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Siluro-Devonian Bungonia Group, Southern Highlands, NSW

. . . . J.A. Bauer

Abstract

The Bungonia Group is a sequence of Late Silurian-Early Devonian biostromal limestone, sandstone and shale constituting marine fill of the Wollondilly Basin, an extensional structure initiated during the Mid-Silurian. The Bungonia Limestone (Carne & Jones, 1919) is elevated to Group status based on detailed mapping and analysis of the facies and faunal assemblages. The following succession of conformable formations and members is formalised: Lookdown Limestone (lowest); Cardinal View Shale; Frome Hill Formation consisting of the Folly Point Limestone Member, Efflux Siltstone Member and Sawtooth Ridge Member (highest).

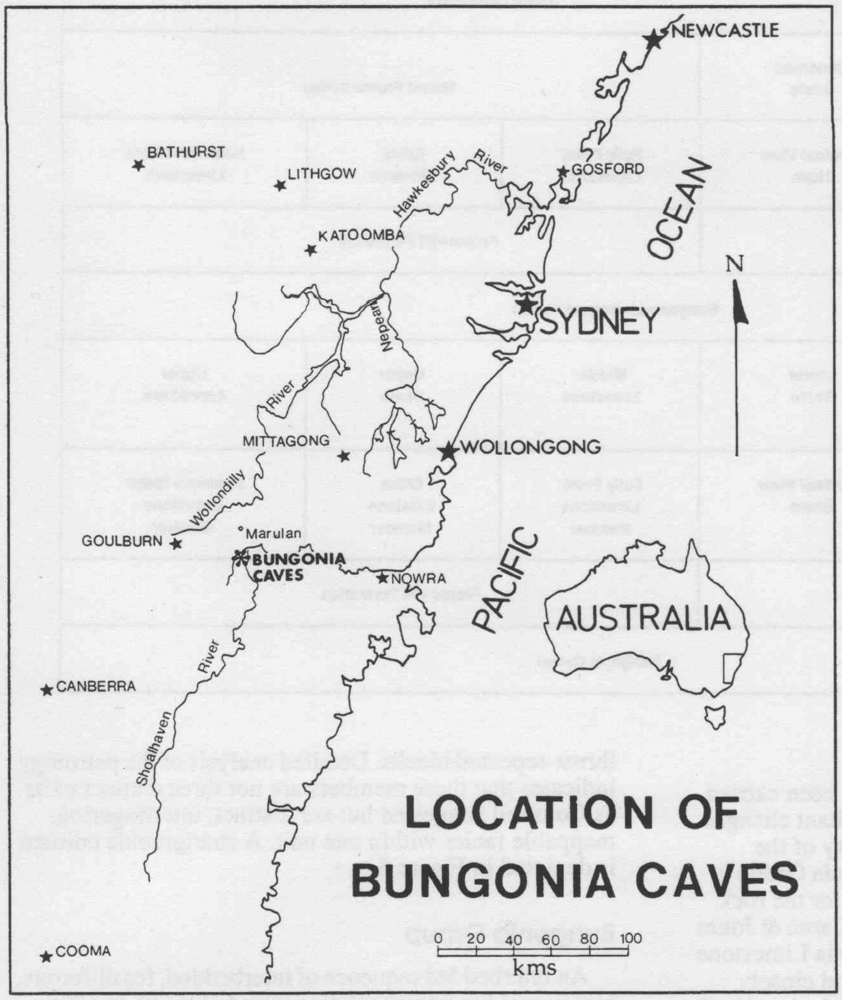

Figure 1. Location of Bungonia Caves

The Bungonia Caves Reserve lies 27 km east of Goulburn in the Southern Highlands of NSW. The study area covers the Caves Reserve, the South Marulan Limestone Quarry to the north and part of the adjoining property "Carne" to the south (Figure 1).

The Bungonia area forms part of the Capertee High on the eastern margin of the Lachlan Fold Belt in NSW and abuts the western margin of the southern Sydney Basin (Carr et al., 1980). Unconformably underlying the Bungonia Group is the Ordovician, a multiply-deformed, deep water turbidite sequence containing age diagnostic graptolites. This sequence was referred to as the Tallong Beds by Wass & Gould (1969) without definition and adopted by Carr et al. (1980). The sequence was then correlated to the Adaminaby Group by Fergusson & Vandenberg (1990) and Vandenberg & Stewart (1992) also without stratigraphic definition. Kaag (1991) defines the Ordovician units in an Honours thesis but remains unpublished. The author refers to this sequence simply as the Ordovician units due to the confusion of nomenclature.

Rifting in the medial Silurian produced the Wollondilly Basin, an extensional structure into which Late Silurian and Early Devonian sedimentary and volcanic sequences were deposited (Simpson, 1990). Interbedded fossiliferous limestone, shale, siltstone and sandstone constitute the Bungonia Group on the eastern edge of this basin. Conformably overlying the Bungonia Group is the Early Devonian Tangerang Formation of shallow marine conglomerate, limestone, and shale interbedded with shallow marine and terrestrial volcaniclastic arenite, tuff and dacitic lava flows (Jones et al., 1984). This onset of silicic volcanism ended carbonate shelf sedimentation in the Bungonia area. These sequences were folded during the Early Devonian Bowning Orogeny, before the intrusion of the Marulan Batholith (Simpson, 1990).

Small outliers of Permian quartzarenite of marine origin unconformably overlie the Bungonia Group, and Tertiary fluviatile sediments provide a patchy cover over the Palaeozoic rocks.

Structure

Regionally the Late Ordovician and Late Silurian strata occupy two asymmetrical meridional synclines, reaching as far north as Wombeyan Caves and extending southwards to Windellama and Bendithera Caves (Carr et al., 1980). Only the eastern limbs are contained within the study area as shown by Figures 2, 3 & 4. One syncline, plunging 10° to 30° contains the Lookdown Limestone and Cardinal View Shale; the western limb is lost due to faulting. The second syncline gives the steep westerly dip to the members of the Frome Hill Formation. The two synclinal structures are separated by the Reevesdale Thrust Fault, as shown on the geological map and cross-sections.

Table 1. Summary of changing nomenclature for the Bungonia Group

Author	Year	BUNGONIA GROUP Lookdown Limestone	Cardinal View Shale	Folly Point Limestone Member	Efflux Siltstone Member	Sawtooth Ridge Limestone Member
Carne and Jones	1919	Eastern Belt (white belt)				Western Belt (blue belt)
		Bungonia Limestone Belt				
Svenson	1950	Lower Limestone Stage	Silicious Intra - Limestone Stage			Upper Limestone Belt
Flinter	1950	Grey Belt				Black Belt
Gould	1966	Lower Limestone	Upper Limestone			
Robinson	1972	Eastern Limestone	Unnamed Shale	Mount Frome Series		
Counsell	1973	Lookdown Limestone	Cardinal View Shale	Folly Point Limestone	Efflux Siltstone	Sawtooth Ridge Limestone
				Frome Hill Formation		
		Bungonia Limestone Group				
Carr	1980	Lower Limestone	Lower Shale	Middle Limestone	Upper Shale	Upper Limestone
Bauer	1993	Lookdown Limestone	Cardinal View Shale	Folly Point Limestone Member	Efflux Siltstone Member	Sawtooth Ridge Limestone Member
				Frome Hill Formation		
		Bungonia Group				

Stratigraphy

Previous geological investigations have been carried out by numerous workers, with many resultant changes to the stratigraphic terminology. A summary of the history of the nomenclature for the Bungonia Group is outlined in Table 1. To date formal names for the rock units in the study area remain as stated by Carne & Jones (1919). The paper herein raises the Bungonia Limestone of Carne & Jones (1919) to group status and closely follows terminology of Counsell's unpublished work of the early seventies. James & Montgomery (1976), Anon (1976) and James et al. (1978) have also followed Counsell's terminology.

The Bungonia Limestone consists of Lookdown Limestone, Cardinal View Shale and Frome Hill Formation. The Folly Point Limestone, Efflux Siltstone and Sawtooth Ridge Limestone are relegated to member status in the Frome Hill Formation. The stratigraphic nomenclature proposed in the paper will supersede all terminology previously published and eliminate the confusion over stratigraphy since 1919.

Other workers such as Robinson (1972) and James et al. (1978) have raised the question of units within the Bungonia Group being repeated by faulting. Palaeontological work by the author on the sequence has indicated that the units are separate entities as opposed to thrust-repeated blocks. Detailed analysis of the petrology indicates that these members are not three distinct units as Counsell suggested but are distinct, interfingering, mappable facies within one unit. A stratigraphic column is depicted in Figure 5.

Bungonia Group

An interbedded sequence of interbedded, fossiliferous, biostromal limestone, sandstone and shale up to 1235 metres in thickness.

