Greenhouse to icehouse: A biostratigraphic review of latest Devonian - Mississippian glaciations and their global effects

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Abstract: The latest Devonian to Mississippian interval records the long term transition from Devonian Greenhouse conditions into the Late Palaeozoic Ice Age (LPIA). This transition was punctuated by three short glaciation events in the latest Famennian, mid Tournaisian and Viséan stages respectively. Primary evidence for glaciation is based on diamictite deposits and striated pavements in South America, Appalachia and Africa. The aim of this review is to assess the primary biostratigraphical and sedimentological data constraining diamictite deposits through this transition. These data are then compared to the wider record of eustasy, mass extinction and isotope stratigraphy in the lower palaeolatitudes. Precise age determinations are vital to integrate high and low palaeolatitude datasets and to understand the glacial control on wider global changes. Palynological techniques currently provide the best biostratigraphic tool to date these glacial deposits and to correlate the effects of glaciation globally. This review highlights a high degree of uncertainty in the known history of early LPIA glaciation as much of the primary stratigraphic data is limited and/or unpublished. Future high-resolution stratigraphic studies are needed to constrain the history of glaciation both spatially and temporally through the latest Devonian and Mississippian.

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The latest Devonian to Mississippian time period saw the onset of the Late Palaeozoic Ice Age (LPIA), marked by three short "precursor" glaciations in the latest Famennian, mid Tournaisian and Viséan respectively (Caputo *et al*. 2008; Montañez & Poulson 2010). In contrast, the earlier Devonian Period had globally warm climates, high sea levels and widespread reef complexes at median palaeolatitudes (Copper 2002; Joachimski *et al*. 2009). The latest Devonian and Mississippian therefore record a transitionary period between these two first-order climate modes, which was characterised by at least three distinct glacial episodes and long-term declining atmospheric CO_2 concentrations (Berner 2006). Within this transitionary period are global oceanic anoxic events associated with mass extinction, eustatic changes and isotopic excursions that approximately coincide with the glaciations in the latest Famennian and mid Tournaisian (Caplan & Bustin 1999; House 2002; Kaiser *et al*. 2007, 2008, 2011, 2015 *this volume*; McGhee 2013; Sallan & Coates 2010; Saltzman 2002; Streel 1986; Yao *et al*. 2015;).

Evidence for LPIA glaciation in Gondwana is based on diamictite deposits and striated pavements in both South America and Africa (Caputo *et al*. 2008; Isaacson *et al*. 2008). Recent work describing latest Devonian diamictites in Appalachia also provides evidence for an additional glacial centre in the low palaeolatitudes of Euramerica (Brezinski *et al*. 2008; 2010). The precise age of these glacial deposits is crucial in understanding the relationship between LPIA glaciation and its wider effects on eustasy, environmental change and mass extinction. There is uncertainty however, over the exact timing of these glacial events. Several authors argue for an expanded range of glaciation that includes the Mid Devonian (Elrick *et al*. 2009) and Frasnian-Famennian (Isaacson *et al*. 1999; McGhee 2013; Streel *et al*. 2000a) based on indirect evidence from isotopes, palaeontology and palynology. Furthermore, the glaciation near the Devonian/Carboniferous (D/C) boundary has been regarded as both discrete, i.e., an individual precursor event (Caputo *et al*. 2008), or intermittent throughout the entire Famennian to earliest Mississippian (Isaacson *et al*. 1999, 2008; Sandberg *et al*. 2002).

Two recent reviews of latest Devonian and Mississippian glaciation are provided by Caputo *et al*. (2008) and Isaacson *et al*. (2008). For reviews of the wider LPIA see Fielding *et al*. (2008), Limarino *et al*. (2014) and Montañez & Poulson (2010). This review does not reiterate these previous contributions but rather approaches the glacial histories of the latest Devonian and Mississippian from a biostratigraphic standpoint. The aims are to: (1) discuss published biostratigraphic schemes, their limitations and correlation into South America; (2) assess the primary biostratigraphical and sedimentological evidence for glacial histories, and (3) to integrate these histories into a global context of mass extinction and environmental change. This will facilitate future research by providing an assessment of the timing of glaciations from the latest Devonian and Mississippian interval.

The review is divided into 'near-field' and 'far-field' phenomena. The former refers to those areas with direct evidence for glaciation, i.e., diamictites and/or striated pavements. 'Far-field' refers to those areas with only proxy evidence for glaciation, which includes sequence-stratigraphic and palaeoenvironmental observations.

PALAEOGEOGRAPHIC AND PALAEOCLIMATIC SETTING

Most of the continents at this time were part of either Euramerica or Gondwana (Fig. 1a). Gondwana was situated in the southern palaeolatitudes and consisted of South America, Africa, the Arabian Plate, India, Australia and Antarctica.

The Panthalassic Ocean bordered western Gondwana along an active margin (Sempere 1995). To the north of Gondwana was the closing Variscan Sea. The subsequent collision of Gondwana with Euramerica during this closure was a key part in the assembly of Pangaea in the Late Palaeozoic. Putative ice-centres have been suggested for the Brazilian Shield, Guiana Shield, Puna Arch and Arequipa Massif in central South America, and along an orogenic highland belt on the southern active margin of Euramerica (Fig. 1a-b; Brezinski *et al*. 2010; Díaz-Martínez & Isaacson 1994; Isaacson *et al*. 2008). In addition, there are poorly-constrained ice-centres postulated in central Africa (Fig. 1c; Isaacson *et al*. 2008).

The Late Devonian is an important interval in the evolution and diversification of land plants. This includes an increase in arborescence (i.e., trees became taller and with deeper root systems) and the evolution of seeds, which allowed vegetation to colonise dryer upland areas (Algeo & Scheckler 1998). The resulting increase in deep-soil formation and continental weathering may have caused the postulated reduction in atmospheric CO_2, thus possibly setting the stage for glaciation in the latest Devonian and Carboniferous (Algeo *et al.* 1995; Algeo & Scheckler 1998; Berner 2006).

PUBLISHED BIOSTRATIGRAPHIC SCHEMES

In Europe and North America, Late Devonian and Mississippian successions are primarily dated using conodonts and goniatites (Becker *et al*. 2012; Davydov *et al*. 2012). These schemes are supplemented by miospore biostratigraphy, which is very well established in Western Europe (Clayton *et al*. 1977; Higgs *et al*. 1988; Maziane *et al*. 1999; Streel *et al*. 1987). The published global and regional biostratigraphic schemes discussed in this section are summarised in Fig. 2.

The D/C boundary Global Stratotype Section & Point (GSSP) is at La Serre, France, and is based on the supposed evolutionary lineage of the conodonts *Siphonodella praesulcata* to *S. sulcata*. The first occurrence of the latter was used to define the base of the *sulcata* Zone and of the Carboniferous Period (Paproth & Streel 1984; Paproth *et al*. 1991). However, the practical use of the siphonodellids has been questioned by Kaiser (2009) based on the occurrence of *S. sulcata* stratigraphically below the level that defines the GSSP. Additionally the GSSP is picked within a reworked oolitic sequence, which hinders its correlation potential. This issue is compounded by difficulties in taxonomic discrimination between *S. praesulcata* and *S. sulcata*, which may represent two morphological end-members of a single species (Corradini *et al*. 2013; Kaiser & Corradini 2011). These findings reduce confidence in the both the current placement of the D/C boundary GSSP and its inter-regional correlation. This is significant as the *praesulcata* **-** *sulcata* interval contains the first of the precursor glaciations in the latest Famennian and also the end-Devonian mass extinction.

The correlation of global schemes into South America

The spore record

The correlation of global biostratigraphic schemes into Gondwanan South America is of significant importance as this region has more reported occurrences of glacial diamictites than any other. Unfortunately the dating of these sediments is problematic as conodonts and goniatites are extraordinarily rare in South America. In addition, the macro-fauna available for regional biostratigraphy, such as brachiopods, are largely endemic (Isaacson 1977). Hence palynological analyses have the greatest biostratigraphic potential owing to the cosmopolitan nature of some miospore species that can be used for extra-Gondwanan correlation (Playford 1991; Table 1). Significant research has improved Palaeozoic South American miospore taxonomy and established a miospore biostratigraphic scheme for the Amazon Basin, Brazil (Loboziak & Melo 2002; Loboziak *et al*. 1986, 1999, 2000a, 2000b, 2005; Melo & Loboziak 2000, 2003; Melo & Playford 2012; Playford & Melo 2009, 2010, 2012). The Amazon Basin scheme has also been calibrated with established miospore biostratigraphy from Western Europe (i.e., Clayton *et al.* 1977; Streel *et al*. 1987). The reference sections for the Amazon Basin scheme unfortunately contain large stratigraphic gaps, which may therefore limit its usefulness outside the basin (Melo & Loboziak 2003; Melo & Playford 2012). Research into Palaeozoic palynostratigraphy in South America is ongoing, which will improve future correlations between Gondwana and Euramerica (see for example di Pasquo 2015; di Pasquo *et al.* 2015; Marshall 2015 *this volume*; Troth *et al.* 2011).

In the latest Famennian the index miospore *Retispora lepidophyta* has a near global distribution in a wide variety of settings. In Western Europe the first occurrences of *Knoxisporites literatus*, *Indotriradites explanatus* (Luber) Playford 1990 and *Verrucosisporites nitidus* subdivide the total range of *R. lepidophyta* into the LL (*lepidophyta* - *literatus*), LE (*lepidophyta* - *explanatus*) and LN (*lepidophyta* - *nitidus*) biozones respectively (Streel *et al*. 1987). However, *K. literatus* and *V. nitidus* are rarely observed in Amazon Basin miospore assemblages, and so the LE/LN zones are often undifferentiated with the LL Zone either missing or not identified (Melo & Loboziak 2003; Melo & Playford 2012). Therefore Melo & Loboziak (2003) proposed a lower Rle (*lepidophyta*) Zone and an upper LVa (*lepidophyta-vallatus*) Zone in the Amazon Basin, based on the first occurrences of *R. lepidophyta* and *Vallatisporites vallatus*. The inception of *V. vallatus* is synchronous with that of *V.*

nitidus in Western Europe; therefore the Rle and LVa zones were argued to be South American equivalents of the LE and LN zones respectively.

The extinction of *R. lepidophyta* occurs 14 cm below the D/C boundary as defined in the GSSP paratype section at Hasselbachtal, Germany (Higgs & Streel 1993). This extinction may not be entirely synchronous with the problematic boundary GSSP, but it is considered a useful global marker for the D/C boundary (Davydov *et al*. 2012). In the Amazon Basin the last occurrence of *R. lepidophyta* and the first occurrence of *Waltzispora lanzonii* define the LVa - AL (*Radiizonates arcuatus-lanzonii*) zonal boundary. However this boundary is an erosional surface and does not represent a continuously preserved D/C boundary sequence (Fig. 2; Melo & Playford 2012).

In the Mississippian there are several key miospores which exist in both Gondwana and Euramerica, the first occurrences of which can therefore be used for correlation. These include *Neoraistrickia loganensis* for the early-mid Tournaisian and several species of *Spelaeotriletes*, such as *S. balteatus* and *S. pretiosus* (Playford & Melo 2009; Playford *et al*. 2001).

Acritarch, prasinophyte and chitinozoan records

Acritarchs and prasinophytes represent the preserved cysts of marine phytoplankton. Their use in Devonian biostratigraphy is more limited than that of spores, but many Late Devonian species are known from both Euramerica and Gondwana (Le Hérissé *et al*. 2000 Molyneux *et al*. 2013). Such cosmopolitan taxa include: *Chomotriletes vedugensis*, *Gorgonisphaeridium ohioense*, and *Stellinium micropolygonale* (Molyneux *et al*. 2013; Table 1). There is a distinct Famennian assemblage in Gondwana characterized by *Umbellisphaeridium saharicum, U. deflandrei, Horologinella quadrispina,* (?)*Schizocystia bicornuta* and *Maranhites mosesii* (Le Hérissé *et al*. 2000; Molyneux *et al*. 2013; Vavrdova & Isaacson 1999). *U. saharicum,* in particular, is associated with *R. lepidophyta* in South America (Daemon & Contreiras 1971; Vavrdova & Isaacson 1999; Wicander *et al*. 2011).

