

Gondwanan tectonics and European events in the Silurian of Australasia

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KEY WORDS - Silurian, Australasia, New South Wales, Victoria, Queensland, Tasmania, bioevents, tectonics, Lachlan Orogen, Lachlan Fold Belt, graptolites, conodonts.

ABSTRACT - Silurian biostratigraphic events defined in north-west Europe correspond with intervals of marked tectonic activity in Australasia (north-east Gondwana) but the accuracy in correlation is not such that a European biostratigraphic event can be tied to a specific Australasian tectonic event. Problems remain in a strict application of European Silurian zonation schemes in Australasia. In the eastern margin of the Australian plate the earlier part of the Silurian (Llandovery-early Wenlock?) is represented mostly by deep water siliciclastic sediments with few calcareous beds in the Lachlan Fold Belt (LFB) and many of those uncertain as to whether autochthonous or allochthonous. Events of any kind are difficult to recognise within the Llandovery in the eastern part of the LFB in New South Wales because of later structural complications, particularly the imbrication of Late Ordovician and early Silurian fault slices which nonetheless have very similar lithologies.

Silurian strata are structurally simpler in the western part of the LFB where the pre-Wenlock is represented by fairly uniform laminate quartzose siltstone in which the late Llandovery *guerichi* Zone is the youngest recorded. Above the *guerichi* fauna is an hiatus of uncertain duration but is interpreted as encompassing the *lapworthi* and *murchisoni* graptolitic bioevents and the *Ireviken*, *Boge* and *Valleviken* events. Above the hiatus is an horizon with a *ludensis-sherrardae* fauna. This hiatus is also apparent in the eastern part of the LFB in the Yass and Goulburn districts. The *ludensis-sherrardae* fauna is overlain with a low angle unconformity by the non graptolitic *Derriwong* Group. The basal unit of the *Derriwong* Group is a pebbly sandstone lacking age diagnostic fossils but overlying the sandstone is a felsic volcanic sequence with interbedded limestones which contain a *remscheidensis*, possibly even *crispa* Zone conodont fauna. The indicated hiatus thus spans much of the Ludlow and overlaps with the timespan covering the *Linde* and *Lau* events. In the eastern part of the LFB there is more or less continuous sedimentation, with notable olistostromes in the *Pridoli*, corresponding to the hiatus during the Ludlow in the western LFB.

Comparisons with Central Victoria show marked similarities in the stratigraphic record for the Llandovery but comparisons with the late Silurian are hindered by a comparatively poor fossil record in Victoria where graptolites are concerned. Silurian graptolite occurrences in Queensland and Tasmania are essentially spot collections and difficult to compare with the more complete sections in New South Wales and Victoria.

RIASSUNTO - [Tettonica gondwaniana ed eventi europei nel Siluriano dell' Australasia] - Gli eventi biostratigrafici siluriani, che sono stati definiti principalmente nell'Europa nord-occidentale, corrispondono a intervalli di marcata attività tettonica in Australasia (Gondwana nord-orientale). Tuttavia la precisione della correlazione non permette di associare un evento biostratigrafico Europeo a un evento di tipo tettonico in Australasia. Infatti, rimangono dei problemi nell'applicazione in Australasia degli schemi di biozonatura del Siluriano europeo (Strusz, 2007). Al margine orientale di Australasia, nel "Lachlan Fold Belt" (LFB), la prima parte del Siluriano (Llandovery-Wenlock inf.?) è rappresentata, per lo più, da sedimenti silicoclastici di acqua profonda con pochi livelli calcarei.

Nella parte orientale della LFB, nell'area di Goulburn, sono difficili da riconoscere eventi tettonici di qualsiasi tipo avvenuti durante il Llandovery a causa di complicazioni strutturali. In questa area, rocce di litologie analoga, di età ordoviciano sup. o siluriana inf., sono giustapposte in una struttura embricata.