Lookdown Limestone

The base of the Lookdown Limestone lies unconformably on the Ordovician sequence. A late Ludlow age has been assigned by Moore (1976) to the Lookdown Limestone based on the presence of the conodonts *Trichonodella symmetrica* and *Spathognathodus inclinatus*. A Ludlow age is also supported by corals and stromatoporoids (Pickett 1972). However this is not absolute (Wright & Bauer, in press).

With an average dip of 70° to 300°, the Lookdown Limestone is the thickest carbonate unit (100-270 m) within the Bungonia Group and contains many of the large caves within the Bungonia Caves Reserve.

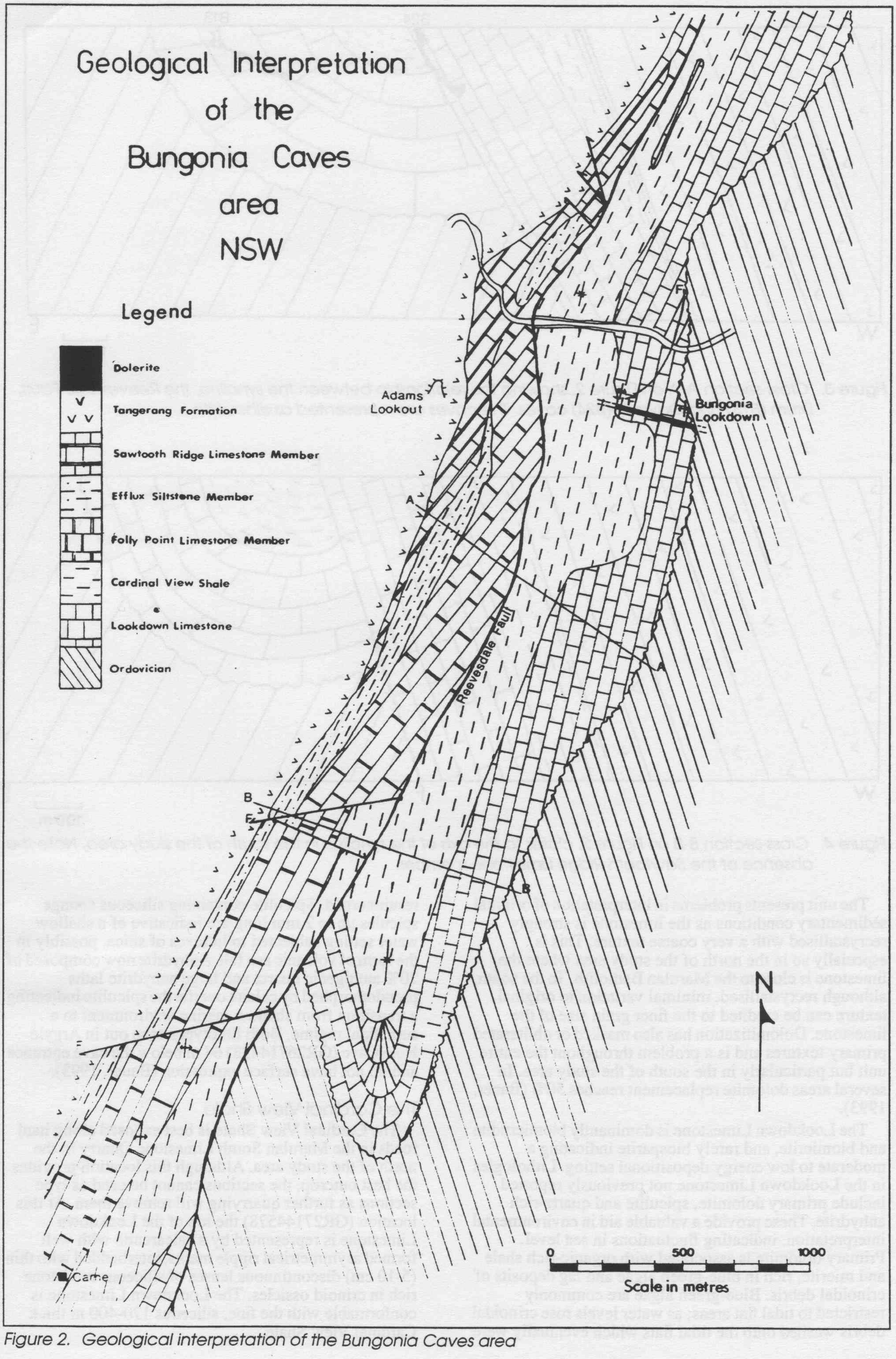

Figure 2. Geological interpretation of the Bungonia Caves area

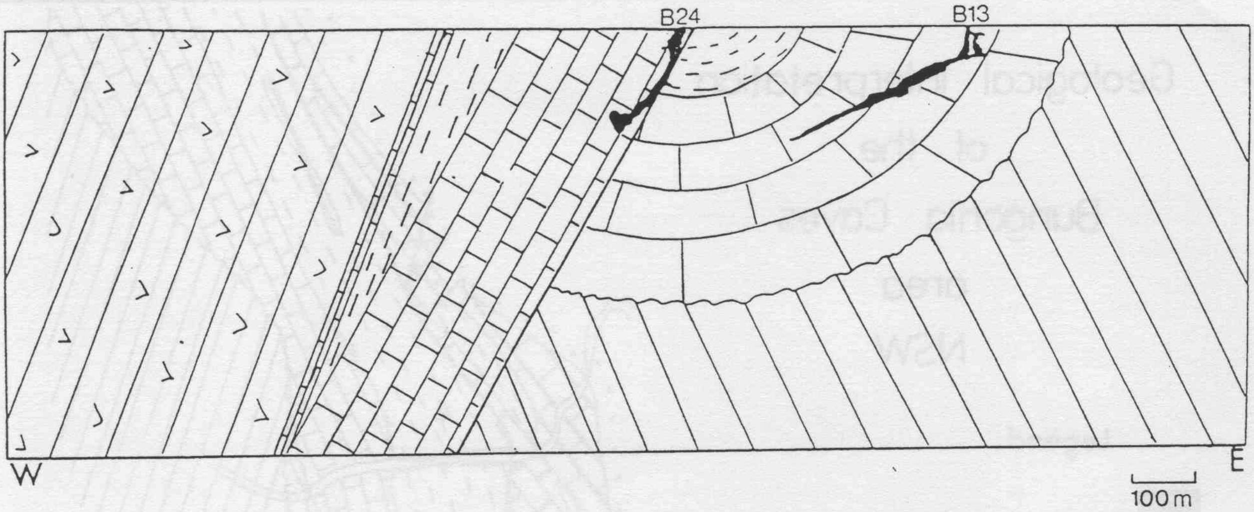

Figure 3. Cross-section A-A on Figure 2, showing the relationship between the syncline, the Reevesdale Fault, Drum (B13) and Odyssey (B24) caves. The caves are represented as silhouette.

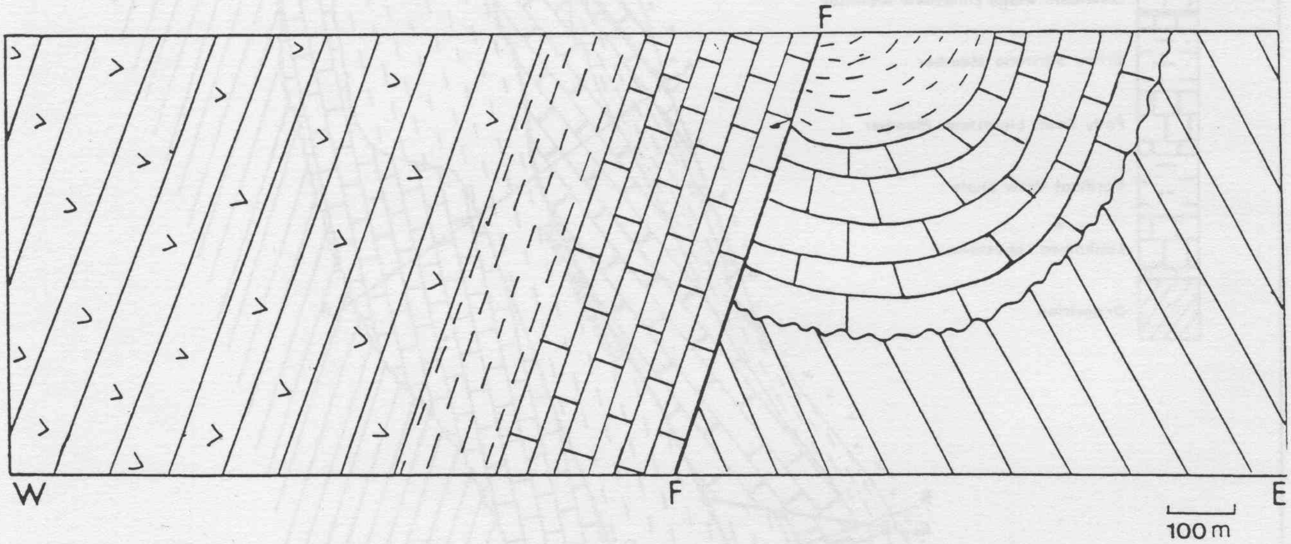

Figure 4. Cross-section B-B on Figure 2, closer to the axis of the syncline in the south of the study area. Note the absence of the Sawtooth Ridge Limestone member.