Acritarchs are of limited biostratigraphic value in the Mississippian since their abundance and diversity became increasingly diminished across the D/C boundary and into the Carboniferous (Mullins & Servais 2008). Marine phytoplankton did not recover until the Mesozoic. This period of low phytoplankton diversity has been termed the Late Palaeozoic Phytoplankton Blackout (Riegel 2008). However, a lack of detailed D/C reference sections for which there are comprehensive palynological records means that the decline in phytoplankton diversity is poorly constrained (Le Hérissé *et al*. 2000; Mullins & Servais 2008).

A global chitinozoan biostratigraphic scheme has been proposed for the Devonian, which is integrated with a regional scheme for Western Gondwana (Grahn 2005; Paris *et al.* 2000). Similarly to other fossil groups, however there is a significant degree of endemism in South America (Troth 2006). Chitinozoa are useful for the wider Devonian Period but suffer total extinction near the D/C boundary. In South America this extinction is reported in the VH Miospore Zone (Grahn 2005; Grahn *et al*. 2006).

NEAR-FIELD LATEST FAMENNIAN GLACIATION

The review by Caputo (1985) first argued for the glacial character of Famennian diamictites in Brazilian basins, which had until that point had remained controversial. Since then, expressions of latest Famennian glaciations have been found to have a much wider geographic extent (Fig. 3). The primary evidence is based on diamictite deposits and striated pavements in Brazil, Peru and Bolivia of central South America (Caputo 1985; Caputo *et al*. 2008; Isaacson *et al*. 2008). In Brazil, this evidence is known from the Solimões, Amazon/Maranhão, Parnaíba and Paraná basins that border the Brazilian Shield (Caputo *et al*. 2008). In Bolivia and Peru there are diamictites in the Altiplano Basin and the Sub Andean Madre de Dios and Tarija basins (Díaz-Martínez & Isaacson 1994; Isaacson *et al*. 1999). Brezinski *et al*. (2008, 2010) have described diamictites from Appalachia, on what was then the southern active margin of Euramerica. These are interpreted to have been deposited in a terrestrial foreland basin under subglacial, englacial and supraglacial settings (Brezinski *et al*. 2010). Evidence for glaciation in Appalachia broadens the geographic extent of latest Famennian glaciation into the lower palaeolatitudes.

Stratigraphic evidence from Brazil

Maranhão and Amazon basins

The Maranhão and Amazon basins contain the Curiri Formation, which outcrops along two 500 km long belts on the northern and southern basin margins (Caputo *et al*. 2008). An erosive unconformity separates the upper Curiri Formation from the diamictite-free lower Curiri Formation (Melo & Loboziak 2003). In subsurface wells the upper Curiri Formation is a ~50 m thick diamictite unit with subordinate siltstone beds (Cunha *et al*. 2007). Maximum glacial advance is represented by lobate diamictite deposits (4000 km^2) that contain "floating" heterogeneous clasts and which overlie offshore to shoreface black shales and siltstones (Carozzi 1979). The diamictites are associated with incised subglacial channels and slump structures. The depositional model of Carozzi (1979) suggests glaciomarine conditions with ice-rafted debris and grounded ice-sheets. Retreat occurs in the very latest Devonian. The upper Curiri Formation grades, both laterally and vertically, into the non-glacial Oriximiná Formation.

The Curiri Formation is associated with the enigmatic *Protosalvinia* fossil, of probably land plant origin, and the ichnofossil *Spirophyton,* a common feature of the uppermost Devonian in northern Brazilian basins (Carozzi 1979; Quijada *et al.* 2015). *Protosalvinia* is Famennian in age but probably pre-*R. lepidophyta* (Loboziak *et al.* 1997; Over *et al*. 2009; Phillips *et al*. 1972). The diamictites of the upper Curiri Formation contain *R. lepidophyta* and are assigned an undifferentiated LE-LN age (Loboziak *et al*. 1997). Melo & Loboziak (2003) indicate an equivalent Rle-LVa age for the upper Curiri Formation. However, there is no lithostratigraphic section which shows the vertical distribution of diamictites compared with the palynostratigraphy of Melo & Loboziak (2003).

Isaacson *et al*. (2008) reported a VCo, VH and LE/LN age range for glaciation in the Amazon Basin. This is likely based on Cunha *et al*. (1994) who showed the Curiri Formation as belonging to Zones 'VII-VIII' of Daemon & Contreiras (1971). These zones correspond roughly to the VCo-LN spore zones of Europe (Melo & Loboziak 2003). However, diamictites only occur within the upper unit of the Curiri Formation and not in the lower unit, so this extended age range down into the VCo Zone is likely an overestimate.

Solimões Basin

The Jaraqui Diamictite Member (Jandiatuba Formation) is restricted to the subsurface in the Solimões Basin (Caputo *et al*. 2008; Filho *et al*. 2007; Isaacson *et al*. 2008). The unit is up to 50m thick and has a distinctive wireline response characterised by high gamma values and sharp changes in porosity, density and resistivity curves (Eiras *et al.* 1994). Eiras *et al.* (1994) label the member as glaciomarine and of Famennian - Tournaisian in age, while Filho *et al*. (2007) show it restricted to the Famennian. The chronostratigraphic chart in Eiras *et al.* (1994) shows the Jaraqui Diamictite Member as belonging to the *"lepidophytus-spelaeotriletes*" Zone. The name "*lepidophytus*" refers to *R. lepidophyta* and so a latest Famennian age (LL-LE-LN) is likely.

Much of the primary sedimentological and biostratigraphical evidence for the glaciomarine deposits in this basin appears to derive from internal and unpublished company reports (for example Caputo & Silva 1990; Eiras *et al.* 1994; Quadros 1988). With the exception of Eiras *et al.* (1994) detailed information for diamictites in the Solimões Basin is not easily available. Although Caputo *et al.* (2008) have provided a brief lithological description of the diamictites and claimed that they are coincident with the upper Curiri Formation in the Amazon Basin.

Parnaíba Basin

The Parnaíba Basin contains the Cabeças Formation, which can be observed both at outcrop and in the subsurface (Caputo *et al*. 2008). This formation consists of fine to medium grained, cross-bedded sandstones with interbedded siltstones and shales, which are interpreted as representing fluvial, deltaic to shelfal depositional environments (Caputo 1985; Caputo *et al*. 2008; Góes & Feijó 1994; Vaz *et al*. 2007). Diamictites occur with greater frequency in the upper part of the Cabeças Formation (Vaz *et al*. 2007). They contain striated clasts and rest upon an unconformity surface and striated pavement (Caputo *et al*. 2008). The orientation of the striations suggests a glacial source area on the Brazilian Shield (Caputo *et al*. 2008). Equivalent deep-water strata are represented by varve-like rhythmites that contain marine acritarchs (Streel *et al*. 2000b).

The diamictites in the Parnaíba Basin were broadly inferred to be synchronous with those from the Amazon Basin by Carozzi (1980) based on their association with a *Protosalvinia* - *Spirophyton* assemblage, similar to the Amazon Basin. Rhythmites in the deeper basin were designated a LN age based on a palynological analysis of individual millimetre-scale rhythmites (Streel *et al*. 2000b). In the subsurface the Cabeças Formation was attributed an undifferentiated LE-LN age by Loboziak *et al*. (1992). A later investigation of sections in the Tocantins River valley produced a LN Zone age for a single sample from the Cabeças Formation (Loboziak *et al*. 2000a).

The palynological investigations in the Parnaíba Basin are essentially based on single spot samples. With the exception of Streel *et al*. (2000b) it is unknown if these spot samples specifically date the diamictite facies or sediments in the associated stratigraphic sequences. There is no available palynostratigraphy to constrain the age of the incision surface at the base of the diamictites or the timing of the retreat, although final retreat is stated to have occurred immediately below the D/C boundary (Caputo *et al*. 2008).

Paraná Basin

Milani *et al*. (2007) informally described a 1.5 m thick diamictite interval as the 'Ortigueira Diamictite' in the uppermost part of the Late Devonian Ponta Grossa Formation. The unit is unconformably overlain by diamictites of the Late Carboniferous - Early Permian Itararé Group (Milani *et al*. 2007). It was extremely difficult to differentiate these latest Devonian diamictites from the overlying Itararé Group. It was only when they were analysed palynologically that a latest Famennian age was constrained (Loboziak *et al*. 1995a). The diamictites contain the following miospores: *R. lepidophyta, V.* cf. *vallatus* and *Vallatisporites hystricosus,* and were interpreted to be of LN age (Loboziak *et al*. 1995a). Loboziak *et al*. (1995a) is however a preliminary report and so does not contain any illustrations/descriptions of the palynological material or any measured sections. Caputo *et al.* (2008) have described the diamictites as grey, muddy with clasts of varying size. No further descriptions of latest Famennian diamictites in the Paraná Basin have been published, and without detailed sedimentary logs and facies descriptions the depositional environment remains unknown.

Stratigraphic evidence from Bolivia

Bolivian Altiplano

The latest Famennian glaciation in the Bolivian Altiplano is represented by the Cumaná Formation exposed near Lake Titicaca (Fig. 4a-b). The entire unit contains striated and polished exotic clasts (Díaz-Martínez & Isaacson 1994). There are three generalised lithofacies: the lowermost lithofacies comprises outer shelf laminated shales with ice-rafted dropstones (Díaz-Martínez & Isaacson, 1994; Díaz-Martínez *et al*. 1999); the second lithofacies consists of massive muddy to sandy diamictites with large blocks, interpreted as sub-aqueous debris flows; the uppermost lithofacies is the most proximal and consists of interbedded cross-stratified sandstones and diamictites deposited within periglacial subaqueous outwash fans. This vertical association was interpreted as a single glacial advance into a glaciomarine environment (Díaz-Martínez & Isaacson 1994).

Palynological samples from the Cumaná Formation and associated stratigraphy were collected from Villa Molino, Hinchaka and Isle del Sol by Díaz-Martínez *et al*. (1999). The samples contain *R. lepidophyta* and *I. explanatus*. The absence of *V. nitidus* means that the LN Zone cannot be recognised. The diamictites were also associated with a relatively diverse marine acritarch and prasinophyte assemblage, which includes *U. saharicum, Maranhites mosesii*, *Pterospermella* spp. and *Exochoderma irregulare*. The D/C boundary was recognised at Villa Molino between samples 9a and 9b (Fig. 4c). Both *R. lepidophyta* and Devonian phytoplankton were reported to disappear above the boundary (Díaz-Martínez *et al*. 1999). Sample 6 at Hinchaka was collected above the diamictites (Fig. 4c), and contained only a single acritarch species and no *R. lepidophyta*, which suggests that the D/C boundary and phytoplankton extinctions occur within or immediately above the diamictite.

Sub Andean Zone - *Madre de Dios/Tarija basins*

Diamictites in the central Cordillera and Subandean Zones are assigned to the Itacua Formation. In the eastern Cordillera diamictites are known in the Saipuru Formation and have been attributed to the *R. lepidophyta* Zone (Caputo *et al*. 2008; Suárez-Soruco & López-Pugliessi 1983).

Towards the southwest, in the Madre de Dios Basin, diamictites form part of the Toregua Formation (Isaacson *et al*. 1995). The Toregua Formation was reported to straddle the D/C boundary as based on the first down-hole occurrence of *R. lepidophyta* and *U. saharicum* in the 'Pando X-1' and 'Manuripi X-1' wells (Isaacson *et al*. 1995; see Fig. 4a for their location).

Sub Andean Zone – the Bermejo section

The most detailed available biostratigraphic evidence regarding latest Devonian glaciation in the Subandean Zone is from Wicander *et al*. (2011), presenting a sedimentary log through the 18 m thick diamictite unit representing the Itacua Formation at Bermejo (Fig. 5; see Fig. 4a for geographic location). The unit contains sandstone lenses, exotic clasts, sandstone lithic boulders and overlies a sheared basal contact. It was interpreted as a glaciomarine environment based on the presence of marine acritarchs. The palynological analysis suggests a sequence of glacial events through the LL, LE and LN zones based on the step-wise occurrence of *R. lepidophyta, I. explanatus* and *V. nitidus*. This is significant as it potentially extends the onset of glaciation into the older LL Zone stratigraphy which is typically missing in Brazil.