Nell'area occidentale del LFB, vicino a Forbes, dove la struttura dei sedimenti siluriani è più semplice, le rocce pre-wenlockiane sono costituite da siltiti quarzose della *Cotton Formation*, nelle quali sono documentate faune a partire dalla Biozona a *guerichi*. In questa formazione il bioevento a graptoliti "*sedgwickii*" coincide con una variazione minore di litologia testimoniata da litotipi distinti e più resistenti nelle biozone a graptoliti a *sedgwickii* e a *guerichi* (Sherwin, 1974; Loydell et al., 1993). La successione prosegue, dopo una ampia lacuna stratigrafica con la base del *Forbes Group*, costituita da un conglomerato polimitico/poligenico cementato da carbonati (*Bocobidgle Conglomerate*) la cui età non è ancora stata stabilita con precisione. La *Mumbidgle Formation* è sovrapposta al conglomerato ed è composta da circa 300 metri di argilliti di colore grigio oliva. La durata dello hiatus fra la *Cotton Formation* e il *Forbes Group* non è certa ma è considerata tale da includere i bioeventi a graptoliti "*lapworthi*" e "*murchisoni*" e i bioeventi a conodonti "*Ireviken*", "*Boge*" e "*Valleviken*". Lo hiatus è anche documentato nella parte orientale del LFB nell'area di Yass e Goulburn (Thomas & Pogson, in stampa). Una debole discordanza separa il *Forbes Group* dal *Derriwong Group*, in cui non sono presenti graptoliti. La base del *Derriwong Group* è costituita da arenarie conglomeratiche prive di fossili diagnostici, seguite da rocce vulcaniche acide intercalate con strati calcarei. Questi livelli carbonatici contengono una fauna a conodonti appartenente alla Biozona a *remscheidensis*, anche se una possibile età poco più antica (Biozona a *crispa*) viene ipotizzata per questi livelli da Pickett & Ingpen (1990). Quindi lo hiatus comprende quasi completamente il Ludlow e coincide in parte con il periodo in cui si sono verificati i bioeventi a conodonti "*Linde*" e "*Lau*". Invece, nella zona orientale del LFB la sedimentazione fu continua con deposizione di olistoliti durante il *Pridoli* (Sherwin, 1971; Thomas & Pogson, in stampa) che testimoniano la presenza di sedimenti corrispondenti allo hiatus nella parte occidentale del LFB.

Confronti con il New South Wales e il Victoria centrale mostrano notevoli similitudini nella documentazione stratigrafica del Llandovery, mentre i confronti sono più complicati nel Siluriano superiore a causa della scarsa presenza di graptoliti in Victoria. I ritrovamenti di graptoliti siluriani in Queensland e in Tasmania sono ancora più rari e limitati a dati sporadici, rendendo molto problematico il confronto con le successioni più ricche documentate in New South Wales e Victoria.

INTRODUCTION

Talent et al. (2003) summarised the Silurian sections in Australasia, with particular emphasis on those in the Lachlan Orogen or Fold Belt (Coney, 1992) of south-east continental Australia (Fig. 1). The Australian conodont zones, especially those established by Bischoff (1986), were reviewed and modified by Simpson (1995) and Cockle (1999). For the late Silurian, Jeppsson et al. (2007) were able to make high resolution correlations between northern Europe and Queensland based upon conodonts. Following upon the summary of the Silurian period in Gradstein et al. (2004), Pogson (2009) reviewed the SHRIMP U-Pb zircon isotopic dates for the Siluro-Devonian of the Lachlan Orogen and made significant changes to the age of the base of all major Silurian subdivisions except the Llandovery. Strusz (2007) assessed the relevance of the standard Silurian time scale to Australian sequences and noted the apparent local lacunae in the internationally recognised graptolite and conodont zones, especially in the early Silurian. This is

partly a reflection of the comparative paucity of carbonates in the largely siliciclastic sequences deposited in the Lachlan Orogen during the early Silurian.

In the Mitta Mitta River area of eastern Victoria, Talent et al. (2005) noted several limestones with conodont faunas broadly dated as *celloni* to *amorphognathoides* zones (late Llandovery to early Wenlock) but acknowledged that opinion is divided as to whether or not these limestones are autochthonous or allochthonous, although they concluded both origins were likely to explain lithological differences observed in outcrops. Furthermore, they noted that because of the lack of fossils in the associated siliciclastic sediments it is uncertain if, should the limestones prove to be allochthonous, they slumped into near contemporary deeper water environments or much later. In the Goulburn district of New South Wales limestone clasts, comparable in age with those in eastern Victoria (ie., *celloni* to *amorphognathoides* zones), in the shale rich Jerrara Formation are associated with a well documented, near contemporary, graptolite fauna ranging in age from the

