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Global mass wasting during the Middle Ordovician: Meteoritic trigger or plate-tectonic environment?

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ABSTRACT

Mass wasting at continental margins on a global scale during the Middle Ordovician has recently been related to high meteorite influx. Although a high meteorite influx during the Ordovician should not be neglected, we challenge the idea that mass wasting was mainly produced by meteorite impacts over a period of almost 10 Ma. Having strong arguments against the impact-related hypothesis, we propose an alternative explanation, which is based on a re-evaluation of the mass wasting sites, considering their plate-tectonic distribution and the global sea level curve. A striking and important feature is the distribution of most of the mass wasting sites along continental margins characterised by periods of magmatism, terrane accretion and continental or back-arc rifting, respectively, related to subduction of oceanic lithosphere. Such processes are commonly connected with seismic activity causing earthquakes, which can cause downslope movement of sediment and rock. Considering all that, it seems more likely that most of this mass wasting was triggered by earthquakes related to plate-tectonic processes, which caused destabilisation of continental margins resulting in megabreccias and debris flows. Moreover, the period of mass wasting coincides with sea level drops during global sea level lowstand. In some cases, sea level drops can release pore-water overpressure reducing sediment strength and hence promoting instability of sediment at continental margins. Reduced pore-water overpressure can also destabilise gas hydrate-bearing sediment, causing slope failure, and thus resulting in submarine mass wasting. Overall, the global mass wasting during the Middle Ordovician does not need meteoritic trigger.

1. Introduction

The Earth's geological record shows mass wasting deposits from the Precambrian to Recent (e.g., Bugge et al., 1987; Hine et al., 1992; Hampton et al., 1996; Spence and Tucker, 1997; Keller et al., 1998; Hoffman and Hartz, 1999; Keller, 1999; Woodcock and Morris, 1999; Weaver et al., 2000; Cooper et al., 2001; Piper et al., 2003; Clift et al., 2004; Maslin et al., 2004; Locat and Lee, 2005; Wendorff, 2005; Ryu et al., 2005; Moscardelli et al., 2006; Valverde-Vaquero et al., 2006; Gee et al., 2007; Ratzov et al., 2007; Callot et al., 2008; Lee, 2009; Strozyk et al., 2009; Hornbach et al., 2010).

The present study focuses on Middle Ordovician mass wasting deposits, comprising mainly sedimentary megabreccias with maximum clast sizes from 1 m to >1 km, which were deposited along the margins of different palaeo-continents, e.g., Avalonia, and on volcanic arcs (Fig. 1). This mass wasting at continental margins on a global scale has recently been related to earthquake-driven slope failure following meteorite impacts (Parnell, 2009). This hypothesis is based on the observation that these megabreccias overlap in time with enhanced occurrence of extraterrestrial chromite and a shift to lower $^{187}Os/^{188}Os$ values in an essentially continuous sequence of Middle Ordovician shallow marine limestones of southern Sweden and several thousand kilometres away in central China (Schmitz et al., 2001, 2003, 2008). They were deposited a few million years after the disruption of the L-chondrite parent body in the asteroid belt at about 470 ± 6 Ma ago (Korochantseva et al., 2007) (Fig. 2). Using semi-quantitative calculations, Parnell (2009) suggested that up to 500 impactors of 100 m in diameter, including 250 impactors if only landward impacts are considered, fell within about 30 km of the 20,000 km long Iapetus coastline. The disruption of a parent body in the asteroid belt will lead to enhanced meteorite influx on Earth in less than one or a few million years (e.g., Schmitz et al., 2001) and may affect the Earth's surface with a number of impact craters. Table 1 lists the known impact structures of Ordovician age but interestingly only

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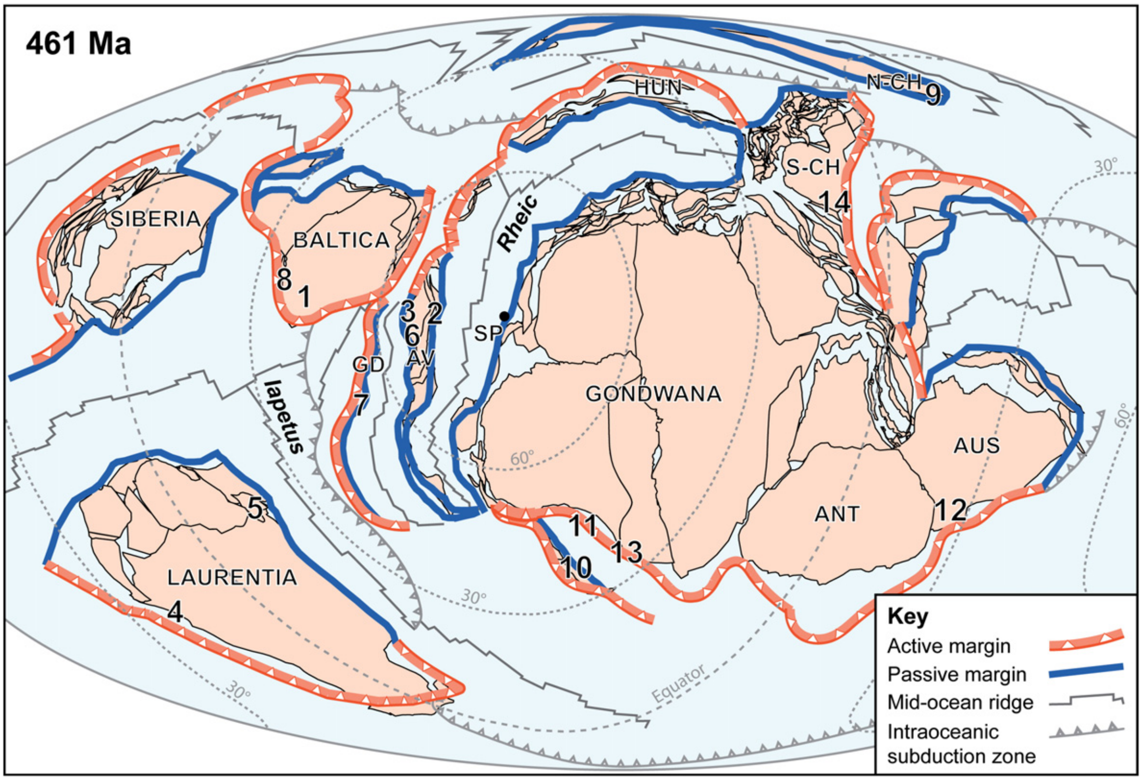

