The Upper Ordovician Kenyu Formation in the Boorowa District, Southeastern New South Wales

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Conodonts obtained during mapping of the Boorowa 1:100000 geological sheet indicate a late Gisbornian to earliest Eastonian age (Late Ordovician: late Sandbian to earliest Katian) for allochthonous limestone in the Kenyu Formation. This age is based on co-occurrence of *Belodina compressa, Phragmodus undatus* and *Yaoxianognathus wrighti*, associated with *Drepanoistodus suberectus, Panderodus gracilis, Periodon aculeatus, Protopanderodus liripipus, Scabbardella* sp. cf. *altipes* and *Yaoxianognathus* sp. The faunal association, including acrotretide, discinide and lingulide brachiopods in addition to the conodonts, indicates that the limestone was probably originally deposited on the shelf edge, prior to being dislodged down the flanks of a volcanic island in a mass flow. The late Gisbornian to earliest Eastonian age recognised for the Kenyu Formation provides an important constraint on the age and cessation of contemporaneous volcanism in the central Macquarie Arc, represented more extensively further north by the Walli Volcanics and Fairbridge Volcanics. No significant break intervened between the end of this volcanism and ensuing deposition of widespread limestones of Eastonian age on the Molong Volcanic Belt.

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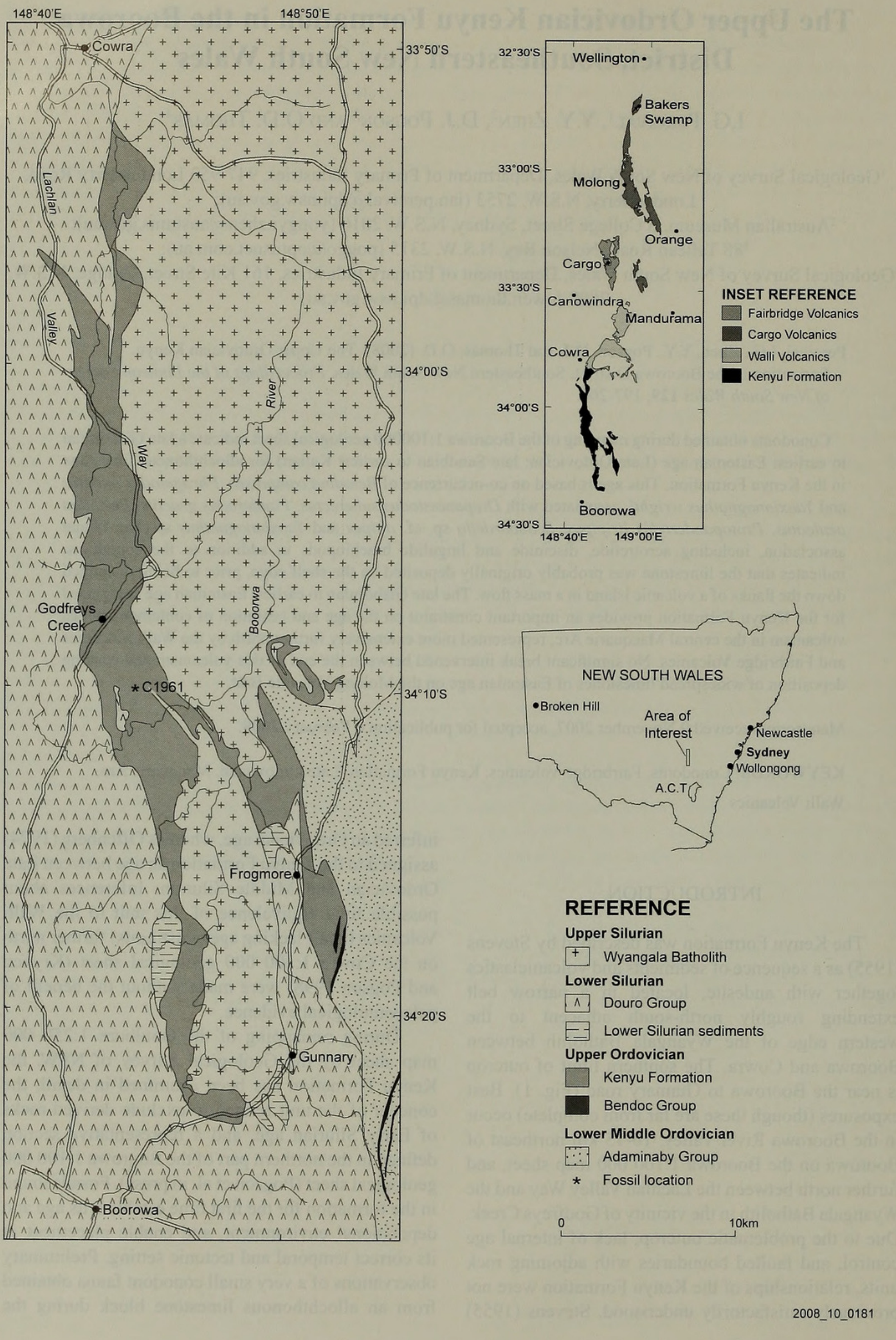
KEYWORDS: Conodonts, Fairbridge Volcanics, Kenyu Formation, Late Ordovician, Macquarie Arc, Walli Volcanics