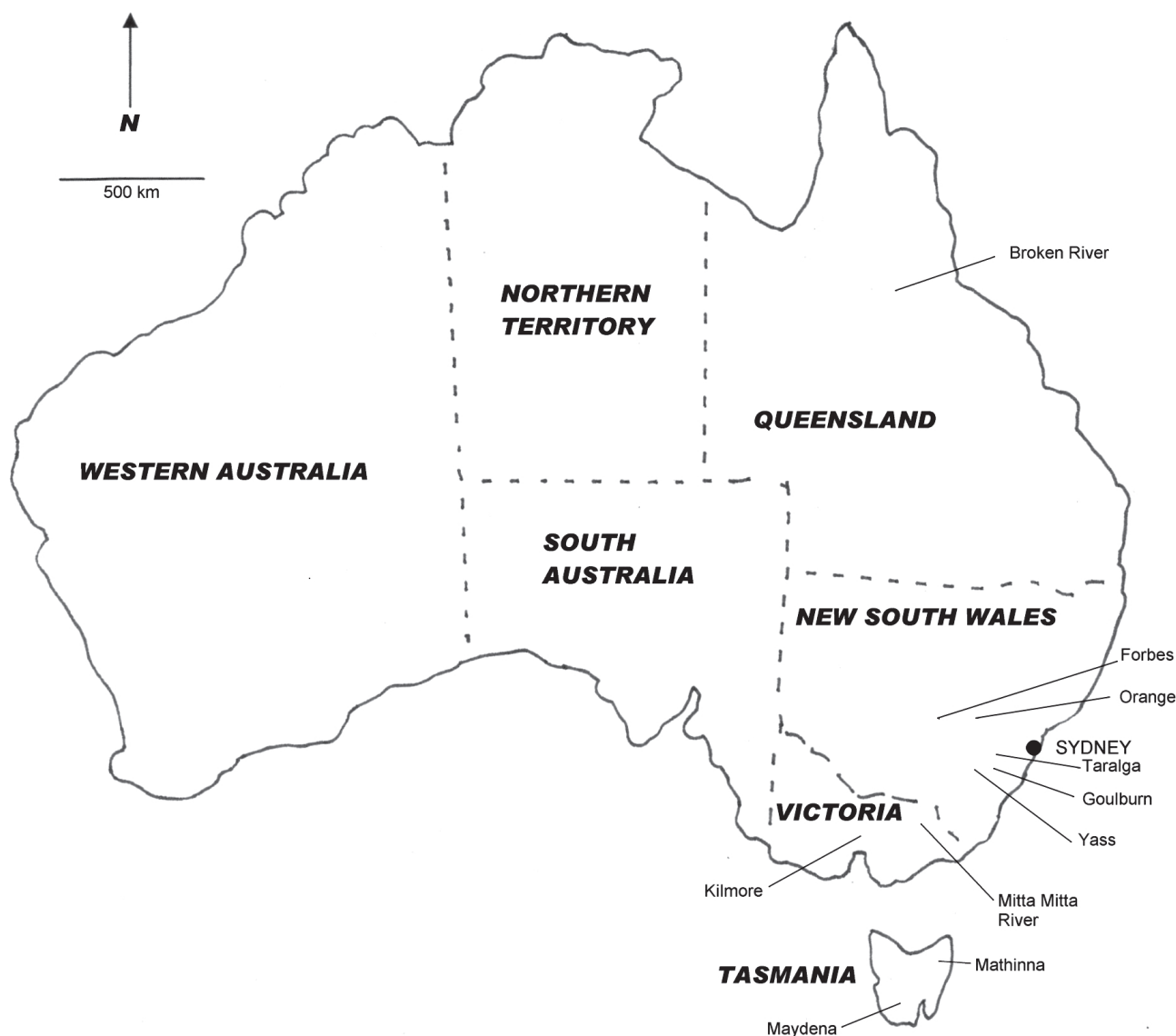


Fig. 1 - Silurian graptolite localities in the Lachlan Fold Belt of eastern Australia mentioned in text.

sedgwicki to *crenulata* graptolite zones (Naylor, 1936; Percival & Sherwin, 2005; Sherwin, in press). Northwest of Goulburn the Hanaminno Limestone (Pogson, in press) has a conodont fauna comparable with that of the clasts in the Jerrara Formation but the extent of this limestone is so limited that uncertainty exists as to whether it is autochthonous or allochthonous. Even the early Silurian limestones from Forbes mentioned by Simpson (1995) are of limited extent and so far have proved totally resistant to attempts at processing for conodonts, being more marl than limestone. South of the Llandovery conodont occurrences near Orange in the Central West region of New South Wales, documented by Bischoff (1986), Simpson (1995) and Cockle (1999), the existence of an extensive early Silurian carbonate platform, or series of platforms, from the Goulburn district to Eastern Victoria depends very much upon the evidence of allochthonous deposits.

