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THE MAGNITUDE OF LATE PALEOZOIC GLACIOEUSTATIC FLUCTUATIONS: A SYNTHESIS

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ABSTRACT: **A comprehensive literature review shows that the magnitude of eustatic fluctuations varied throughout the Carboniferous and Permian and that at least eight distinct phases can be recognized. Facies juxtapositions in carbonate successions and erosional relief in clastic successions indicate that glacioeustatic fluctuations of 20–25 m, and occasionally as much as 60 m, took place throughout the early Mississippian (Tournaisian)—a widely recognized glacial period. Middle Mississippian (mid-Chadian through Holkerian) shallow marine carbonate and clastic successions indicate that eustatic fluctuations were 10–25 m, a decrease that matches well with the paucity of coeval glacial deposits. Late Viséan (Asbian through mid-Brigantian) glacioeustatic fluctuations of 10–50 m record the initial phases of ice accumulation in advance of the widespread mid-Carboniferous glacial event. The latest Mississippian–earliest Pennsylvanian (mid-Brigantian through Langsettian) was a time of widespread glaciation, and strata of this age commonly exhibit evidence of glacioeustatic fluctuations of as much as 40–100 m. Although middle Pennsylvanian (Duckmantian through Asturian) glacial deposits are present in eastern Australia, paleovalley depths suggest that coeval glacioeustatic fluctuations were less than 40 m. Glacioeustatic fluctuations of as much as 100–120 m have been widely reported from late Pennsylvanian–earliest Permian (Stephanian through mid-Sakmarian) successions in North America, an increase that corresponds to the growth of large ice sheets across much of Gondwana and the accumulation of ice in the northern hemisphere. Incision and facies juxtaposition in Early–middle Permian (mid-Sakmarian through Kungurian) successions in eastern Australia indicate that glacioeustatic fluctuations of 30–70 m occurred during the waning stages of major glaciation. Erosional relief in paleoequatorial carbonates and the presence of coeval glacial deposits in Australia suggests that eustatic fluctuations of 10–60 m occurred during the final stages of glaciation in the middle to Late Permian (Roadian through Capitanian), but the modest size of most of these fluctuations makes it difficult to isolate the glacioeustatic signature.**

This review demonstrates that far-field cyclic successions record changing glacial conditions in Gondwana, that the magnitude of glacioeustatic fluctuations was directly related to the volume of glacial ice, that Carboniferous–Permian glacioeustasy was more variable than previously recognized, and that generalizations from short temporal intervals are probably not representative of the late Paleozoic ice age as a whole. Although any attempt to quantify the magnitude of ancient eustatic changes is based on caveats and assumptions, this review incorporates the results of over 100 published papers on the topic in an attempt to minimize the errors inherent in any one study.

INTRODUCTION

Wanless and Shepard's (1936) hypothesis that northern hemisphere cyclothems record glacioeustatic change caused by the dynamics of Gondwanan glaciation remains an important paradigm in sedimentary geology. Over the past seventy years numerous studies in Gondwana and Euramerica have supported aspects of their hypothesis and provided compelling evidence that "icehouse" conditions existed, at least intermittently, from the Late Devonian through the middle Permian (Veevers and Powell 1987). Although the economic importance of northern hemisphere cyclothems has encouraged extensive research for over a century, intensive study of coeval deposits in Gondwana has commenced only in the last few decades. In a synthesis of southern hemisphere data, Isbell et al. (2003) concluded that the late Paleozoic ice age was not a single protracted event with numerous advances and retreats, but rather consisted of three glacial intervals (20–30 Myr in duration) separated by distinctly non-glacial periods of similar duration. Additionally, their modeling suggests that large (50–115 m) glacioeustatic fluctuations could only have occurred during the peak of late Paleozoic glaciation in the late Pennsylvanian and Early Permian. Although the Isbell et al. (2003) hypothesis of dynamic glaciation represents a major step forward in our understanding of the late Paleozoic ice age, several major issues remain unresolved, most notably (1) the existence of Australian and possibly South American glacial deposits during "non-glacial" phases, (2) the unknown timing and extent of possible northern hemisphere glaciers, (3) the present inability to precisely correlate glacial events between Gondwanan continental remnants, (4) uncertainties about the volume and distribution of ancient glaciers, and (5) the lack of an alternate mechanism to explain the large eustatic changes documented in Mississippian–middle Pennsylvanian far-field successions. The concept of dynamic late Paleozoic glaciation has been confirmed by Fielding et al. (2008), who recently documented eight discrete glacial intervals in eastern

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Australia, some of which are also preserved in Antarctica and can be confidently linked to the floral and climate proxy record of paleoequatorial regions (Montañez et al. 2007).

In the present paper we plot previously published estimates of late Paleozoic glacioeustasy against time in order to compare results derived from different data sets and to look for temporal changes in the magnitude of sea-level change. These data are compared against the known distribution of glaciers in eastern Australia (Fielding et al. 2008), Siberia (Chumakov 1994; Epshteyn 1981a, 1981b; and Raymond and Metz 2004), and across Gondwana (Isbell et al. 2000). This approach provides a significant advance in our understanding of late Paleozoic glacioeustasy because it includes results derived from different proxies and collected from across Euramerica and Gondwana, and benefits from recent advances in the understanding of the spatial and temporal distribution of glaciers during the late Paleozoic.

METHODS AND RATIONALE

This review draws upon previously published estimates of the magnitude of eustatic change during the late Paleozoic that are based on observations of erosional and depositional relief, facies juxtaposition, cycle thicknesses, geochemical proxies, and model predictions. We compare a variety of methods from numerous locations in order to overcome the problems that arise from the caveats and assumptions that accompany each method and local and basinal overprinting and uncertainties. Any attempt to quantify the magnitude of eustatic changes during the late Paleozoic requires assumptions and interpretations to be made. Despite these issues, a comprehensive overview of the literature is a necessary first step in fully understanding the dynamics of the late Paleozoic ice age.

Estimates of late Paleozoic sea-level fluctuations discussed in this paper were interpreted to record eustatic/glacioeustatic processes *by the original authors*. With the exception of the Kinderhookian–Osagean and Mississippian–Pennsylvanian unconformities, the geological features recording sea-level fluctuations occur within high-frequency (< 0.5 Myr) cyclic successions. A comprehensive table outlining the source of the information, stratigraphy of the unit(s), and details about the original author's justification for a eustatic interpretation is provided in JSR's Data Archive (http://www.sepm.org/jsr/jsr_data_archive.asp). Although the late Paleozoic was a time of major tectonic reorganization, tectonoeustatic changes occur orders of magnitude more slowly than glacioeustatic changes and could have caused no more than a few meters of change during the accumulation of an individual high-frequency cycle (tectonoeustatic rates are less than 1 cm/Myr, see Donovan and Jones 1979; Hallam 1992; Miller et al. 2003; Miller et al. 2004; and Miller et al. 2005 for a fuller discussion).