INTRODUCTION

The Kenyu Formation was described by Stevens (1955) as a sequence of sediments and volcaniclastics together with andesite, located in a narrow belt extending roughly north-south adjacent to the western edge of the Wyangala Batholith between Boorowa and Cowra. The southern limit of outcrop is near the Boorowa to Gunnary road (Fig. 1). Best exposures (though these are far from complete) occur in the Boorowa River valley, 10-15 km northeast of Boorowa on the Boorowa 1:100 000 map sheet, and further north between the Lachlan Valley Way and the Wyangala Batholith in the vicinity of Godfreys Creek. Due to the problematic outcrop, lack of internal age control, and faulted boundaries with adjoining rock units, relationships of the Kenyu Formation were not previously satisfactorily understood. Stevens (1955) inferred an Ordovician age, whereas Offenberg (1974) assigned to the Kenyu Formation an age between Late Ordovician and Middle Silurian. Inferences about possible time equivalence of this unit to the Walli Volcanics (itself lacking age constraints) further north on the Cowra 1:100 000 geological sheet (Krynen and Pogson 1998) were made without the benefit of palaeontological evidence.

During remapping of the Goulburn 1:250 000 map sheet by the Geological Survey of NSW, the Kenyu Formation has been examined in detail, the concept of the unit refined to exclude derived rocks of Early Silurian age, and a representative section defined in the northern part of the Boorowa 1:100 000 geological sheet (Pogson et al. in press). Fossils found in the formation for the first time establish its age and depositional environment, and enable placement in its correct temporal and tectonic setting. Preliminary observations of a very small conodont fauna obtained from an allochthonous limestone block during the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148°50'E
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34°10'S
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Lachlan
Valley
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River
Boorowa
Godfreys Creek
C1961
Frogmore
Gunnary
Boorowa
32°30'S
33°00'S
33°30'S
34°00'S
34°30'S
148°40'E
149°00'E
Wellington
Bakers Swamp
Molong
Orange
Cargo
Canowindra
Mandurama
Cowra
Boorowa
INSET REFERENCE
Fairbridge Volcanics
Cargo Volcanics
Walli Volcanics
Kenyu Formation
NEW SOUTH WALES
Broken Hill
Area of Interest
Newcastle
Sydney
Wollongong
A.C.T
REFERENCE
Upper Silurian
Wyangala Batholith
Lower Silurian
Douro Group
Lower Silurian sediments
Upper Ordovician
Kenyu Formation
Bendoc Group
Lower Middle Ordovician
Adaminaby Group
Fossil location
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10km
2008_10_0181

early phase of the remapping project enabled Percival (2001) to deduce a Gisbornian age. Subsequent resampling of this limestone yielded a significantly larger and more diverse fauna, documented in this paper, that has allowed precise correlations with other volcanic and volcaniclastic-dominated units in the Macquarie Arc, thus providing important age constraints on the cessation of Phase 2 volcanism (Crawford et al. 2007) in the Molong Volcanic Belt.