For the late Silurian the conodont sequences are much more complete, although in eastern Victoria there are undeniable structural complications (Talent et al., 2005). The abovementioned studies in Queensland and the Central West of New South Wales have been supplemented by earlier work in the Yass district (Link & Druce, 1972), west of Goulburn, where the conodont zones can be correlated with graptolite faunas (Rickards & Wright, 1999) from interbedded siliciclastic units.

In comparison with the work done on conodonts there are comparatively few on graptolites, especially outside of New South Wales and Victoria. Strusz (2007, p. 161) noted "...that the sequence of graptolite faunas in Australia (in comparison with Europe and Kazakhstan at least) is fragmented and incomplete". The reason for some of these hiatuses is the theme of this paper, which represents an update of problem areas following recent mapping by the Geological Survey of New South Wales. The extensive areas in Western Australia and the Northern Territory believed to be of Silurian age are not known to contain either conodonts or graptolites and the sedimentology is suggestive of evaporites or continental deposits (Walley et al., 1990).

AUSTRALASIAN SILURIAN EVENTS

The relationship between critical events in graptolite evolution and eustatic changes in various parts of the world has been discussed at length by several workers, including Johnson & McKerrow (1991), Koren' & Urbanek (1994) and Loydell (1998). In the Lachlan Fold Belt (LFB) the most detailed study of this type is that for the late Wenlock to early Ludlow interval by Rickards et al. (1995). Many of the better dated sections illustrated by Talent et al. (2003) show a distinct, widespread break between the late Llandovery and late Wenlock. In some locations the sedimentary hiatus is associated with felsic volcanics. The difficulty in obtaining precise dates on the length of this hiatus is the problem of recognising standard Wenlock graptolite zones. These depend very much upon cyrtograptids, a group notably rare in Australasia and Gondwana in general (Sherwin 1982). The species near Orange (Fig. 1), described by Rickards et al. (1995), were doubtfully assigned to *Cyrtograptus* and none of their

specimens displayed any branching. South of Orange, Jenkins (1978) noted a break between the Ordovician and Silurian and another between the *argenteus* and *turriculatus* (= *guerichi*?) graptolite zones. The limestones associated with shales bearing graptolites representative of the *triangulatus* to *argenteus* zones contain a conodont fauna (Bischoff, 1986) but the coral and algal content indicated a shallower environment than usual for most other early Silurian sequences in the LFB, including those in Victoria. Sherwin (1975) proposed that the observed hiatuses were caused by eustatic rather than local tectonic activity. Bischoff's zones in the Orange district were revised by Cockle (1999) and related to the then recognised local and world wide Silurian events. A brachiopod turnover across the Ireviken Event in the Orange has also been described (Valentine et al., 2003).

East Lachlan Fold Belt - Yass-Goulburn district

The Silurian stratigraphy near Goulburn, New South Wales, in the east of the LFB, a problematic area for Talent et al. (2003), has since been much revised (Thomas & Pogson, in press) although the relationship between the Ordovician and Silurian in this region is still unclear. No graptolites, or indeed any fossils, have been found in the sandstone dominated Margules Group (Fig. 2) representative of zones between the Late Ordovician mid Bolindian stage and the late Llandovery *crispus* Zone and even the latter are known only from fault bounded slices of the shale dominant Jerrara Formation (Sherwin, in press). Most of the observed contacts between the Late Ordovician (early Silurian?) and mid Silurian (represented by the Mount Fairy Group) in this region are faulted but the few that have been observed are marked by probable angular unconformities and sharpstone conglomerate at the base of the Mount Fairy Group. The mid Silurian (late Wenlock) age in this instance is based upon pentamerid brachiopod occurrences. However, it is clear that the *murchisoni* and *lapworthi*, possibly even the *lundgreni*, bioevents correspond to a major regional hiatus in this region of the east LFB.

