps), which has puzzled all observers since the area was first examined, abuts the Jenolan Caves Limestone over a short distance in the vicinity of Caves House (Fig. 5). Chemical analysis by Stone (in Süssmilch and Stone 1915) showed it was originally of basaltic-andesitic composition. Two rock types are present: a fine-grained augite-andesite, and a porphyritic augite-andesite which occurs as inclusions within the fine-grained rock. Chalker (1971) suggested that the andesite represented an intrusive body, although it has more generally been interpreted as a flow, apparently conformable with the limestone. However, it is probable that the andesite unit has been brought into position by faulting along McKeowns Fault and that its stratigraphic position is, therefore, uncertain. Doughty (1994) noted that close to Caves House, the Jenolan Caves Limestone contains clasts of andesite, indicating an unconformable or disconformable relationship with the andesite body. Presence of an unconformity is supported by the observation that in the eastern Lachlan Fold Belt, andesitic rocks are characteristic of the Ordovician, rather than the Silurian. Accordingly, the andesite is most likely of Ordovician age, making it the oldest rock unit exposed in the Jenolan region.

2. Campbells Group equivalents (Lower Silurian)

The 'Western Jenolan Beds' of Stewart (1987) consist of two broad units, an older quartz-rich sandstone unit, and a younger 'cherty' sequence (Fig. 6). The sandstone unit includes fine and medium-grained sandstones, with very minor slates, and a thin tuffaceous layer (possibly more than one). The unit is dark to light grey with a distinctive blocky outcrop, and occupies the ridge tops. In thin-section it is seen to be composed mainly of rounded, strained grains of quartz, with 5 to 10% of lithic fragments, and about 1% of mica fragments, and about the same volume of matrix, composed of white mica, calcite, sphene, chlorite and epidote. Iron oxide cement is present, usually only about 1%, but in exceptional cases it may make up about 20% of the rock, imparting a dark colour to some hand specimens. The tuffaceous layer is mainly composed of weathered felspar. This sandstone unit continues west of the mapped area and its thickness exceeds 450 m.

There is a distinct, but not sharply delineated, lithological change to the overlying finer-grained sequence. This sequence, about 500 m thick, is made up of wide bands of thinly-bedded radiolarian-rich black siltstones, interbedded with slates and minor beds of quartz sandstone. The siltstone bands contain tight slump folds, show graded bedding, small-scale erosional features, and flame structures, which indicate an easterly facing. In thin section the siltstone consists mainly of a dark chlorite and quartz matrix, with larger spheroids of microcrystalline quartz. These are casts of radiolaria, often visible to the naked eye, but they are generally poorly preserved and cannot be readily identified. Occasional specimens display a relict internal structure, and some bear short robust spines.

Although evidence is slight in the immediate vicinity of Jenolan, exposures to the north (in McKeowns Valley) show that these 'Western Jenolan Beds' have a faulted, and probably unconformable, contact with the overlying limestone succession. Süssmilch and Stone (1915) recognized an overthrust fault, subsequently mapped by Stewart (1987) as a high-angle reverse fault (the McKeowns Fault, interpreted as a near-vertical thrust defined by a thin layer of fractured rock) that separates this succession from the Jenolan Caves Limestone. This fault is noted also on the western end of the detailed section measured by Stewart (1987) along Navies Creek (Fig. 6).

On the western side of McKeowns Valley there is a 90 m wide zone of brecciation, consisting mainly of cherty clasts (Fig. 6). Neither the displacement nor the amount of strata missing can be determined, but there appears to be no angular discordance between the two units. However, in view of the apparent lack of chert in the succession as it is mapped south to Jenolan and beyond, it may be that this fault runs slightly obliquely to the general strike of the beds and cuts out the cherts. The width of the fault zone certainly suggests that the effect of the fault could be quite significant.

The 'Western Jenolan Beds' have previously been assigned an Ordovician age by some authors (e.g. Stewart 1987), although Pratt (1965) thought they might range into the early Silurian. Packham (1969) suggested that they could be correlated with the Rockley Volcanics, cropping out to the west. Other authors (Chalker 1971; Talent et al. 1975; Lishmund et al. 1986) have regarded the rocks underlying the main limestone belt to be of Silurian age.

Recent mapping by the Geological Survey of NSW suggests that much of the Rockley Volcanic Belt should now be regarded as Silurian, with reported evidence of Ordovician ages (e.g. Fowler and Iwata 1995) from this tract to the west of Jenolan being

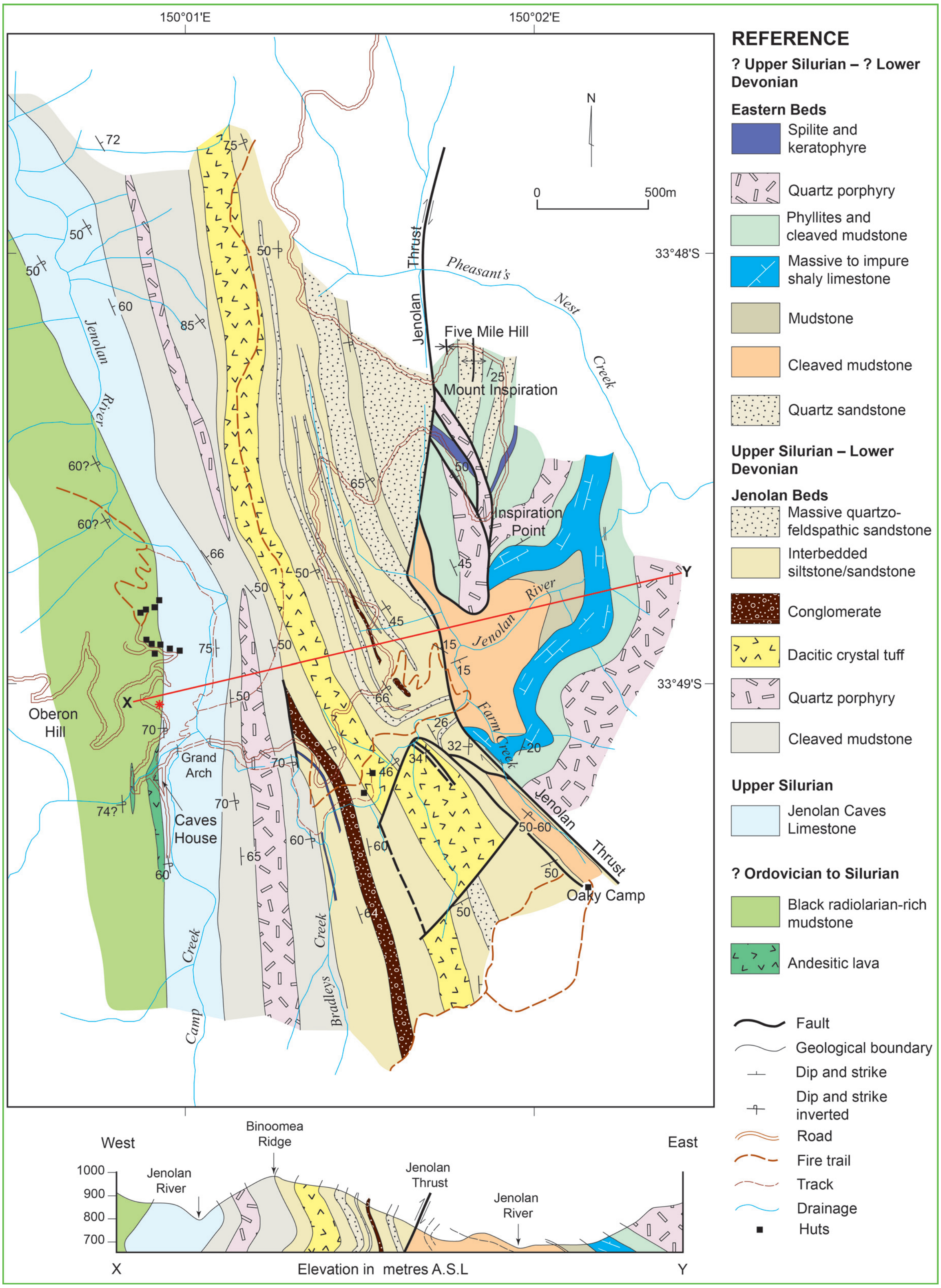

Fig. 5. Geological Map and cross section, modified from Allan (1986). Note that stratigraphic names utilized in the Legend (except for Jenolan Caves Limestone) are informal.

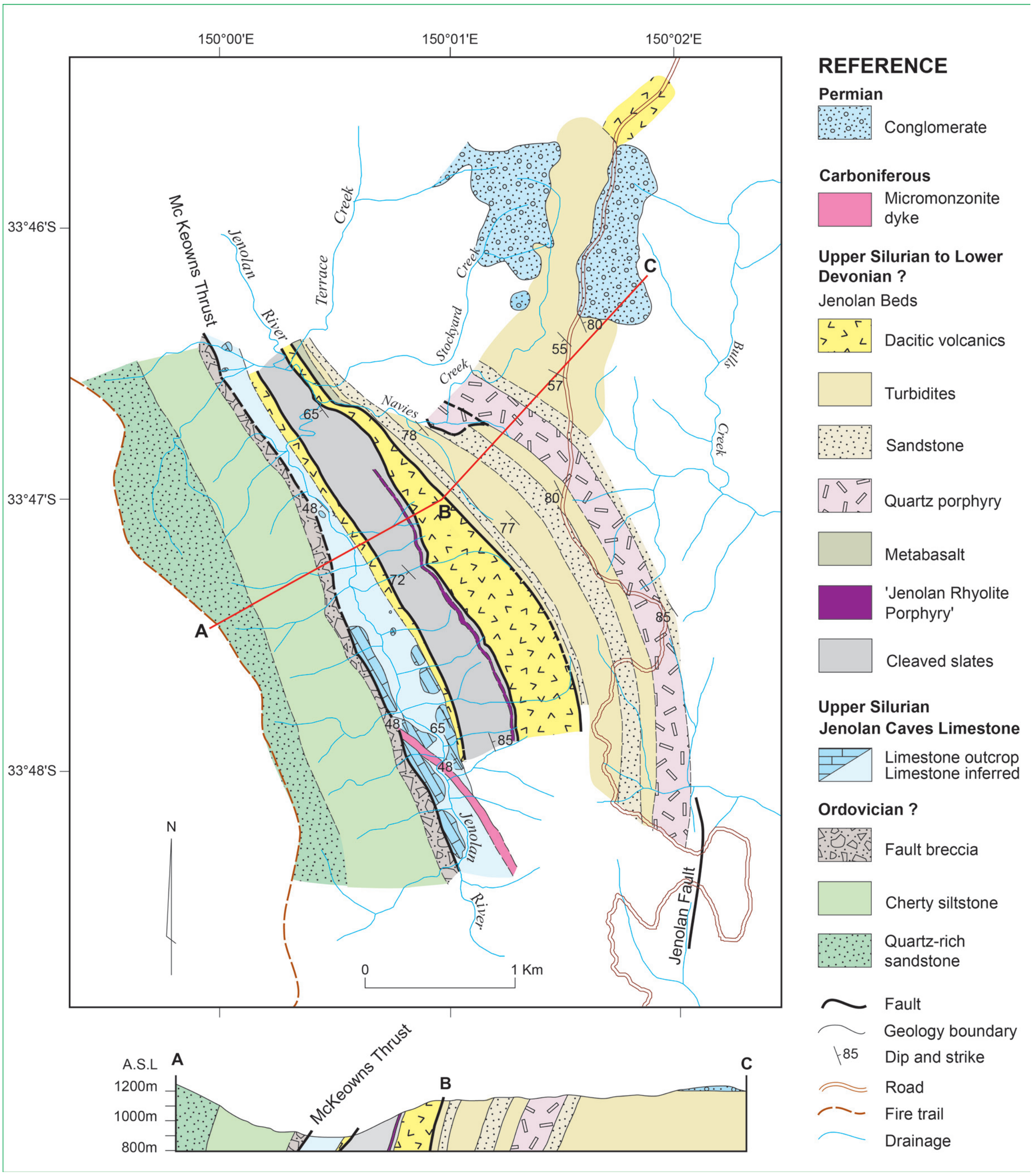

Fig. 6. Geological Map and cross sections, modified from Stewart (1987). Note that stratigraphic names utilized in the Legend (except for Jenolan Caves Limestone) are informal.

reinterpreted as derived from allochthonous blocks redeposited in the Silurian (C.D. Quinn, pers. comm. 2011). If so, this challenges the widely-held view that the rocks west of the main limestone belt are necessarily Ordovician in age, particularly in view of the lack of fossil evidence.