LITHOLOGICAL CHARACTERISTICS

For much of its exposure the Kenyu Formation occupies a narrow fault-bounded belt, in contact with Early Silurian volcanic rocks of the Douro Group to the west and faulted against the Wyangala Batholith to the east (Johnston et al. 2001). On the Cowra 1:100 000 geological sheet south of the Lachlan River outcrop is very poor, being restricted to a handful of exposures that are surrounded by alluvium. In this area, the extent of the formation is largely defined by its strong aeromagnetic response (Krynen and Pogson 1998). Further south in areas of better exposure, the Kenyu Formation is intruded by the Licking Gully Granite (of the Wyangala Batholith). In the Frogmore area (Fig. 1) several fault-bounded blocks of Kenyu Formation abut the Early to Middle Ordovician Adaminaby Group, Late Ordovician Bendoc Group and the Early Silurian Douro Group. Other Early Silurian sedimentary rocks, previously included within the Kenyu Formation, but now recognised as a new formation (to be defined by Pogson et al. in press), occupy three fault-bounded blocks near Frogmore, Gunnary, and immediately west of the southern belt of Kenyu Formation (Fig. 1).

Faulting and the lack of continuous outcrop limits the potential for a type section. The area where the allochthonous limestone blocks occur is to the southeast of Godfreys Creek (Fig. 1). Here, representative lithologies of the Kenyu Formation (as briefly described below – more detail is presented in Pogson et al. in press) are exposed along Right Hand Creek and tributary gullies (GR 661065 6218310 to GR 657960 6219380) and along Narrallen Creek in the vicinity of GR 661073 6215719. Isolated dip directions and depositional younging trends in this area imply that the limestone blocks lie in the upper part of the formation. Total thickness of the Kenyu Formation is unknown, as both the top and bottom of the unit are faulted out.

The bulk of exposures of the Kenyu Formation consist of dark green to grey, very thinly bedded to medium bedded cherty mudstone (commonly silicified) and siltstone often interbedded with fine-grained mafic volcaniclastic sandstone. Large pavements along Narrallen Creek display parallel bedding laminations, grading and erosional bases, consistent with deposition by turbidity currents. Examples of soft-sediment deformation in this area include flame structures and slump folds. The stratigraphic relationship between these sedimentary rocks, and nearby sequences dominated by primary volcanics and volcaniclastic conglomerates is unclear.

A variety of plagioclase-phyric and pyroxene-phyric andesites and pillow basalts is present in the Kenyu Formation. Black, aphanitic to porphyritic, flow-banded basalt occasionally displaying pillow structures occurs in several locations. One of these pillows (at GR 660628 6218239) is partially enveloped by chert which unfortunately lacks microfossils.

In the Right Hand Creek area, the Kenyu Formation is dominated by volcaniclastic deposits including polymictic conglomerate with subrounded to angular clasts up to cobble and small boulder size of volcanic sandstone and siltstone, and occasionally enclosing masses of porphyritic (feldspar-phyric) andesite/basalt, indicating primary volcanism. Rare allochthonous limestone blocks of various dimensions (the largest up to 250 x 50 m) occur within volcaniclastic sediments in the Right Hand Creek and Narrallen Creek areas. They are all strongly recrystallised, with a definite tectonic foliation. Conodont CAI values of 5+ attest to the effects of considerable post-depositional heat and pressure on these limestones.