There is a degree of palynological reworking observed in the Bermejo section, which may affect any biostratigraphic interpretations. Wicander *et al.* (2011) recognised several of the acritarch and prasinophyte species in the diamictites Itacua Formation were likely reworked from the Middle Devonian. In addition Late Devonian miospore species have been reworked into the Mississippian Saipuri Formation sitting directly above the Itacua diamictites (Perez-Leyton 1991; Streel *et al.* 2013). The latest Devonian miospores in the Itacua Formation however are likely not reworked considering that no exclusively Carboniferous species were identified by Wicander *et al.* (2011).

Before the publication of the data from Bermejo, the Bolivian diamictites had been interpreted as representing a single glacial advance (e.g. Díaz-Martínez & Isaacson 1994). Wicander *et al*. (2011) in contrast, suggest that a series of glacial events spanned the entire LL-LE-LN range of *R. lepidophyta*. This range defines the "Strunian" interval in Belgium, which has an estimated duration of 1 - 3 million years, suggesting that the glaciations were of a similar duration (Streel *et al.* 2006; Trapp *et al*. 2004). A sandstone lithic boulder clast (i.e., a non-diamictite lithology) in the Itacua Formation at Bermejo was palynologically dated as of LN Zone age ('exotic block' in Fig. 5). The surrounding country rock however was interpreted as the older LE Zone. This suggests the boulder was transported by ice in a frozen state and re-deposited into older unconsolidated sediment (Wicander *et al*. 2011). The 1 - 3 million year duration and evidence of ice-reworking makes it unlikely this is a single glacial cycle. Rather the succession was interpreted as a composite of several deglaciation events shedding sediment into a glaciomarine environment (Wicander *et al*. 2011).

Streel *et al*. (2013) challenged the interpretation of Wicander *et al*. (2011) and argue that the entire Itacua Formation is more likely to have been deposited over a single 100,000 year glacial event within part of the LE-LN zones. They base their challenge on three lines of reasoning: (1) that the LE-LN zones are not easily differentiated in Brazil due to the rarity of *V. nitidus* specimens. The absence therefore of *V. nitidus* in country rock surrounding the exotic boulder would not necessarily be indicative of the LE Zone; (2) that the taxonomic assignment of their figured specimen of *V. nitidus* is questionable, and (3) that the record at Bermejo appears to contradict the far-field eustatic and oxygen isotope response observed in Europe, which indicates a cold regressive interval within a much narrower age range in the LN zone only (Kaiser *et al*. 2007, 2008, 2015 *this volume*; Streel *et al*. 2013; Walliser 1984).

The palynological sampling at Bermejo was systematic over a continuous section and the published range chart in Wicander *et al*. (2011) only shows *V. nitidus* occurrences in the upper part of the Itacua Formation. The occurrence of *V. nitidus* was not sporadic, but was instead stratigraphically confined, which is why the upper part of the Itacua Formation was interpreted as of LN Zone age. The observation of rare *V. nitidus* in Brazilian spore assemblages may therefore not be comparable to contemporaneous assemblages in Bolivia. In addition, using an indirect far-field record to reinterpret primary near-field biostratigraphic data may be unwise and could lead to circular reasoning. Whether glaciation in the latest Devonian consists of a single short event or a composite of many is a contentious issue and requires further investigation. Furthermore, stacked glacial cycles may be difficult to recognise, as the younger glacial cycles would remove evidence of earlier glaciation during erosive ice-advances.

Stratigraphic evidence from Peru

Diamictites in south eastern Peru have been reported in various conference abstracts and termed the Ccatcca Formation (Carlotto *et al*. 2004; Cerpa *et al*. 2004; Díaz-Martínez 2004). This formation has been correlated to the Cumaná Formation in Bolivia based on its lithological similarity and is stated to be of late Famennian age (Díaz-Martínez 2004; Isaacson *et al*. 2008). The Ccatcca Formation is ~100 m thick and has been split into 3 distinct units (Isaacson *et al*. 2008). The lowest consists of laminated shales containing dropstones, overlain by massive diamictites with evidence for gravitational reworking. The uppermost unit consists of sandstones with "disharmonic" folding and hummocky-swaley cross-stratification (Isaacson *et al*. 2008). This vertical association is similar to the Cumaná Formation on the Bolivian Altiplano 400 km to the south-east.

Stratigraphic evidence from Libya

Latest Famennian glaciation is postulated to have existed in south Libya by Streel *et al.* (2000a). This is based on an unpublished study of the A.1-NC 58 wildcat well in Ghadames Basin. It was noted that this well contained conglomerates, sandstones and diamictites in the Tahara Formation that were interpreted to be of glacial origin (Streel *et al.* 2000a). The Tahara Formation is latest Famennian age and contains *R. lepidophyta* (Coquel and Moreau-Benoit 1986).

Stratigraphic evidence from South Africa

Putative pre-Dwyka Group glacial events have been recognised in the Devonian to Early Carboniferous Witteburg Group by Almond *et al.* (2002) in South Africa. The stratigraphic lowest of these is within the Perdepoort Member of Famennian age. The Perdepoort Member is predominantly a texturally-mature orthoquartzite, which contains lenticular to tabulate diamictite units. These diamictites are clast-poor, sandy, weakly-bedded and have a lateral extent of hundreds of kilometres. They were interpreted by as slump deposits formed during rapid deglaciation events by Almond *et al.* (2002). A glacial interpretation is supported by the reports of clasts within the diamictite bearing striated surfaces (Almond *et al.* 2002).

Stratigraphic evidence from North America

Recent evidence has strongly suggested an additional glacial centre in the Appalachian Basin, then situated in the temperate latitudes (Brezinski *et al*. 2008, 2010; Blaine Cecil *et al*. 2004). This is based on mudstone and diamictite sequences in the Spechty Kopf and Rockwell formations exposed along a 400 km outcrop belt (Brezinski *et al*. 2008, 2010; Brezinski & Blaine Cecil, 2015). These were deposited within a glacio-lacustrine to proglacial terrestrial environment and consist of a single preserved ice advance and retreat trend (Brezinski *et al*. 2010). Evidence for glaciation also extends into Kentucky, where a 3-tonne granitic boulder clast (i.e., a dropstone) can be observed in the black mudstones of the Cleveland Member of the offshore-marine Ohio Shale Formation (Lierman and Mason 2007; Ettensohn 2008; Ettensohn *et al*. 2008, 2009). Ice likely nucleated on highland areas generated by the Acadian Orogeny and expanded north-westwards into the central Appalachian Basin (Lierman, 2007).

The diamictites are reported to contain *R. lepidophyta* and correlate to the *praesulcata* Condont Zone (Brezinski *et al*. 2008; Ettensohn 2008). Woodrow & Richardson (2006) report that the diamictite sequences of the Spechty Kopf Formation represent a minor portion of the LE Zone. In contrast, the exotic granitic boulders in the Ohio Shale Formation are apparently situated within country rock dated as LN age. The latter LN age-determinations of the Ohio Shale were cited as unpublished written communications (Brezinski *et al*. 2010 - page 276; Ettensohn *et al*. 2009 - p. 31). An LE to LN zonal range is not unreasonable, but insufficient biostratigraphic data are currently available, and it is not known whether the palynological analyses were based on spot samples or a more systematic study. Furthermore, Rooney *et al*. (2015) noted that detailed biostratigraphic resolution of the Cleveland Member is difficult due to the uniform palynological assemblage which is dominated by amorphous organic matter.

NEAR-FIELD MID TOURNAISIAN GLACIATION

The mid Tournaisian glacial event has a lesser geographic extent compared to that of the latest Famennian, and is only known from Brazil (Fig. 3), Falkland Islands and South Africa. Detailed evidence for the mid Tournaisian glaciation event is poorly-constrained, with limited published data (Caputo *et al*. 2008).

Brazilian basins

Amazon Basin

In the Amazon Basin the Tournaisian section of the Oriximiná Formation is reported to contain diamictites restricted to the subsurface (Caputo *et al*. 2008). They consist of claystones with mixed sand, gravel and pebble clasts. However there is no reference of diamictite facies in published well sections that penetrate the Oriximiná Formation (e.g., Cunha *et al*. 2007, Melo & Playford, 2012). The stratigraphic distribution, depositional environment and age-determination of diamictites in the Oriximiná Formation are therefore unknown.

Solimões Basin

In the subsurface of the Solimões Basin Tournaisian diamictites are reported in the upper part of the Jaraqui Member (Caputo *et al*. 2008). However Filho *et al*. (2007) show the Jaraqui Member restricted to the Famennian only. The diamictites are said to have been correlated to the BP-PC zones of Western Europe by Caputo *et al*. (2008), however two of the cited references for this age-determination are unpublished reports (Loboziak *et al*. 1994a, 1994b). The third cited reference, Loboziak *et al*. (1995b), does not mention Tournaisian diamictites, and provides no palynological descriptions or illustrations. Caputo *et al*. (2008) do however provide a relatively detailed lithological description of the diamictites; however no original sources were cited. As such, interpretations of the depositional environment and age of diamictites in the Solimões Basin cannot be validated.

Parnaíba Basin

The Parnaíba Basin provides the most detailed account of mid Tournaisian diamictites, which are constrained to the upper part of the Longá Formation (Playford *et al*. 2012). The diamictites are 63 m thick in the UN-24 well in the northern part of the basin and are interbedded with thin shales and sandstones (Playford *et al*. 2012). Diamictites are poorly-sorted, mudstone-dominated, and with randomly orientated pebble clasts. They are interpreted as ice rain-out deposits affected by gravitational reworking and ice-keel scouring (Lobato 2010, reported in Playford *et al*. 2012). The diamictites contain a well-preserved palynological assemblage that was correlated to the PC Zone (Playford *et al*. 2012). This was based on the occurrences of *Colatisporites decorus, N. loganensis*, *S. balteatus, S. pretiosus* and *Raistrickia clavata* amongst others.

South Africa

The LPIA in South Africa is represented by diamictites of the Dwyka Group, which unconformably overly Late Devonian-Mississippian pre-glacial sediments. This basal contact contains evidence of glacially influenced soft-sediment deformation in the uppermost pre-glacial Waaipoort Formation, indicating the latter was still unconsolidated sediment by the time of the first glacial advance in South Africa (Streel & Theron 1999). The biostratigraphic dating of the Devonian and Mississippian sequences has historically been difficult due to contradictory ages suggested by miospore, floral and vertebrate remains, and the high degree of thermal maturity that degrades and darkens palynological material (Theron 1993). It was Streel & Theron (1999) who described identifiable palynological material for the first time in the Waaipoort Formation: miospores including *S. balteatus* and *S. pretiosus* were interpreted to be no older than mid Tournaisian. As these sediments contain evidence of glacially influenced soft-sediment deformation, these palynological data suggest a mid Tournaisian phase of glaciation in South Africa immediately after the deposition of the uppermost Waaipoort Formation.

The Miller Diamictite in the Kommadagga Subgroup is laterally discontinuous but sits stratigraphically above the Waaitpoort Formation and below the Dwyka Group (Evans 1999; Goossens 2002; Swart 1982; Theron 1993). The units association with the underlying Waaipoort Formation could suggest a glacial origin of this unit. The Miller diamictite is up to 6 m in thickness and consists of fine to medium grained muddy-sandy matrix with clasts up to 2 cm in diameter (Swart, 1982). The depositional environment of the Miller Diamictite was described as “problematic” by Swartz (1982), who interpreted it as a debris flow deposit, within a prograding delta on the basis of there being no conclusive evidence of a glacial origin. Further work is needed to better constrain the depositional environment and age of the Miller Diamictite. Despite being succeeded by the overlying Dwyka Group, of definitive glacial origin, these units separated by a significant unconformity (Isbell *et al.* 2008; Swartz 1982), and so any interpretations derived from the Dwyka Group should not be applied to the underlying sequence.