Ordovician quartz-rich sandstones and cherts of the Abercrombie Formation are extensively distributed in the northern half of the Taralga 1:100,000 mapsheet to the SW of the Jenolan area (Thomas and Pogson 2012). These homogeneous sandstones are described as quartz arenites, with sublitharenites at the base of the succession. Flame structures, flute marks and load casts are present in some sandstone beds, and the cherts frequently contain relict radiolaria (seen as amorphous silica blebs). The presence of tuffaceous layers in the 'Western Jenolan Beds' is atypical of the Ordovician Abercrombie Formation. Therefore, it is thought more likely that the ‘Western Jenolan Beds’ correlate with the lower Silurian to Lower Devonian Campbells Group. This does not, however, explain the age of the ‘Caves House andesite’ which remains an enigma.

If, as surmised by Lishmund et al. (1986), the strata west of the Jenolan Caves Limestone are lithological equivalents of the Kildrummie Formation (now included in the Campbells Group), this may provide an age constraint on the overlying rocks to the east. Conodont assemblages reported by de Deckker (1976) led him to conclude a late Ludlovian age (upper *crispus* to lower *steinhornensis* Zones) for the upper Kildrummie Formation. Simpson (1995) reinterpreted the specimens that de Deckker referred to *“Spathognathodus” crispus* as Pa elements of *Kockelella ranuliformis*, and thus suggested an age no younger than basal *siluricus* Zone for the upper part of the Formation. This age determination was influenced by co-occurrence of other conodonts from the Kildrummie Formation referred by de Deckker (1976) to *Diadelognathus primus* and *Distomodus curvatus*. As recognised by Simpson (1995), these clearly represent elements of the apparatus of *Coryssognathus dubius*, which ranges as high in the Yass succession as the Hume Limestone, from which Link and Druce (1972) recorded the zonal species *Polygnathoides siluricus*. However, *Kockelella ranuliformis* first appears locally in the *amorphognathoides* Zone that spans the Llandovery–Wenlock boundary, and typically occurs in the eponymous *ranuliformis* conodont biozone of lower to mid-Sheinwoodian age (early Wenlock). Its local upper limit was placed by Bischoff (1986) within the *K. amsdeni* to *K. variabilis* zones (late Sheinwoodian to mid-Homerian, or about mid-Wenlockian). Thus it is likely that the age of the upper Kildrummie Formation is no younger than mid Wenlock. Correlation of the rocks immediately west of the Jenolan Caves Limestone with the Kildrummie Formation therefore implies that they are equivalent to the lower Silurian portion of the Campbells Group.

B. Jenolan Caves Limestone

Prior to the present paper, the Jenolan Caves Limestone (Chalker 1971) was the only formally named stratigraphic formation in the karst conservation area. This unit is dominantly a light to dark grey bioclastic limestone, sometimes bedded, sometimes massive, but it contains occasional mudstone lenses and minor dolomite, and there is some evidence of brecciation in places. The limestone outcrop extends in a north-south linear belt for some 11 km. At the northern end it is covered by younger rocks and alluvium, but has become noticeably thinner, while at the southern end it appears to have been cut off by faulting. The succession shows some variations in lithology as mapped by Osborne (1991) in the Binoomea cut. Doughty (1994) suggested there are four facies in the ‘southern’ limestone, including (1) thin-bedded limestone and calcareous mudstone (at the basal and top boundaries), essentially lenticular and occasionally dolomitic); (2) massive recrystallised limestone with thin mudstone partings, forming the bulk of the Jenolan Caves Limestone; (3) massive, discontinuous limestone composed of fossil fragments; and (4) calcareous mudstone with minor siltstone partings, which is intercalated with the other three facies.

Doughty indicated a thickness of 350 m for the limestone in the vicinity of Caves House, with a considerably reduced section of 50 m in the south, and noted that sudden reductions in thickness are due to faulting which has usually removed the lower section of the limestone. Just north of Dillons Creek, the limestone is a maximum of 285 m thick and it thins to 75 m in the vicinity of Navies Creek. Here it passes conformably upwards into limy shale about 5 m thick, which in turn passes into cleaved slate, a few metres thick, indicating continuous deposition, but with a change in environment (and source). Alternatively, cessation of massive carbonate production and replacement by fine-grained mud-rich clastics may have been caused by relatively rapid subsidence of the carbonate platform below optimal water depths. We regard these strata as the uppermost preserved beds of the Jenolan Caves Limestone.

Cross-bedding and graded bedding can be found in the limestone at one locality behind Caves House. The cross-bedding has an eroded top, indicating an easterly facing. This is supported by the overlying graded bedding unit, which fines to the east.

Outcrops are variable, and particularly at the northern end of the limestone belt it becomes difficult to map the edge of the limestone accurately. In fact although karst features, such as dolines, have been used to map the western edge of the limestone, it seems likely that the presence of large quantities of water along the boundary may have caused dissolution (or at least erosion and subsequent collapse) of the adjacent “shales”, so the boundary of supposed limestone may not be as accurate as one would wish. The limestone dip is generally easterly, but close to vertical, although it is often difficult to observe or measure. The limestone shows considerable topographic variation, which is in part the result of facies variability, but also may be due to faulting, as indicated by Shannon (1976).

In places the limestone is abundantly fossiliferous, as seen at the entrance to the Binoomea Cut where disarticulated pentameride brachiopod valves are

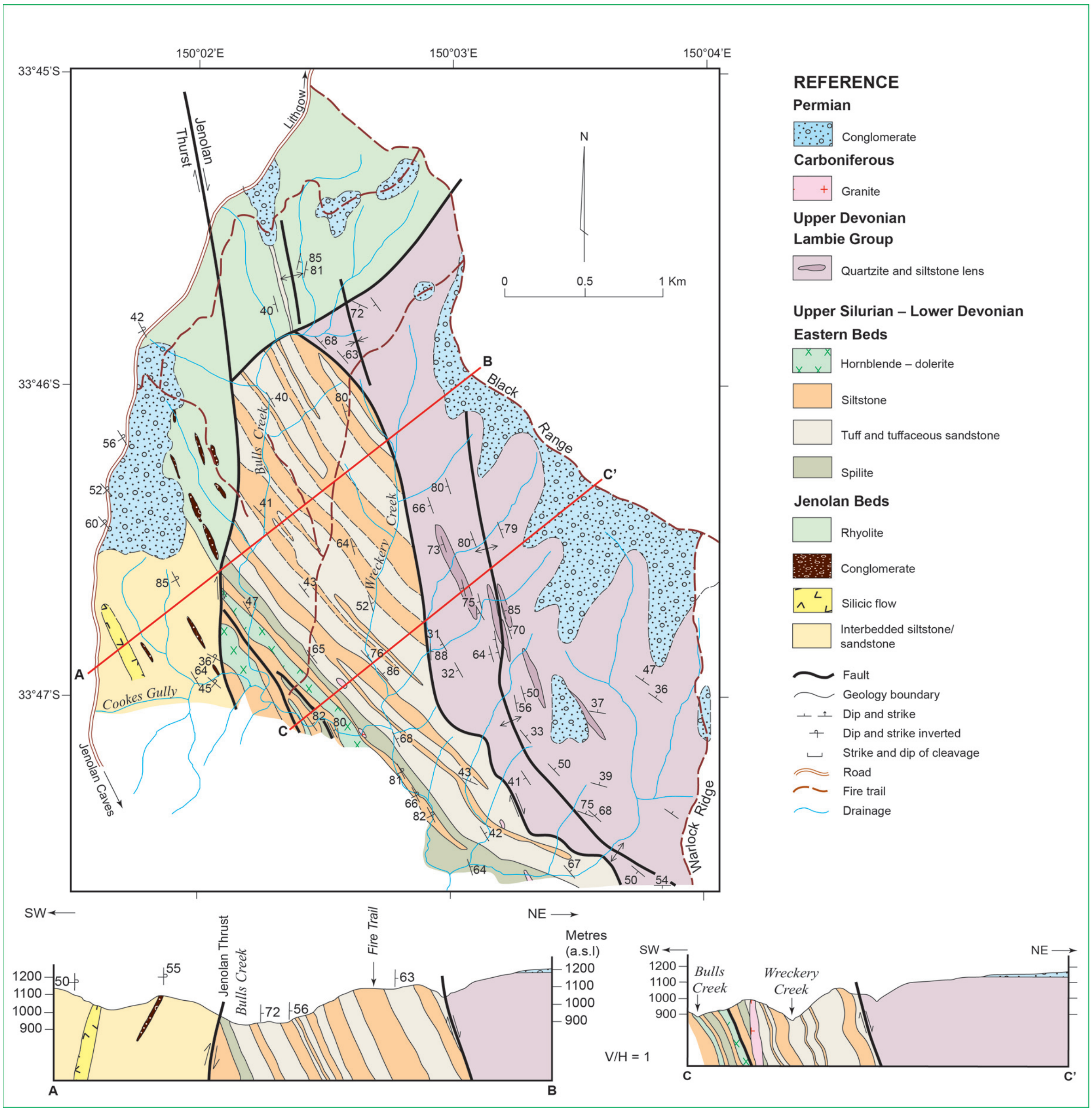

Fig. 7. Geological Map and cross section, modified from Hallett (1988). Note that stratigraphic names utilized in the Legend are informal.

crowded in layers, perhaps representing storm deposits. Elsewhere, corals (*Favosites*, *Heliolites*, *Tryplasma*, *Phaulactis*) and stromatoporoids (*Actinostroma*, *Clathrodictyon*) occur sporadically, previously regarded as indicative of a general Ludlovian (late Silurian) age (Chalker 1971; Pickett 1981, 1982). Unfortunately, age-diagnostic conodonts are rare in the limestone. The material identified by Pickett (1981) includes Pa elements of *Kockelella ranuliformis* (Walliser, 1964), illustrated in Fig. 9. As discussed earlier, this species appears to have a much longer range in Australia than elsewhere; nonetheless, the youngest possible age is no younger than mid-Homerian (mid-Wenlockian). This is the same species which provides the best age control on the Kildrummie Formation, so the conodont assemblages do not permit a differentiation in age between the two units. Previously the most significant biostratigraphic information derived from unpublished work carried out in the early 1970s by P.D. Molloy, subsequently reported by Talent et al. (1975:64) and Talent et al. (2003:198), that indicated the presence of conodont assemblages of *Ozarkodina crispa* Zone age (latest Ludlow) in the uppermost beds of the Jenolan Caves Limestone. Regrettably, this material remains unpublished. Endeavours to locate Molloy's samples