PALAEONTOLOGY

Insoluble residue of an allochthonous strongly recrystallised limestone sampled at GR 660085 6217818 (conodont sample C1961 – locality shown

Figure 1 (LEFT). Main map depicts geological units simplified from the Boorowa 8629 1:100 000 geological sheet south of 34°S, together with data interpreted from the Cowra 8630 1:100 000 geological sheet above this latitude, showing inferred extent of Kenyu Formation and localities mentioned in the text. Note that all boundaries between the Kenyu Formation and adjacent units are faulted. Fossil locality C1961 is identical in position to C2362. Inset map shows spatial relationship of Kenyu Formation to Walli Volcanics, Fairbridge Volcanics, and Cargo Volcanics on Molong Volcanic Belt.

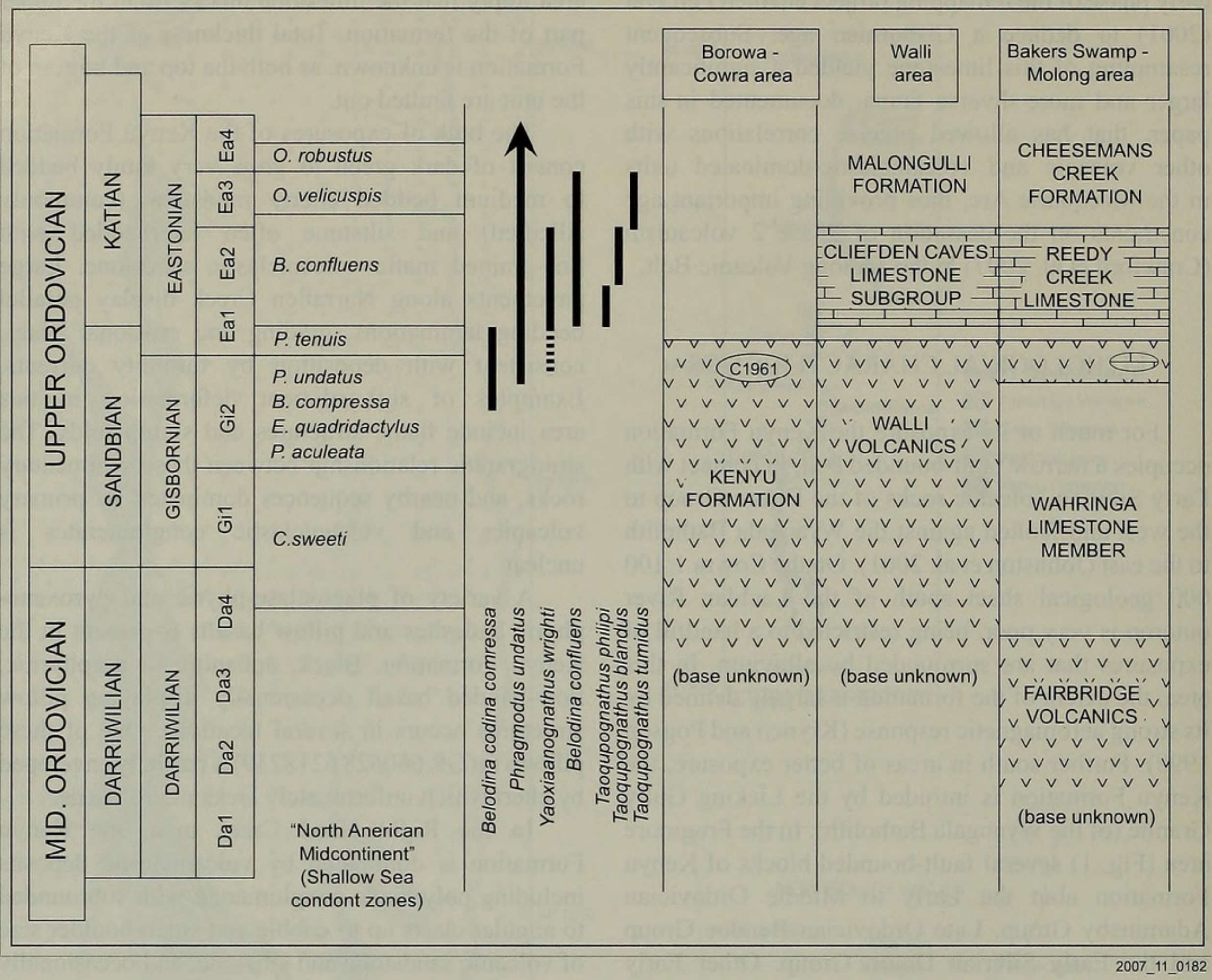

Figure 2. Stratigraphic correlations along the Molong Volcanic Belt (right-hand columns) and ranges of key species (central column), plotted against segment of the Middle to Upper Ordovician timescale and conodont zonation (after Webby et al. 2004 and Goldman et al. 2007). Note that the Yuranigh Limestone Member of the Fairbridge Volcanics is not shown; it equates to the uppermost part (late Gisbornian) of the Wahringa Limestone Member.

on Fig. 1), obtained after acid dissolution in 10% acetic acid and separation in sodium polytungstate, yielded 14 elements referrable to *Protopanderodus liripipus* and *Panderodus gracilis*. Resampling of this limestone block (conodont sample C2362) produced 99 identifiable elements, distributed amongst nine species including *Belodina compressa*, *Drepanoistodus suberectus*, *Panderodus gracilis*, *Periodon aculeatus*, *Phragmodus undatus*, *Protopanderodus liripipus*, *Scabbardella* sp. cf. *altipes*, *Yaoxianognathus wrighti* and *Y.* sp., indicating a late Gisbornian to earliest Eastonian age (Fig. 2). This age corresponds to the late Sandbian to earliest Katian stages of the Late Ordovician, approximately 457-455 Ma on the age scale of the International Commission on Stratigraphy (Cooper and Sadler 2004).