NEAR FIELD VISÉAN GLACIATION

The known evidence for Viséan glaciation comes from the Brazilian basins, Argentina and the Falkland Islands (Fig. 3; Caputo *et al*. 2008; Limarino *et al*. 2014; Hyam *et al*. 1997).

Brazil

The Faro Formation, in the Amazon Basin, consists of ~400 m of sandstones and shales interpreted as representing fluvial-deltaic to storm-influenced shelfal conditions (Cunha *et al*. 1994, 2007). Diamictites are reported from the subsurface of "possible glacial derivation" by Caputo *et al*. (2008). These are potentially correlative to similar deposits in the Jandiatuba Formation of the Solimões Basin.

In the Parnaíba Basin, Caputo *et al*. (2008) describe sandstones and diamictites in the Poti Formation, which contains clasts of varying size dispersed in a muddy matrix. These are reported to be exposed at outcrop. The sedimentologic information reported in Caputo *et al.* (2008) comes from an unpublished PhD thesis (Andrade 1972). Vaz *et al*. (2007) describe the Poti Formation in the subsurface as tidal to deltaic in nature, consisting of a lower unit of sandstones overlain by shales and coals, and do not mention diamictites.

The Faro and Poti formations have been constrained to the Mag Zone in the midde to late Viséan, defined by the range of the miospore *Reticulatisporites magnidictyus* (Melo & Loboziak 2000; Melo & Loboziak 2003; Melo & Playford 2012). Streel *et al.* (2013) have provided a list of miospore species present in the Poti Formation with photomicrograph plates provided. No diamictite facies are shown in published well or outcrop data that include either the Faro or Poti formations (Cunha *et al*.

2007; Melo & Loboziak 2000; Melo & Playford 2012; Vaz *et al*. 2007). Detailed sedimentological and biostratigraphical data regarding Viséan diamictites in Brazilian basins is therefore extremely limited and difficult to validate.

Stratigraphic evidence from Argentina and the Falkland Islands/Islas Malvinas

The evidence for Viséan glaciation in the Río Blanco Basin of Argentina is very well constrained and based on integrated sedimentological, palynological and U-Pb ages (Gulbranson *et al*. 2010; Perez Loinaze *et al*. 2010), and represents the initiation of the Viséan - Serpukhovian Glacial Stage in the LPIA (Isbell *et al*. 2003; Limarino *et al*. 2014). Diamictites belong to the Cortaderas Formation and consist of dropstones in shale facies and massive to stratified diamictites interpreted as an ice-distal glaciomarine environment (Perez Loinaze *et al*. 2010). There is a rich and well-preserved miospore assemblage that contains *R. magnidictyus*, *Rugospora australiensis* and *Verrucosisporites quasigobbettii*. These are of biozonal significance and have first occurrences in the mid to late Viséan. The spore assemblage was determined by Perez Loinaze *et al*. (2010) as belonging to the MQ (*Reticulatisporites magnidictyus* - *Verrucosisporites quasigobbettii*) biozone of western Argentina, correlated to the Mag Zone in the Amazon Basin (Melo & Loboziak 2003; Melo & Playford 2012; Perez Lionaze 2007). It is interesting that evidence of glaciation in the Mag zone of the Viséan in South America contrasts with early Viséan warm-water faunal elements in northern Argentina, characterised by the goniatite *Michiganites scalabrinii* (House 1996).

In the Falkland Islands there are sub-vertical diamictite dykes hosted within (?)Ordovician - Devonian strata (Hyam *et al*. 1997). These were interpreted as the downward injection of diamicton into a sedimentary host rock during an episode of glaciation. The diamictites were analysed palynological and found to contain *R. magnidictyus* and *V. quasigobbettii* (Hyam *et al*. 1997). This indicates a late Viséan age with a palynoflora correlative to that of Argentina.

Bolivia − Mississippian glaciation(s)?

Diamictite deposits are reported in the Tournaisian/Viséan Kasa Formation in the Bolivian Altiplano are interpreted as sediment gravity flows (Fig. 4d; Díaz-Martínez 1991, 1996; Díaz-Martínez *et al*.

1993; Oviedo Gomez 1965). These are thought to be the distal expression of proglacial outbursts that would have occurred in more proximal coastal or braided alluvial settings (Díaz-Martínez & Isaacson 1994; Díaz-Martínez 1993; Díaz-Martínez *et al*. 1993; Isaacson *et al*. 2008). These deposits are not known to contain independent ice-indicators, such as faceted clasts or striated pavements, nor are they constrained biostratigraphically. Therefore to prove whether these deposits represent additional Mississippian glaciations in the Bolivian Altiplano requires additional study (Caputo *et al*. 2008).

Diamictites of glaciomarine origin are reported in the Mississippian Kaka Formation of the Bolivian Subandean Belt (Caputo *et al*. 2008; Suárez-Soruco 2000). These deposits are not associated with any published sedimentological or biostratigraphical data, but are said to be correlative to the Kasa Formation in the Bolivian Altiplano (Caputo *et al*. 2008).

An early Viséan age has been assigned to diamictites of the Itacua Formation at Balapuca in southern Bolivia (di Pasquo 2007a, 2007b). At Bermejo, some 500km north of Balapuca, the lowermost 18m of the Itacua Formation have been dated as latest Famennian (Wicander *et al.* 2011). The Sub Andean mid-Palaeozoic record contains several hiatuses and it is likely that older glacial episodes have been directly, and unconformably, overlain by younger ones in the preserved stratigraphic record (Streel *et al.* 2013).

Stratigraphic evidence in east Asia

The Chepor Member in the Kubang Pasu Formation of northwest Malaysia contains a diamictite facies (pebble clasts in muddy sandstones) interpreted as suspension fall-out deposits in a glaciomarine environment (Meor *et al.* 2014). The Chepor Member is fossiliferous with diverse communities of brachiopods, trilobites, gastropods, tabulate corals and bivalves (Meor *et al.* 2014). A Viséan to Late Viséan age was interpreted by Meor *et al.* (2014) primarily based on the bivalve *Posidonia* sp., the trilobite assemblage and the goniatite genus *Praedaraelites*.

NEAR FIELD GLACIATION OF UNCERTAIN AGE IN CENTRAL AFRICA

The Mambéré Formation crops out in the southwest of the Central African Republic and is interpreted as lacustrine to glaciolacustrine (Censier *et al*. 1985). Based on palaeomagnetic arguments, an age within the Mid Devonian to Mississippian interval was estimated. This fits generally into the presence of Late Devonian to Mississippian glaciations, but provides no further detail and should be regarded as questionably dated. There are additional reported occurrences of pre-Viséan diamictites in Niger (Lang *et al*. 1991; Isaacson *et al*. 2008).

FAR-FIELD EVIDENCE

Hangenberg Crisis and End-Devonian Mass Extinction

The Hangenberg Crisis in the latest Devonian and earliest Tournaisian was a protracted biotic event associated with mass extinction, eustatic changes and positive carbon isotope excursions (Brand *et al*. 2004; Kaiser *et al*. 2007, 2008, 2011, 2015 *this volume*; Walliser 1984). The associated mass extinction is considered a ‘top-6’ event in terms of ecological severity (McGhee *et al*. 2012, 2013). Its effects were wide ranging, affecting marine benthic realm (ostracods, stromatoporoids, and trilobites), pelagic realm (conodonts, ammonoids and forams) to extinctions of terrestrial vertebrates and land plants (Becker 1992; Caplan & Bustin 1999; Clack 2007; Hallam & Wignall 1999; Kaiser *et al.* 2015 *this volume*; Sallan & Coates 2010; Streel *et al*. 2000a).

The Hangenberg Crisis *sensu stricto* is defined in reference sections exposed in the Rhenish Massif of Western Europe (Fig. 6), which begin with the transgressive Hangenberg Black Shale (HBS) in the latest Famennian mid *praesulcata* Zone. The HBS contains the main extinction pulse and is correlated with geographically widespread black shale deposition, marine anoxia, and positive isotope excursions in both organic and inorganic carbon (Fig. 7; Kaiser *et al*. 2007). Positive carbon isotope excursions associated with the Hangenberg Crisis are widely believed to have been caused by a global increase in the burial of organic carbon (Kaiser *et al.* 2008, 2015 *this volume*).

The HBS is overlain by a regressive unit known as the Hangenberg Sandstone (HS) in the Rhenish Massif. Elsewhere in the Rhenish Massif some 100 m of incision is represented by the Seiler Channel, which is infilled by the Seiler Conglomerate and Hangenberg Shale. The incision is interpreted as being due to sea-level drawdown constrained to the LN Zone (Bless *et al*. 1992; Higgs & Streel 1993). Regression across Western and Eastern Europe has been correlated with the HS using gamma ray, geochemical and sedimentological proxies (Kumpan *et al*. 2013, 2014). Incision is also observed near the D/C boundary throughout North America (Fig. 15 in Brezinski *et al*. 2010). In northern Gondwana, there is a significant pulse of siliciclastic sediment and 100 m of relative sea-level fall immediately below the D/C boundary in the Moroccan Anti-Atlas, which was correlated with the HS in the Rhenish Massif (Kaiser *et al*. 2011). In the Central Asian Orogenic Belt there is evidence for increased detrital supply just below the D/C boundary, which extends evidence for a eustatic drawdown into an open-ocean island arc environment (Carmichael *et al*. 2015). Regression on a global scale, which is represented by the HS in the Rhenish Massif, has been inferred to be synchronous with the main pulse of glaciation at high palaeolatitudes (Kaiser *et al*. 2011).

Above the HS there is marine transgression containing a secondary extinction pulse at the D/C boundary, which affected the miospores, acritarchs/prasinophytes and clymeniid ammonoids (Kaiser *et al*. 2011; Kaiser *et al.* 2015 *this volume*). There is also a secondary isotope excursion constrained to this level (Kaiser *et al.* 2015 *this volume*).

Late Devonian biotic events, which include the Hangenberg Crisis, have been shown to group into long-period (2.4 Myr) eccentricity cycles (de Vleeschouwer *et al*. 2013). Within this longer term cyclicity are shorter periodicities of 100 kyr duration. The transgressive - regressive couplet of the Hangenberg Crisis may have occurred over one such short 100 kyr eccentricity cycle. This would be consistent with the suggestion of Streel *et al*. (2013) of a single 100,000 year glacial cycle in Gondwana and potentially the single advance of glaciation both in Appalachia and the Bolivian Altiplano (Brezinski *et al*. 2008, 2010; Díaz-Martínez & Isaacson 1994). However, more precise information as to the nature and timing of the precursor glaciations is needed before an orbital control can be identified.

Lower Alum Shale and *Siphonodella isostichia* isotope excursions

In Germany there is a transgressive black shale unit known as the "Liegender Alaunschiefer" (Lower Alum Shale), interpreted as the result of eutrophication, anoxia and high organic productivity (Becker 1993; Siegmund *et al*. 2002). The Lower Alum Shale is overlain by prograding highstand carbonates and an erosional sequence boundary in the Velbert area (Fig. 2 in Siegmund *et al*. 2002). The stratigraphic extent of the Liegender Alaunschiefer ranges through the mid to late Tournaisian (Tn2-Tn3 zones), which overlaps with Tournaisian glaciation South America during the PC/PD zones (Siegmund *et al*. 2002; Playford *et al*. 2012). Transgression and anoxic conditions during the Lower Alum Shale have been correlated to the Gondwanan record in the Anti-Atlas Mountains, Morocco, and dated to the base of the mid Tournaisian (Kaiser *et al*. 2011, 2013). Weathered black shales, interpreted as representing anoxic conditions, are overlain by regressive sandstones at the El Atrous section, a lithological signature similar to that of the Hangenberg Crisis lower down in the same section (Kaiser *et al.* 2005, 2011, 2013, 2015 *this volume*). The Lower Alum Shale could represent a mid Tournaisian 'Hangenberg Crisis equivalent', in which glaciation is associated with a transgressive - regressive couplet and marine anoxia in the far-field records. Further study is needed to integrate these near-field and far-field records in the mid Tournaisian.