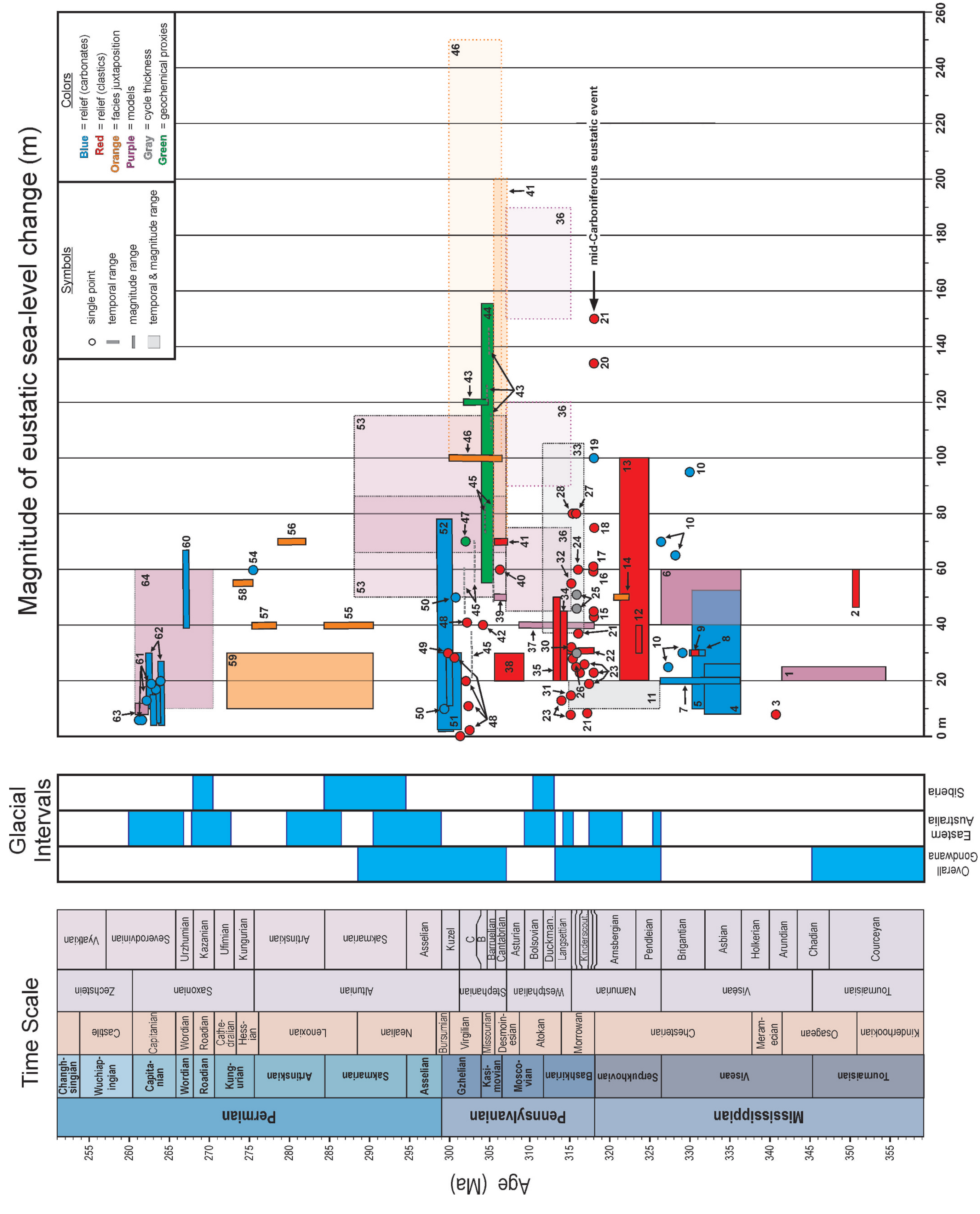
The purpose of this paper is not to debate the legitimacy of the methods and conclusions of each study but to provide a comprehensive and up-to-date synthesis of present knowledge about late Paleozoic eustatic and glacioeustatic change. We plot all of the relevant literature on the summary diagram (Fig. 1) and discuss our preferred interpretations (Fig. 2) in the body of the text. Of the hundreds of papers that discuss late Paleozoic cyclicity and glaciation, we limit our focus to papers in which the original authors focus on a specified stratigraphic unit(s), a discrete temporal interval, and specifically attribute the observed changes to eustatic or glacioeustatic processes. Datasets that made broad generalizations about the magnitude of eustatic sea-level change (e.g., Eyles 1993, p. 155) or that document changes in relative sea level caused by, or strongly overprinted by, tectonism were excluded (e.g., Greb and Chestnut 1996 and many others). We include a comparison with the coastal onlap curves of Ross and Ross (1987), but this dataset is not reproducible and has little in common with the other studies (Fig. 3). Data are plotted using the time-scale terminology of Davydov et al. (2004) and Wardlaw et al. (2004) and discussed using European and Russian stage names. Numerical ages are provided as a reference, but Figure 1 was constructed using biostratigraphy and the distribution of datapoints is tied directly to the stage names; new radiogenic isotope ages are likely to change the absolute ages provided herein.

Different methods produce very different estimates of the magnitude of eustatic fluctuations, and each approach is subject to a set of caveats and assumptions. Oxygen isotope records derived from brachiopods and conodonts provide a record of global ocean chemistry that can be used to estimate eustatic fluctuations. However, such data must be viewed with caution: $\delta^{18}O$ values from marine carbonates may be diagenetically overprinted and, in epicontinental settings, $\delta^{18}O$ records can potentially reflect local rather than global conditions. Modeling studies of eustatic changes caused by fluctuations in ice volume also operate at a global level, but without a detailed understanding of the spatial and temporal distribution of glaciers, the results remain only crude approximations that may or may not be supported by field observations. Estimates of glacioeustatic fluctuation are difficult to obtain from sedimentological studies because of uncertainties in determining paleo-bathymetry and the variable influence of tectonism and climate on erosional or depositional relief (Feldman et al. 2005). Paleovalley depth is a measurement commonly used to approximate the magnitude of sea-level change (Church and Gawthorpe 1994; Matchen and Kammer 2006; a variation of the pinning-point method of Goldstein and Franseen 1995); we use only depths of bodies that can confidently be interpreted as paleovalleys. Like aspects of all measures of ancient eustatic change, the paleovalley-depth method is somewhat problematic, but it remains useful because these values are easily measured and widely reported, and because paleovalley depth seems to increase during icehouse phases of earth history (Gibling 2006). Despite the issues with individual techniques, a multidisciplinary synthesis of this kind remains the best hope for removing local and regional biases from the data and to develop a truly global understanding of this complex process.