Fossils are locally abundant in the Mount Fairy Group, mostly in calcareous beds near the base, but conodont yields are poor and graptolites are abundant only in the lower third of the unit where *Bohemograptus bohemicus* subsp. are very abundant in a black silty shale which weathers to an off white colour at the surface. The Mount Fairy Group as a whole contains a variety of lithologies and hence formations but this graptolitic black shale is particularly widespread beyond the limits of the Goulburn district as far as Yass to the west and north-west beyond Orange. This particular *Bohemograptus* proliferation has been correlated with the *kozłowskii* bioevent, though given the near universal flattened state of the material it is more appropriately understood in the sense of Holland & Palmer (1974). Above this *Bohemograptus* proliferation 'zone', to the north of Goulburn and west of Orange, there is a widespread olistostrome horizon with angular limestone clasts up to 10 metres in length. West of Orange this olistostrome horizon (Sherwin, 1971) is associated with a *transgrediens* Zone fauna (Sherwin & Rickards, 2002), clearly placing this phase of olistostrome deposition at the *transgrediens* bioevent. Elsewhere at about this level in the Goulburn district the

CHRONOSTR.	GRAPTOLITE ZONES	BIOEVENTS	LACHLAN FOLD BELT STRATIGRAPHY	
			FORBES	GOULBURN
Lochkov	uniformis	Klonk <i>transgrediens</i>	Derriwong C	volcanics
Pridoli	transgrediens bouceki lochkovens-branchensis parultimus-ultimus		Group	Mount Fairy Group
Ludlow	formosus bohemicus tenuis-kozłowski leintwardinensis-linearis scanicus nilssoni		C	olistostromes sediments
Wenlock	ludensis praedeubeli-deubeli parvus-nassa lundgreni/testis perneri-rigidus riccartonensis murchisoni centrifugus	Kiev <i>spineus</i>	angular	G
		Lau <i>kozłowski</i>	unconformity	
		leintwardinensis Linde		
Llandovery	lapworthi-insectus spiralis crenulata-griestoniensis crispus turriculatus guerichi sedgwickii convolutus argenteus pectinatus-triangulatus cyphus vesiculosus acuminatus ascensus	Mulde <i>lundgreni</i>	G Forbes	angular unconformity
		Boge	Group	
		murchisoni Ireviken		
Bolindian	persculptus	lapworthi	hiatus	G Jerrara Formation
		S-P <i>utilis</i>		
		sedgwickii Sandvika	G Cotton	
		acuminatus	G marl horizon	hiatus?
			Formation	Margules Group

Fig. 2 - Postulated correlation of European Silurian events (after Gradstein et al., 2004) with tectonic/eustatic events of the Lachlan Fold Belt within New South Wales (north east Gondwana). Graptolite occurrences indicated by "G" and conodonts by "C" in the columns.

Mount Fairy Group contains several felsic to intermediate volcanic formations.

East Lachlan Fold Belt - Forbes district

The Silurian stratigraphy in the Forbes district has a mid Silurian hiatus broadly comparable with that in the east around Goulburn but differs in the late Silurian (Fig. 2). The Cotton Formation, essentially well laminated siltstone, does not show any significant lithological change across the Ordovician-Silurian boundary, although not every one of the standard graptolite zones has been recorded. This can be attributed at least in part to the

generally poor outcrop of the Cotton Formation, although the youngest confirmed graptolite zone in this formation is that of *guerichi* or possibly *turriculatus* (Sherwin, 1974; Loydell et al., 1993). The hiatus between the Cotton Formation and overlying Forbes Group is associated with a slight angular discordance but the duration is uncertain. The only graptolites known from the Forbes Group are near the top of the group and indicative of the *ludensis-sherrardae* zone. It is likely this hiatus corresponds to the *utilis*, *lapworthi* and possibly also the *murchisoni* bioevents. The Forbes Group consists largely of olive silty mudstone but the conglomeratic base is cemented

by algal limestone, a distinct contrast with the underlying Cotton Formation. This marked change in sedimentary environment is associated with the Ireviken and possibly also the Boge event.

The history of this western region for the Ludlow and Pridoli is a marked contrast with that in more easterly regions such as Orange and Goulburn. There is no sedimentary record for all but the very late Ludlow and consequently no evidence at all for the otherwise widespread *Bohemograptus* proliferation 'zone' which is characteristic of the eastern LFB. The Derriwong Group, which overlies the Forbes Group with a distinct angular unconformity, has a sandy to conglomeratic basal unit, cross bedded in part, comparable with Old Red Sandstone facies of Europe. Overlying the basal sands and pebble conglomerates are felsic to intermediate volcanics, interbedded with limestone and thinly bedded shale. The conodont fauna indicates a mostly Pridoli to early Lochkovian age (Pickett, 1978; Pickett & Ingpen, 1990), with one sample possibly as old as *crispa* Zone. The complete lack of graptolites to date in the Derriwong Group makes it difficult to draw any conclusions with respect to late Silurian graptolite bioevents. However, using conodont evidence the Derriwong Group, and its distinctive lithology, does appear to follow upon the Lau event. Most or all of the Silurian outcrops shown in Fig. 1 to the north-west of Forbes are comparable with the Derriwong Group in age and lithology.