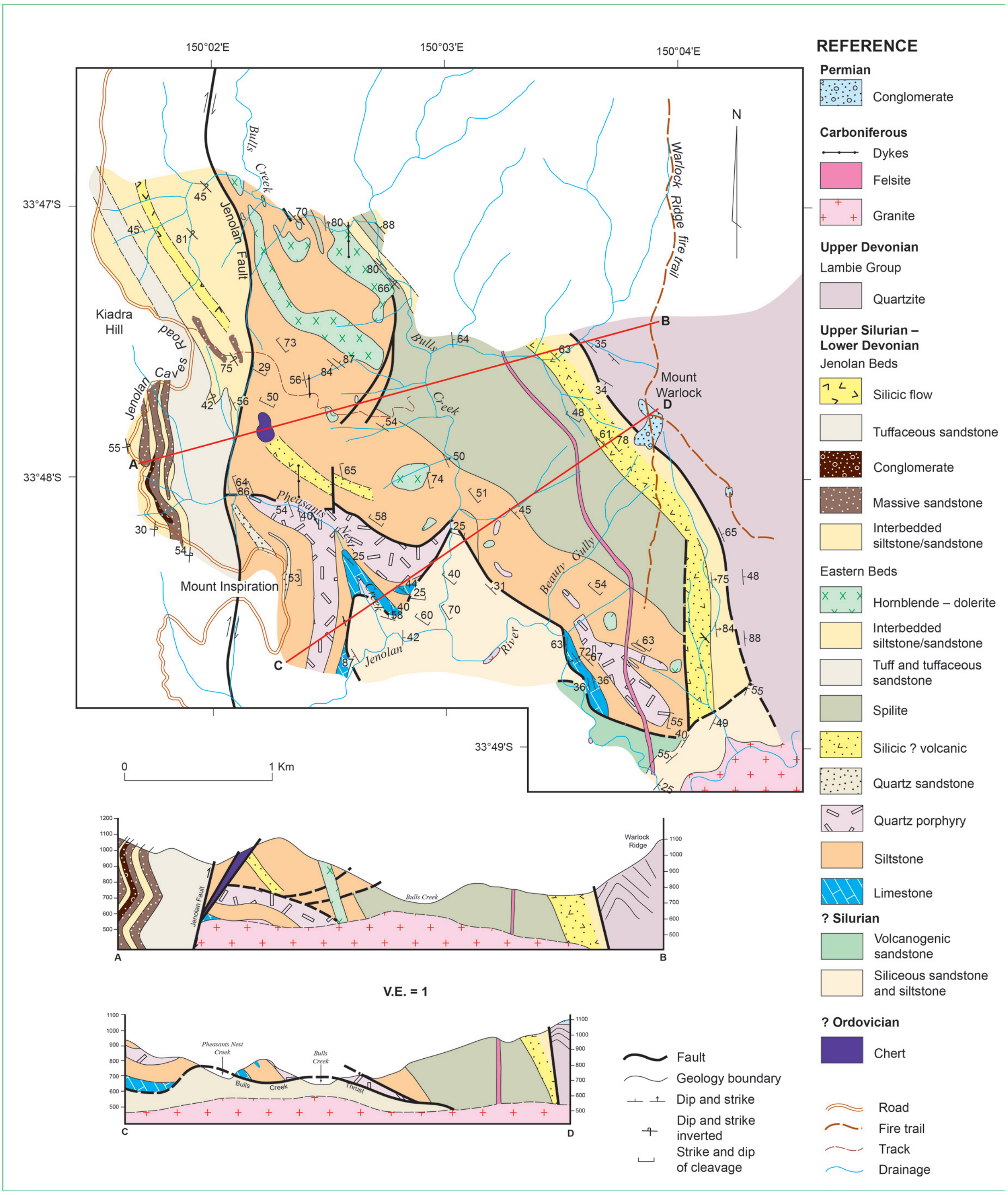

Fig. 8. Geological Map and cross sections, modified from House (1988). Note that stratigraphic names utilized in the Legend are informal.

proved fruitless, so they must be regarded as lost. The age suggested by Pickett's samples conflicts with Molloy's result, but since the latter can no longer be checked, these should be disregarded. There appears to be no basis at all for the assumption of a Pridoli age for the Jenolan Caves Limestone, as claimed by Scheibner and Basden (1998:478-479).

Halysitid corals have never been reported from the Jenolan Caves Limestone, in marked contrast to the Kildrummie Formation from which de Deckker (1976:68) listed at least four species of halysitids. Based on their absence, a comparison with the Yass section thus implies an age at least equivalent to that of the Hattons Corner Group (specifically the

Silverdale Formation) which lacks halysitids. Further support for this correlation comes from faunas of the 1050 m thick Molong Limestone, from which Pickett (2003) reported conodonts of the *ploeckensis* and *siluricus* Zones, the boundary between these zones lying 120 m stratigraphically above the last halysitids in the section. These last halysitids are accompanied by the rugosan *Palaeophyllum oakdalense* Strusz, typical of the "Dripstone Fauna" of Strusz and Munson (1997), to which they assigned an age range of late Sheinwoodian to earliest Gorstian (i.e. mid-Wenlockian to basal Ludlovian), approximately *ranuliformis* to earliest *crassa* Zones. This accords with the likely age for the Kildrummie Formation deduced from conodonts (see preceding discussion), and indicates that although the Jenolan Caves Limestone is most probably younger, the difference in age is slight.

In summary, taking the small conodont assemblages as the most reliable indicators, but considering the absence of halysitids, an age for the Jenolan Caves Limestone near the top of the Australian range of *K. ranuliformis* is most probable; that is, mid-Homerian (mid-Wenlockian).

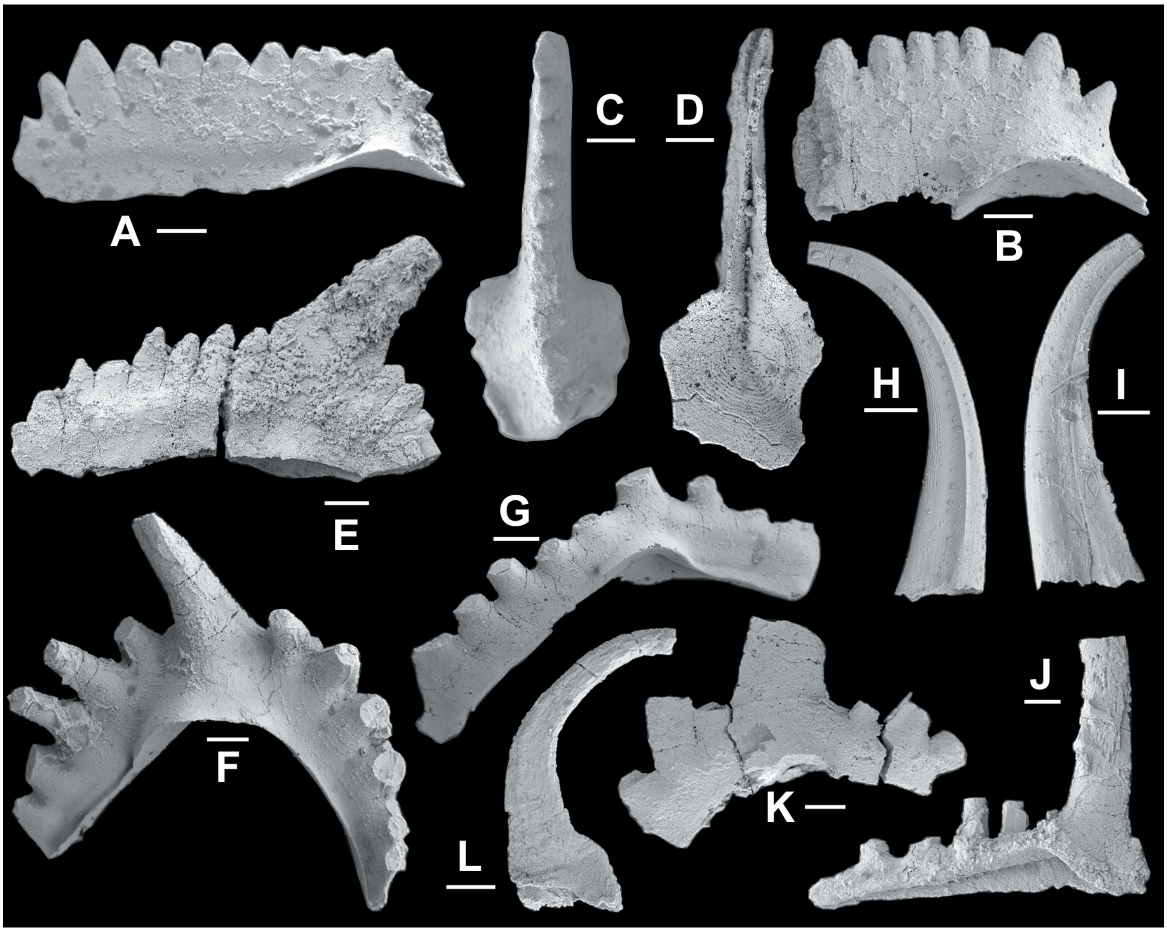

Fig. 9. Scanning Electron Microscope images of conodonts from the Jenolan Caves Limestone (A-J) and limestone within the Inspiration Point Formation (K, L). A, C from GSNSW conodont sample C697; B, D-J from GSNSW conodont sample C683 (for locations see Pickett 1981). Scale bars in all cases represent 100 microns. A-D, *Kockelella ranuliformis* (Walliser, 1964). A, Pa element in lateral view, MMMC4411; B, Pa element in lateral view, MMMC4412; C, Pa element in aboral view, MMMC4413; D, Pa element in oral view (note concentric growth lines around basal cavity), MMMC4414; E, *Ozarkodina* sp., Pb element in lateral view, MMMC4415. F, G, J, *Oulodus* sp. F, Sb element in inner lateral view, MMMC4416; G, Pb element in inner? lateral view, MMMC4417; J, M element in inner lateral view, MMMC4418. H-I, *Panderodus unicostatus*. H, element in outer lateral view (unfurrowed side), MMMC4419; I, element in outer lateral view (furrowed side), MMMC4420. K, specimen identified as the form-species *Ozarkodina ziegleri tenuiramea* Walliser, 1964 by House (1988), MMMC4421; L, unknown coniform element in lateral view, MMMC4422.