Terminology

With the exception of the previously mentioned unconformities, eustatic sea-level changes discussed in this paper are derived from high-frequency cycles roughly 0.1 to 0.5 Myr in duration, broadly within the timeframe expected for Milankovitch-driven glacioeustatic cycles. We specifically avoid designating "orders" of sea-level change (*sensu* Vail et al. 1977) because many of the original authors did not employ this terminology, significant changes in the Carboniferous timescale are still occurring (cf. Menning et al. 2000; Davydov et al. 2004; Ramezani et al. 2007), and because significant complications inevitably arise from the overlap and confusion that exist with this hierarchical terminology.

We use the terms "relative sea level" to refer to changes in sea level relative to a datum, regardless of the cause (tectonism, eustasy, sediment supply), "eustatic" as a general term to refer to any global change in sea level (regardless of cause) and "glacioeustatic" to refer specifically to changes in global sea level that can confidently be attributed to changes in ice volume. Building upon the work of previous authors (Read et al. 1995; Church and Coe 2003; Miller et al. 2004; Butts 2005) and natural trends in the data described in this paper, we refer to eustatic changes of < 10 m as small, 10–25 m as moderate, 25–100 m as large, and > 100 m as very large. Although a variety of mechanisms can cause eustatic fluctuations, it must be remembered that the examples considered in the present paper were formed in association with high-frequency cycles that had a duration of < 0.5 Myr (excluding the two unconformity-related studies mentioned above). At the timescales considered by the original authors, small (< 10 m) eustatic changes could be caused by thermohaline volume changes, small changes in the volume of glacial ice, the amount of liquid water on land, or changes in the volume of the ocean basins (Plint et al. 1992). Moderate (10–25 m) eustatic changes could also be a product of one or more of the previously mentioned causes and although glacioeustasy


Magnitude of eustatic sea-level change (m)
Glacial Intervals
Time Scale
Symbols
single point
temporal range
magnitude range
temporal & magnitude range
Colors
Blue = relief (carbonates)
Red = relief (clastics)
Orange = facies juxtaposition
Purple = models
Gray = cycle thickness
Green = geochemical proxies
mid-Carboniferous eustatic event
Overall Gondwana
Eastern Australia
Siberia
Age (Ma)
Permian
Pennsylvanian
Mississippian
Changhsingian
Wuchiapingian
Capitanian
Wordian
Roadian
Kungurian
Artinskian
Sakmarian
Asselian
Gzhelian
Kasimovian
Moscovian
Bashkirian
Serpukhovian
Visean
Tournaisian
Castile
Capitanian
Wordian
Roadian
Cathedralian
Hessian
Leonardian
Nealian
Bursumian
Virgilian
Missourian
Desmoinesian
Atokan
Morrowan
Chesterian
Meramecian
Osagean
Kinderhookian
Zechstein
Saxonian
Autunian
Stephanian
Westphalian
Namurian
Viséan
Tournaisian
Vyatkian
Severodvinian
Urzhumian
Kazanian
Ufimian
Kungurian
Artinskian
Sakmarian
Asselian
Kuzel
C
B
Barruelian
Cantabrian
Asturian
Bolsovian
Duckman.
Langsettian
Kinderscout.
Arnsbergian
Pendleian
Brigantian
Asbian
Holkerian
Arundian
Chadian
Courceyan

may well represent an important component of these fluctuations, the glacial contribution is difficult to isolate and a contribution from other drivers cannot be ruled out. Consequently, we consider moderate (10–25 m) eustatic fluctuations within high-frequency cycles as suggestive, but not necessarily diagnostic of glacioeustasy. The 25 m cutoff represents a conservative value, in as much as Miller et al. (2003) and Miller et al. (2004) convincingly argue that > 25 m eustatic changes that occur in less than 1 Myr (twice the duration of cycles discussed in this paper) are largely a consequence of glacioeustasy. Large and very large values in excess of 25 m can confidently be attributed to glacioeustasy.

In preparing this review, it became apparent that inconsistent sea-level-curve terminology has caused significant confusion in the literature. According to Jackson (1997), the amplitude of a wave (or, in this case, a sea-level cycle) is equal to half the vertical distance between a wave crest and the adjacent trough; the total vertical distance between a crest and adjacent trough would thus be referred to as the height. This usage is consistent with the mathematical terminology applied to sine and cosine functions, for which the amplitude equals one half of the vertical range and the period equals the crest-to-crest or trough to trough distance. Using this nomenclature, the amount of change from the highest to lowest point in a sea-level cycle would be referred to as the height [or magnitude] of a sea-level fluctuation; the amplitude would be equal to one half of this value. Goldhammer et al. (1994) document ''fourth-order amplitudes'' of ~ 25 m and describe this value as the amount of departure from mean sea level; thus the total height or amount of sea-level change in one of their cycles would be 50 m (see their fig. 18). Confusion arises because ''amplitude'' is also understood to mean the ''greatness of size'' (Soukhanov 1984). Soreghan and Giles (1999) convincingly document nearly 80 m of relief along exposure surfaces and go on to state that this evidence supports glacioeustatic ''amplitudes'' of this amount or more; without careful scrutiny, this usage could be misunderstood to mean that sea level varied by 160+ m in individual cycles. This inconsistent terminology has the potential to create confusion in the literature, particularly when making the transition from field-based studies to modeling. We suggest that future authors abandon the term amplitude (unless specifically defined) and use the ''height,'' ''magnitude,'' or ''amount'' of sea-level change when referring to the difference between the sea level at its highest and lowest points in a cycle.

Although the entire late Paleozoic is generally considered to be an ''icehouse'' phase of Earth's climate history, recent studies suggest that it can be subdivided into discrete ''glacial'' periods when glaciers were widespread (as recorded by abundant glacial deposits) and ''nonglacial'' periods when glaciers presumably were restricted or absent (Isbell et al. 2003; Fielding et al. 2008). These glacial and nonglacial phases generally lasted millions of years and should not be confused with Milankovitch-driven, glacial–interglacial cycles, which are tens to hundreds of thousands of years in duration.