The most significant species supporting this age determination are *Belodina compressa* and *Phragmodus undatus*. *Belodina compressa* is mainly differentiated from the succeeding species, *B. confluens,* in having a distinctly flattened section of the anterior margin at the antero-basal corner in inner lateral view (Fig. 3A). Absence of *B. confluens* from the assemblage in the Kenyu Formation allochthonous limestone implies that the latter was not contemporaneous with the widespread Eastonian limestones of the Macquarie Arc in which *B. confluens* is prolific. Grandiform and compressiform elements of *B. compressa*, represented by eight specimens recovered from sample C2362 (Fig. 3A, B), are identical with those obtained from the upper part of the Wahringa Limestone Member (in the Bakers Swamp area further north on the Molong Volcanic Belt) and from allochthonous limestone blocks in the immediately overlying Fairbridge

Volcanics (Zhen et al. 2004). In the North American Midcontinent succession typical of warm shallow seas, *B. compressa* is recognized as an index zonal species with a stratigraphic range from the *compressa* Zone of late Gisbornian age-equivalence to the *tenuis* Zone of the early Eastonian (Sweet 1988).

Co-occurrence of *Phragmodus undatus*, represented by four S and three M elements in sample C2362, further restricts this age range from latest Gisbornian to earliest Eastonian (*undatus* to *tenuis* zones). In the North American Midcontinent succession, *P. undatus* defines the eponymous Zone immediately above the *compressa* Zone with a range extending from the *undatus* Zone to the end of the Ordovician (Sweet 1988). The species has been widely recorded in Eastonian-age carbonates of central NSW (Zhen and Webby, 1995; Trotter and Webby 1995; Zhen et al. 1999, 2003).