C. Lower Palaeozoic rocks east of the main Jenolan Caves Limestone belt

The succession east of the Jenolan Caves Limestone is complicated by faulting (Fig. 4). The general stratigraphy (shales, lavas, and graded-bedded sandstones) determined by Süssmilch and Stone (1915) for rocks lying between the Jenolan Caves Limestone and the Jenolan Fault – previously referred to as the 'Jenolan Beds' by Allan (1986), following Gulson (1963) and Chand (1963) – has remained largely unchanged to the present, except that the igneous units (felsic to intermediate types) were variously interpreted as intrusives, while other geologists regarded them as extrusives. Equivalent rocks east of the generally north-south trending Jenolan Fault were informally termed the 'Eastern Beds' by Allan (1986) (Fig. 5). These two lithostratigraphic divisions were adopted by Hallett (1988) (Fig. 7) and House (1988) (Fig. 8). Based on mapping in the vicinity of Wombeyan Caves, 55 km S of Jenolan, Simpson (1986) suggested correlation of this succession with the Bindook Volcanic Complex (now Bindook Group). The Bindook Group is a variable association of volcanic, volcaniclastic, clastic and carbonate rocks of Early Devonian age, united by their silicic volcanic affinities, in particular the presence of dacite. Outcrop of this association is known to extend north as far as Yerranderie, 35 km SE of Jenolan (Simpson et al. 1997). However, new fossil finds reported here support a late Silurian age for limestone interbedded with the steeply-dipping strata overlying the Jenolan Caves Limestone. Accordingly, we formally define a new stratigraphic unit, the Inspiration Point Formation, that is characterized by felsic volcanics and associated sedimentary rocks, and correlate it with the lower to middle part of the Mount Fairy Group, which is exposed in a NNE-trending belt (the Goulburn Basin) on the eastern side of the Goulburn 1:250,000 sheet (Thomas et al., in Thomas and Pogson 2012).

Inspiration Point Formation (nov.)

Derivation of name: from Inspiration Point, the eastern extremity of a prominent hairpin bend of the Jenolan Caves Road below Mount Inspiration (Fig. 5).

Synonymy: the formation includes rocks informally designated as the 'Jenolan Beds', the 'Eastern Beds', the 'Northern Beds', and the 'Eastern Limestone'.

Constituent units: no formal members are proposed, but the formation includes several prominent marker beds, including limestone, conglomerate, quartz porphyry, and dacite.

Distribution: the formation extends from the eastern margin of the Jenolan Caves Limestone to at least the Black Range (eastern extent of the area mapped in detail) (Fig. 4).

Geomorphic expression and outcrop: forms rugged topography intersected by deep valleys; outcrop is most accessible in creek beds and road cuttings.

Type area: due to the structural complexity, steep and rugged topography, and heavily vegetated slopes, it is not practicable to nominate a type section. However, a type area can be designated north of Jenolan Caves, bounded by the eastern margin of the main limestone belt in McKeowns Valley and proceeding eastwards across Binoomea Ridge to the main Jenolan Caves access road (with good sections along this road particularly between the Five Mile Hill in the Mount Inspiration area and the Grand Arch at the Caves), thence extending generally east from the main road to Mount Warlock, and further north in the valley of Bulls Creek.

Boundary relationships: the Inspiration Point Formation is interpreted as conformably overlying the Jenolan Caves Limestone, despite the sporadic absence of a felsic volcanic unit at the base of the formation (probably faulted out) that allows purple and grey cleaved mudstone slightly higher in the succession to abut directly the Jenolan Caves Limestone east of the Grand Arch.

Thickness: a total thickness in excess of 3220 m is estimated for the former 'Jenolan Beds', comprising (from oldest to youngest) felsic volcanics to 30 m thick; 350 m of purple and grey cleaved mudstone; a prominent quartz porphyry with maximum thickness about 150 m; an unspecified thickness of siliceous mudstones interbedded with felspathic siltstones and sandstones and containing a prominent conglomerate bed 60 m thick; altered dacitic crystal tuff of 350 m maximum thickness; a turbidite succession about 200 m thick in total; quartz-felspathic sandstone up to 145 m thick; turbidites about 85 m thick; a distinctive crystal-rich tuffaceous sandstone about 200 m thick; a further succession of turbidites about 1400 m thick; and culminating in a series of massive volcanic rocks with occasional conglomeratic lenses, more than 350 m in total.

Lithological variation: In the vicinity of Navies Creek, grey slate at the top of the Jenolan Caves Limestone is overlain by a band of felsic volcanics up to 30 m thick forming the basal unit of the Inspiration Point Formation. The volcanics disappear in the south, about 400 m north of Dillons Creek. Outcrop is patchy, but the unit probably sits directly on the limestone south of Navies Creek. Lateral variation in texture is rapid and common, and a lack of continuity is not unexpected in such a unit, which consists of fine ash, volcanic breccia with lapilli-sized fragments and several flows of quartz porphyry and banded dacite. The volcanic band is bounded on the east by a shear zone, which may account partly for the lack of continuity. Displacement on the fault, however, seems to be restricted to the north, so that to the south an apparently conformable contact probably exists between the felsic volcanics and the overlying unit, which consists of purple and grey cleaved slaty mudstone 350 m thick. This is the unit which appears to abut directly against the limestone just east of the Grand Arch. When weathered it becomes quite red. This unit contains numerous shear zones, but they seem to occur only within possible bedding planes, although bedding is rarely seen. In thin section this mudstone consists of fine quartz grains in a matrix of white mica, plagioclase and finer quartz. Doughty (1994) indicated that a few thin beds of interbedded volcanoclastic sandstones are present south of the Grand Arch.

Occurring within the slaty mudstone is the prominent quartz porphyry named ‘Jenolan Rhyolite Porphyry’ by Süssmilch and Stone (1915), equivalent to the ‘Binoomea Quartz Porphyry’ of Doughty (1994), which is easily identified just to the east of the Blue Pool. The porphyry occurs as two separate bodies north from the tourist area, on about the same stratigraphic horizon, but the more northerly body approaches closely to the eastern boundary of the mudstone and continues north with noticeable thinning until about 500 m south of Navies Creek. South from the tourist area, Doughty (1994) mapped the porphyry as widespread around Green Ribbon Hill, possibly as the result of folding (which apparently has affected the limestone: Allan 1986), although Doughty suggested that there are separate porphyry masses in this area. The southern extent of the porphyry is obscured under the Permian beds of Mount Whitely. In hand specimen the porphyry is white with green patches and contains large, fragmental phenocrysts of quartz and felspar in an aphanitic groundmass, formerly of fine glassy ash, now altered to chlorite, albite, calcite, prehnite and sphene. The quartz crystals average about 3 mm, and make up some 10-20% of the rock. The felspar crystals (dominantly orthoclase), which comprise about 15%, are altered, dull white and usually smaller than the quartz phenocrysts. Biotite is visible occasionally in hand-specimen. Evidence of flow banding, pumice fragments (Fig. 10) and absence of contact metamorphism indicates that the porphyry is a primary pyroclastic rock (i.e. not reworked). Its maximum thickness is about 150 m.

The purple and grey mudstone succession is followed by slightly coarser siliceous mudstones with interbedded fine felspathic siltstones and sandstones. The siltstones consist of interlocking mats of fine white mica and biotite with occasional very fine (< 0.1 mm) quartz grains. There is a dominance of grain growth sub-parallel to bedding, probably reflecting an original fissility. A prominent conglomerate bed (60 m thick) within this package contains clasts of limestone, spilite and mudstone ranging in size from boulders to pebbles; cobbles and pebbles being dominant. The matrix is relatively coarse sand, composed of altered plagioclase (andesine) felspar, calcite and spilite interspersed with finer grained calcite, quartz, chlorite and white mica. South of the Jenolan River the mudstone and siltstone units appear to be conformable, but the conglomerate bed swings northwesterly when crossing the Five Mile Hill Road and runs directly into the purple-grey mudstone unit. Allan (1986) attributed this swing to faulting, and showed a fault of limited extent, striking N-S, to explain the phenomenon, but the trend of the nearby dacitic tuff (see below) shows a similar bend and suggests that there might be a disconformable boundary between the mudstones and the siltstones. There is little or no evidence of an extensive continuous fault along this boundary.

The sedimentary succession is interrupted by a prominent dacitic unit, referred to by Allan (1986) as an altered crystal tuff, but to the north interpreted by Stewart (1987) as a flow. Its nature is concealed by alteration. The unit crops out well as a distinctive resistant band, weathering along joints and breaking into large blocks. It varies in thickness from about 70 m in the vicinity of Navies Creek to 350 m two kilometres to the south east. It is 120 m thick in the Five Mile Hill road cutting, east of the Grand Arch, and more than 300 m thick south of the Jenolan River. These variations are probably largely stratigraphic, although Stewart (1987) indicated that there is evidence, in the form of brecciation of the dacite and some sheared slates in a few places, that the eastern boundary of the dacite may be faulted. The rock has a characteristic pink-green groundmass, mottled with dark green and light yellow-green patches, making it readily identifiable in the field. The main primary minerals are large grains of plagioclase, smaller grains of quartz and finer quartz within the groundmass, which also contains K-felspar. Chlorite patches probably represent altered biotite. Granophyric and micrographic textures suggest a flow rather than a

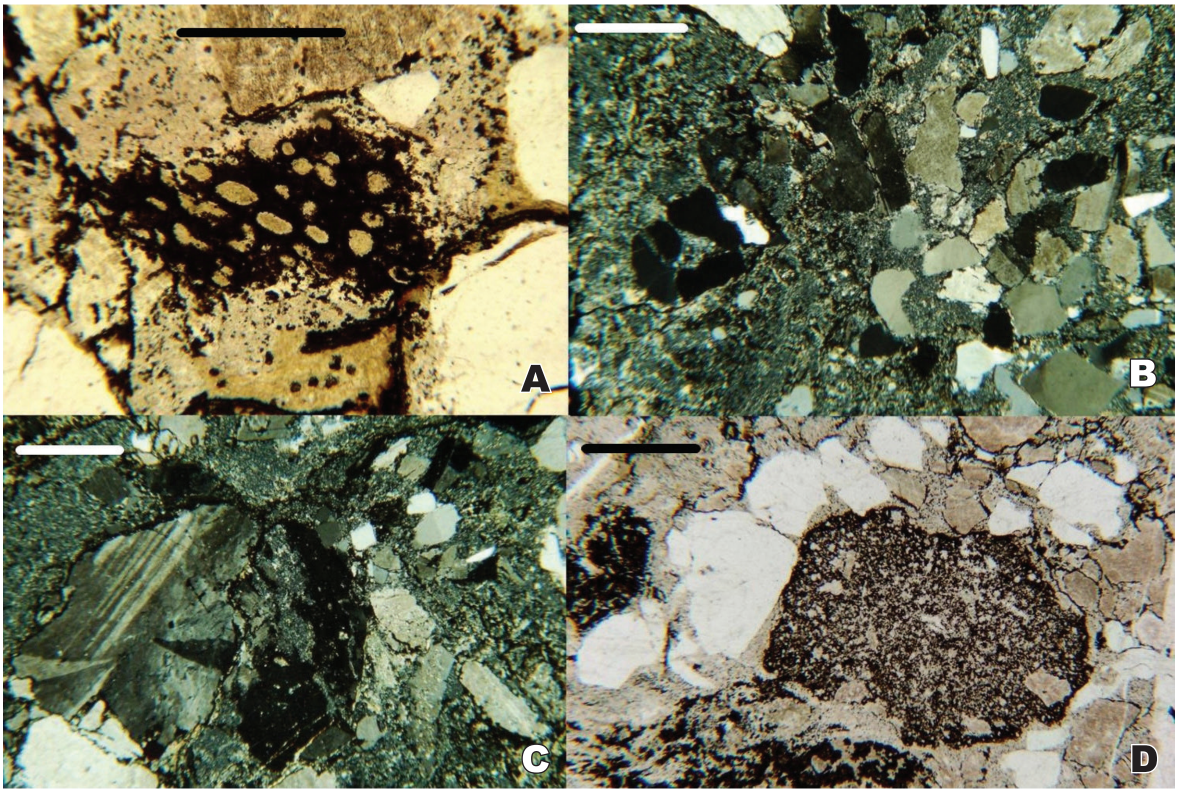

Fig. 10. Photomicrographs of thin sections of quartz porphyry (GSNSW T88825) from outcrop just east of the Blue Pool at Jenolan Caves (identified as 'Jenolan Rhyolite Porphyry' by Süssmilch and Stone 1915), showing the pyroclastic origin of this rock. A, with large pumice fragment in centre of field of view; B, showing rounded volcanic quartz grains; C, with large plagioclase crystal on left side of field of view, exhibiting twinning; D, with rounded volcanic rock fragment (dark grey speckled appearance) in centre of field of view. Scale bar for A = 0.5 mm, for B, C, D = 1.0 mm.

pyroclastic origin. Alteration minerals, in addition to chlorite, include epidote, albite, prehnite, pumpellyite, calcite and white mica.