ESTIMATES OF LATE PALEOZOIC GLACIOEUSTATIC FLUCTUATIONS

Tournaisian (Courceyan to mid-Chadian)

Overall, the Tournaisian is regarded as a glacial period (Fig. 1; Bruckschen and Veizer 1997; Mii et al. 1999), although debate continues over the timing and magnitude of glaciation (Isbell et al. 2003). The upper Kinderhookian–Osagean (upper Tournaisian–Viséan) Lodgepole Formation is a dominantly carbonate succession that contains juxtaposed facies interpreted to record 20–25 m glacioeustatic fluctuations (Elrick and Read 1991; Read et al. 1995). In Ohio, the Blackhand Sandstone has recently been reinterpreted as a paleovalley formed in response to a 60 m glacioeustatic sea-level fall during the development of the Kinderhookian–Osagean unconformity in North America (Matchen and Kammer 2006). Although this hiatus may have lasted as long as six million years, Matchen and Kammer (2006) provide compelling evidence that tectonism was not a major influence on the development of the Black Hand paleovalley. The Courceyen–Chadian boundary may represent a second, high-amplitude glacioeustatic event during the Tournaisian, but no estimates of the amount of sea-level fall have been published (Faulkner et al. 1990; Wright and Vanstone 2001). The probable glacioeustatic origin of these events is supported by the work of Richardson (2006) and Richardson and Ausich (2004), who interpreted Tournaisian strata in the central USA as having a stratigraphic architecture driven by glacioeustasy. Given these lines of evidence, we interpret the Tournaisian as a period that regularly experienced moderate eustatic changes of 20–25 m, and on at least one occasion, a large 60 m glacioeustatic event (Fig. 2). The presence of glaciers in Gondwana makes variations in ice volume the most likely driver for these fluctuations, although the moderate size of the 20–25 m fluctuations means that other drivers of eustatic change may have been important.

Early Viséan (mid-Chadian through Holkerian)

Although Isbell et al. (2003) identified the Viséan as a distinctly nonglacial interval, poorly constrained Viséan glacial deposits (Veevers and Powell 1987; Crowell 1983; Caputo and Crowell 1985; Garzanti and Sciunnach 1997) may record local glacial conditions. The geochemical record suggests post-Viséan warming and deglaciation (Mii et al. 1999), but fluctuations within the record hint at possible glacial influence (Bruckschen and Veizer 1997; Bruckschen et al. 1999). Regardless, glacial ice appears to have been considerably less extensive than in previous and subsequent intervals. As mentioned above, the Lodgepole Formation contains evidence of moderate eustatic fluctuations (20–25 m) that continued through the Arundian (Fig 1; Elrick and Read 1991; Read et al. 1995). Chadian through Holkerian shallow-water carbonates in the British Isles lack pronounced exposure surfaces and exhibit a stratigraphic architecture that does not appear to be a consequence of glacioeustasy (see Wright and Vanstone 2001 and references therein), and

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FIG. 1.—Glacioeustatic estimates and the known distribution of glacial deposits throughout the Carboniferous and Permian. Timescale is based on Davydov et al. (2004) and Wardlaw et al. (2004) and was created using the Time Scale Creator (v. 2.1), available at www.stratigraphy.org. The distribution of glacial deposits across Gondwana is from Isbell et al. (2003), Fielding et al. (2008), and Siberia from Epshteyn (1981a, 1981b) and Chumakov (1994). Eustatic data are from 1) Elrick and Read (1991); 2) Matchen and Kammer (2006); 3) Graham (1996); 4) Horbury (1989); 5) Wright and Vanstoe (2001); 6) Barnett et al. (2002); 7) Walkden and Davies (1983); 8) Smith and Read (1999); 9) Leetaru (2000); 10) Smith (1996); Smith and Read (2000, 2001); Read (1998); 11) Ramsbottom (1979); 12) Davies et al. (1999); 13) Miller and Eriksson (2000); 14) Butts (2005); 15) Archer and Greb (1995); 16) Howard and Whitaker (1988); 17) Droste and Keller (1989); 18) Siever (1951); 19) Lemosquet and Pareyn (1983); 20) Bristol and Howard (1971); 21) Beuthin (1994) and Blake and Beuthin (2008); 22) Bowen and Weimer (2003); 23) Sonnenberg et al. (1990), Krystinik and Blakeney (1994), Blakeney et al. (1990); 24) Church and Gawthorpe (1994); 25) Maynard and Leeder (1992); 26) Wignall and Maynard (1996); 27) Jones and Chisholm (1997); 28) Wignall and Maynard (1996); 29) Hampson et al. (1997); 30) Church and Gawthorpe (1994); 31–32) Hampson et al. (1997); 33) Leeder (1988); 34–35) Hampson et al. (1999); 36) Crowley and Baum (1991); 37) Della Porta et al. (2002); 38) Gibling and Wightman (1994) and Gibling and Bird (1994); 39) Goldhammer et al. (1991, 1994); 40) Heckel et al. (1998); 41) Schenk (1967); 42) Heckel (1975) cited in Heckel (1977); 43) Joachimski et al. (2006); 44) Bates and Lyons (2006); 45) Klein (1994); 46) Heckel (1977, 1986, 1994); 47) Adlis (1988); 48) Feldman et al. (2005); 49) Fischbein (2006); 50) Goldstein (1988); 51) Rankey et al. (1999); 52) Soreghan and Giles (1999); 53) Isbell et al. (2003); 54) Koša et al. (2003); Kerans et al. (2000); 55) Rygel et al. (2008); 56) Fielding et al. (2006); and data presented in Table 1; 57) Facies data from Thomas et al. (2007) and modified in Table 1; 58) Facies data from Bann et al. (in press) and as modified in Table 1; 59) Eyles et al. (1998); 60) Kerans and Nance (1991); 61) Osleger (1998); Kerans and Harris (1993); 62) Rankey and Lehrman (1996); 63) Borer and Harris (1991, 1995); 64) Ye and Kerans (1996).