Broad support for a late Gisbornian to earliest Eastonian age assignment for the Kenyu Formation limestone is provided by the co-occurrence of *Protopanderodus liripipus*, *Periodon aculeatus* and *Yaoxianognathus wrighti* in the fauna. *P. liripipus* has an age range from the late Gisbornian to near the end of the Ordovician (Sweet 1988). It was recorded in the upper Wahringa Limestone Member also in association with *B. compressa*, *Periodon aculeatus* and *Panderodus gracilis* (Zhen et al. 2004), and from the Bowan Park Limestone Subgroup (Zhen et al. 1999) in central New South Wales. *Yaoxianognathus wrighti*, widely distributed in the Fossil Hill Limestone, Bowan Park Limestone Subgroup, and other time equivalent limestones in central New South Wales, is represented only by the Pa element (Fig. 3U) with seven specimens recovered from sample C2362. Its presence in the Kenyu limestone most likely indicates an extension of its age range into slightly older rocks than was previously known.

Two fragmentary specimens from the same sample are referred to Pb elements (Fig. 3V) of *Yaoxianognathus* sp. and an additional specimen from sample C2366 is a bipennate ramiform element assignable to the S (most likely Sc) position (Fig. 3W). These specimens show marked differences from corresponding elements of *Y. wrighti*, but due to the limited material it is uncertain whether they represent elements of a single additional species of *Yaoxianognathus*.

DISCUSSION

Age connotations

Although the age range deduced for the conodont fauna from the Kenyu Formation is relatively restricted, the fact remains that these fossils were extracted from allochthonous limestone which is poorly constrained stratigraphically within this unit. The late Gisbornian to earliest Eastonian age merely indicates the maximum age (for the originally deposited limestone) and the allochthonous blocks may either have been penecontemporaneously redeposited, or else could be significantly younger. As discussed below, regional correlations strongly support the former view. The widespread volcanic hiatus (Packham et al. 2003, Percival and Glen 2007) that extended throughout the western Molong Volcanic Belt in Eastonian time precludes Kenyu Formation volcanicity during that interval. Large feldspar phenocrysts, observed in Kenyu Formation andesites located in the vicinity of the allochthonous limestone blocks, are also characteristic of other pre-Eastonian lavas in the Molong Volcanic Belt, such as the Walli, Fairbridge and Cargo Volcanics, and do not suggest similarities with post-Eastonian Phase 4 volcanics.

Previously proposed correlations (Krynen and Pogson 1998, Percival and Glen 2007) equated the Kenyu Formation with the upper part of the Walli Volcanics, exposed in the Walli-Cliefden Caves area between Mandurama and Canowindra, 90 km north of Boorowa (Fig. 1). The late Gisbornian to earliest Eastonian age now established for part of the Kenyu Formation supports this correlation. The Walli Volcanics contain no internal evidence of age; however, this unit is overlain (with minor disconformity) by shallow water sedimentary rocks of the Fossil Hill Limestone (Cliefden Caves Limestone Subgroup) at Fossil Hill, near Cliefden Caves (Webby and Packham 1982). As these strata contain early Eastonian (middle Late Ordovician: early Katian Stage) conodonts (Zhen and Webby 1995), any time break between deposition of volcaniclastic conglomerates at the top of the Walli Volcanics (eroded from immediately underlying andesitic lavas), and the intertidal mudstones and impure limestones which infilled the irregular topography of the underlying volcanic island, must have been minimal. Correlation between part of the Kenyu Formation of late Gisbornian to earliest Eastonian age and the upper Walli Volcanics does not preclude both formations from having a depositional history extending back into the Darriwilian, in common with other volcanics in the Macquarie Arc (Percival and Glen 2007).

Elsewhere in the northern Molong Volcanic Belt of the Macquarie Arc, strata contemporaneous with limestone in the Kenyu Formation include the Yuranigh Limestone Member of the Fairbridge Volcanics in the vicinity of Molong (Percival et al. 1999). Of the depauperate conodont fauna obtained from this very shallow water limestone, only *Belodina compressa* (initially identified as *B. confluens* by Percival et al. 1999, but reassigned by Zhen et al. 2004) is in common with the deeper water Kenyu assemblage. Approximately 1300 m of volcaniclastic sandstones and conglomerates, intruded by felsic igneous rocks and hornblende-bearing dykes, intervenes between the Yuranigh Limestone Member and the Reedy Creek Limestone of early Eastonian age. A comparable situation occurs in the Bakers Swamp area, 35 km north of Molong, where the upper beds of the Wahringa Limestone Member of the Fairbridge Volcanics (Zhen et al. 2004) contains, inter alia, the conodonts *B. compressa*, *Panderodus gracilis* and *Periodon aculeatus*, again from a relatively shallow water setting. The Wahringa Limestone Member is overlain by a substantial but unknown thickness of volcaniclastics, rare lavas and allochthonous limestone pods, which equate to the section of Fairbridge Volcanics overlying the Yuranigh Limestone Member.