In North America there is a ≤7 ‰ positive carbon isotope $\delta^{13}C_{carbonate}$ excursion within the mid Tournaisian *Siphonodella isosticha* conodont Zone of the Kinderhookian regional stage (Fig. 7). This is roughly coincident with both the Lower Alum Shale and mid Tournaisian glaciation in Gondwana (Saltzman 2002; Playford *et al*. 2012). Positive carbon isotope excursions can be correlated to the Russian Platform (Mii *et al*. 1999) and South China (Yao *et al*. 2015; Qie *et al*. 2011, 2015). The cause of these excursions is interpreted as the global-scale burial of organic carbon (Yao *et al*. 2015). Despite the apparent global scale of the event, there is a wide variation in the magnitudes and absolute values of $\delta^{13}C_{carbonate}$ excursions, which Yao *et al.* (2015) attributed to spatial differences in marine nutrient concentrations.

Mid Tournaisian $\delta^{13}C_{carbonate}$ excursions in South China are accompanied by a positive shift in $\delta^{15}N$ of 1.5 - 4.2 ‰, which was interpreted to reflect enhanced water-column denitrification (Yao *et al.* 2015). Significantly this positive shift in $\delta^{15}N$ did not return to pre-excursion values but rather remained relatively positive into the lower part of the *G. typicus* Conodont Zone. This positive shift in the mid Tournaisian is inferred to be the initiation of elevated global $\delta^{15}N$ values throughout the entire LPIA (Algeo *et al*. 2014; Yao *et al*. 2015), caused by changes in oceanic circulation and lower eustatic sea-level during icehouse climate modes, which favoured enhanced water-column denitrification in continental margin oxygen minimum zones. These perturbations in carbon-nitrogen isotopes are synchronous with sustained decreases in oxygen isotopic data, suggesting long-term global cooling from the mid Tournaisian onwards (Buggisch *et al*. 2008; Yao *et al*. 2015). Yao *et al*. (2015) have interpreted these isotopic trends as reflecting the mid Tournaisian onset of sustained continental glaciation during the LPIA.

There is additional evidence of top Tournaisian regression and palaeovalley incision throughout North America at the Kinderhookian/Osagean regional stage boundary (Kammer & Matchen 2008). This implies that regression and incision in North America may immediately post-date positive carbon isotope excursions reported from the mid to late Kinderhookian (Saltzman 2002).

Viséan

Smith & Read (2000) interpret a Viséan onset of the LPIA within the *G. bilineatus* Conodont Zone, based on a sequence stratigraphic interpretation of the Illinois Basin. This is correlative to the Mag Zone in the Amazon Basin (Fig. 2). They describe five sequences that have extensive deep palaeovalley incision at their sequence boundaries. This suggests that the Visean glaciation event may have consisted of multiple glacial cycles of advance and retreat, resulting in multiple stacked sedimentary cycles in the Illinois Basin.

DISCUSSION

Uncertainties in the near-field record

This review has highlighted a relative paucity of detailed analyses of LPIA glacial deposits in the public domain. Brazil is particularly problematic, not least because many reported diamictite occurrences are from proprietary subsurface well-data (Caputo *et al*. 2008). In Fig. 8, only those reports of glaciation that are either stratigraphically and/or biostratigraphic constrained with original and fully published data are shown. This demonstrates that only a minority of studies provide integrated sedimentological, biostratigraphical and/or chronostratigraphical data through the diamictite sequences (e.g., di Pasquo 2007a, 2007b; Díaz-Martínez *et al*. 1999; Hyam *et al*. 1997; Playford *et al*. 2012; Gulbranson *et al*. 2010; Perez-Loinaze *et al*. 2010; Wicander *et al*. 2011). The LPIA can be shown to be strongly diachronous across certain regions and between individual basins (Limarino *et al*. 2014; Montañez and Poulson 2010). This diachroneity combined with the limited published data means that it is difficult to confidently assess the precise timing of glacial events in the latest Devonian to early Mississippian interval.

Where latest Famennian diamictites have been palynologically analysed they are typically associated with *R. lepidophyta* and *U. saharicum*. As such, there is no direct near-field evidence that support an extended duration of glaciation in the Middle Devonian (Elrick *et al*. 2009), at the Frasnian/Famennian boundary (Streel *et al*. 2000a), nor through the entire Famennian to earliest Tournaisian (Isaacson *et al*. 1999, 2008; Sandberg *et al.* 2002). Diamictites are typically associated with sheared or erosional basal contacts. There is little biostratigraphic constraint on the timing of erosion and ice-retreat, which would give a maximum estimate of glacial duration.

The validation of mid Tournaisian and Viséan glaciations in Brazil and Bolivia is difficult. Mid Tournaisian glaciation is supported by only one detailed published study (Playford *et al*. 2012). Viséan glaciation in Brazil is not as yet supported by any published measured sections or palynological descriptions. The reported diamictites in the Mississippian Kasa Formation in Bolivia are interesting but need to be accurately dated. Further work constraining Mississippian diamictite occurrences would test the assertion of Yao *et al.* (2015) of established, permanent continental glaciation from the mid Tournaisian onwards.

Far-field integration

Palynological methods have shown great potential for the dating and global correlation of uppermost Devonian-lower Carboniferous sediments, with assemblages characterised by the miospore *R.*

lepidophyta and the acritarch *U. saharicum*. However the distribution, evolution and extinction of palynological groups over the latest Famennian glaciation require further study (di Pasquo 2007c; di Pasquo & Azcuy 1997; Le Hérissé *et al.* 2000; Mullins & Servais 2008). It is not currently known if palynological extinctions are synchronous with the main glacial pulse or with the initial post-glacial transgression. Due to problems with the D/C boundaries as defined in both Europe and the Amazon Basin (i.e., the problems with the GSSP in the former, and erosion in the latter) the timing of these extinctions could provide an additional D/C boundary proxy. By defining the relationship between glaciation and palynological extinctions, it will then be possible to determine how these compare to wider palaeoclimatic and glacio-eustatic changes.

An additional correlation tool would be to recognise the wider climatic, oceanographic, biotic and isotopic events to which the glaciations were likely related. The latest Famennian and mid Tournaisian glacial events in particular are associated with positive carbon and nitrogen isotope excursions, indicating that glaciation is reflecting and/or driving wider changes in the global Earth system (Kaiser *et al*. 2007, 2008; Saltzman 2002).

There are several potential triggering mechanisms for these events (see Kaiser *et al.* 2015 *this volume*); one being the long-term decline in atmospheric CO_2, possibly related to the expansion of terrestrial vegetation (Algeo *et al*. 1995; Berner 2006). These large-scale processes may have controlled the long-term greenhouse to icehouse transition, but do not adequately explain discrete glaciation events or positive carbon isotopes excursions, which occurred on much shorter timescales. The trigger for global organic carbon burial at the Hangenberg Crisis is debatable, but appears to have been geographically wide-ranging, evidenced by anoxic conditions in both continental basins and open ocean environments (Carmichael *et al*. 2015; Kaiser *et al*. 2007, 2011). The known geographic extent of anoxia and isotopic excursions in the mid Tournaisian is increasing with evidence in both Euramerica and Gondwana (Kaiser, 2005; Kaiser *et al.* 2011, 2013; Le Yao *et al*. 2015; Siegmund *et al*. 2002). The coincidence of global environmental perturbations with evidence for glaciation at Hangenberg Crisis and mid Tournaisian Lower Alum Shale suggests similar global triggering mechanisms between these two events (see Kaiser *et al*. 2015 *this vol.*).

Any glacial-interglacial cycles within each glacial episode would be orbital controlled and their correlation could provide additional stratigraphic constraint, as based on the concepts of sequence stratigraphy and cyclostratigraphy. It remains necessary to determine if latest Famennian glaciation was associated with a single glacial event lasting 100,000 years, or multiple stacked glacial advances of estimated 1 - 3 million year duration (Streel *et al*. 2013; Wicander *et al*. 2011). The mid Tournaisian event appears to be correlated with one regressive event whereas the Viséan sequences are associated with multiple stacked sequence boundaries, which suggests they may be a composite of many glacial-interglacial cycles. Future research will need to be driven by high-resolution multi-proxy stratigraphic studies to answer these questions.

CONCLUSIONS

- This review highlights uncertainty in the known stratigraphic and geographic extent of glaciation in the latest Devonian and Mississippian due to a relative lack of detailed published glacial sections in which sedimentological and biostratigraphical data are integrated.

- This paucity of data leads to uncertainty between direct near-field records and the wider far-field effect on glacioeustasy, mass extinction and carbon isotope stratigraphy.

- The latest Famennian to Mississippian represents a long-term greenhouse to icehouse transition, likely controlled by the long-term drawdown of atmospheric CO_2.

- Superimposed on this transition are short and discrete glacial events which can be correlated to regressive intervals, mass extinctions, positive carbon isotope excursions and global marine anoxia. These near-globally recognised events are the Hangenberg Crisis in the latest Devonian and Lower Alum Shale Event in the mid Tournaisian.

- Palynological analyses can be employed constructively to date near-field deposits, and to correlate the far-field effects globally due to cosmopolitan plant miospores recognised in Gondwana and Euramerica. The most widely recognised miospore during the latest

Famennian glaciation event is *R. lepidophyta*, which in South America is typically associated with the marine acritarch *U. saharicum*.

- Future work is needed to further constrain near-field glacial records. This requires multi-proxy and high resolution stratigraphic studies in which sedimentology, palynology and geochemical techniques are synergistically combined.

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Fig. 1. (**a**) Palaeotectonic reconstruction for the Early Carboniferous (350 Ma) with putative ice-centres overlain, redrawn from Domeier and Torsvik, 2014. *N. Am* - North America, *S. Am* - South America, *Af* - Africa. (**b**). Palaeozoic basin map of South America, redrawn from Caputo *et al*. 2008. (**c**). Location of Central African Republic and Niger in sub-Saharan Africa, with shields regions overlain, redrawn from Isaacson *et al*. 2008.

Fig. 2. Published biostratigraphic schemes for the Famennian, Tournaisian and Viséan Stages. Chronostratigraphic age, Stage/Period boundaries and standard conodont & ammonoid schemes from Becker *et al*. 2012 and Davydov *et al*. 2012 (with corrections from Becker *pers. comms*).

Fig. 3. A summarised overview of published diamictite occurrences and their stratigraphic position. Peru stratigraphy referenced from Díaz-Martínez (2004). Bolivia - Díaz-Martínez and Isaacson (1994), Isaacson *et al*. 1995, Troth (2006) and Wicander *et al*. (2011). Brazil - Caputo e*t al*. (2008), Cunha *et al*. (2007), Filho *et al.* (2007), Melo & Playford (2012), Milani *et al*. (2007) and Vaz *et al*. (2007). Argentina - Perez-Loinaze *et al*. (2010) and Limarino *et al*. (2014). Falklands Islands/Las Malvina - Hyam *et al.* (1997). South Africa - Evans (1999), Streel & Theron (1999) and Theron (1993). Central Africa - Isaacson *et al*. (2008). Libya - stratigraphy based on Klett (2000), with diamictites postulated in the Tahara Formation by Streel *et al.* (2000a). USA Appalachian Basin - Brezinski *et al*. (2010) and Ettensohn *et al.* (2009). State abbreviations, *PA* – Pennsylvania, *MD* – Maryland, *WV* – West Virginia, *KY* - Kentucky. Malaysia - Meor *et al.* (2014).

Fig. 4. Stratigraphic evidence for latest Famennian glaciation in the Bolivian Altiplano. (**a**) Tectonic map of Bolivia redrawn from Barnes *et al*. 2012 and Sempere 1995. *AP* - Altiplano, *EC* - Eastern Cordillera, *IA* - Interandean Zone, *SA* Subandean Zone. Location of Manuripi X-1 and Pando X-1 onshore wells shown, as is Bermejo section of Wicander *et al.* 2011 (see Fig. 5) (**b**) Geographic map of the Bolivian Altiplano near Lake Titicaca, with location of key sections shown. (**c**) The Villa Molino, Hinchaka and Isle del Sol sections, which have been sampled for palynology, and their geographic location. Redrawn from Díaz-Martínez *et al*. 1999. (**d**) Stratigraphic log from the Cumaná Peninsula that shows the stratigraphic position of Mississippian diamictites. Redrawn from Díaz-Martínez 1996.