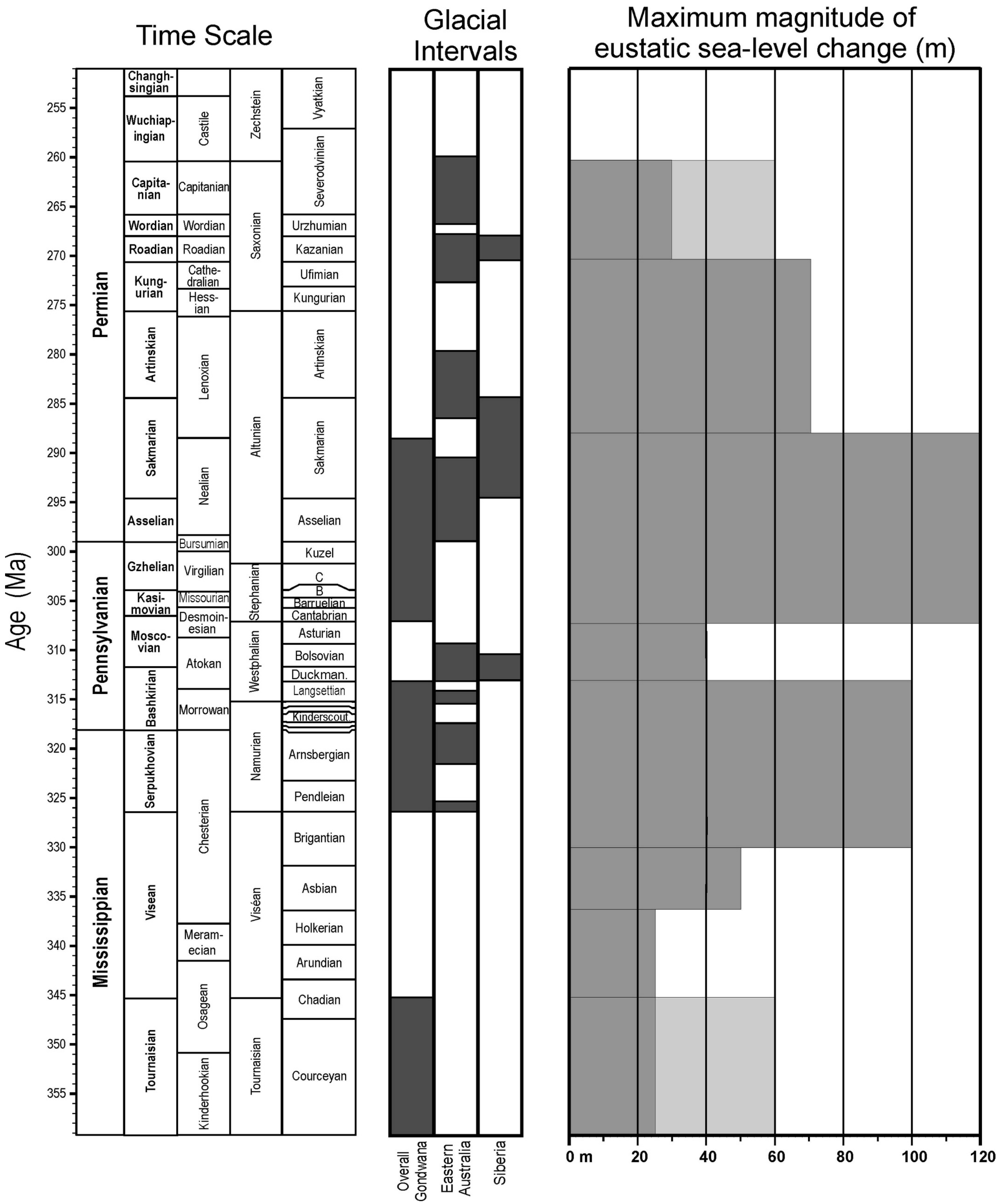

FIG. 2.—Simplified version of Figure 1 showing the eight eustatic phases described in this paper. Dark gray boxes in the maximum magnitude section are common values, light gray boxes represent the size of rare events. See text for further discussion.

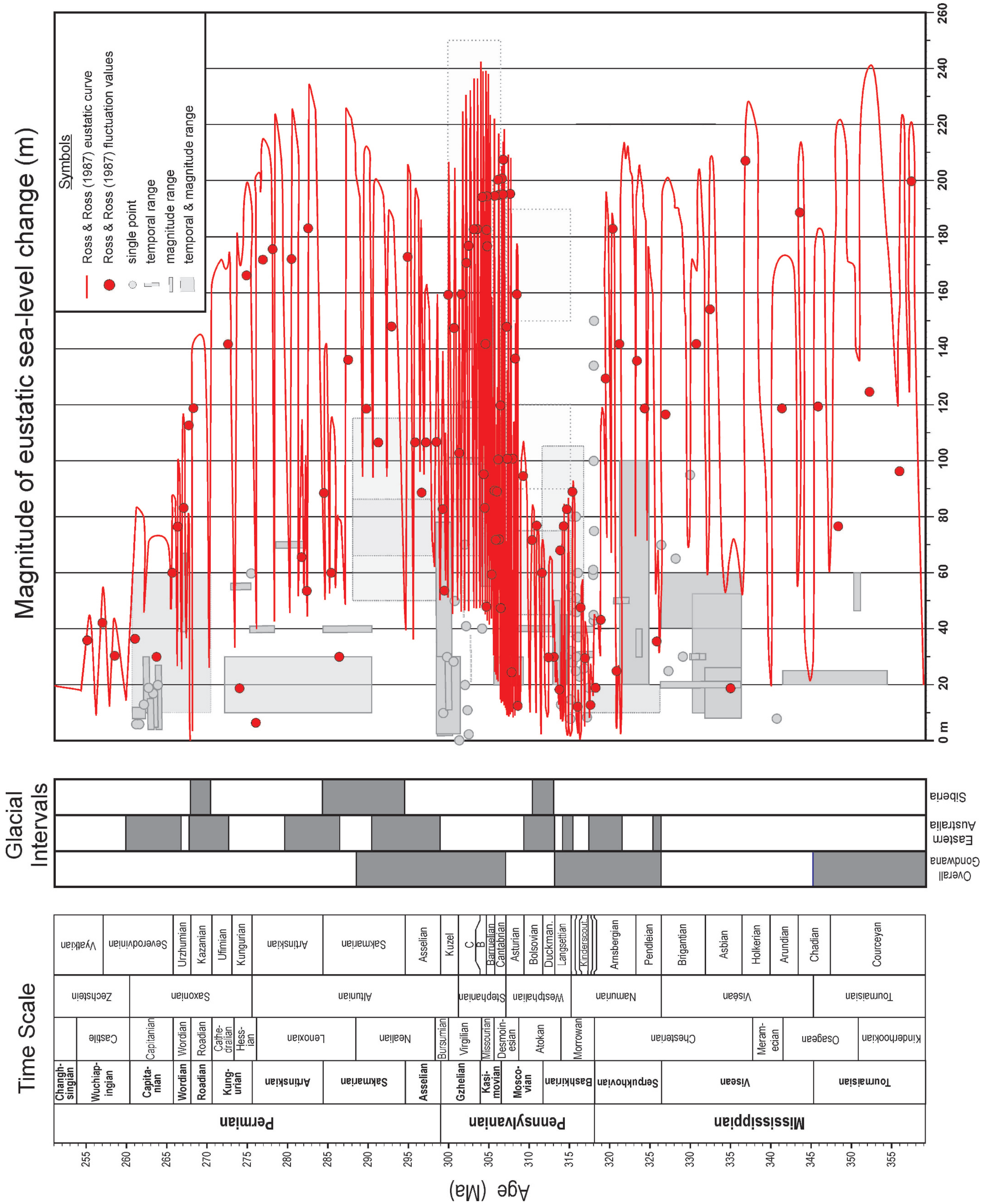

FIG. 3.—Modified version of Figure 1 showing the studies described in this paper (gray) and the eustatic changes of Ross and Ross (1987).

incised channels in the Mullaghamore Sandstone suggest minimum sea-level falls of 8 m (Graham 1996).