In the Bowan Park area between Orange and Cudal, on the western side of the Molong Volcanic Belt, the Cargo Volcanics is overlain by the Bowan Park Limestone Subgroup which is of early to late Eastonian age (Zhen et al. 1999). Pickett (1974) recorded a solitary specimen of *Belodina* from a limestone lens within the Cargo Volcanics south of Cargo, though unfortunately Simpson et al. (2007) were unable to relocate this lens to determine whether its relationship to the enclosing volcanics was conformable or allochthonous. Simpson et al. (2007) recognised a significant discordance between bedding orientations in the uppermost volcaniclastic-dominated successions of the Cargo Volcanics and those in the overlying Bowan Park Limestone Subgroup. This observation, combined with correlations (based on time planes recording the cessation of terrigenous erosional input) between the Bowan Park and Cliefden Caves carbonate successions which suggest that clastic deposition commenced as much as half a zone earlier in the Fossil Hill Limestone (Webby and Packham 1982; Packham et al. 2003; Simpson et

Figure 3 (RIGHT). Scanning electron microscope photomicrographs of conodonts from allochthonous limestone in the Kenyu Formation. MMMC and C refer to registered specimen numbers and sample numbers, respectively, in the Microfossil Collection of the Geological Survey of NSW, Londonderry; numbers commencing with IY indicate digital photofiles from the Electron Microscope Unit, Australian Museum, Sydney.

A, B. *Belodina compressa* (Branson and Mehl, 1933); A, compressiform element, MMMC4367, C2362, inner lateral view (IY102001); B, grandiform element, MMMC4368, C2362, outer lateral view (IY102005).

C, D. *Scabbardella* sp. cf. *altipes* (Henningsmoen, 1948); c element, MMMC4369, C2362, C, furrowed side (IY102010), D, unfurrowed side (IY102009).

E-G. *Drepanoistodus suberectus* (Branson and Mehl, 1933); E, Sb element, MMMC4370, C2362, inner lateral view (IY102023); F, M element, MMMC4371, C2362, posterior view (IY102022); G, Sd element, MMMC4372, C2362, inner lateral view (IY102024).

H-J. *Panderodus gracilis* (Branson and Mehl, 1933); H, falciform element, MMMC4373, C1961, furrowed side (IY037006); I, graciliform? element with distally recurved cusp, MMMC4374, C2362, furrowed side (IY102028); J, graciliform element, MMMC4375, C1961, furrowed side (IY037007).

K-N. *Periodon aculeatus* Hadding, 1913; K, M element, MMMC4376, C2362, anterior view (IY102017); L, M element, MMMC4377, C2362, posterior view (IY102016); M, Sc element, MMMC4378, C2362, inner lateral view (IY102018); N, Sc element, MMC4379, C2362, outer lateral view (IY102019).

O, P. *Phragmodus undatus* Branson and Mehl, 1933; O, M element, MMMC4380, C2362, posterior view (IY102021); P, Sc element, MMMC4381, C2362, inner lateral view (IY102020).

Q-T. *Protopanderodus liripipus* Kennedy, Barnes and Uyeno, 1979; Q, R, Sa element, MMMC4382, C2362, lateral views (IY102025, IY102026); S, Sb? element, MMMC4383, C1961, inner lateral view (IY037004); T, P element, MMMC4384, C2362, inner lateral view (IY102027).