West Lachlan Fold Belt - Central Victoria

Rickards & Sandford (1998) recognised most of the Llandovery graptolite zones in the Kilmore district of Central Victoria, in this respect having much in common with the Cotton Formation of the Forbes district in the East Lachlan Fold Belt. In the same region of Central Victoria, 'unnamed strata at Macclesfield' span much the same timeslot as the Jerrara Formation in the Goulburn district. In common with the East Lachlan Fold Belt there is a marked hiatus between the Llandovery and Wenlock coinciding with the Ireviken event. Comparison of the post Wenlock sequences of Victoria with those in New South Wales is hindered by the comparatively poor knowledge of later Silurian graptolites in the West Lachlan Fold Belt. The stratigraphic nomenclature introduced by Rickards and Sandford (1998) has been criticised by Vandenberg et al. (1999).

Lachlan Fold Belt - Tasmania

In Tasmania the Lachlan Fold Belt has been divided into Western and Eastern Tasmanian Terranes (Powell & Baillie, 1992). In the Western Tasmanian Terrane near the town of Maydena a limited graptolite fauna (Baillie et al., 1978) indicates the time slice represented elsewhere in the Lachlan Fold Belt by the 'unnamed strata at Macclesfield' in Central Victoria or the Jerrara Formation and uppermost Cotton Formation in New South Wales. The graptolites from Mathinna in the Eastern Tasmanian Terrane are of Early Devonian age (Rickards & Banks, 1979), but later a Ludlow graptolite fauna was found in the same area (Rickards et al., 1993). The position of the graptolite horizon within the Mathinna Beds is uncertain because of structural and metamorphic complications but the reported association of

Monograptus dalejensis and *Bohemograptus bohemicus* ssp. is very reminiscent of the assemblage in the Goulburn-Taralga district of New South Wales in the East Lachlan Fold Belt and the *Bohemograptus* proliferation 'zone' in general.

North Queensland Orogen - Broken River Province

The conodont faunas from the Broken River Province in northern Queensland have been correlated with those of Gotland in northern Europe with a high precision but only for the late Silurian (Jeppsson et al., 2007). The late Silurian limestone formations of the Broken River Province overlie the siliciclastic Quinton Formation and northwards are reported to have an interfingering relationship (Withnall & Fleming, 1993), implying conformity. However, the youngest graptolite faunas in the underlying siliciclastic formations are clearly of late Llandovery age (Rickards & Jell, 2002), comparable with those reported from the Lachlan Fold Belt to the south preceding the Ireviken event. Given the reported conformable relationship within the Silurian of the Broken River Province the lack of any Wenlock graptolite faunas in the Quinton Formation is presumed to be a lack of any preserved or sufficient searching rather than the hiatus corresponding to the Ireviken event in the Lachlan Fold Belt.

The Broken River Province is separated from the Lachlan Fold Belt by more than 1000 km of the Thomson Fold Belt (Fergusson et al., 2007), in which case some differences might be expected in the tectonic history of the respective Silurian sequences. However, it is clear from Fig. 2 that there are marked differences within just the East Lachlan Fold Belt between the sequences at Forbes and Goulburn. Burton (2010) has also queried whether or not the Thomson Fold Belt is a distinct entity from the Lachlan Fold Belt.

CONCLUSIONS

Many of the European Silurian bio and other events are associated with distinctive tectonic events, hiatuses or unconformities, in the Lachlan Fold Belt, in particular the well researched sequences in the eastern part of New South Wales and Central Victoria. However, the lacunae noted in Australasian conodont and graptolite zones during the Silurian mean that it is currently not always possible to correlate specific European events with Australasian hiatuses. In particular, within LFB the strato-tectonic history differs from west to east during the Silurian.

ACKNOWLEDGEMENTS

This paper is published with the permission of the Director, Geological Survey of New South Wales, and benefited considerably from commentary by Professor John Talent. I am grateful to Carmen and Steve Trigg for the Italian translation of the extended abstract.

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