The consistency among far-field datasets suggests that maximum eustatic fluctuations were $<$ 25 m for the Chadian through the Holkerian (Fig. 2). Elrick and Read (1991) favor a glacioeustatic origin for these fluctuations, but their modest size makes this interpretation difficult to establish unequivocally.

Late Viséan (Asbian through mid-Brigantian)

The Asbian through mid-Brigantian represents a transition between largely nonglacial conditions during the early Viséan and the second major phase of Gondwanan glaciation during the mid-Carboniferous (Fig. 1; Wright and Vanstone 2001; Isbell et al. 2003). Although poorly constrained, numerous reports of Viséan glacial deposits suggest that glaciers may have been present locally (Veevers and Powell 1987; Crowell 1983; Caputo and Crowell 1985; Garzanti and Sciunnach 1997; Gonzalez 2001). Iannuzzi and Pfefferkorn (2002) describe warm climate floras across much of Gondwana during the late Viséan through earliest Surpukhovian, but in eastern Australia the units described in their paper occur between glacial intervals (Fielding et al. 2008), indicating that fluctuations between warm and cold climate occurred (at least regionally) during this time.

Moderate to large eustatic fluctuations (10–30 m) are widely reported from Asbian to early Brigantian shallow marine successions from across Euramerica (Fig. 1; Horbury 1989; Walkden and Davies 1983; Smith and Read 1999; Leetaru 2000). Although the forward stratigraphic model of Barnett et al. (2002) ran with fluctuations of up to 60 m, they cite the 10–50 m estimate of Wright and Vanstone (2001) as the basis for this number. Consequently we use the Wright and Vanstone estimate of 50 m as the maximum for this interval.

As originally suggested by Wright and Vanstone (2001), the Asbian through the mid-Brigantian is interpreted as a transitional interval characterized by moderate to large glacioeustatic fluctuations of 10–50 m (Figs. 1, 2). Although direct evidence of glaciation is equivocal in this interval, these fluctuations likely record glacioeustasy associated with local glaciation in advance of the widespread phase of Namurian–early Westphalian glaciation.

Latest Viséan (mid-Brigantian) through early Westphalian (Langsettian)

Glacial deposits are locally present in latest Viséan strata in South America (Gonzalez 2001), near the Bashkirian–Moscovian boundary in Siberia (Epshteyn 1981b), and Namurian through early Westphalian (Pendleian through Langsettian) rocks across much of Gondwana (Isbell et al. 2003), including eastern Australia (Fielding et al. 2008). The widespread distribution of glacial deposits matches well with the overall cooling trend indicated by the geochemical record from North America (Mii et al. 1999).

As noted by Wright and Vanstone (2001), the 25–95 m of relief along unconformities in carbonates of the Bethel and Glen Dean formations (Smith 1996; Read 1998; Smith and Read 1999, 2000, 2001) marks a dramatic increase in the magnitude of high-frequency eustatic fluctuations compared to those of the Asbian and the early Brigantian. Paleovalley depths and sequence thicknesses (Miller and Eriksson 2000; Davies et al. 1999), facies stacking patterns (Butts 2005), and cycle thicknesses (Ramsbottom 1979) indicate that moderate to large fluctuations (10 to 100 m) persisted throughout the rest of the Mississippian (Fig. 1).

The Mississippian–Pennsylvanian unconformity represents a global eustatic event during the Alportian–Chokierian (Saunders and Ramsbottom 1986)—an interval that corresponds to widespread glaciation across Gondwana (Isbell et al. 2003) and broadly equivalent to a glacial event in eastern Australia (Fielding et al. 2008). This eustatic event formed paleovalleys with 35–150 m of relief in eastern North America (Siever 1951; Bristol and Howard 1971; Rice 1984; Howard and Whitaker 1988; Droste and Keller 1989; Beuthin 1994; Archer and Greb 1995; Blake and Beuthin 2008) and 100 m of relief in paleokarst in North Africa (Lemosquet and Pareyn 1983). These authors generally interpret this event as largely eustatic in origin, but the temporal gap represented by the unconformity surface spans at least 4 Myr (Blake and Beuthin in press) and likely contains an element of tectonic enhancement (Quinlan and Beaumont 1984; Ettensohn 1994).

The persistence of glaciers through the end of the Langsettian was accompanied by large glacioeustatic fluctuations as recorded by paleovalleys 20–80 m deep in western Europe (Church and Gawthorpe 1994; Wignall and Maynard 1996; Hampson et al. 1997; 1999; Jones and Chisholm 1997) and North America (Blakeney et al. 1990; Sonnenberg et al. 1990; Krystinik and Blakeney 1990; Davies et al. 1999; Bowen and Weimer 2003). These values match well with the 40 m values predicted by the modeling of Della Porta et al (2002), the 60 $\pm$ 15 m model prediction of Crowley and Baum (1991), and the 30–105 m estimates derived from cycle thicknesses in European strata (Leeder 1998; Maynard and Leeder 1992). Larger estimates of 90–120 m and 150–190 m predicted by variations of Crowley and Baum's (1991) ICE model were not favored by the original authors and exceed the maximum values reported in other studies (Fig. 1).

Given the widespread distribution of glacial deposits and the deep incision associated with high-frequency cycles, we suggest that moderate to large glacioeustatic fluctuations of 20–100 m characterized the mid-Brigantian through Langsettian (Figs. 1, 2). Although the mid-Brigantian fluctuations predate any well-constrained glacial deposits, the large size of these fluctuations strongly suggests that glacioeustasy was active by this time. The mid-Carboniferous eustatic event may record a very large fluctuation in excess of 100 m, but the duration of the hiatus makes it difficult to isolate the eustatic signal from tectonic overprinting.