The unit presents problems in interpretation of original sedimentary conditions as the limestone is strongly recrystallised with a very coarse texture. This is especially so in the north of the study area where the limestone is close to the Marulan Batholith. To the south, although recrystallised, minimal variation to original texture can be credited to the finer grain size of the limestone. Dolomitization has also masked or obliterated primary textures and is a problem throughout the entire unit but particularly in the south of the study area. In several areas dolomite replacement reaches 50% (Bauer, 1993).

The Lookdown Limestone is dominantly biomicrudite and biomicrite, and rarely biosparite indicating a moderate to low energy depositional setting. Lithologies in the Lookdown Limestone not previously reported include primary dolomite, spiculite and quartz-rich anhydrite. These provide a valuable aid in environmental interpretation, indicating fluctuations in sea level. Primary dolomite is associated with organic-rich shale and micrite, rich in blue-green algae and lag deposits of crinoidal debris. Blue-green algae are commonly restricted to tidal flat areas; as water levels rose crinoidal debris washed onto the tidal flats which eventually were resubmerged. Spiculite containing siliceous sponge spicules up to 2 mm long are indicative of a shallow water setting subjected to influxes of silica, possibly in the form of volcanic ash fall. Anhydrite now composed of 20% authigenic quartz and large anhydrite laths pseudomorphed by calcite overlie the spiculite indicating a transition from shallow marine environment to a supratidal regime. Both lithotypes crop out in Argyle Hole Cave (GR26714438) 64 m below the cave entrance and do not have surface expression (Bauer, 1993).

The Cardinal View Shale

The Cardinal View Shale is best exposed along haul roads in the Marulan South Limestone Quarry in the north of the study area. Although this location provides the best outcrop, the sections cannot be used as type sections as further quarrying will remove them. At this location (GR27144578) the top of the Lookdown Limestone is represented by a calcarenite with well formed asymmetrical ripple marks, interbedded with thin (5-10 cm) discontinuous lenses of siliceous mudstone rich in crinoid ossicles. The Lookdown Limestone is conformable with the fine, siliceous 170-400 m thick Cardinal View Shale.

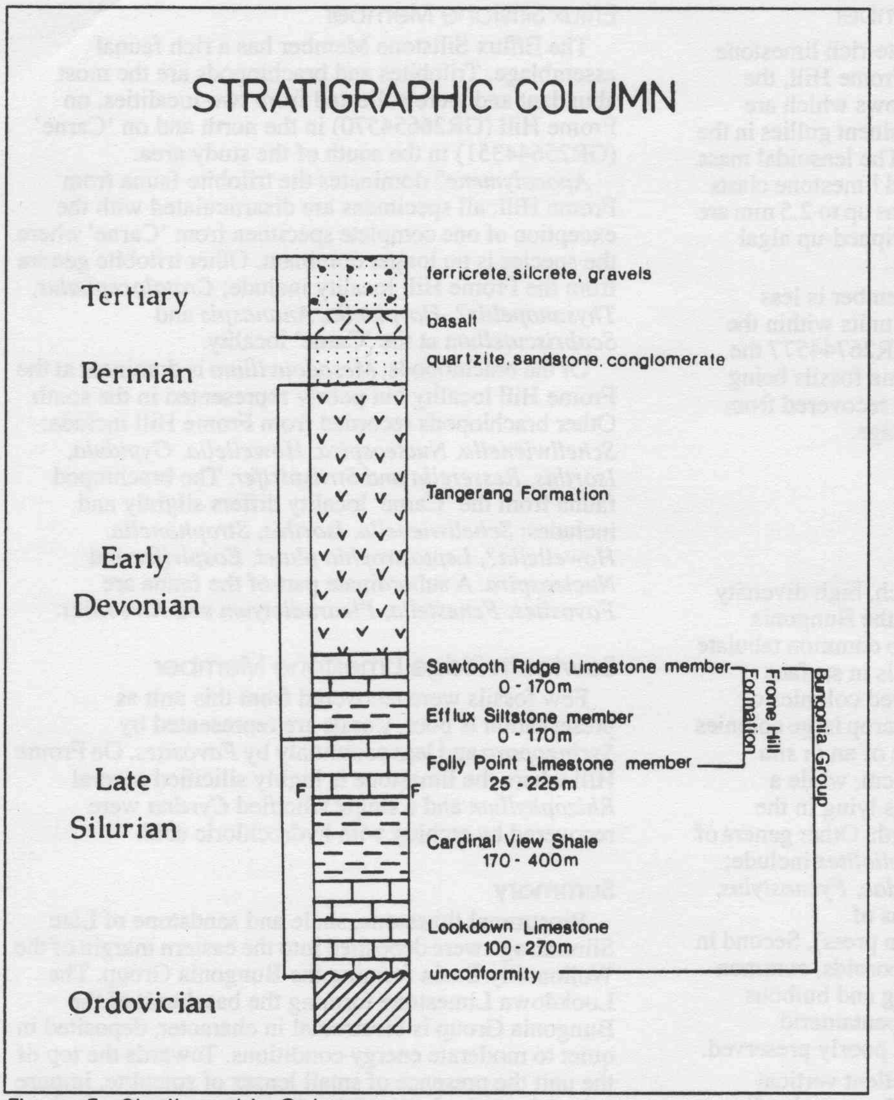

Figure 5. Stratigraphic Column

The Cardinal View Shale is a Bouma sequence with several beds containing wave generated ripple marks indicating a shallow water turbidite sequence. The basal beds of the unit consists of very fine-grained shale, siltstone and sandstone. Individual beds are fining upwards in this overall coarsening upward sequence. Mass flow units up to 4 m in thickness occur within the unit; the lowest flow unit contains sandstone and shale clasts, probably derived from an Ordovician source. The next flow unit contains limestone clasts only, suggesting active tectonism such as uplift of the Lookdown Limestone or basin subsidence.

The middle of the Cardinal View Shale is marked by a 20 m thick pod of limestone previously referred to as the Main Gully limestone as it lies in close proximity to the topographic feature, Main Gully (Counsell, 1973). This biolithite contains encrusting forms of algae, stromatoporoids, bryozoans and juvenile favositids. Mass flows recorded in the sequence above the Main Gully limestone contain well-rounded clasts, ranging in size from 1 mm to 20 cm in a matrix of silt and sand sized particles. The top of the Cardinal View Shale is dominated by coarsening-upward beds of fine to coarse sandstone containing cross-beds and scours. Clast size indicates a proximal facies in the north of the study area, while smaller clasts to the south of Bungonia Gorge represent a distal facies to the source.

Frome Hill Formation

The Frome Hill Formation was named after Frome Hill, a prominent topographic feature on the northern side of Bungonia Gorge. Until 1966 this feature was referred to as Mount Frome when it was officially renamed Frome Hill in accordance with the Geographical Names Act (Counsell, 1973). However, the geological units on Frome Hill, the Mount Frome Series (after Robinson, 1972) retained its name. Counsell (1973) suggested this be changed to the Frome Hill Formation and the author also adopts this name. The units within the Frome Hill Formation are renamed as members in this paper on the basis of detailed field mapping.

Folly Point Limestone Member

The base of the unit in this area is mostly coincident with the Reevesdale Fault. The unit consists of fossiliferous limestone interbedded with well-sorted, medium-grained, fossiliferous sandstone. The average attitude is 65° to 300°; the unit thins to 25 m in the north of the study area from 225 m in the south. Of the limestone fraction, biomicrite and biomicrudite are the dominant textural types; however, there is also a high occurrence of biosparrudite containing crinoidal detritus. From north of Bungonia Gorge to Folly Point terrigenous detritus, mostly quartz, increases to 5% where the limestone is interbedded with calcareous sandstone and decreases south of Folly Point to be absent in the limestone on 'Carne'. West of Folly Point (75 m) a 1 m bed of black chert interbedded with laminated micrite indicates low energy conditions and the introduction of silica into the system. Thin section analysis revealed an early phase of recrystallisation of this unit, which was originally a lime mud. Although recrystallised, the fine texture allowed primary textures to be retained. The age of Folly Point Limestone Member is undetermined.

Efflux Siltstone Member

Conodonts from this unit by Jones et al., (1981) led to the assignment of a Lochkovian age; Mawson (1986) has queried the limited conodont data. The 0-170 m thick unit lenses out at or is faulted out at GR26414509 and reappears on the northern side of Bungonia Gorge. Outcrops continue north for 425 m where the unit is terminated by faulting. South of GR25904396 the Efflux Siltstone Member forms the top of the Bungonia Group as the Sawtooth Ridge Limestone Member lenses out.