North of Navies Creek, and separated from the dacite on the east by just a few metres of turbidites, a thin layer of metabasalt crops out. It is a dark green rock consisting of generally aligned, altered plagioclase and clinopyroxene, partly replaced by actinolite. Other metamorphic minerals — chlorite, epidote, albite, prehnite, calcite and sphene — are present.

The siltstone overlying the dacitic unit grades up into medium-coarse grained quartz-felspathic sandstones, with bed thicknesses varying from 5 to 50 m, often grading up from conglomeratic bases. These pass easterly into well-bedded siltstones and sandstones typical of turbidite successions, which are about 200 m thick in total. Most of the sandstones have volcanogenic sources and are composed of rounded quartz grains (25%), altered plagioclase felspar (up to 45%), lithic fragments (5-15%) and matrix. The siltstones in this succession consist dominantly of quartz, both as fragments and in the matrix.

The turbidites east of, and overlying, the dacite are overlain in turn by quartz-felspathic sandstone which is up to 145 m thick. It is coarse-grained, pink and green, making it easily recognised. The southern end of its outcrop, southwest of Mount Inspiration, is cut off by the Jenolan Fault (see later). A succession of turbidites about 85 m thick follows conformably. Then follows a distinctive crystal-rich tuffaceous sandstone about 200 m thick. This is a dark grey, fine to coarse-grained inequigranular rock, consisting of sub-angular grains of quartz, up to 5 mm across, and euhedral altered white felspar (both plagioclases and alkali types) up to 2 mm long, in a finer dark cryptocrystalline groundmass, made up of quartz, ?albite and chlorite. There has possibly been some re-working, so the unit is called a crystal-rich tuffaceous sandstone rather than a crystal tuff. However, Stewart (1987) suggested there is evidence that the unit grades upwards from tuff into a quartz-felspar porphyry flow.

A further succession of turbidites follows, about 1400 m thick, exposed along both the Jenolan Road and in the various branches of Cookes Gully (Fig. 7). It contains several mappable lenses of conglomerate. The turbidites are interrupted, about 250 m above the base, by what House (1988) and Hallett (1988) referred to as a silicic flow. This rock is light grey to pale yellow in hand specimen, aphanitic, marked by black spots up to 2 mm across, and with numerous fine pyrite grains. It was apparently originally a fine-grained dacitic flow with phenocrysts of plagioclase, mica and amphibole set in a fine glassy groundmass, which devitrified to give fine quartz and albite. Later low-grade regional metamorphism produced calcite and chlorite.

The youngest unit of the 'Jenolan Beds' is exposed along the Jenolan Road, where it has a thickness of rather more than 350 m. The boundary with the underlying turbidites is obscured by Permian conglomerates, but it is probably conformable. This uppermost unit is a series of massive, poorly-layered volcanic rocks with occasional conglomeratic lenses. The volcanic rocks range from siliceous rhyolitic flows, sometimes with orbicular accretions, overlain by a series of pink and green quartz-felspar agglomerates.

A series of similar volcanic rocks, referred to by Hallett (1988) as his 'Northern Beds', occurs east of the Jenolan Fault along the Jenolan Road, and extends along the Black Range Road. The 'Northern Beds' are separated from the 'Eastern Beds' by a northeast trending fault, extending from the Jenolan Fault and continuing at least 1.5 km to beyond the Black Range Road (Fig. 7).

The stratigraphy of the area east of the Jenolan Fault (previously referred to as the 'Eastern Beds') is more complicated than to the west. This is the result of faulting and the effects of contact metamorphism, superimposed on regional metamorphism. In addition the difficulties of access have made the interpretation of the geology very challenging.

The oldest unit in this area is a small circular exposure of buff white, intricately folded, laminated chert, and associated fine-grained silicic sandstone, found on a hillside 300 m north of Pheasants Nest Creek. It may represent an allochthonous 'window' of material and appears similar to lithologies in the Campbells Group west of Jenolan. Possibly associated with the chert is a 15 m thick bed of silicic tuff which crops out nearby.

Volcanogenic sandstone, overlain by siliceous buff-grey fine sandstone fining upwards into siltstone over several cycles, occurs along the valley of the Jenolan River and the lower reaches of Bulls Creek, and probably represents the next oldest strata in the area. The sandstone forms thick massive layers with good outcrop, but exposure of the siltstone is relatively poor. These beds are of undetermined thickness and bedding is rarely readily identifiable, but there is some evidence of younging to the east. The sequence is cut off to the north by the shallow-dipping Bulls Creek Thrust. This thrust has emplaced a structurally overlying succession of limestone, siltstone, spilite and tuffaceous sandstone which is exposed in Pheasants Nest Creek, the upper reaches of Bulls Creek and Beauty Gully (Fig. 8). All these "upper" (?younger) beds have a distinct north-west trend, which distinguishes them from the trend in the 'Northern Beds' (Hallett 1988), and in most of the 'Jenolan Beds', although the trend of the last named does range from north-south to northwest-southeast.

A second belt of limestone, interrupted by complicated folding and faulting, crops out about 2 km east of the main belt (Fig. 4). It extends below Mount Inspiration on both sides of the Jenolan River, and forms outcrops on Pheasants Nest Creek and again on the north side of the Jenolan River south of Beauty Gully. House (1988) mapped this 'Eastern Limestone' in the form of a continuous body some 40 m thick (Fig. 8), rather than a series of isolated pods as depicted by Carne and Jones (1919) and Chalker (1971). However, on the south side of the Jenolan River, upstream from the junction with Pheasants Nest Creek, the limestone tends to occur in the form of large lenses that grade vertically and laterally into shaly sediments, as shown by Allan (1986) (Fig. 5). The well-bedded shaly lower portion comprises interbedded calcareous shales and massive limestone layers ranging from 5 to 30 cm thick. Up sequence the ratio of shale to limestone decreases and it passes into a massive limestone, occasionally developing small caves. Macrofossils are generally not obvious in the limestone due to its pervasive sheared appearance. House (1988) reported tabulate corals, brachiopods, crinoid stems and gastropods from one outcrop, and extracted from acid-insoluble residues three conodont elements, one identified as the form species *Ozarkodina ziegleri tenuiramea* Walliser, 1964. However, reexamination of this specimen (Fig. 9K) suggests that it is too incomplete, with missing denticles, to be so precisely identified. Recent fieldwork by Pickett and others, investigating exposures of this limestone south of the Jenolan River between Farm Creek and Pheasants Nest Creek, led to recognition of the tabulate coral *Propora*, a rugose coral identified as *Pycnostylus* (catalogued in the Geological Survey of NSW Palaeontological Collection as MMF45233) and large pentamerid brachiopods similar to *Conchidium*, all indicating an age no younger than late Silurian.

The limestone passes upwards gradationally into siltstone, about 50 m thick, with rare thin lenses of quartz sandstone, the siltstone being succeeded by a thick yellow-green to grey quartz porphyry up to 130 m thick, exposed in Pheasants Nest and Bulls Creeks, and forming large pods to the east, below Warlock Ridge. Both siltstone and limestone clasts have been found within this unit. It appears to have an erosional boundary with the underlying siltstone, but its upper (northeastern) boundary is irregular and might be faulted. A further thick siltstone with well-developed cleavage, in reality a phyllitic succession, up to 360 m thick, ranging from purple-brown to grey and grey-green, follows. It contains a prominent lens of silicic ?tuff. Towards the top of the siltstone succession there are several lensoidal intrusions of hornblende dolerite (see below). Thin layers of spilite are also present.

The siltstone unit is followed by a very thick spilite (ranging from 500 m in the south to 900 m in the north), which to the northwest is intercalated with tuffaceous sandstones and siltstones. The thickness may possibly be exaggerated by repetition through faulting. The spilite is a dark green-grey rock of varying grainsize, depending on the degree of recrystallisation, which alternates between vesicular and massive types, with evidence of auto-brecciation and pillows (up to 50 cm across) towards the top of the unit.

North of, and ?faulted in places against the spilites, is a thick sequence of massive grey coarse-grained tuffaceous sandstones interbedded with laminated siltstones. Some of the sandstone units are probably scarcely reworked tuffs, containing occasional clasts of siltstone and limestone. This sequence occurs in a number of fining-up cycles, each 30 to 100 m thick. Hallett (1988) indicated a total thickness in excess of 1200 m.

While thickness of each of the units varies greatly, the stratigraphic succession remains consistent. The succession is cut off by a north-north-west trending fault, bringing it against Upper Devonian Lambie Group rocks.

Age and correlation: Internal evidence of age of the Inspiration Point Formation is meagre, being restricted to the occurrence of *Propora* sp. and pentamerid brachiopods. A constraint on the maximum age of the Inspiration Point Formation is provided by the underlying Jenolan Caves Limestone, of mid-Wenlockian age. The Inspiration Point Formation conformably overlies the Jenolan Caves Limestone and includes limestone that contains sparse fossils no younger than late Silurian. Hence an age range of latest Wenlockian or Ludlovian, possibly extending to the Pridolian, is most likely for the Inspiration Point Formation, correlating it with the lower to middle part of the Mount Fairy Group described from the Goulburn 1:250,000 map area SW of Jenolan. The Mount Fairy Group in the Goulburn Basin ranges in age from mid-Wenlock (early Silurian) to mid-Lochkovian (Early Devonian). Thomas et al. (in Thomas and Pogson 2012) describe the lower to mid portion of the Mount Fairy Group as comprising clastic sedimentary rocks (including siltstone, mudstone and fine-grained sandstone) and limestone lenses near the base, interfingering with mainly felsic volcanics, consisting of rhyolite, rhyodacite, dacite and andesite lavas and volcaniclastic rocks. Graptolitic black shales, and in other areas a succession of thick, regionally extensive, fine- to very coarse-grained, quartzose to lithic–quartz sandstone of turbiditic origin, interbedded with siltstone and mudstone, overlies the lower portion of the group. The upper portion of the Mount Fairy Group overlying the turbidite sequence is characterised by a thick succession of felsic to intermediate lavas and volcaniclastic sedimentary rocks with minor basaltic lavas. Thus there are considerable lithological similarities with the Inspiration Point Formation.