Middle to Late Westphalian (Duckmantian through Asturian)

The entirety of the Duckmantian through the Asturian was considered to be a nonglacial period by Isbell et al. (2003), but the presence of glacial deposits in eastern Siberia and Australia (Epshteyn 1981b; Fielding et al. 2008) suggests the possibility of glacioeustasy (Fig. 1). Far-field estimates of eustatic sea-level change are limited to paleovalleys 20–30 m deep in the Sydney Mines Formation (Gibling and Bird 1994; Gibling and Wightman 1994; Gibling et al. 2004) and the 40 m values predicted by Della Porta et al. (2002). Crowley and Baum (1991) applied their model to the whole of the Westphalian, but the absence of widespread glacial deposits during this interval makes the predicted values irrelevant.

Overall, a modicum of far-field evidence suggests that glacioeustasy was active during this time, but the magnitude of the fluctuations ($<$ 40 m) is significantly less than other Pennsylvanian fluctuations, a change that likely reflects a decrease in the volume of glacial ice (Figs. 1, 2). Further investigation will be necessary to fully resolve the glacial dynamics of this key interval.

Stephanian through mid-Sakmarian

Peak late Paleozoic glaciation occurred in the latest Pennsylvanian through the Early Permian as glaciers returned to much of Gondwana during the early Stephanian (Isbell et al. 2003), and to eastern Australia and Siberia in the Asselian (Chumakov 1994; Fielding et al. 2008). The onset of widespread glaciers in high latitudes was accompanied by a return to strongly cyclic deposits with deeply incised erosional surfaces in paleoequatorial regions (Fig. 1). Many estimates of the magnitude of glacioeustatic sea-level change have been derived from the midcontinent cyclothems of the USA, including paleovalleys up to 70 m deep (Schenk 1967; Heckel et al. 1998; Feldman et al. 2005; Fischbein 2006), 40 m of paleotopography (Heckel 1975 cited in Heckel 1977), estimates of $\sim$ 100 m water depth to the pycnocline (Heckel 1977, 1986, 1994), and

TABLE 1.—*Comparisons used to approximate water depths in Permian successions in eastern Australia and the interpreted magnitude of glacioeustasy recorded within these units (facies data for Australian units from Fielding et al. 2006; Thomas et al. 2007; Rygel et al. 2008; Bann et al. in press).*

Depth to coarse-grained ripples	Location	Source
37	New Jersey	values from Leckie (1987)
79	South Australia	
40	Scotia Shelf	
90	French Shelf	
80	Grand Banks	
90	South Africa	
58	Spanish Sahara	
42	Rhode Island	
108	Great Britain	
150	Celtic Sea	
58	Southwest England	
60	Maryland Coast	
36	Tasman Sea	
60	Bay of Biscay	Lesueur et al. (2002)
71	**average**	
	Paleo water depth estimates	
Depth (m)	Environment	Source
15	middle shoreface	1/2 fairweather wave base
30	fairweather wave base	Leseuer et al. (2002)
70	storm wave base	see part 1 above
	Estimates of Permian Eustatic Fluctuations	
Unit	Amount of change (m)	Justification
Wandrawandian Siltstone	55	channel filled with middle shoreface deposits rests erosionally atop offshore transition
	55	channel filled with middle shoreface deposits rests erosionally atop offshore transition strata
Snapper Point Formation	40	4 transitions between prodelta (offshore transition) and delta front (shoreface)
Upper Pebbley Beach Formation	70 m	channels filled with estuarine facies (0 m?) erosionally overlie offshore transition strata (−70 m)
Wasp Head Formation	55 m	parasequences with offshore transition rest atop middle shoreface deposits

oxygen isotope variations suggesting ~ 120 m and 55–155 m glacioeustatic fluctuations within individual cyclothems (Joachimski et al. 2006 and Bates and Lyons 2006, respectively). Even when climate and tectonism are factored in to the interpretation of the midcontinent cyclothems, the cyclicity still appears to be a result of 20–150 m glacioeustatic fluctuations (Klein 1994).

Oxygen isotope data from the Necessity Shale (Adlis et al. 1988) and erosional surfaces with 2–95 m of relief in carbonate-dominated successions in the southwest USA (Goldstein 1988; Goldhammer et al. 1991, 1994; Rankey et al. 1999; Soreghan and Giles 1999) indicate that large glacioeustatic fluctuations persisted throughout at least the latest Pennsylvanian. Cyclic successions have been described from many far-field, earliest Permian successions, where the eustatic signature may have been overprinted by climate or tectonism (Rankey 1997).

The estimates of glacioeustatic fluctuations listed above are comparable with the 50–115 m values predicted by Isbell et al.'s (2003) updated ICE model of Glacial III, an interval that spans the late Pennsylvanian (Stephanian) to the Early Permian (mid-Sakmarian). Given this evidence, we interpret the mid-Asturian to middle Sakmarian as a time when large to very large glacioeustatic fluctuations (100–120 m) were common (Figs. 1, 2). Although several authors suggest that fluctuations may have reached 150–250 m (Schenk 1967; Heckel 1977; Klein 1994; and the largest values reported by Bates and Lyons 2006), a maximum of 120 m seems to be the best supported by the evidence provided in the original papers.

Middle Sakmarian through Kungurian

The collapse of continental-scale glaciers occurred across much of Gondwana during the middle Sakmarian (Isbell et al. 2003; Montañez et al. 2007), although local glaciation persisted in eastern Australia and Siberia until the latest Capitanian (Epshteyn 1981a; Chumakov 1994). The few far-field estimates of eustasy at this time are derived from 60 m of relief along paleokarst in New Mexico (Kerans et al. 2000; Koša et al. 2003).

Data from the Talaterang Group in eastern Australia provide useful near-field documentation of the magnitude of possible glacioeustatic fluctuations (Fig. 1; Table 1). Within these units, abrupt transitions between offshore transition, shoreface, and estuarine facies are common and appear to record glacioeustatic fluctuations (facies data from Fielding et al. 2006; Thomas et al. 2007; Rygel et al. 2008; Bann et al. in press). By comparison with modern coastal areas in similar climatic and tectonic settings (Leckie 1987; Lesueur et al. 2002), storm wave base is approximated as 70 m water depth, fair-weather wave base at 30 m (the depth at which Lesueur et al. 2002 show mud starting to accumulate), and estuarine facies were likely deposited at or near sea level. Given these assumptions, it appears that high-frequency glacioeustatic fluctuations of 40–70 m were common during this time (Table 1). Because of differences in facies interpretations (see Fielding et al. 2006 for discussion), these values are larger than the 10–30 m glacioeustatic fluctuations called upon by Eyles et al. (1998). In all cases, the near-field estimates are consistent with the estimated values from far-field successions. Given the presence of glacial deposits in Australia and Siberia, we interpret the middle Sakmarian through the Kungurian as a broadly glacial interval during which glacioeustatic fluctuations of up to 30–70 m occurred (Fig. 2).