In the northernmost outcrops the Efflux Siltstone Member is a medium-grained, well sorted, fossiliferous sandstone at its base grading to shale at the top of the unit. In the vicinity of Adams Lookout Road the unit is a fine white shale rich in crinoidal material. The sandstone and shale within the unit show lateral variation in grain size.

Sawtooth Ridge Limestone Member

This unit is a well laminated, micrite-rich limestone with up to 2% of detrital quartz. On Frome Hill, the limestone is interbedded with mass flows which are topographically expressed as the prominent gullies in the vertical southern face of Frome Hill. The lensoidal mass flow units contain coral, bryozoan and limestone clasts up to 3 cm in size. Angular quartz grains up to 2.5 mm are common, as are chert fragments and ripped-up algal material.

The Sawtooth Ridge Limestone Member is less fossiliferous than the other carbonate units within the Bungonia Group. On Frome Hill at GR26744577 the limestone is highly silicified, with some fossils being prominent in outcrop. A *Cyrtina* shell recovered from this unit indicates an Early Devonian age.

Fauna

Lookdown Limestone

The Lookdown Limestone has a rich, high diversity fauna compared to other units within the Bungonia Group. The fauna is dominated by two common tabulate corals, *Favosites* and *Heliolites*. Corals in surface outcrop occur as small poorly preserved colonies or fragments; however, in subsurface outcrop large colonies are preserved. In Drum Cave the base of an *in situ ?Tryplasma* reaches a diameter of 60 cm, while a longitudinal section of the same genus lying in the bedding plane measured 80 cm in length. Other genera of coral subordinate to *Favosites* and *Heliolites* include; *Syringopora, Pachyporidae, Proporidae, Pycnostylus, Hedstroemophyllum?* and a new genus of *Arachnophyllidae* (Wright & Bauer, in press). Second in abundance to the corals are stromatoporoids, common frame-builders occurring in encrusting and bulbous forms. Brachiopods, particularly the pentamerid brachiopod *Kirkidium* are present but poorly preserved.

Flying Fortress Cave exposed excellent vertical sections and the relationship between fauna and sediment type could be easily investigated. Carbonate with 30-35% lime mud supported a rich and diverse fauna, including stick bryozoans, corals, sponges and rhodophyta. The limestone in the main cave passage has been surficially silicified and etched fossils are left protruding. Large articulated, thick-shelled megalodont bivalves and septate gastropods (Cook, 1994) discovered here have not previously been reported. Ostracods preserved in the clay matrix within these bivalves include; *Bairdia sp., Bairdiocypris sp.* (or *Silensis sp.*), *Baschkirina sp.* (or *Pseudorayella sp.*), *Bulbosohnia sp.*, *Microcheilinella sp.* and "*Longiscula*" *sp.* cf. *smithii* (P. Jones, pers. comm.)

Cardinal View Shale & Main Gully Limestone

Disarticulated crinoid detritus were the only fossils recovered during the present study from the clastic fraction of the Cardinal View Shale. Fauna in the Main Gully Limestone include; *in situ* juvenile *Favosites*, encrusting stromatoporoids and stick bryozoans. Fragmental debris includes echinoderm, brachiopod, mollusc, coral and algal material, as well as sponge spicules up to 1 mm in size.

Folly Point Limestone Member

The carbonate fraction of the Folly Point Limestone Member is dominated by corals, stromatoporoids, stick bryozoans and coralline algae. The 0-65 m thick sandstone lens at Folly Point contained fenestellid bryozoans, calymenid trilobites and crinoids.

Efflux Siltstone Member

The Efflux Siltstone Member has a rich faunal assemblage. Trilobites and brachiopods are the most abundant and were collected from two localities, on Frome Hill (GR26654570) in the north and on 'Carne' (GR25644351) in the south of the study area.

Apocalymene? dominates the trilobite fauna from Frome Hill; all specimens are disarticulated with the exception of one complete specimen from 'Carne' where the species is no longer dominant. Other trilobite genera from the Frome Hill locality include; *Crotalocephalus, Thysanopeltis?, Harpidella, Ananaspis* and *Scabriscutellum* at the 'Carne' locality.

Of the brachiopods, *Mesodouvillina* is dominant at the Frome Hill locality but poorly represented in the south. Other brachiopods recorded from Frome Hill include; *Schellwienella, Nucleospira, Howellella, Gypidula, Isorthis, Resserella and Striispirifer*. The brachiopod fauna from the 'Carne' locality differs slightly and includes; *Schellwienella, Isorthis, Strophonella, Howellella?, Leptostrophia platei, Eospirifer* and *Nucleospira*. A subordinate part of the fauna are *Favosites, Fenestella, Pleurodictyum* and *Alveolites*.

Sawtooth Ridge Limestone Member

Few fossils were recovered from this unit as preservation is poor. Corals are represented by *Syringopora* and less commonly by *Favosites*. On Frome Hill where the limestone is highly silicified several *Rhizophyllum* and a single silicified *Cyrtina* were recovered by etching with hydrochloric acid.

Summary

Biostromal limestone, shale and sandstone of Late Silurian age were deposited into the eastern margin of the Wollondilly Basin forming the Bungonia Group. The Lookdown Limestone forming the basal unit of the Bungonia Group is biostromal in character, deposited in quiet to moderate energy conditions. Towards the top of the unit the presence of small lenses of spiculite, impure anhydrite and primary dolomite indicate shallowing during a minor regression. Spiculite and anhydrite rich in authigenic quartz indicate silica entering the system, possibly as ashfall into these shallowing lagoons. Volcanism was common during the Late Silurian, as the extensive Deakin Volcanics which occur in the Canberra region (Henderson & Strusz, 1982) were deposited synchronously with the Lookdown Limestone.

During a regressive sea level phase, the carbonate sequence was subjected to influxes of clastic material which formed the Cardinal View Shale. Fine siltstone at the base of the unit represents a distal facies of a delta system. The medium to coarse-grained, ripple, cross-bedded sandstone at the top of the Cardinal View Shale represents the submarine portion of a more proximal facies to this prograding delta system in which mass flows were common. Uplift of the Ordovician sequence along the basin margins provide the source of material found in the basal mass flow units within the Cardinal View Shale. The inclusion of limestone clasts in subsequent mass flow units suggests active tectonism such as uplift of the Lookdown Limestone or basin subsidence.

The overlying Frome Hill Formation is separated from the underlying units by the Reevesdale Thrust Fault. Facies delineation and faunal community analysis has indicated that members of the Frome Hill Formation are slightly deeper water facies than the Lookdown Limestone and Cardinal View Shale. Facies analysis has enabled the stratigraphy to be elucidated and allowed the Bungonia Limestone to be elevated to Group status. Carbonate deposition was terminated by widespread volcanism leading to the deposition of the Tangerang Formation which conformably overlies the Bungonia Group.

Acknowledgments

Most of the fossils from the Efflux Siltstone Member are in collections made previously by Carr, Jones & Wright. The brachiopod and trilobite identifications have been supplied by Wright. I thank NPWS and the Carne property owner for allowing access and P. Williamson and A.J. Wright for their comments on the manuscript.

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Appendix: Stratigraphic terminology

The following are formal definitions of the new stratigraphic units introduced in this paper.

Name of unit: Bungonia Group

Derivation of name

The group is named after the small township of Bungonia in the Southern Highlands of NSW (34.8°S, 150.0°)

Type Section

None specified.

Lithology

The group consists of a conformable succession of fossiliferous limestone, siltstone, sandstone and shallow water turbiditic shale.

Thickness

Total thickness is approximately 1235 metres.

Relationships And Boundary Criteria

The base lies unconformably on the multiply-deformed units of Ordovician age. The top of the group is conformably overlain by the Early Devonian Tangerang Formation.

Age and structure

The age of the base of the group is still somewhat unclear. Conodonts (Moore, 1976), corals and stromatoporoids (Pickett, 1972) indicate a Ludlow age. The top of the group is of Early Devonian age based on a single *Cyrtina* in the Sawtooth Ridge Limestone Member, and the underlying Efflux Siltstone Member has been assigned a Lochkovian age based on conodont data (Jones et al., 1981).

Name of unit: Lookdown Limestone

Derivation of name

The Lookdown Limestone derives its name from the Bungonia Lookdown (GR27194503) perched on top of the 350 m high Troy Walls.

Type section

None specified; typical outcrops occur in Becks (Tanners) Gully (GR26974230), and Drum Cave doline (type locality; GR26854410). This unit is exposed in Bungonia Gorge but is strongly recrystallised in this area. Many subsurface outcrops provide excellent exposures but are not generally accessible and therefore have not been recommended here.

Lithology

The Lookdown Limestone is a fossiliferous, biostromal carbonate sequence. Limestone is dominantly biomicrudite and biomicrite occurring with small lenses of primary dolomite, spiculite and quartz-rich anhydrite. Basalt dykes cut the unit but are best seen in subsurface outcrop.