D. Intrusive hornblende dolerite

The hornblende dolerite (mentioned above) is a dark green, medium-grained holocrystalline rock, the essential minerals consisting of dark green hornblendes and white felspars with minor and smaller green minerals which are probably epidotes. The felspars (mainly albite) are up to 4 mm long, and form an interlocking mass with coarse amphiboles (to 5 mm), which makes up more than 50% of the rock. Because the amphiboles are primary, the term ‘hornblende dolerite’ is preferred to other names, such as amphibolite, which has the connotation of a regionally metamorphosed rock. Using comparisons with mafic rocks described by Joplin (1931, 1933, 1935, 1944) at Hartley, Macara (1964) suggested that similar occurrences on the Kanangra Road were associated with granite of Carboniferous age. However, the occasional foliation which occurs in the rocks here described, and even folding of individual grains, indicates that these rocks are considerably older, most probably pre-dating the Middle Devonian Tabberabberan Orogeny (Fig. 3).

E. Lambie Group

Sedimentary strata assigned to the Upper Devonian Lambie Group are medium to fine-grained white-buff, well-bedded quartzites, quartz-rich sandstones and siltstones (phyllites). Conglomerates, which are typical of the basal Lambie Group in the eastern Lachlan Fold Belt, are missing in the Jenolan area, and have possibly been faulted out. Lambie Group rocks have not been overturned but are folded more broadly than the older units to the west, except where the beds have been deformed adjacent to the boundary fault, where they crop out in tight plunging inclined folds. These rocks have been described by Hallett (1988) and House (1988). While they would not be seen by the casual visitor to Jenolan, they occupy a significant place in the regional history of erosion and karstification. Chand (1963) mapped these beds extending well beyond Black Range, and indicated the position of several fold axes of broad folds. Hallett (1988) also mapped the more westerly of these fold axes (Fig. 7), and noted the presence of brachiopod fossils in the more phyllitic bands; these indicate that the Lambie Group in the Jenolan region was deposited in a marine environment.

F. Carboniferous Intrusive Rocks

The major intrusion in the area, here named the Hellgate Granite, crops out on the Jenolan River about 3 km downstream from the Caves Reserve (Fig. 4), and is equivalent in age (early to mid Carboniferous) to the multiphase Bathurst Batholith (Fig. 3). The edge of this intrusion was mapped by Chand (1963), who regarded it as an offshoot of the Hartley Granite (Joplin 1931, 1933, 1935), and by House (1988) (Fig. 8). Two phases can be recognized – a red granite and a white marginal granite. The red granite making up the main part of the body is a fine to coarse (up to 8 mm) inequigranular, wholly crystalline rock. Pink–brown coarse grains of quartz constitute more than 40% of the rock, pink felspars consist of 35% plagioclase and K–felspar 22%, with white mica making up 4%. The plagioclase is frequently altered. The white granite is a medium–grained equigranular, wholly crystalline rock with quartz (to 4 mm) comprising 35%, plagioclase (29%), K-felspar (25%), white mica (up to 5 mm) (10%) and garnet (1%).

The contact with the country rock is sharp and the granite roof, which is irregular, is often marked by a 5–10 cm thick layer of coarse pegmatitic material. A few smaller outcrops separate from the main body occur upstream on the river.

In the south–eastern and topographically lower portion of the mapped area, the Hellgate Granite has caused noticeable contact metamorphism within the 'Eastern Beds' and the Lambie Group. The effects of the contact metamorphism appear to be more dependent on the depth of the granite below, than the lateral distance from any granite exposure. A contact aureole approximately 400 m wide has been mapped (House 1988). In the inner 100 m an assemblage characteristic of the hornblende hornfels facies occurs. The outer 300–350 m of the aureole contains an assemblage characteristic of the albite–epidote hornfels facies.

A felsite dyke averaging about 10 m thick, first mapped by Chand (1963), runs northerly as an offshoot from the granite, cropping out continuously for more than 2 km to Warlock Creek, cutting obliquely across the beds it intrudes. It is a pink–brown flesh–coloured, equigranular fine–grained, wholly crystalline rock, composed almost entirely of pink felspars (alkali felspar 60%, plagioclase 30%, accessories 10%), indicating a syenitic composition. Hallett (1988) identified it as a syenite/monzonite where it crops out at Warlock Creek. Several dykes identified as micromonzonites were also mapped by Hallett (Fig. 7). Another micromonzonite dyke, weathered orange and dipping steeply SW, was mapped by Stewart (1987) cutting NW across his 'Jenolan Beds' and the Jenolan Caves Limestone, north of Dillons Creek (Fig. 6), and cut off by the McKeowns Fault, thus antedating it [?post Carboniferous]. It is 50 m thick, mainly granular, but has some porphyritic phases, and contains equal proportions of K–felspar and plagioclase and about 5% of quartz and minor groundmass.

G. Permian rocks

Conglomerates (with distinctive white quartz pebbles) and sandstones, regarded as outliers of the Shoalhaven Group (possibly equivalent to the Megalong Conglomerate) of the Sydney Basin, crop out sporadically. They occur mainly on ridge tops on an old erosion surface, forming a plateau which can be recognised extending far north to Mudgee and beyond (Branagan and Packham 2000). In the vicinity of Jenolan these sedimentary rocks occur particularly along the Kanangra Road. However, there are patches at various levels, sometimes lying directly (unconformably) on the Jenolan Caves Limestone, and very likely occurring also as cave fill in some places (Osborne and Branagan 1985).

METAMORPHISM AND MINERALIZATION

Rocks of the Jenolan region are characterized by low-grade regional metamorphism, mostly within the greenschist facies range. In the pelites and tuffs of the Inspiration Point Formation the regional pattern is within the biotite zone in the upper greenschist facies. Regional metamorphism has caused albitisation of original basalts and andesites, producing spilites. North of Jenolan, within the Inspiration Point Formation, the sedimentary rocks occasionally fall within the pumpellyite–prehnite facies, chlorite being associated with green biotite, but a chlorite–epidote–calcite–pumpellyite association is more common in these strata. Actinolite occurs in a few instances in doleritic rocks.

In the higher (topographically) country NW towards the Jenolan Fault, contact metamorphic effects diminish away from the granite intrusion at Hellgate Gorge, but can still be recognized as an overprinting on the earlier regional metamorphism. Occasional retrograde metamorphism, marked by the occurrence of laumontite, occurs within fractures and veins in the spilites, and is probably attributable to circulation of hydrothermal fluids. Minor mineralization (pyrite, chalcopyrite and arsenopyrite), occurring pervasively and in narrow veins, is possibly related to the metamorphism.

Copper mineralisation (bornite, malachite and azurite) associated with the spilites occurs in several places in the Inspiration Point Formation. A little bornite ore was extracted from a 20 m long adit early in the 20th century (Carne 1908), and shallow pits have been dug in malachite mineralisation in a 2 m wide shear zone, where the malachite occurs in thin veins throughout the rock and on cleavage surfaces.

STRUCTURE AND TECTONICS

The Silurian succession at Jenolan has been structurally complicated (thus obscuring stratigraphic relationships) by the effects of deformation during three significant tectonic episodes: the earliest Devonian Bowning Orogeny, the mid-Devonian Tabberabberan Orogeny, and the early Carboniferous Kanimblan Orogeny. The present attitude of the Jenolan Caves Limestone and the Inspiration Point Formation represents the combined effect of all three of these orogenies. Upper Devonian Lambie Group strata were affected only by the latter folding episode. Permian strata are gently-dipping rocks, which post-date the major folding and faulting. Folding of the lower Palaeozoic succession is complex, with several styles recognisable, restricted to different domains that are separated by faults (most apparent, but some interpreted). Within the newly-defined Inspiration Point Formation (including Allan's 'Jenolan Beds') and the Jenolan Caves Limestone, Allan (1986) mapped a series of large scale, open and fairly symmetrical, near-recumbent folds (wave lengths of the order of 400 m), the fold axes plunging northerly, on which smaller-scale parasitic folds (wave length of less than 40 m) are superimposed. To the east there are large-scale anticlinal structures, gently plunging north-easterly, on which are developed (at outcrop scale) both asymmetrical kink folding and fairly tight symmetrical folds. In some areas both cleavage and bedding can be clearly seen to be folded. Allan (1986), Hallett (1988) and House (1988) deal in considerable detail with the complexities of folding in the region.

Thrusts, or steeply-dipping reverse faults, dipping both east and west, are probably extensive. North-south striking vertical faults, probably in part strike-slip, are also common. The major (and some minor) faults mapped or interpreted are shown on Fig.4. Several of the faults are of regional significance, in particular the fault bordering (or close to) the Jenolan Caves Limestone on the west (Stewart's McKeowns Fault), and the Jenolan Fault striking generally north-south just west of Mount Inspiration.

The Jenolan Fault separates the two lithostratigraphic and structural domains previously informally termed the 'Jenolan Beds' and the 'Eastern Beds'. Its outcrop pattern indicates that it is consistently close to vertical. Although Allan (1986) believed this was a high-angle thrust fault, House (1988) presented evidence that it was more likely a dextral strike-slip fault with some normal component of displacement. The evidence is of two types: shallowing and bending of cleavage in the 'Eastern Beds', and drag of bedding in the 'Jenolan Beds', as the fault is approached. There is also the indirect evidence of differences in metamorphic grade, the 'Jenolan Beds' having a noticeable lower grade, siltstones west of the fault giving way to phyllites on the east. House (1988) also suggested that the fault post-dates the Jenolan granite intrusion (Hellgate Granite herein), as the contact metamorphism evident in the 'Eastern Beds' in Pheasant Creek adjacent to the fault is missing from the 'Jenolan Beds'.

Evidence for the low angle Bulls Creek Thrust of House (Figs 4, 8) is given by the sharp low-angle boundary separating probably older siliceous sandstone and siltstone from outcrops of the limestone and nearby quartz porphyry within the Inspiration Point Formation. This boundary is marked by shearing of the beds, brecciation of quartz blocks, and considerable slickensiding. The evidence suggests thrusting from the southeast with the folding plunging shallowly to the north.

Shannon (1976) showed five faults cutting across the limestone belt in McKeowns Valley. The three southern ones, two south of and one north of Dillon's Creek are parallel, trending NNE, with the southern sides displaced easterly a small distance. The two more northerly faults, north and south of Hennings Creek, trend SSE. However, all five appear to have little regional significance as no displacement has been recognized in the adjacent beds, either on the west or the east. These faults were reproduced on the geological map in Kelly and Knight (1993).

GEOMORPHOLOGY

Jenolan Caves is situated at an altitude of 790 m in the deeply-incised east-trending valley of the Jenolan River. The sides of the valley are marked by several prominent benches in the landscape. Although partly caused by lithological variations these benches are almost certainly old erosion surfaces (Kiernan 1988, Osborne 1987), suggestive of valley-in-valley formation, indicating episodic uplifts following long periods of stability and slow down-cutting.