Fig. 5. Measured section of the latest Famennian and glaciomarine Itacua Formation at Bermejo. See Fig. 4a for geographic location of this section and Fig. 4c for lithology symbol key. Numbered arrows represent collected samples. Redrawn from Wicander *et al*. 2011.

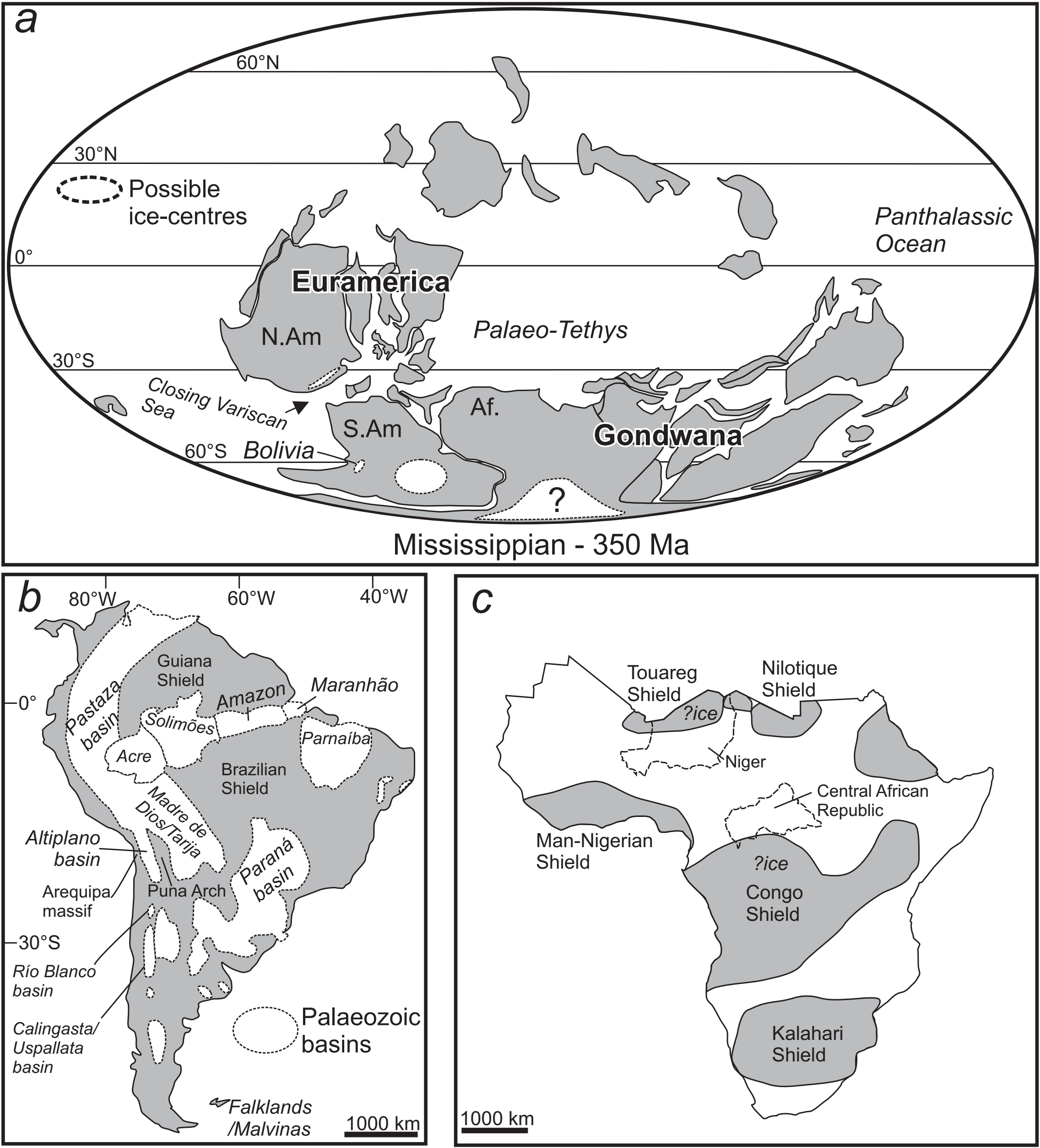
Fig. 6. Lithostratigraphy and biostratigraphy of the Hangenberg Crisis *sensu stricto* in the Rhenish Massif, Germany. Redrawn from Kaiser *et al*. 2011.

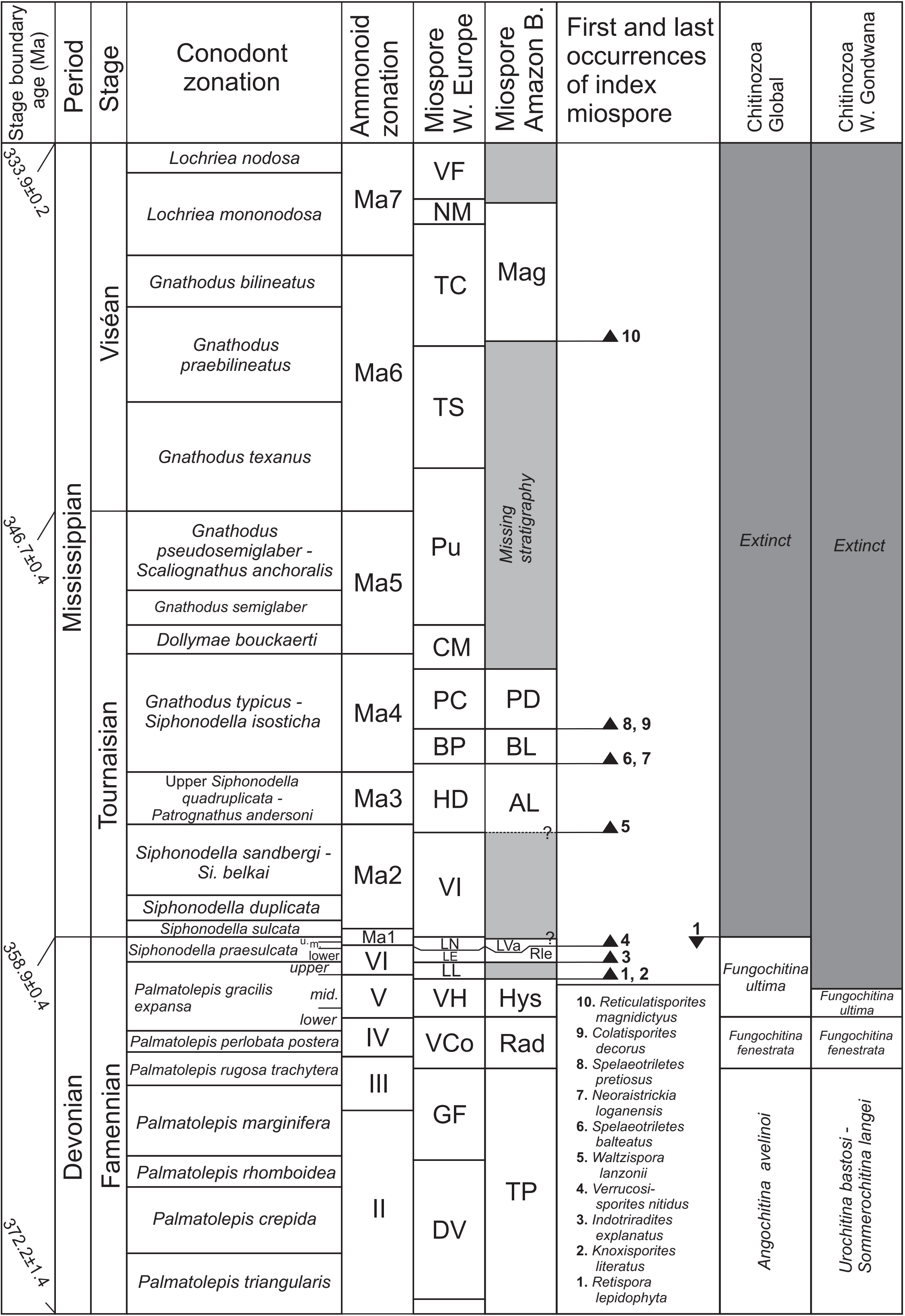
Fig. 7. Positive carbon isotope excursions in the latest Famennian *praesulcata* conodont Zone and the mid Tournaisian *isostichia* conodont Zone from reference sections in the Rhenish Massif and Idaho Basin. HBS = Hangenberg Black Shale *sensu stricto.* HS - Hangenberg Sandstone *sensu stricto*.

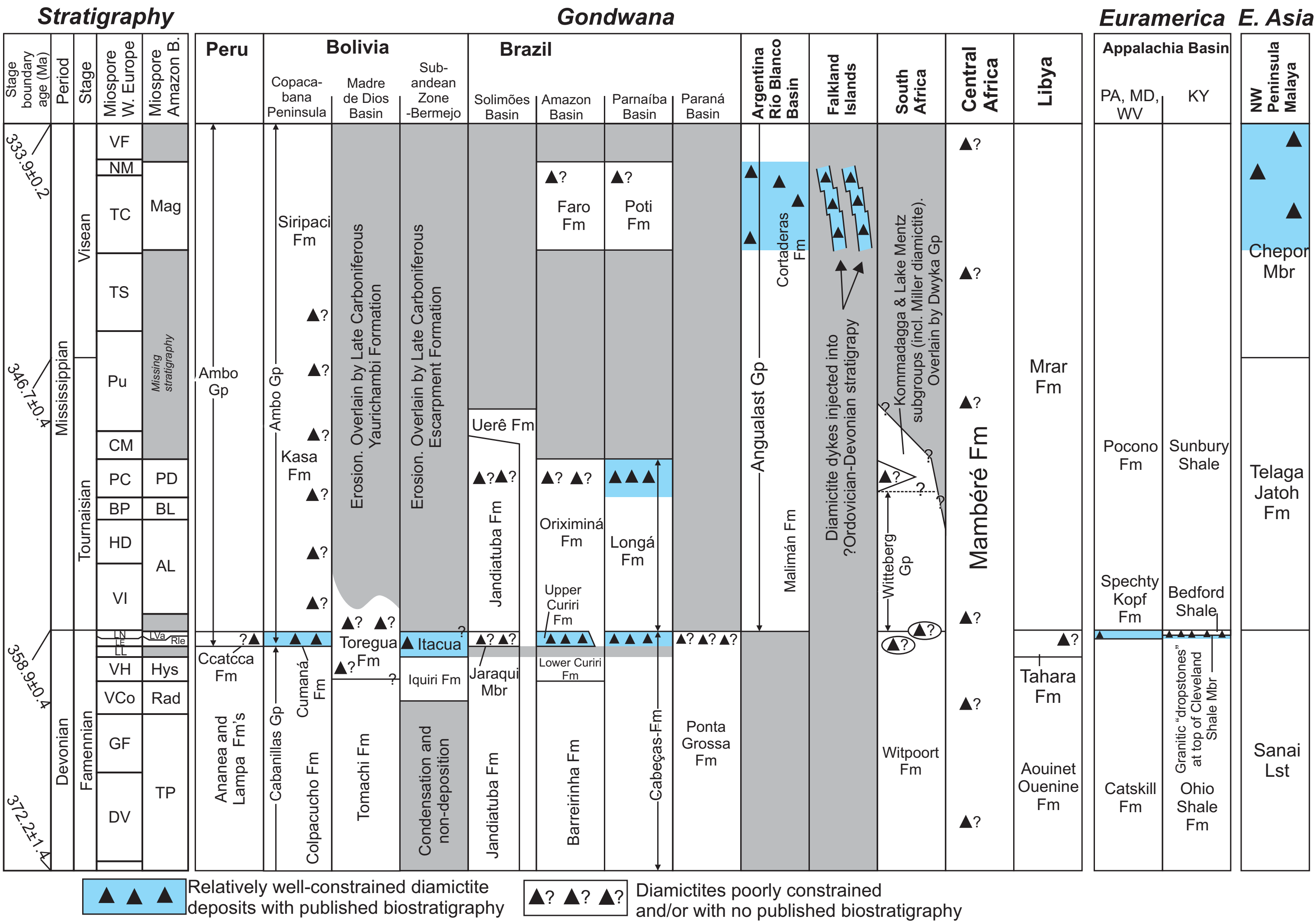
Fig. 8. Summary of published diamictite occurrences that are well-constrained and associated with detailed published sedimentological, stratigraphical and/or biostratigraphical data.