Thickness

The unit ranges in thickness from 100-270 metres.

Relationships and boundary criteria

The base of the Lookdown Limestone has an unconformable boundary with the underlying Ordovician Adaminaby Group, best exposed at GR27204490 and GR27224502 (here the contact is folded). The top of the unit has a conformable boundary with the overlying Cardinal View Shale best exposed in the South Marulan Limestone Quarry at GR27144578.

Age and structure

The age for the Lookdown Limestone remains unclear as described above. The unit has an average orientation of 70° to 300°. The unit is folded into a gently northerly plunging syncline, plunging at 10°; the fold axis trends 30° parallel to the strike of the limestone. The hinge of the syncline is exposed in the Railway Tunnel of Drum Cave (B13) but is inaccessible to all but experienced cavers.

Name of unit: Cardinal View Shale

Derivation of name

The unit derives its name from Cardinal View (GR2704510), a vantage point above Bungonia Gorge, 140 m northwest of Bungonia Lookdown.

Type section

The unit is best exposed along haul roads in the South Marulan Limestone Quarry. MS1-GR27304630 to GR27204628, MS2-GR27614635 to GR27214631 and MS3-GR27274637 to GR27384640. MS1-3 correspond to measured sections in Bauer 1993. These outcrops are not regarded as type sections because of their non-permanent nature. The type locality is situated on Frome Hill GR26934590.

Lithology

The Cardinal View Shale is sequence of shale, siltstone, sandstone, conglomerate and limestone. The clastic fraction of the unit is a Bouma sequence, the presence of wave generated ripple marks indicate a shallow water turbidite sequence. The carbonate lens within the Cardinal View Shale is a biolithite with characteristic juvenile frame builders *in situ*.

Thickness

The Cardinal View Shale ranges in thickness from 170-400 m. The unit is thickest in the vicinity of The Lookdown at GR27054505.

Relationships and boundary criteria

The base of the Cardinal View Shale has a conformable boundary with the underlying Lookdown Limestone and a faulted boundary with the overlying Folly Point Limestone Member. This faulted boundary is best seen below Folly Point at GR26624496.

Age and structure

The Cardinal View Shale is assigned a Late Ludlow age based on the presence of *Monograptus bohemicus tenuis* (Moore, 1976). The Cardinal View Shale is folded into the core of a gently north plunging syncline.

Name of unit: Frome Hill Formation

Derivation of name
The Frome Hill Formation derives its name from a prominent topographic feature on the northern side of Bungonia Gorge. The Frome Hill Formation contains the Folly Point Limestone Member, Efflux Siltstone Member and Sawtooth Ridge Limestone Member.

Type section
None specified.

Lithology
The formation consists of fossiliferous limestone, fossiliferous, calcareous sandstone, shale, mudstone and breccia.

Thickness
The formation ranges in thickness from 25-565 m.

Relationships and boundary criteria
The base of the Frome Hill Formation is a faulted boundary while the top of the formation is conformable with the overlying Tangerang Formation.

Age
The basal member within the formation is of undetermined age, the top most member is assigned an Early Devonian age.

Name of unit: Folly Point Limestone Member

Derivation of name
The Folly Point Limestone Member derives its name from Folly Point, a truncated bluff overlooking Bretons Creek and Bungonia Gorge (GR26594497).

Type section
None specified. Typical outcrops occur in the vicinity of Folly Point between GR26534497 and type locality GR26624497.

Lithology
The member consists of fossiliferous limestone interbedded with well sorted, medium-grained, fossiliferous, calcareous sandstone. Biomicrite and biomicrudite are the dominant carbonate textural types, however in the Folly Point area biosparrudite containing crinoidal detritus is also present. The biosparrudite and associated lithotypes a representative of a marine barrier system.

Thickness
On the northern side of Bungonia Gorge the unit is only represented by limestone up to 25 m in thickness. To the south on the 'Carne" property the unit retains a uniform thickness of 225 m. The calcareous sandstone is lensoidal reaching a maximum thickness of 65 m at Folly Point.

Relationships and boundary criteria
The base of the unit is faulted against the underlying Cardinal View Shale. South of GR26804571 the unit has a conformable contact with the Efflux Siltstone Member, north of GR26874585 the unit has a conformable contact with the Sawtooth Ridge Limestone Member.

Age
Undetermined.

Name of unit: Efflux Siltstone Member

Derivation of name
The Efflux Siltstone Member derives its name from the area's permanent spring, the Efflux (B67; GR26574497) found below Folly Point.

Type section
None specified. Typical outcrops occur at GR26654670 (type locality), GR26684570 and GR26604565 which are conodont bearing.

Lithology
In the north of the study area the unit is a medium-grained, well sorted, fossiliferous sandstone at its base grading to shale at the top of the unit. In the vicinity of Adams Lookout Road (GR25494427) the unit is represented by a white mudstone rich in disarticulated crinoidal material.

Thickness
The Efflux Siltstone Member ranges in thickness from 0-170 m, the thickest section occurs in the south where the unit forms the top of the Bungonia Group.

Relationships and boundary criteria
The base of the unit is conformable with the Folly Point Limestone Member. North of GR25904396 the top of the unit is conformable with the overlying Sawtooth Ridge Limestone Member, south of this grid reference the Efflux Siltstone Member is conformably overlain by the Tangerang Formation. In the north (GR26804575) the Efflux Siltstone Member is terminated by faulting.

Age
A Lochkovian age has been assigned to the Efflux Siltstone Member based on the conodonts recovered from shaly carbonate nodules within the unit (Jones et al., 1981).

NAME of unit: Sawtooth Ridge Limestone Member

Derivation of name
The Sawtooth Ridge Limestone Member derives its name from the long sharp ridge that runs below Adams Lookout north to Bungonia Creek. This ridge is also referred to as the Devils Staircase.

Type section
None specified. The best fossil bearing outcrops and type locality can be found at GR26704575.

Lithology
The unit is a well laminated micrite-rich limestone containing 1-2% terrigenous quartz. On Frome Hill the limestone is interbedded with mass flow units containing pebble sized coral, bryozoan and limestone clasts. Angular quartz grains up to 2.5 mm, chert clasts and ripped up algal mat material are also common. The mass flow beds are lensoidal and restricted to Frome Hill.

Thickness

The Sawtooth Ridge Limestone Member ranges in thickness from 0 m at GR25904396 to 170 m. The unit is thickest in Bungonia Gorge, thinning both north and south of this locality. To the north the continuity of the unit is disrupted by faulting. In the north of the study area the unit is uniformly 60 m in thickness.

Relationships and boundary criteria

Between Bungonia Gorge and GR25904396 the base of the Sawtooth Ridge Limestone Member forms a conformable contact with the Efflux Siltstone Member. In the Gorge itself it can be seen at depth to be in contact with the Folly Point Limestone Member. Between GR26824572 and GR26874584 where down faulting has occurred the base of the Sawtooth Ridge Limestone Member comes into contact with the Cardinal View Shale. North of GR26874584 the base of the unit forms a conformable contact with the Folly Point Limestone Member. The top of the Sawtooth Ridge Limestone Member is conformably overlain by the Tangerang Formation.

Age

Based on a single silicified *Cyrtina* shell an Early Devonian age is assigned to this unit. This is feasible as both the underlying and overlying units are Early Devonian (Jones et al., 1981; Simpson, 1990)

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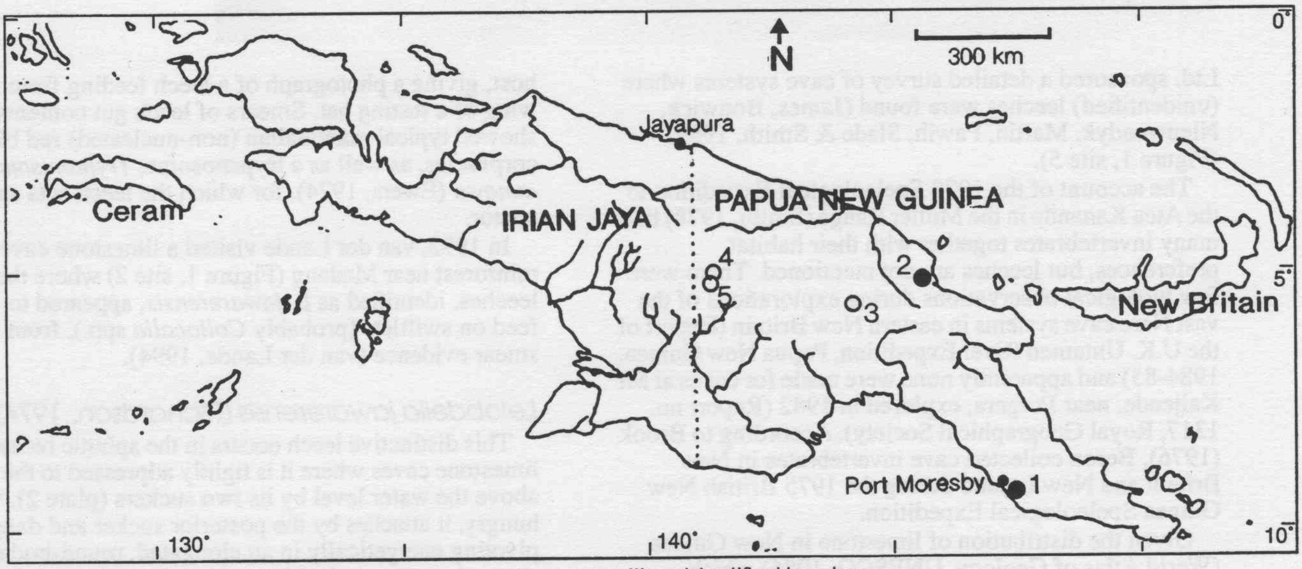
Cavernicolous leeches in Papua New Guinea *

Virginia M. van der Lande

Abstract

At least two limestone caves in Papua New Guinea harbour the unique leech, *Leiobdella jawarerensis*, the only haemadipsid (land) leech known without cutaneous pigmentation. The species probably occurs in at least three other widely separated sites. The leeches feed on blood extracted from bats and swiftlets inhabiting the caves. Directions for preserving the leeches are given.