U. *Yaoxianognathus wrighti* Savage, 1990; Pa element, MMMC4385, C2362, outer lateral view (IY102011);

V, W. *Yaoxianognathus* sp.; V, Pb? element, MMMC4386, C2362, outer lateral view (IY102015); W, Sc? element, MMMC4387, C2366, inner lateral view (IY102036). Scale bars are 100 µm.


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al. 2007), imply that the Cargo block had a different geological history from that of the contiguous central Molong Volcanic Belt to the east.

Depositional environment

The association of large allochthonous limestone blocks with poorly sorted volcaniclastic conglomerates in the upper Kenyu Formation suggests that the limestones were redeposited downslope via mass slumping. Evidence for an original depositional environment on an unstable shelf edge comes from the microfauna extracted from the residues (samples C1961 and C2362) of the limestone. The conodont fauna includes some forms (eg *Belodina compressa* and *Phragmodus undatus*) that typically characterise shallow waters, associated with *Periodon aculeatus* and *Protopanderodus liripipus* that tend to inhabit interpreted deeper water environments. The fauna also includes acrotretide (*Scaphelasma*?) and discinide (*Orbiculoidea*) brachiopods together with large indeterminate thick-shelled lingulides, flat-spired gastropods, hyolithids and associated opercula. Unfortunately these specimens are all either fragmented or tectonically strained, preventing precise identifications (and detracting from their documentation by illustration in this paper). This ecological association is somewhat reminiscent of the fauna from allochthonous limestones in the Malongulli Formation (overlying the Cliefden Caves Limestone Subgroup), which are believed to represent periplatform deposits originally deposited on the shelf edge or upper slope and subsequently dislodged into deeper water (Webby 1992).

The association in the Kenyu Formation of allochthonous limestones with volcanics is typical of successions accumulating around oceanic islands and seamounts, where the steep flank gradients ensure proximity of a variety of rock types and allow for intermixing of otherwise disparate facies. Much of the Kenyu Formation can be interpreted as volcaniclastic and sedimentary deposits forming an apron proximal to a source of primary volcanism, represented in the Kenyu Formation by pillow basalts and minor flows issuing from localised vents. Submarine eruption of the correlative Walli Volcanics to the north, indicated by the presence of pillow basalts (Smith 1967, 1968), built the southern region of the Molong Volcanic Belt up to depths where limestones were deposited on the submarine flanks of this major volcanic centre.

CONCLUSIONS

Limestone within the Kenyu Formation is determined as having a late Gisbornian to earliest Eastonian depositional age, primarily on the basis of co-occurrence of the conodonts *Belodina compressa* and *Phragmodus undatus*. This age constraint supports previously conjectured correlation of part of the Kenyu Formation with the upper part of the undated Walli Volcanics. Furthermore, a consistent age relationship is recognisable along the entire length of the central Molong Volcanic Belt, where limestones of late Gisbornian age (Yuranigh and upper Wahringa Limestone Members of the Fairbridge Volcanics) are overlain by subsequent volcanic and volcaniclastic deposits that are directly succeeded in the Molong area by early Eastonian limestones. The Walli Volcanics, that formed the volcanic island around which the volcaniclastic-dominated apron of the Kenyu Formation accumulated, are in turn overlain by the early Eastonian age Fossil Hill Limestone. The time interval between cessation of volcanism and subsequent erosion, leading eventually to extensive carbonate deposition, must have been very brief in geological terms. Any suggestion of an angular unconformity between the Walli Volcanics and the Cliefden Caves Limestone Subgroup (cf Smith 1968) is almost certainly not due to contemporaneous tectonic activity, but rather results either from differences in original depositional gradient, or else is due to subsequent faulting. The situation in the Cargo block on the western flank of the Molong Volcanic Belt appears to differ, with both tectonic activity and a significant depositional hiatus intervening between the Cargo Volcanics and the overlying Bowan Park Limestone Subgroup.

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