Table 1. *List of selected miospore, acritarch and prasinophyte taxa useful for stratigraphic correlation between Euramerica and Gondwana.*

Miospore species
Retispora lepidophyta (Kedo) Playford 1976
Knoxisporites literatus (Potonié & Kremp) Neves 1961
Indotriradites explanatus (Luber) Playford 1990
Verrucosisporites nitidus Playford 1954
Vallatisporites vallatus Hacquebard 1957
Waltzispora lanzonii Daemon 1974
Neoraistrickia loganensis (Winslow) Coleman and Clayton 1987
Spelaeotriletes balteatus (Playford) Higgs 1996
Spelaeotriletes pretiosus (Playford) Utting 1987
Raistrickia clavata (Hacquebard) Playford 1964
Reticulatisporites magnidictyus Playford and Helby 1968
Rugospora australiensis (Playford and Helby) Jones and Truswell 1992
Verrucosisporites quasigobbettii Jones and Truswell 1992
Acritarch and prasinophyte species
Chomotriletes vedugensis Naumova 1953
Gorgonisphaeridium ohioense (Winslow) Wicander 1974
Stellinium micropolygonale (Stockmans and Williére) Playford 1977
Umbellisphaeridium saharicum Jardine et al. 1974
Umbellisphaeridium deflandrei (Moreau-Benoit) Jardine et al. 1974
Horologinella quadrispina Jardiné et al. 1972
(?)*Schizocystia bicornuta* Jardiné *et al*. 1974


a
60°N
30°N
0°
30°S
60°S
Possible ice-centres
Panthalassic Ocean
Euramerica
Palaeo-Tethys
N.Am
Closing Variscan Sea
S.Am
Af.
Gondwana
Bolivia
?
Mississippian - 350 Ma
b
80°W
60°W
40°W
0°
30°S
Guiana Shield
Amazon
Maranhão
Pastaza basin
Solimões
Parnaíba
Acre
Brazilian Shield
Madre de Dios/Tarija
Altiplano basin
Arequipa massif
Puna Arch
Paraná basin
Río Blanco basin
Calingasta/ Uspallata basin
Palaeozoic basins
Falklands /Malvinas
1000 km
c
Touareg Shield
?ice
Nilotique Shield
Niger
Central African Republic
Man-Nigerian Shield
?ice
Congo Shield
Kalahari Shield
1000 km


Stage boundary age (Ma)
Period
Stage
Conodont zonation
Ammonoid zonation
Miospore W. Europe
Miospore Amazon B.
First and last occurrences of index miospore
Chitinozoa Global
Chitinozoa W. Gondwana
333.9±0.2
346.7±0.4
358.9±0.4
372.2±1.4
Mississippian
Devonian
Viséan
Tournaisian
Famennian
Lochriea nodosa
Lochriea mononodosa
Gnathodus bilineatus
Gnathodus praebilineatus
Gnathodus texanus
Gnathodus pseudosemiglaber - Scaliognathus anchoralis
Gnathodus semiglaber
Dollymae bouckaerti
Gnathodus typicus - Siphonodella isosticha
Upper Siphonodella quadruplicata - Patrognathus andersoni
Siphonodella sandbergi - Si. belkai
Siphonodella duplicata
Siphonodella sulcata
Siphonodella praesulcata
u.
m.
lower
upper
Palmatolepis gracilis expansa
mid.
lower
Palmatolepis perlobata postera
Palmatolepis rugosa trachytera
Palmatolepis marginifera
Palmatolepis rhomboidea
Palmatolepis crepida
Palmatolepis triangularis
Ma7
Ma6
Ma5
Ma4
Ma3
Ma2
Ma1
VI
V
IV
III
II
VF
NM
TC
TS
Pu
CM
PC
BP
HD
VI
LN
LE
LL
VH
VCo
GF
DV
Mag
Missing stratigraphy
PD
BL
AL
?
?
LVa
Rle
Hys
Rad
TP
10
8, 9
6, 7
5
4
3
1, 2
1
10. Reticulatisporites magnidictyus
9. Colatisporites decorus
8. Spelaeotriletes pretiosus
7. Neoraistrickia loganensis
6. Spelaeotriletes balteatus
5. Waltzispora lanzonii
4. Verrucosisporites nitidus
3. Indotriradites explanatus
2. Knoxisporites literatus
1. Retispora lepidophyta
Extinct
Extinct
Fungochitina ultima
Fungochitina ultima
Fungochitina fenestrata
Fungochitina fenestrata
Angochitina avelinoi
Urochitina bastosi - Sommerochitina langei