● cave with *Leiobdella jawarerensis* ○ cave with unidentified leeches

1 Jawarere, Sogeri 2 Og, Sein

3 Kaimono, Chuave 4 Selminum Tem, Tabubil 5 Lukwi, Tabubil

Figure 1. Papua New Guinea showing the location of leech caves studied.

Introduction

It has long been known that caves harbour leeches. Turquin (1984) recently received the literature relating to the cave-dwelling leeches of the Palaearctic; all belong to the family Erpobdellidae (jawless) and comprise species of *Dina, Haemopis, Trocheta and Erpobdella*. Of these, *D. absoloni* (Yugoslavia), *D. vignai* (Turkey) and *D. anoculata* (U.S.A) are eyeless and without pigmentation.

An unpigmented cave leech (Annelida: Hirudinea) belonging to the family Haemadipsidae (jawless; land leeches) is among the troglobitic invertebrates which are unique to Papua New Guinea. It probably also occurs in Irian Jaya. However, biospeleological observations are minimal from this under-explored side of the island (see Brook, 1976, and annual issues of *Current Titles in Speleology*) although there have been some climbing (eg. to Carstenz Mts; Boardman, 1982) and caving expeditions, such as those to the Upper Baliem Valley in 1992 following reconnaissance expeditions in 1985 (*Bulletin of the Cave Research Association*, 17, April 1990) and 1988.

But throughout the island, logistics are formidable since communications are poor and terrain is among the most difficult in the world. None of the great pre-World War II expeditions, which were mainly conducted in Dutch- and German-administered areas (Frodin & Gressitt, 1982), appear to have studied caves.

In Papua New Guinea, the Port Moresby speleologists discovered caves at Sogeri with an unpigmented haemadipsid leech which was subsequently identified as *Leiobdella jawarerensis* (Richardson, 1974) (Figure 1, site 1) (Ewers, 1974). Another cave near Goroka with unidentified leeches (Figure 1, site 3) was also found. A remote area in the Star Mountains near Tabulil, opened up by mining operations, provided a collection of some twenty cave invertebrates, including leeches, during the 1975 British New Guinea Speleological Expedition (Figure 1, site 4) (Brook, 1976). In 1989, Ok Tedi Mining

* Contribution no. 130 from the Christensen Research Institute, Madang

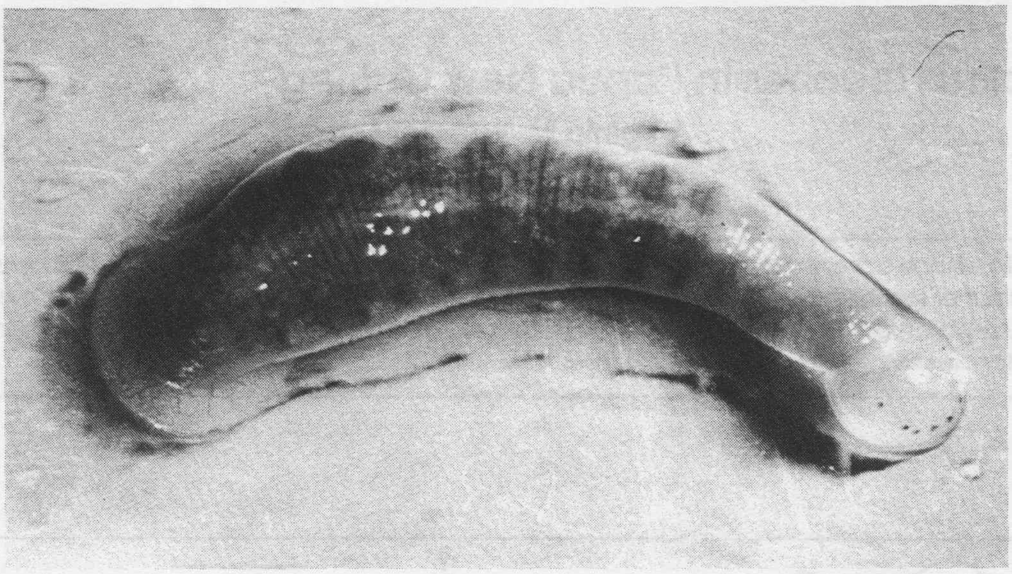


Plate 1. Resting Leiobdella jawarerensis (in viva dorsal view). Note the two circular suckers, the anterior one with ten eyespots arranged in a "U". The capillaries of the leech circulatory system show clearly in both suckers. The lobes of the crop containing ingested blood are also visible. x 4.5.

— Prof. L. G. Harris

Ltd. sponsored a detailed survey of cave systems where (unidentified) leeches were found (James, Bonwick, Nieuwendyk, Martin, Pawih, Slade & Smith, 1989) (Figure 1, site 5).

The account of the 1978 Speleological Expedition to the Atea Kananda in the Muller Range (Smith, 1978) lists many invertebrates together with their habitat preferences, but leeches are not mentioned. There were few biological observations during explorations of the vast Nare cave systems in eastern New Britain (Report of the U.K. Untamed River Expedition, Papua New Guinea, 1984-85) and apparently none were made for caves at Mt Kaijende, near Porgera, explored in 1982 (Report no. 1317, Royal Geographical Society). According to Brook (1976), Beron collected cave invertebrates in New Britain and New Ireland during the 1975 British New Guinea Speleological Expedition.

Given the distribution of limestone in New Guinea (World Atlas of Geology, UNESCO, 1986) which harbours cave systems which are among the deepest and most extensive in the southern hemisphere (Brook, 1976), cavernicolous leeches are probably far more widely distributed than present reports suggest. Few biologists are cavers, and the objectives of speleological expeditions are rarely biological. Leeches rarely interest the non-specialist.

Cave faunas in Papua New Guinea

Many invertebrates lack skin pigmentation and have reduced or absent eyes, or other structural and behavioural features associated with a cavernicolous habitat (Holsinger, 1988). According to Gressitt (1982), the Papua New Guinea cave fauna includes endemic arthropods (crustacea, acari, phalangidae, diplopods, chilopods, insects - both larval and adult stages), as well as members of other arachnid groups, temnocephalids, molluscs and annelids (a polychaete and leeches) (Chapman, 1976, Smith, 1978). As yet, no troglobitic onychophorans (velvet worms) have been reported in New Guinea caves despite their occurrence in Jamaica, South Africa and New Zealand (Ruhberg, 1985). This rare group is important in evolutionary and biogeographical studies, and rainforest forms are otherwise quite well represented in New Guinea (van der Lande, 1992); cavernicoles are to be expected.

L. jawarerensis occurs (Ewers, 1974) on the walls of limestone caves in rainforests near Sogeri (haemadipsids are typically non-aquatic). Ewers describes how a vespertilionid microchiropteran bat, *Miniopterus tristis* (= *M. propitristis*; Peterson , 1981), acts as a temporary host, giving a photograph of a leech feeding from the wing of a resting bat. Smears of leech gut contents showed typical mammalian (non-nucleated) red blood corpuscles, as well as a trypanosome, *Trypanosoma aunawa* (Ewers, 1974), for which the leech acts as a vector.

In 1992, van der Lande visited a limestone cave in rainforest near Madang (Figure 1, site 2) where the cave leeches, identified as *L. jawarerensis*, appeared to also feed on swiftlets (probably *Collocalia* spp.), from blood smear evidence (van der Lande, 1994).