The Jenolan River valley is located at the southern edge of a slightly undulating plateau, named the Jenolan Plateau by Craft (1928), which is a partly-exhumed, gently-domed surface of Late Palaeozoic age revealed by the partial removal of a thin cover of Permian glacial and fluvio-glacial and (possibly) Triassic rocks (Branagan 1983). Craft (1928) gave considerable latitude to the definition of the plateau, writing that it "extends vertically from 3700 feet (1125 m) to 4400 feet (1338 m) above sea level (the highest point is Mount Bindo, 1359 m), with an average elevation slightly greater than 4000 feet (1216 m)". The surface is generally fairly even, and extends at the higher level westerly to Oberon. This high level continues extensively south and southwest (as the Boyd Plateau) from Jenolan, but northeast it is less extensive, the surface here with elevation above 900 m consisting of Warlock Ridge, the narrow easterly trending Black Range ridge, and further north Mini Mini Range, with Gibraltar Rocks (1070 m) at its easterly culmination.

The Caves area is drained by the Jenolan River, which commences in McKeowns Valley on the west side of the Jenolan Caves Limestone, flowing southerly and controlled by the strike of the limestone and associated beds, then continuing underground through the limestone belt before emerging on the east side of the Grand Arch. Then it flows easterly, possibly structurally controlled by recumbent folding plunging towards the south and north (Kiernan 1988), through Hellgate Gorge, then north-easterly to join the Cox River at a 'concordant' junction, indicating perhaps that the Jenolan River is a long-established part of the Cox River system. Taylor (1958:145), possibly following Süssmilch (1911:40), suggested that water from McKeowns Valley flowed through the caves system, at five different levels at different times in its history, marking possibly five separate phases of erosion (down-cutting) in the formation of the Jenolan Valley. While the uppermost reach of the Jenolan River (McKeowns Valley) has a course largely controlled by the structural trend of the Jenolan Caves Limestone, its swing across the limestone and consequent eastern flow are oblique to the geological 'grain', and may represent superposition of an old course on an uplifted surface.

The eastern slope of the Jenolan valley is drained by the south-flowing Bulls Creek (the main tributary, nearly 8 km long, of the Jenolan River), which heads several km east from the north end of Binoomea Ridge. The lower reaches of this stream contain some alluvial terraces where flow is intermittent, and the valley floor is relatively wide (House 1988).

The region east of Jenolan has been lowered by the action of the long-established Cox River and its numerous small tributaries. The Cox River has a complex pattern, beginning in a shallow, broad valley in the vicinity of Blackmans Flat (near Lidsdale), in Permian rocks, then cutting deeply (structurally controlled) through Late Devonian quartzites west of Mount Walker (near Marrangaroo), flowing south of Wallerawang in deeply-weathered rock (part of the Bathurst-Hartley granite intrusion), now flooded by construction of the Lyell Dam (Howes and Forster 1997). From near Lawson's Sugarloaf, about 4 km upstream from the junction of the Cox and the River Lett, the main stream of the Cox River follows a meandering course in a fairly broad valley for about 38 km, dropping steadily over a distance of about 19 km from an altitude of about 760 m near the Old Bowenfels-Rydal Road to 600 m five km north of the Cox River Rd-Lowther Road. It subsequently proceeds another 19 km through an increasingly narrow valley, decreasing to 510 m west of Megalong; then over only 7 km, dropping to 304 m (near Pinnacle Ridge on the east and Gibraltar Rocks on the west), then to 150 m. The level of the Cox River then declines very slowly over more than 30 km to well beyond its junction with the Kowmung River.

We disagree with Craft (1928) who believed that the older Palaeozoic rocks were less resistant to erosion than the adjacent beds of the Sydney Basin Permian-Triassic succession, and that they were worn down relatively more rapidly. To explain the present relationship between the higher Jenolan Plateau and the Sydney Basin landscape, Craft suggested that the Jenolan Plateau surface had been uplifted with 'greater recent elevation than the remainder of the surrounding country'. However, there seems little reason to explain the history of local landscape development thus. Our field observations indicate that the Sydney Basin sedimentation was restricted essentially to the region presently covered by these rocks. The present highest point on the Sydney Basin occurs a short distance east of Cullen Bullen, at approximately 1280 m, whereas the Jenolan Plateau has numerous points well above this elevation, as mentioned previously. North from the Jenolan Plateau, Permian and Triassic sedimentation of the Sydney Basin is restricted in the Portland-Cullen Bullen-Ben Bullen region by resistant ridges of Devonian and Silurian rocks, and nearer to Jenolan, Sydney Basin sedimentation is similarly restricted by Late Devonian quartz-rich rocks at Mount Lambie to the west.

Scott and Pain (2006), based on work of the BMR Palaeogeographical Group (1993), indicated that the Jenolan Plateau is part of a much larger late Palaeozoic erosion surface covering a wide area of mid-western New South Wales and much of the Lachlan Fold Belt region south in Victoria (see also Blewett 2012:259, fig. 5.5). Examples of this ancient landscape can be clearly seen east of Mudgee, near Ben Bullen, and at the western edge of the Capertee Valley where the surface on which the sediments of the Sydney Basin began to be deposited is clearly dipping easterly, tilted by late Carboniferous movement. The existence of this old erosion surface accords with the now generally accepted idea, based on considerable evidence, that much of Australia's landscape is old and that modification has been slow (Young 1983, Bishop 1985, Gale 1992, Twidale and Campbell 1993). However, contradictory evidence based on apatite fission-track thermo-chronology (Blewett 2012:261, fig. 5.23) suggests considerable denudation (up to 4 km) over vast areas of Australia, including much of the supposed long-exposed landscape. These contradictions provide a major problem which, at present, shows little sign of resolution.

The Bathurst- Hartley-Jenolan Granite problem

An important event in the geological history of the region was the post-orogenic intrusion of the Kanimblan age Bathurst-Hartley granite body and associated smaller intrusions, such as that cropping out on the Jenolan River east of the caves (Hellgate Gorge). While the granite intrusions took place after the folding of the early-mid Palaeozoic Lachlan Fold Belt rocks, there is little evidence of the depth at which the intrusion was emplaced. Timing of the unroofing of this body is a key element in the understanding of the geomorphological history of the region, particularly given the suggestion by Osborne et al. (2006) that some cave sediments are of early Carboniferous age, and that the Jenolan region must have been essentially uncovered during the Carboniferous.

Vallance (1969) discussed the geology of the Bathurst (and associated) intrusions, dealing with its petrological variations and notably those mapped by Joplin at Hartley (Joplin, 1931, 1933, 1935, 1944), and suggested that the cover at the eastern end of the main igneous body was 'not more than 1500 m'. According to Vallance (1969) the granite had not been deeply eroded, although Howes and Forster (1997) indicate that weathering at the Lyell damsite was greater than expected.

Assuming this interpretation of cover thickness is correct, erosion of the material capping the Bathurst granite must have been very rapid, assuming that it took place essentially during Carboniferous to earliest Permian time. This leads directly into another important question: where were these considerable quantities of eroded sediments redeposited? Süssmilch (1911:38) pointed out that a cutting south of Lowther consisted of Permian conglomerate containing 'large water-worn boulders of quartzite and granite imbedded in a matrix of granite detritus (arkose), the whole resting upon an eroded granite surface'. Süssmilch recognised the conglomerate as belonging to what is now called the Shoalhaven Group, the basal Permian unit of the Sydney Basin succession. We now accept this unit as being, at least in part, of glacial or fluvio-glacial in origin, a matter that was not considered by the earlier workers. So erosion, possibly with some reworking, had clearly unroofed much of the granite by early Permian time, involving removal of possibly 1500 m of cover over an interval of some 50 million years. However, there is little record of the deposition of Carboniferous sediments adjacent to the zone of suggested erosion. The nearest evidence of late Carboniferous-earliest Permian deposition is found at the south-western edge of the Sydney Basin, where Herbert (1980) delineated a fluvioglacial drainage pattern (Talaterang Group – see also Tye et al. 1996) and a northerly 'tributary', the Burrawang Conglomerate, largely buried beneath younger Sydney Basin sedimentary rocks, and whose north-western extent is uncertain.

Modification of the Jenolan landscape clearly continued though Permian and Mesozoic time, with eroded material contributing to the formation of the Sydney Basin, although most evidence indicates that the bulk of that sedimentation came from the north and south. There is little evidence of an easterly-flowing drainage pattern which contributed to such erosion and consequent deposition. The relatively recent modifications of the Jenolan region in the Cenozoic are the result of differing surface weathering with the development of a variable regolith, and erosion, mainly by the Cox River and its tributaries (draining south and then east), and the Fish River and its tributaries on the west, draining northerly and then west and northwest in the Macquarie system.

While much of the above discussion is speculative, it seems appropriate to draw attention to these questions, which have not been previously addressed, but which impinge on our understanding of landscape evolution in the region.

Minor landscape-forming events and features

The Jenolan Fault has significant topographic expression between Mount Inspiration and the northern end of Pheasants Nest Creek, controlling saddle development. Further north it has little effect on topography, probably the result of relatively recent exhumation from beneath Permian conglomerates.

Scree slopes, slumps and rockslides are common throughout the region, but particularly in the eastern area. The surface below Mount Inspiration has prominent scarps with toes of slumps, consisting of jumbled masses of blocks and boulders, which cover the bedrock. House (1988) recorded a recent slump which included a much greater proportion of fine-grained material, and which clearly moved as a fluid.

Block streams with blocky, angular fragments (ranging up to two m in maximum dimension) of altered mafic volcanics and hornblende-bearing dolerites that occur on the steeper slopes (up to 45°) of gullies flanking Bulls Creek have been noted particularly by Hallett (1988). The streams are narrow, less than 20 m wide, and about 200 m long. In the northwestern part of the area, Stewart (1987) identified a series of block streams on eastern ridges high above the river and not reaching it, whereas debris flows and outwash fans were mapped at river level along the Jenolan River (McKeowns Valley), south of Navies Creek, the majority coming from the eastern side of the valley (Fig. 4).

Consolidated gravels occur at various levels. While some of these deposits are clearly related to relatively recent changes in the presently established streams, others, including some resting at high points on the Jenolan Caves Limestone, may represent events as far back as the Permian (Osborne and Branagan 1985). Consequently there is a considerable variability in outcrop, and accessibility to the ‘solid’ rock. The upper reaches of the tributary streams of the Jenolan River generally show considerable outcrop, but the lower reaches do not. Hill slopes are quite variable, depending in part on the rock type, the more resistant silica-rich units naturally being better exposed, but siltstones often show surprisingly extensive outcrops. In places the region is thickly vegetated, creeks are very steep, often with waterfalls, and talus often obscures outcrops, but there are some exceptions, as noted by Hallett (1988), who suggested that some rather smooth creek valley cross-sections indicated the preservation of Permian valleys, possibly developed through glacial or fluvioglacial processes.

GEOLOGICAL EVOLUTION AND HISTORY OF KARSTIFICATION

The Jenolan story can only be understood in relation to the history of the much wider picture of the Lachlan Fold Belt. In general terms we are looking at an area that was the focus of the deposition of sediments in a gradually shallowing (and stabilising) marine environment from Silurian to ?Early Devonian times, followed by another period of subsidence and shallowing (largely shallow marine to terrestrial) in Late Devonian time. Volcanic activity was a continuing factor. Intrusion of granite followed with some strong earth movements, and the region underwent erosion until early to mid-Permian time when the region was subjected to glacial or peri-glacial conditions, and sediments were deposited at the edge of a shallow sea that deepened to the east.