Stratigraphy
Gondwana
Euramerica
E. Asia
Stage boundary age (Ma)
Period
Stage
Miospore W. Europe
Miospore Amazon B.
333.9±0.2
346.7±0.4
358.9±0.4
372.2±1.4
Mississippian
Devonian
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Tournaisian
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VF
NM
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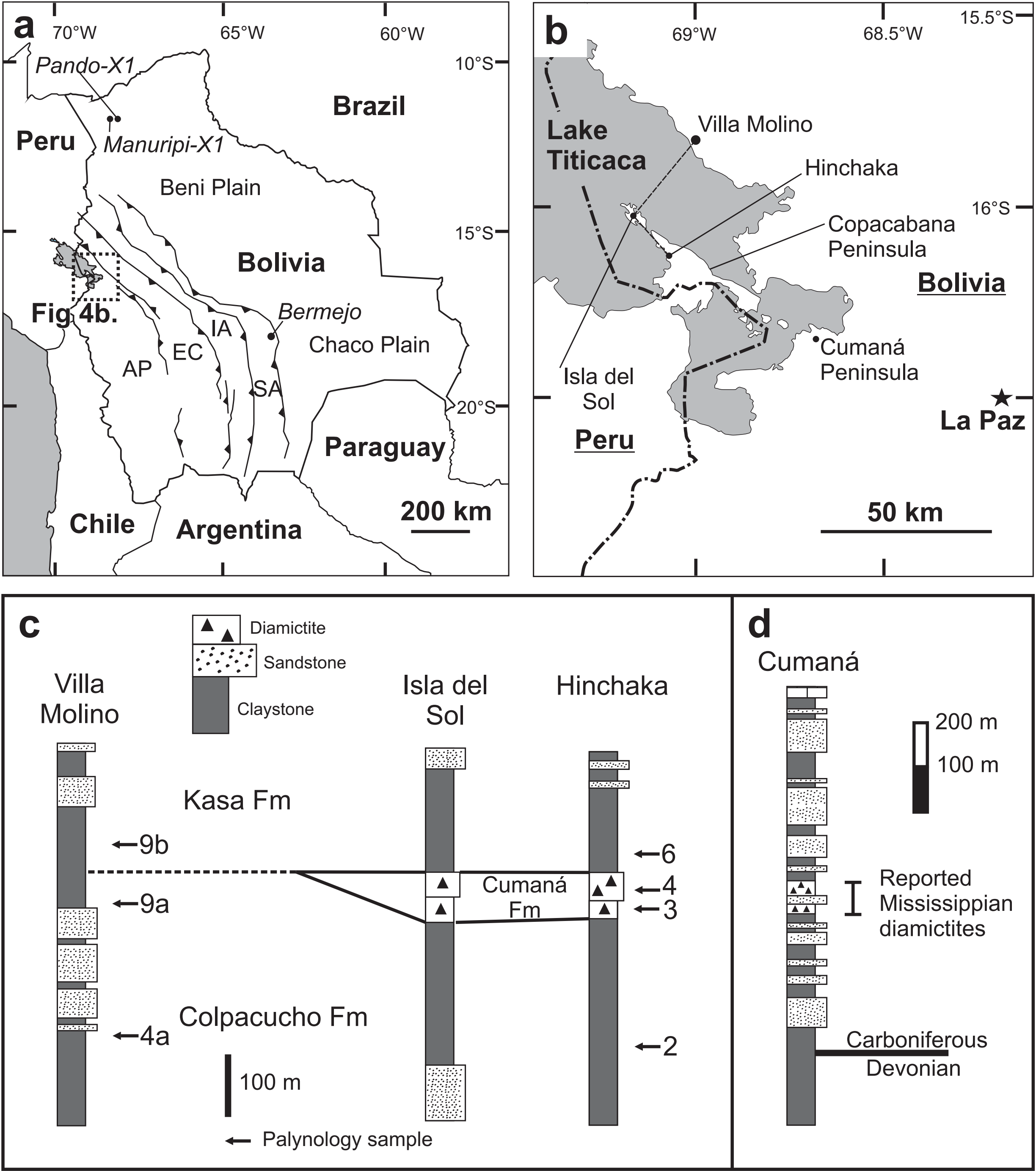
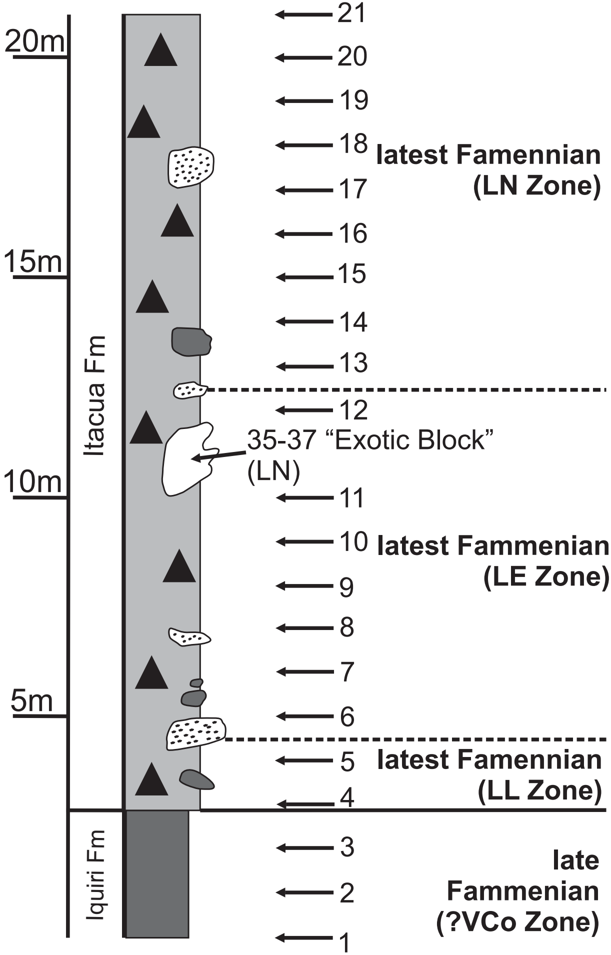
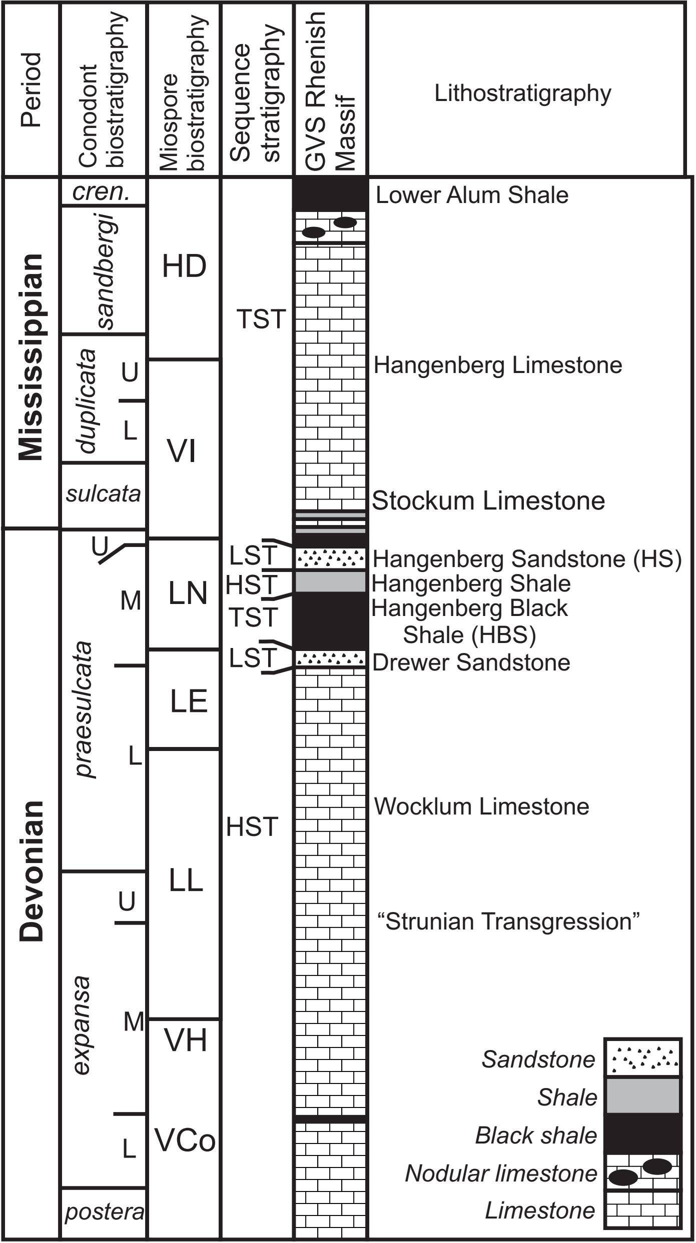
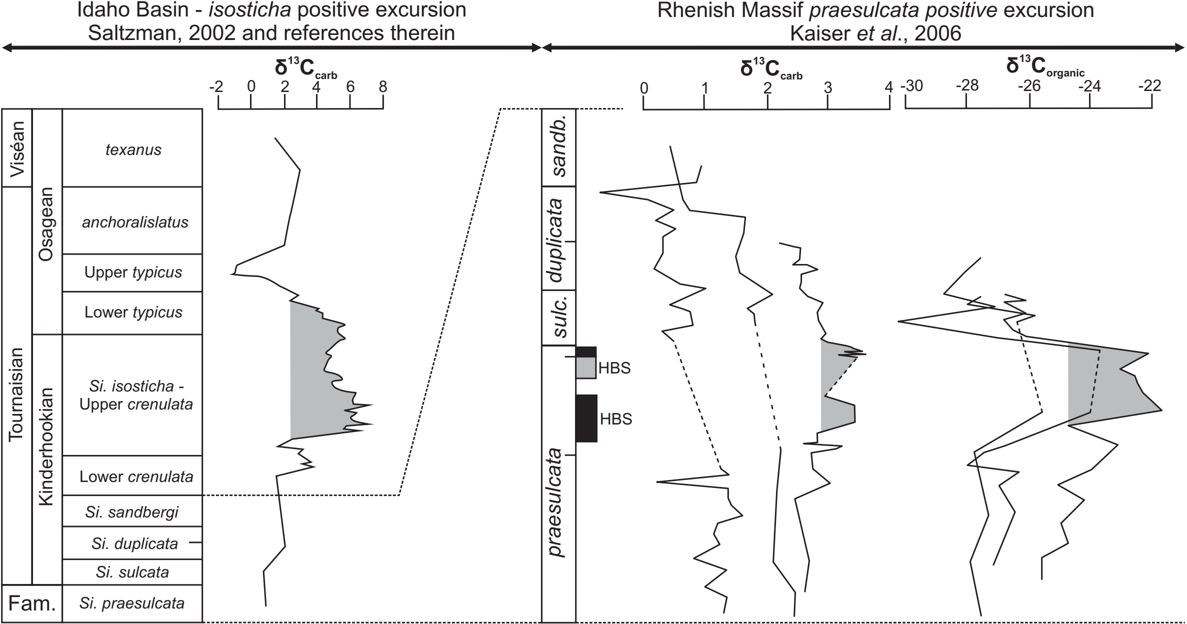
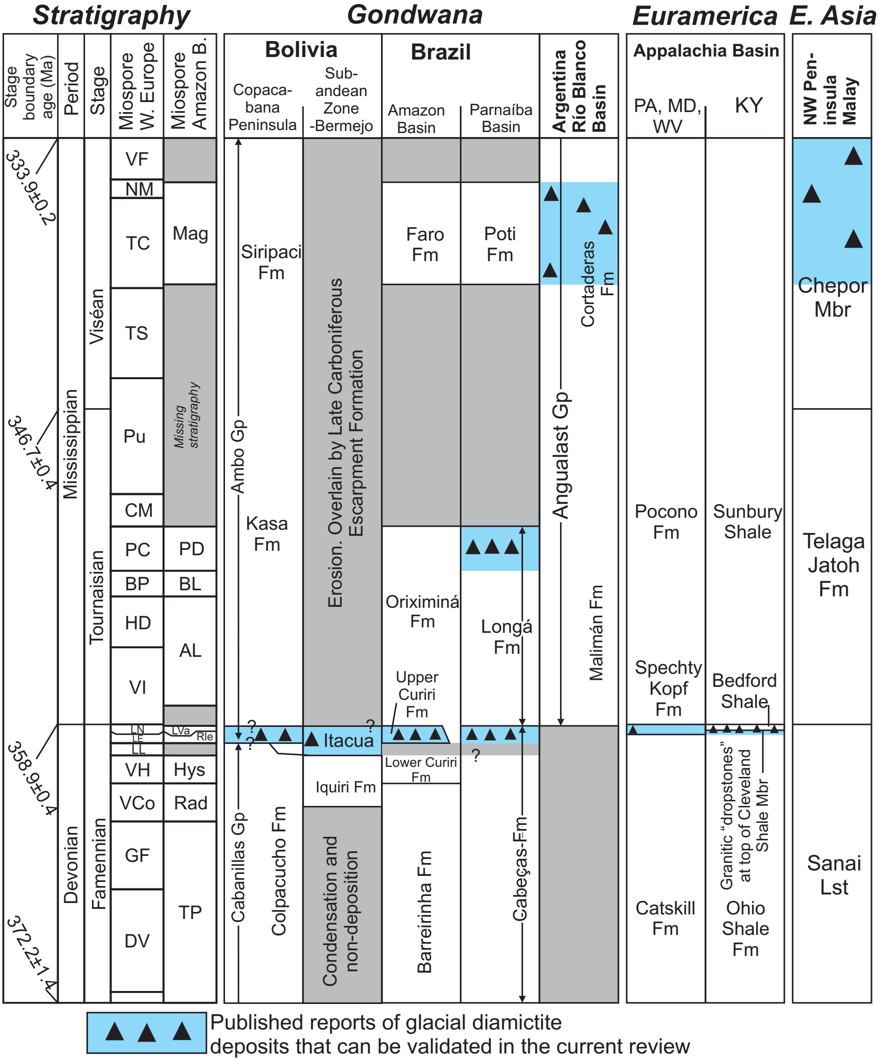
CM
PC
BP
HD
VI
LN
LE
LL
VH
VCo
GF
DV
Mag
Missing stratigraphy
PD
BL
AL
LVa
Rle
Hys
Rad
TP
Peru
Ambo Gp
Ccatcca Fm
Ananea and Lampa Fm's
Bolivia
Copacabana Peninsula
Siripaci Fm
Ambo Gp
Kasa Fm
Cumaná Fm
Cabanillas Gp
Colpacucho Fm
Madre de Dios Basin
Erosion. Overlain by Late Carboniferous Yaurichambi Formation
Toregua Fm
Tomachi Fm
Sub-andean Zone -Bermejo
Erosion. Overlain by Late Carboniferous Escarpment Formation
Itacua
Iquiri Fm
Condensation and non-deposition
Brazil
Solimões Basin
Uerê Fm
Jandiatuba Fm
Jaraqui Mbr
Jandiatuba Fm
Amazon Basin
Faro Fm
Oriximiná Fm
Upper Curiri Fm
Lower Curiri Fm
Barreirinha Fm
Parnaíba Basin
Poti Fm
Longá Fm
Cabeças Fm
Paraná Basin
Ponta Grossa Fm
Argentina Río Blanco Basin
Cortaderas Fm
Angualast Gp
Malimán Fm
Falkland Islands
Diamictite dykes injected into ?Ordovician-Devonian stratigrapy
South Africa
Kommadagga & Lake Mentz subgroups (incl. Miller diamictite). Overlain by Dwyka Gp
Witteberg Gp
Witpoort Fm
Central Africa
Mambéré Fm
Libya
Mrar Fm
Tahara Fm
Aouinet Ouenine Fm
Appalachia Basin
PA, MD, WV
Pocono Fm
Spechty Kopf Fm
Catskill Fm
KY
Sunbury Shale
Bedford Shale
Granitic "dropstones" at top of Cleveland Shale Mbr
Ohio Shale Fm
NW Peninsula Malaya
Chepor Mbr
Telaga Jatoh Fm
Sanai Lst
▲?
?
▲ ▲ ▲ Relatively well-constrained diamictite deposits with published biostratigraphy
▲? ▲? ▲? Diamictites poorly constrained and/or with no published biostratigraphy


a
70°W
65°W
60°W
10°S
15°S
20°S
Pando-X1
Manuripi-X1
Peru
Brazil
Beni Plain
Bolivia
Fig 4b.
Bermejo
IA
EC
AP
SA
Chaco Plain
Paraguay
Chile
Argentina
200 km
b
69°W
68.5°W
15.5°S
16°S
Lake Titicaca
Villa Molino
Hinchaka
Copacabana Peninsula
Bolivia
Cumaná Peninsula
Isla del Sol
Peru
La Paz
50 km
c
Diamictite
Sandstone
Claystone
Villa Molino
Isla del Sol
Hinchaka
Kasa Fm
Cumaná Fm
Colpacucho Fm
9b
9a
4a
6
4
3
2
100 m
Palynology sample
d
Cumaná
200 m
100 m
Reported Mississippian diamictites
Carboniferous
Devonian


20m
15m
10m
5m
Itacua Fm
Iquiri Fm
21
20
19
18
17
16
15
14
13
12
35-37 "Exotic Block"
(LN)
11
10
9
8
7
6
5
4
3
2
1
latest Famennian
(LN Zone)
latest Fammenian
(LE Zone)
latest Famennian
(LL Zone)
late
Fammenian
(?VCo Zone)


Period
Conodont biostratigraphy
Miospore biostratigraphy
Sequence stratigraphy
GVS Rhenish Massif
Lithostratigraphy
Mississippian
Devonian
cren.
sandbergi
duplicata
U
L
sulcata
U
M
praesulcata
L
U
expansa
M
L
postera
HD
VI
LN
LE
LL
VH
VCo
TST
LST
HST
TST
LST
HST
Lower Alum Shale
Hangenberg Limestone
Stockum Limestone
Hangenberg Sandstone (HS)
Hangenberg Shale
Hangenberg Black Shale (HBS)
Drewer Sandstone
Wocklum Limestone
"Strunian Transgression"
Sandstone
Shale
Black shale
Nodular limestone
Limestone


Idaho Basin - isosticha positive excursion
Saltzman, 2002 and references therein
Rhenish Massif praesulcata positive excursion
Kaiser et al., 2006
δ13Ccarb
-2 0 2 4 6 8
δ13Ccarb
0 1 2 3 4
δ13Corganic
-30 -28 -26 -24 -22
Viséan
Tournaisian
Fam.
Osagean
Kinderhookian
texanus
anchoralislatus
Upper typicus
Lower typicus
Si. isosticha - Upper crenulata
Lower crenulata
Si. sandbergi
Si. duplicata
Si. sulcata
Si. praesulcata
sandb.
duplicata
sulc.
praesulcata
HBS
HBS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Pocono Fm
Spechty Kopf Fm
Catskill Fm
Sunbury Shale
Bedford Shale
Granitic "dropstones" at top of Cleveland Shale Mbr
Ohio Shale Fm
Chepor Mbr
Telaga Jatoh Fm
Sanai Lst
Published reports of glacial diamictite deposits that can be validated in the current review