Leiobdella jawarerensis (Richardson, 1974)

This distinctive leech occurs in the aphotic recesses of limestone caves where it is tightly adpressed to the walls above the water level by its two suckers (plate 2). When hungry, it attaches by the posterior sucker and dangles, pivoting energetically in an elongated, round-bodied state when approached by potential hosts (plate 3). The jaws cannot perforate intact human skin; indeed this leech does not feed from humans (Ewers, 1974; van der Lande, 1993), unlike land-leeches encountered in forests in New Guinea and the Indo-Malayan tropics.

Mature, living adults varied in length between 20 mm (contracted; plate 2) and 55 mm (extended; plate 3). *In situ* by torchlight, a leech looks bright pink or liver-coloured owing to the enlarged, blood-filled crop (see Figure 2 in van der Lande, 1994) and its own haemoglobin-containing circulatory system, which show through the transparent, pigment-free body wall. Other organ-systems such as the green-brown excretory tissue and opaque-white reproductive organs, are also recognisable. Five pairs of small, black-pigmented eyespots are conspicuous (plate 2).

L. jawarerensis is noticeably more soft-bodied than its terrestrial relatives and only **slightly** pimply when contracted, compared with forest-inhabiting species of New Guinea. Richardson (1974) and van der Lande (1994) give detailed accounts of its anatomy and biology.

The leeches are probably dispersed as juveniles while attached to bats and swiftlets, and are distributed when their hosts fly between caves. However, no leeches have been reported among the ectoparasites of cave bats or swiftlets in the Austro-Malayan subregion.

Like other leeches, they probably copulate in pairs and later form cocoons which perhaps adhere to the cave wall rather than the host with which the adult haemadipsids normally only have temporary contact (Ewers, 1974). From observations on the size variations of Sogeri individuals during April and November, it seems that

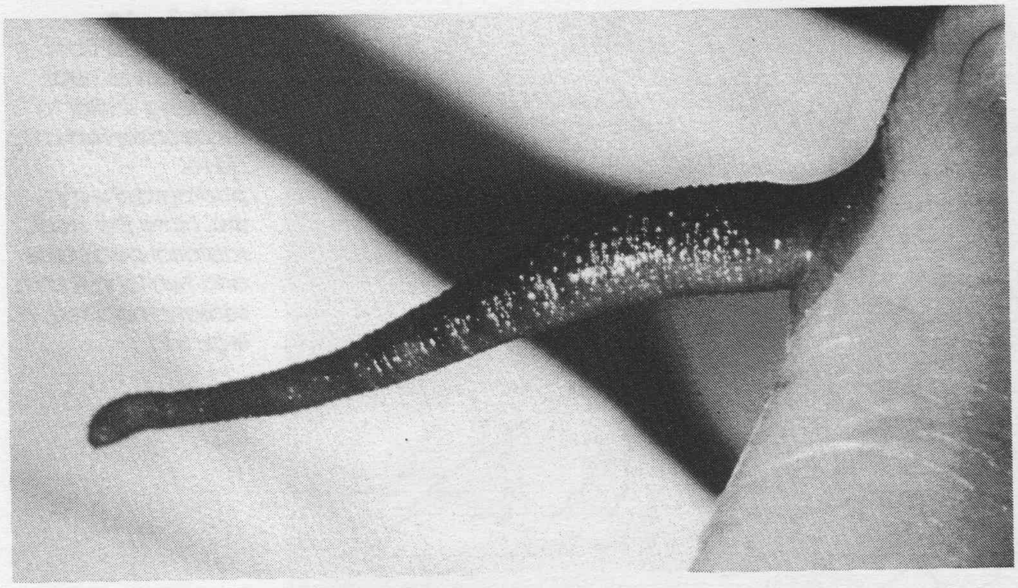


Plate 2. Extended Leiobdella jawarerensis (in viva lateral view). The leech is showing "hungry" behaviour, pivoting around the attached posterior sucker. The body annuli (rings) and the slightly pimply structure of the skin can be seen. At this stage, both toothed jaws are retracted into the expanded anterior sucker. X2. — Prof. L. G. Harris

breeding is seasonal, with cocoons hatching around the latter months (Ewers, 1974). Two of the larger specimens from Og Cave obtained in August had a clitellum, the transient glandular cocoon-forming structure which only develops in the breeding season. However, the mode of distribution and life-history of *L. jawarerensis* are speculative.

Caves in Papua New Guinea with *leiobdella jawarerensis* (Figure 1)

1. Jawarere Cave near Musgrave, Sogeri (9°26'S: 147°29'E), alt. ±450 m (Ewers, 1974; Richardson, 1974); Type locality. Figure 1, site 1.

The Port Moresby speleologists have explored many caves in New Guinea, including those at Sogeri (*Papua New Guinea Cave Talk*, April 1961, p. 2), some 80 km north-east of Port Moresby. *Niugini Caver* **1** (3) gives details of access, a location map and a survey of the Jawarere cave, the type locality of the 1968 collection (Richardson, 1974); specimens collected by J. Barnaby in 1960 (Richardson, 1974) probably also originated from Sogeri. Ewers writes (personal communication, 1993) that a guide familiar with the caves and a 4-wheel drive need to arranged at Sogeri. There is a two hour trek; the wet season should be avoided. He describes how the bats left the caves after gunshots and speculates on how this could affect the leech population.

2. Og Cave, Sein village, near Madang (5°16'S: 145°42'E), alt. 40 m (van der Lande, 1993). Figure 1, site 2.

T. Reardon (South Australian Museum) first noticed (1989) leeches in Og Cave, which lies in a relatively accessible area (Humphreys, Jebb & Awramik, 1992). Og Cave extends some 300 m into a limestone face and houses bats and swiftlets (*Collocalia* sp.), as well as invertebrates. The cave floor is rocky, with flowing water and the walls are wet and alkaline to pH paper. The chambers are up to 10 m in height but were not explored beyond the area with leeches. The leeches were accessible without special equipment.

During a short visit in 1992 (van der Lande, 1993), eighteen leeches (only) were found in two clusters 3 - 4 m apart in the aphotic area, one in the vicinity of nests with *Collocalia* nestlings, and the other at a bat roost recognisable (M. Jebb) by characteristic claw marks on the walls. No leeches showed feeding behaviour, although this had been seen (M. Jebb) on previous visits. It was later found that all eighteen specimens had recently ingested blood.

Crop blood from leeches near the swiftlets had nucleated erythrocytes, whereas that from leeches near the bat roost was typically (non-nucleated) mammalian. The species of bats inhabiting Og Cave, other than *Hipposideros cervinus* (T. Reardon) are unknown. According to lists in Christensen Research Institute Report No. 3 (1987), caves in the Madang area harbour the vespertilionid *Miniopterus medius*, but distribution maps in Flannery (1990) show no species of *Miniopterus* in the area. Ewers (1974) states that out of the ten bats listed for Sogeri cave, only *M. tristis* serves as host.

The population size and density of leeches at Og were less than at Sogeri where Ewers (1974) found up to a dozen per square foot. A cursory inspection showed that other fauna included crickets, amblypygids (a group related to spiders; plate 4), assorted spiders and isopods, none of which were unpigmented or eyeless. There were numerous volant swiftlets and at least two species of bat; this cave fauna deserves further study.

Caves with leeches of unknown identity

3. Kaimono Cave, Chuave. 70 km (road) west of Goroka (6°4'S: 145°4'E), alt. 1670 - 2900 m. Figure 1, site 3.

Cave Talk Talk February 1963 **3** (1) describes Miocene limestone caves at Chuave with a map and details of access. The fauna comprised "leeches, spiders, silverfish, crabs, worms, beetles, bats and swiftlets (possibly *C. esculenta*)". The leeches occurred in lower numbers than at Jawarere; the account implies that they were the same species, ie. *L. jawarerensis*, although the leech had not at that time been described by Richardson (1974).

4. Caves in the vicinity of Tabubil, Star Mountains (Western Province)

Finim Tel (5°10'S: 141°19'E). Figure 1, site 4.