Roadian through Capitanian

The ultimate demise of the late Paleozoic ice age is recorded in Roadian to Capitanian glacial deposits in eastern Australia and Siberia (Epshteyn 1981a; Chumakov 1994; Fielding et al. 2008). Although all far-field estimates of eustatic fluctuations are derived from the Guadalupian (Roadian–Capitanian) Delaware Mountain Group, the interpretations vary widely (Fig. 1). Erosional surfaces with 4–30 m of relief in the Seven Rivers and Yates formations indicated fluctuations of similar size (Kerans and Nance 1991; Kerans and Harris 1993; Rankey and Lehrman 1996; Osleger 1998). Modeling studies of the Yates Formation indicate fluctuations of 8–12 m (Borer and Harris 1991, 1995) whereas back-stripping calculations of the entire interval suggest fluctuations of 10–60 m (most < 40 m; Ye and Kerans 1996). Given the modest extent of glaciers and widespread agreement on modest fluctuations, we interpret this interval as a time of moderate to large fluctuations (< 40 m) with possible events of as much as 60 m (Fig. 2). Presumably the size of eustatic fluctuations would have decreased to < 25 m following the demise of the late Paleozoic ice age in the Capitanian.

DISCUSSION

Despite the difficulty in precisely correlating events with one another and with near-field records of glaciation, the data can be grouped into eight discrete temporal intervals (Fig. 2). The mid-Chadian through the Holkerian is interpreted as a largely nonglacial interval with moderate eustatic fluctuations (< 25 m) that may or may not have had a glacioeustatic component. Glacioeustatic fluctuations of 25–40 m, and occasionally up to 60 m, occurred during times of alpine or regional glaciation (Tournaisian, Asbian through mid-Brigantian, Duckmantian–Asturian, Roadian–Capitanian). The Asbian through the mid-Brigantian is particularly interesting in that it represents a transition between broadly nonglacial and glacial conditions (Wright and Vanstone 2001). Large to very large fluctuations (60–120 m) occurred during times of widespread glaciation (mid-Brigantian through Langsettian and Stephanian through mid-Sakmarian, mid-Sakmarian through Kungurian). The magnitude of eustatic change in high-frequency cycles presumably decreased to < 25 m following the final collapse of the late Paleozoic ice age.

To the best of our knowledge, this paper is the first comprehensive review of evidence for glacioeustasy during the late Paleozoic ice age. It builds upon the pioneering work of Read et al. (1995), Read (1998), and Wright and Vanstone (2001) wherein the marked differences and transitions between late Paleozoic "greenhouse" and "icehouse" eustatic changes were documented and contrasted. This review demonstrates that the trend in the literature to cite several well known studies (typically Heckel 1977; Crowley and Baum 1991; Soreghan and Giles 1999) on the assumption that these values are representative of much of the late Paleozoic is flawed and oversimplifies the complex feedbacks between glaciation and sea level that took place during this lengthy icehouse phase of Earth history.

This review also highlights significant shortcomings in our knowledge of late Paleozoic glaciation and resulting glacioeustasy. Beyond the inherent difficulties in estimating the magnitude of ancient sea-level change, the most significant obstacle to compilation of a global dataset is the difficulty in making correlations between Europe and North America and between the paleotropics and paleopolar regions. Improvements in radiogenic isotope dating such as the ID-TIMS U-Pb method allows sub-million year resolution (Schmitz et al. 2005), but it may take decades until enough ages have been collected to fully correlate the far-field and near-field records.

Lastly, we compare the data from our literature review with the coastal-onlap and eustatic curves of Ross and Ross (1985, 1987), the latter of which is widely cited as a comprehensive account of late Paleozoic sea level (Hallam 1992 and many others). We argue that this curve (Fig. 3) should be ignored because it is based on confidential data and cannot be duplicated, because it is presently impossible to make the type of global correlations necessary to construct these types of curves for the late Paleozoic, and because there are conceptual problems with the long-term trends shown on the curve (e.g., their long-term "second order" highstands correspond to times of maximum glaciation). Additionally, they call for eustatic fluctuations in excess of 100 m throughout the late Paleozoic, an interpretation that has not been supported by any prior or subsequent research (Fig. 3). Consequently, we regard the Ross and Ross (1987) eustatic curves with skepticism.

CONCLUSIONS

Data derived from a comprehensive literature review suggest that glacioeustasy varied systematically through the Carboniferous and the Permian and that at least eight distinct subdivisions can be recognized. Continued data collection from, and correlation between, near-field and far-field areas will continue to improve our understanding of late Paleozoic glacioeustasy.

Although the whole of the late Paleozoic is generally considered an icehouse phase of Earth's climate history, we recognize three different types of glacioeustatic signatures. During temporal intervals that are largely devoid of glacial deposits (mid-Chadian through Holkerian), strata deposited in tectonically quiescent areas may have a strongly cyclic architecture and contain evidence of eustatic fluctuations of up to 25 m. Although glacioeustasy may have influenced stratal architecture, the modest size of the fluctuations makes it possible that other processes may have contributed to the observed eustatic fluctuations. Moderate to large glacioeustatic fluctuations of 25–60 m correspond to times of regional glaciation (Tournaisian, Asbian through mid-Brigantian, Duckmantian–Asturian, Roadian–Capitanian), and large to very large fluctuations of 60–120 m occurred during phases of widespread, possibly continental-scale glaciation (mid-Brigantian through Langsettian, Stephanian through mid-Sakmarian, mid-Sakmarian through Kungurian). Overall, comparison of the eustatic record and the glacial record shows good correspondence between interpretations of ice volume and the magnitude of high-frequency sea-level change.

Estimates of the magnitude of glacioeustasy during the late Paleozoic vary dramatically, and studies from a particular area or restricted temporal interval should not be considered representative of the late Paleozoic as a whole.

Each method of estimating the magnitude of sea level change is based on a set of caveats, assumptions, and uncertainties, and individual studies might suffer from local overprinting and biases. Although individual studies are the building blocks for understanding the late Paleozoic ice age, a comprehensive synthesis is the best way to understand the complexities of glacial history and glacioeustasy.

A more detailed understanding of glaciation, glacioeustasy, and sedimentary cyclicity in the late Paleozoic will probably come from (1) improved radiogenic isotope dating, (2) a detailed understanding of the spatial and temporal distribution of glaciers both Gondwana and the Northern Hemisphere, and (3) and continued study of late Paleozoic atmospheric and ocean chemistry.

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