Until the 1980s the age of karstification at Jenolan and most other eastern Australian karst was quite dogmatically stated as Quaternary, or at the oldest, Pleistocene, post-dating the so-called Kosciusko Uplift in Pliocene time. This is the heritage of E.C. Andrews (1911). Ideas on the age of formation of karst have been very strongly influenced by Andrews’s Kosciusko Uplift hypothesis, which became the revealed truth or dogma of Australian geomorphologists until the 1970s. Andrews brought the idea of very recent uplift, peneplanation and erosional activity back to Australia after a visit to America in 1908, where he was strongly influenced by G.K. Gilbert and W.M. Davis. To some extent these ideas of recent activity were also held by J.N. Jennings, the result of his European experience, and his influence among Australian speleologists here was considerable during the 1960s-80s. It is probable that Jennings was modifying these ideas before his untimely death in 1984.

Karstification may have occurred during three main periods: Middle Devonian, late Carboniferous-early Permian and post Triassic. While modifications to the cave system have occurred since Tertiary times, the major karstification probably occurred earlier. The difficulties of terrain and outcrop mean that many problems remain to be elucidated in this challenging area.

The development of karst in eastern Australia has been a specific study of Armstrong Osborne, and his findings are set out in a number of papers published over the past twenty years (Osborne 1987, 1991, 1993, 1994, 1995, 1999; Osborne and Branagan 1985, 1988; Osborne et al. 2006). They are especially summarised in Osborne (1999) and Osborne et al. (2006), in which the complexity of the story is pointed out, with evidence for exhumation of McKeowns Valley post-Permian, and the presence also of Cenozoic bone-bearing gravels and a variety of surface and underground drainage paths of various ages (see also Kelly 1988). As Osborne (1984) showed, and reiterated (Osborne 1999:14) the Jenolan Caves 'are not the product of a single recent event during which a single process operated, but, rather, are the product of a number of different events, during which a variety of processes operated'. These events took place over a geologically significant period of time.

Constraints on age of cave development

Evidence that karst development has been proceeding since Carboniferous or even Early Devonian time was proposed by Osborne et al. (2006), who obtained K-Ar isotopic ages on illites from cave deposits from a range of localities at Jenolan, the oldest being late Emsian (Early Devonian), with no fewer than nine results providing early Carboniferous isotopic ages in the range 357 – 335 Ma, and a further three falling into the later Carboniferous (325 – 313 Ma). A single sample yielded a late Permian age (258.7 Ma). These results must be viewed within the context of the overall geological history of the area, and it is here that we observe certain areas of conflict which we outline below. For rapid reference, an extract of Osborne's data is provided in Table 1, with dates revised according to the latest geological time scale (Gradstein et al. 2012).

Tectonic constraints.

The Silurian succession at Jenolan has been affected by three significant tectonic episodes: the earliest Devonian Bowning Orogeny, the mid-Devonian Tabberabberan Orogeny, and the early Carboniferous Kanimblan Orogeny. The present attitude of the Jenolan Caves Limestone and its associated sediments represents the combined effect of all three of these orogenies.

The Kanimblan Orogeny, the last tectonic episode within the Lachlan Fold Belt, concluded with the intrusion of the Bathurst Batholith. Timing of both these events has been the subject of recent study, with ages for various phases of the Batholith interpreted to range between 340 Ma and 312 Ma (Pogson and Watkins 1998). Intrusions forming part of the Batholith crop out less than 2 km from Jenolan; the emplacement of these coarse granitic bodies implies a depth of cover of the order of 1.5 km (Vallance 1969).

The duration of movements related to the Kanimblan Orogeny appears to have been remarkably brief. Glen (2013:337 and fig. 3) indicated an age of 340 Ma with no stated range; it was likely confined to a brief interval in the earliest Visean. It follows that any cave deposits still in original attitude must be no older than this. This means that it is improbable that any cave sediments of either Devonian or earliest Carboniferous age could be horizontal.

The isotopic ages quoted in Table 1 cluster around the Tournaisian and Visean, either coeval with the Kanimblan Orogeny or just before it. There is also significant overlap with the isotopic ages determined for phases of the Bathurst Batholith. As emplacement of coarse-grained granitic bodies requires substantial depth, we can only conclude that dates for cave deposit formation falling within this period have to be regarded with caution. Furthermore, the range of K-Ar isotopic ages on illites determined by Osborne et al. (2006) from individual samples was considerable. The two most extreme cases (JIC1, DCH4) covered intervals of 83.04 Ma (mid Visean to late Permian) and 55.42 Ma (latest Emsian to mid Visean).

Caymanite.

Cave deposits identified by Osborne et al. (2006:379) as caymanites, by analogy with marine deposits from Caribbean occurrences, occur notably in the Devils Coachhouse, apparently from the locality of their sample DCH4 for which ages ranging from late Early Devonian to the later early Carboniferous were determined. These horizontally to sub-horizontally bedded sediments include crinoid columnals that are certain indicators of marine conditions.

Marine sediments of this attitude necessarily post-date the Kanimblan Orogeny, for simple geometric reasons. Since no marine deposits of Carboniferous age are known from anywhere within the Lachlan Fold Belt, and in any case the succession now exposed in the Jenolan area was of the order of 1.5 km below the surface, the Carboniferous age suggested by dating from sample DCH4, is, to say the least, extremely unlikely, and it quite improbable that this sample could be as old as Early Devonian. The sole interval since the Carboniferous during which the Jenolan area was under marine conditions is the Permian, by which time the Bathurst Batholith had already been unroofed. This is evident in the area around Hartley and to the south, where basal Sydney Basin marine sediments referred to the Berry Formation directly and extensively overlie granites

Age	Sample	Location	Age (Ma)	Time-scale (Veevers 2000)	GTS 2012
Permian	JIC1	Imperial, Selina	258.7 ± 5.12	Permian (Late Ufimian)	Late Permian (Earliest Lopingian)
Carbo-niferous	JIC1	Imperial, Selina	313.58 ± 6.21	Carboniferous (Namurian - Bashkirian)	Mid Moscovian (middle Late Carboniferous)
	O1	Orient, Jungle	320.19 ± 6.34	Carboniferous (Namurian - Serpukhovian)	Bashkirian (early Late Carboniferous)
	BR6	Temple of Baal	325.81 ± 6.43	Carboniferous (Namurian - Serpukhovian)	Middle Serpukhovian (latest Early Carboniferous)
	JI74	River, Mud Tunnels	335.02 ± 6.62	Carboniferous (Visean - Arundian)	Mid Visean (mid Early Carboniferous)
	O1	Orient, Jungle	336.71 ± 6.66	Carboniferous (Visean - Arundian)	Mid Visean (mid Early Carboniferous)
	O1	Orient, Jungle	338.25 ± 6.7	Carboniferous (Visean - Arundian)	Mid Visean (mid Early Carboniferous)
	DCH4	Devils Coach House	339.45 ± 6.72	Carboniferous (Visean - Arundian)	Mid Visean (mid Early Carboniferous)
	JIC1	Imperial, Selina	341.74 ± 6.76	Carboniferous (Visean - Chadian)	Mid Visean (mid Early Carboniferous)
	JRV7	River Lethe	342.40 ± 6.77	Carboniferous (Visean - Chadian)	Mid Visean (mid Early Carboniferous)
	JRV9	River, Junction	342.50 ± 6.97	Carboniferous (Visean - Chadian)	Mid Visean (mid Early Carboniferous)
	DCH4	Devils Coach House	351.12 ± 6.99	Carboniferous (Tournaisian - Hastarian)	Mid Tournaisian (Early Carboniferous)
	JRV9	River, Junction	357.30 ± 7.06	Carboniferous (Tournaisian - Hastarian)	Near basal Tournaisian (earliest Carboniferous)
Devonian	W5	Wilkinson Branch	389.24 ± 6.58	Devonian (late Eifelian)	Upper Eifelian (mid Middle Devonian)
	JRV9	River, Junction	391.47 ± 7.75	Devonian (Early Eifelian)	Early Eifelian (early Middle Devonian)
	DCH4	Devils Coach House	394.87 ± 7.85	Devonian (Late Emsian)	Latest Emsian (Late Early Devonian)

Table 1. Data selected from Osborne et al. (2006) showing K-Ar isotopic age dates determined on illites separated from samples of clay and caymanite within Jenolan Caves; samples from identical sites are colour-coded. The ages determined in the original paper have been recalibrated to the latest international time scale (Gradstein et al. 2012).

of the Batholith (Bryan et al. 1966). Consequently a Permian age for the caymanites, equivalent to that of the Berry Formation, remains the most probable.

Mineralisation.

Osborne (1999) has put forward the attractive idea that cupolate caves result from preferential erosion of zones of sulphide-mineralised limestone. Such mineralisation requires a source, and a review of potential sources can provide significant data relevant to both timing and origin. Subjacent sources are suggested by the close proximity of components of the Bathurst Batholith, as noted above. To these can be added older sources, almost contemporaneous with the Jenolan Caves Limestone itself. The acid tuff, first noted by Süssmilch and Stone (1915) as "rhyolite porphyry", includes pumiceous fragments (Fig. 10), indicating an eruptive origin and the relatively close proximity of acid volcanism. The numerous porphyries of probable Late Silurian age shown on Figures 3-6 offer a further potential source. Mineralization associated with the spilites generally includes copper, which would almost certainly result in staining of limestone in the caves. As this has not been observed, this latter source is discounted.

CONCLUSIONS

We have clarified the proliferation of informal stratigraphic names throughout the Jenolan area, confirming correlation of the majority of rocks west of the Jenolan Caves Limestone with the lower part of the lower Silurian to Lower Devonian Campbells Group. The age of the Jenolan Caves Limestone (equivalent to the basal Mount Fairy Group) is revised as mid-Wenlock. Conformably overlying the Jenolan Caves Limestone to the east is a newly-defined unit, the Inspiration Point Formation, characterized by felsic volcanics and associated sedimentary rocks that resemble the succession in the lower to mid Mount Fairy Group (Fig. 3). The Inspiration Point Formation includes limestone (previously referred to as the 'Eastern limestone') that contains rare corals and brachiopods of probable late Silurian age, thus separating these outcrops from the Jenolan Caves Limestone in both time and space.

With the exception of the younger units (Permian conglomerates) that post-date the Kanimblan Orogeny during the early Carboniferous and are essentially flat-lying, the other stratigraphic units (in particular, the steeply-dipping Jenolan Caves Limestone) become progressively younger to the east, as determined by bedding (often overturned).

Major faulting (e.g. McKeowans and Jenolan faults) in the region mainly trends N-S. The type of faulting is not always clear, but some strike-slip is implied, as well as possible thrusting (Bulls Creek Thrust). The faults separate the region into a number of structurally-controlled domains, and tend to obscure stratigraphic and depositional relationships in a succession that is (apart from the Jenolan Caves Limestone) generally devoid of fossil control. However, some marker beds are recognized in the Inspiration Point Formation, which assists in mapping and correlation across faulted boundaries.

The present geomorphology of the region probably evolved from late Carboniferous-early Permian time, and the general plateau surface, representing this feature, has been widely exhumed around Jenolan. "Steps" in the deep valleys indicate episodic periods of valley formation.

Cave formation may have occurred during at least three main periods (Middle Devonian, late Carboniferous-early Permian and post Triassic), but the evidence for Devonian and Carboniferous periods of karstification must be treated with caution. While modifications to the cave system have occurred since Tertiary times, the major karstification probably occurred much earlier.

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