Extensive caves in the Finim Tel plateau (20 km north-east of Tabulil) were explored by the 1975 British Speleological Expedition (Brook, 1976). "Smooth, pink leeches" were found in the Stoat Inlet passage of the Selminum Tem, a huge fossil phreatic trunk channel connected to numerous streams and passages. However, from Table 2 (Chapman, 1976) it appears that they

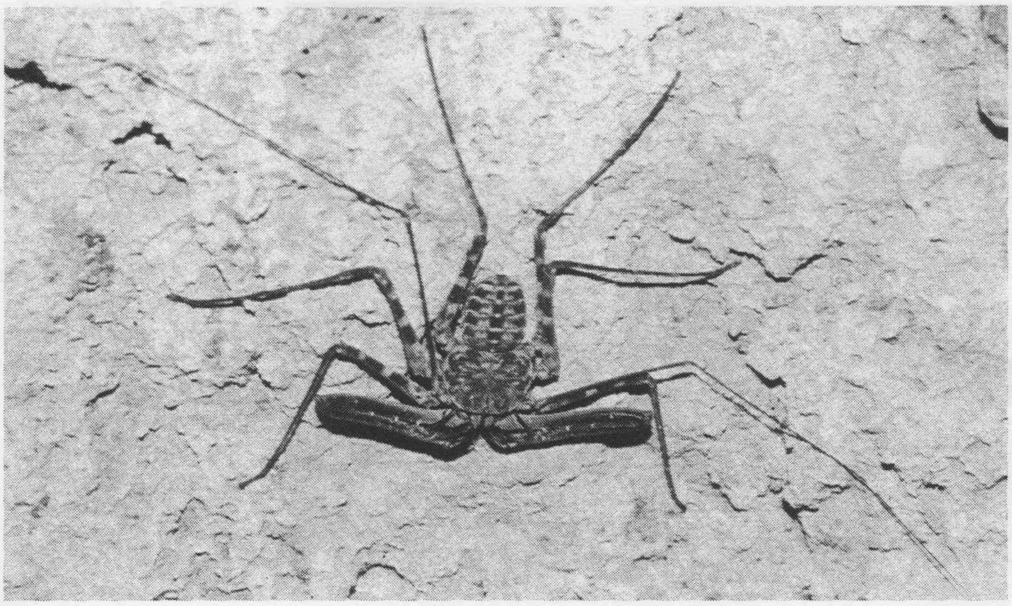


Plate 3. An amblypygid from Balek caves near Madang similar to those observed in Og cave, photographed in situ. Note the stout, raptorial pedipalps and two long tactile, sensory-modified legs. x 2.

inhabited water, and are therefore unlikely to be haemadipsids. Bats (*Dobsonia* spp?) and swiftlets, as well as varieties of invertebrates, were recorded, some of the latter displaying eyelessness and a lack of cutaneous pigmentation.

Pimply-skinned terrestrial cavernicoles (leeches) were also found in Okeminal Tem and Kabim Tem (Ilam Valley) (Table 1; Chapman, 1976). By implication, it seems that these do not lack skin pigment. The account is unclear about their precise location; the vestibule of caves is a known habitat for haemadipsids (see Sawyer, 1986).

The "aquatic" habitat of the smooth, pink leeches is questionable since haemadipsids avoid water. Or perhaps there exists a second, unknown species of cavernicolous leech which is aquatic. Such a leech is likely to be an erpobdellid, a group with aquatic members which includes, among other cave-dwelling forms, three troglobitic species if *Dina* (see above; also Richardson, 1974; Turquin, 1984; Sawyer, 1986). But there has been no response from Dr. Petar Beron (Bulgarian Academy of Science) who retained the Selminum Tem and Ilam valley specimens which therefore, remained unidentified. Both records clearly need confirmation.

Caves at Lukwi (5°21'S: 141°11'E). Figure 1, site 5.

The caves 13 km south-west of Tabubil were studied in 1985; James *et al.* (1989) give locations and maps. Roosting bats (species?) were found in cave LV18 ("Leech Cave") and an adjacent passage, "Railway Tunnel" (photograph, plate 4 in James *et al.*, 1989), in which rows of leeches hung from the roof "waiting for the bats to return with their blood meal". The leeches are not identified, but habitat and behaviour suggest a population of *L. jawarerensis*.

Preservation of leeches in the field

70% ethyl alcohol is a suitable general preservation, although some specimens should be preserved if possible in a formalin-based fixative, such as Bouin, for microscopy. Specimens should not be dropped into preservative without prior relaxation otherwise they die contracted and coiled, making dissection and identification difficult. Relaxation is carried out by adding, drop by drop, 70% alcohol to the water in which the leech is submerged until it fails to respond to gentle pressure (roughly half an hour). This fluid is removed and after removing any mucus, the leech is rearranged on a piece of absorbent (filter) paper in a flat-bottomed, lidded container (eg. petri dish) so that it is straight and **slightly** stretched. More paper is laid over the specimen, and 70% alcohol is added gently, using an eye-dropper. After hardening, the leech can be transferred to a data-labelled vial with fresh preservative.

Smears of crop blood must be prepared from living, unanaesthetised animals; for staining, a standard technique employing Geimsa used by Ewers (1974) is suitable.

Discussion

Turquin (1984) and Sawyer (1986) mentioned other troglobitic leeches which include species of the macrophagous, freshwater-inhabiting, jawless erpobdellid *Dina*; the latter are eyeless and lack cutaneous pigmentation. The possession of eyes by *L. jawarerensis*, albeit reduced, suggests a fundamental difference in biology. Perhaps this relates to a phase in the life-cycle when photo-reception is important, such as a dispersal stage when juveniles are transported via a bat or swiftlet host (adults *in situ* did not react to torchlight; VML, 1992). Eyes are irrelevant under aphotic conditions.

There is no data on bat movements between caves in Papua New Guinea. According to T. Reardon (personal communication, 1994), there have been no banding or population genetic studies on the movements of individual species. However, according to Flannery (1990), at least one species, *Miniopterus australis*, probably migrates seasonally. The role of bats (or swiftlets) in distributing leeches is therefore speculative, especially if the restricted distribution of the leeches compared with their hosts is considered.

Factors associated with breeding and/or dispersal might account for the rarity of caves harbouring leeches, unless they have an environmental requirement only satisfied in a minority of the caves which are otherwise acceptable to bats and swiftlets. Long-term studies of the bats and leeches inhabiting a particular cave system are needed.

Despite the uniform climate within caves, the observations (Ewers, 1974) on size variation in *L. jawarerensis* suggests a seasonal breeding cycle. One can speculate as to whether this is controlled by hormones in the blood of their host, since the stable cave environment will buffer the leeches against external climatic and seasonal changes.

When inside the aphotic recesses of caves, this active sanguivore depends on non-visual sensory stimuli (air movement, smell and taste, temperature, touch, and carbon dioxide concentration; Sawyer, 1986) to recognise, and make quick contact with, a potential host which may be stationary (Ewers, 1974) or in flight (James *et al., 1989*). For aquatic and macrophagous leeches which scavenge as well as predate, there will be constantly-available sources of food which will be detectable by similar sensory input. Sanguivores such as *L. jawarerensis*, in common with other haemadipsids, can probably endure month of starvation if their hosts vacate the caves. Normally their food source (bat or swiftlet blood) is more reliable than that of forest-dwelling haemadipsids which may have to endure long intervals between encounters with vertebrate hosts.

Caves on islands such as Ceram, which have extensive limestone formations, may also harbour leeches. The Nare cave systems in the Miocene karst near the Nakanai Mountains in eastern New Britain, have been well explored but, as in many speleological expeditions, biological observations are limited (Report of the U.K. River Expedition, Papua New Guinea 1984-5: Royal Geographical Society Report no. 1930) and only bats (unidentified), and "hand-sized spider [*sic*] crabs with walnut-sized bodies" which were almost transparent, are mentioned. There are no biological observations for the caves near Pogera, which were explored in 1982 (N. Montgomery; Report no. 1317 at the Royal Geographical Society).

That all the leech caves are in limestone is probably incidental in that this formation can develop cavities which are extensive enough to afford the stable physical conditions required by their hosts, and thus the leeches which parasitise them. Much of the limestone of New Guinea is subject to exceptionally high rainfall and therefore, erodes extensively. However, volcanic caves inhabited by bats merit investigation.

Clearly, geographical barriers such as mountains, have not prevented these highly specialised leeches from colonising caves which are far apart and that vary in altitude. Additional records of *L. jawarerensis* are to be expected, especially from Irian Jaya. Speleology in the New Guinea region continues to be an exciting, under-studied subject.

Acknowledgments

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Contributors from all fields of study related to speleology will be considered for publication. Suitable field include Earth Sciences, Speleochemistry, Hydrology, Meteorology, Conservation, Biospeleology, History, Major Exploration (Expedition) Reports, Equipment and Techniques, Surveying and Cartography, Photography and Documentation. Comprehensive descriptive accounts of the exploration and morphology of individual caves will be welcomed, but simple trip reports and brief cave descriptions are not adequate. Papers overall should not exceed 20 printed pages in length. Contributors intending to write at greater length or requiring any advice on details of preparation are invited to correspond with the Editors. All manuscripts will be read by referees. Short "Letters to the Editor", expressing a personal view or giving a preliminary report of interesting findings, are welcomed, and will be given preference for speedy publication.

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GREY, M.R., 1973 Cavernicolous spiders from the Nullarbor Plain and south-west Australia. *J. Aust. ent. Soc.* 12: 207-221.

VANDEL, A., 1965 Biospeleology. *The Biology of the Cavernicolous Animals.* Pergamon, London. Pp. xxiv, 524.

WIGLEY, T.M.L. and WOOD, I.D., 1967 Meteorology of the Nullarbor Plain Caves. In: J.R. DUNKLEY and T.M.L. WIGLEY (eds), *Caves of the Nullarbor. A Review of Speleological Investigations in the Nullarbor Plain. Southern Austalia*: 32-34. Speleological Research Council, Sydney.

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