Fig. 1. Plate-tectonic reconstruction for the Middle Ordovician, about 461 Ma ago (after Stampfli et al., 2009) showing mass wasting sites (numbers after Parnell, 2009). Mollweide projection. Abbreviations: ANT — Antarctica, AUS — Australia, AV — Avalonia, GD — Ganderia, HUN — Hun-Terranes, N-CH — North China, S-CH — South China, SP — South Pole. See Section 6 of the current paper for brief descriptions of the mass wasting sites.

three craters within the age range of the megabreccias (468–461 Ma) have been found so far. Furthermore, shatter cones, microscopic planar deformation features (PDFs) in quartz, high-pressure mineral phases and high-temperature glasses and melts (or their relics) related to impact events (e.g., Dypvik and Jansa, 2003; French and Koeberl, 2010) have not yet been found in 468–461 Ma-old strata, although that may simply be because these features have been overlooked or may have been destroyed by terrestrial processes (e.g., erosion, subduction) since their formation (French and Koeberl, 2010). Two exceptions are PDFs in quartz grains from Darriwilian breccias of the Osmussaar area in northwestern Estonia and from a polymict breccia of the Granby structure in Sweden. The former are likely recycled ejecta material from the nearby early Cambrian Neugrund crater (Suuroja et al., 2003; Ainsaar et al., 2007), whereas the latter may be real impact-related features of Middle Ordovician age (Alwmark, 2009).

In our opinion, earthquake-driven slope failure producing the Middle Ordovician mass wasting was not necessarily caused by bombardment of the Earth's surface with large meteorites over a period of almost 10 Ma. The most striking and important feature, which led to our alternative hypothesis, is the distribution of the mass wasting sites along and close to active continental margins, arc terranes, and rift basins in Middle Ordovician palaeotectonic reconstructions (Fig. 1). Note that in the Quaternary, for instance, all active continental margins (e.g., Gee et al., 2007; Ratzov et al., 2007; Strozyk et al., 2009; Hornbach et al., 2010, and references therein) and passive margins (e.g., Bugge et al., 1987; Piper et al., 2003; Lee, 2009, and references therein) have large mass wasting deposits. Thus, finding them in the Middle Ordovician sedimentary record is not surprising.

In this paper, we present an alternative explanation for the global Middle Ordovician mass wasting without the need of extraterrestrial support. We propose that destabilisation of continental margins causing this global mass wasting was simply due to earthquakes and instability of slopes, related to plate-tectonic processes. Global sea level changes may also have triggered destabilisation of carbonate platforms and continental margin sediments. Nonetheless, we want to emphasise that we do not neglect the enhanced influx of extraterrestrial material on the Earth during the Ordovician. This influx has probably been responsible for local mass wasting (e.g., Hummeln structure: Lindström et al., 1999; Kärdla structure: Lindström, 2003) rather than global.

2. Mass wasting

Mass wasting is a general term describing down slope movement of sediment and rock. Common mass wasting deposits are debris flows, slides and slumps (e.g., Bugge et al., 1987; Einsele, 1993; Weaver et al., 2000; Locat and Lee, 2005; Lee, 2009). The formation of mass wasting deposits depends on the configuration of the terrain and relies on soil and rock mechanics parameters and failure criteria (Locat and Lee, 2005). Submarine slides, for instance, are most common in fjords, active river deltas on the continental margins, submarine canyon-fan systems, the open continental slopes, and oceanic volcanic islands (Hampton et al., 1996). In some settings, up to 70% of the entire slope and deepwater succession is composed of mass wasting deposits (Moscardelli et al., 2006). Earthquakes are seen as a prominent candidate to cause instability along continental margins triggering mass wasting (e.g., Bugge et al., 1987; Hampton et al., 1996; Locat and Lee, 2005, and references therein). As pointed out by Locat and Lee (2005), earthquakes can increase the shear stress within the sediment column and generate excess pore pressures. Furthermore, they can trigger the formation of a thin film of water at the interface of layers with contrasting hydraulic properties. This will create a zone of very low strength, which can cause rapid failure even at a bedding plane dipping less than 1°. Alternatively, rapid sediment failure triggering mass wasting may be induced amongst others by storm waves, sea level changes, rapid sediment accumulation,

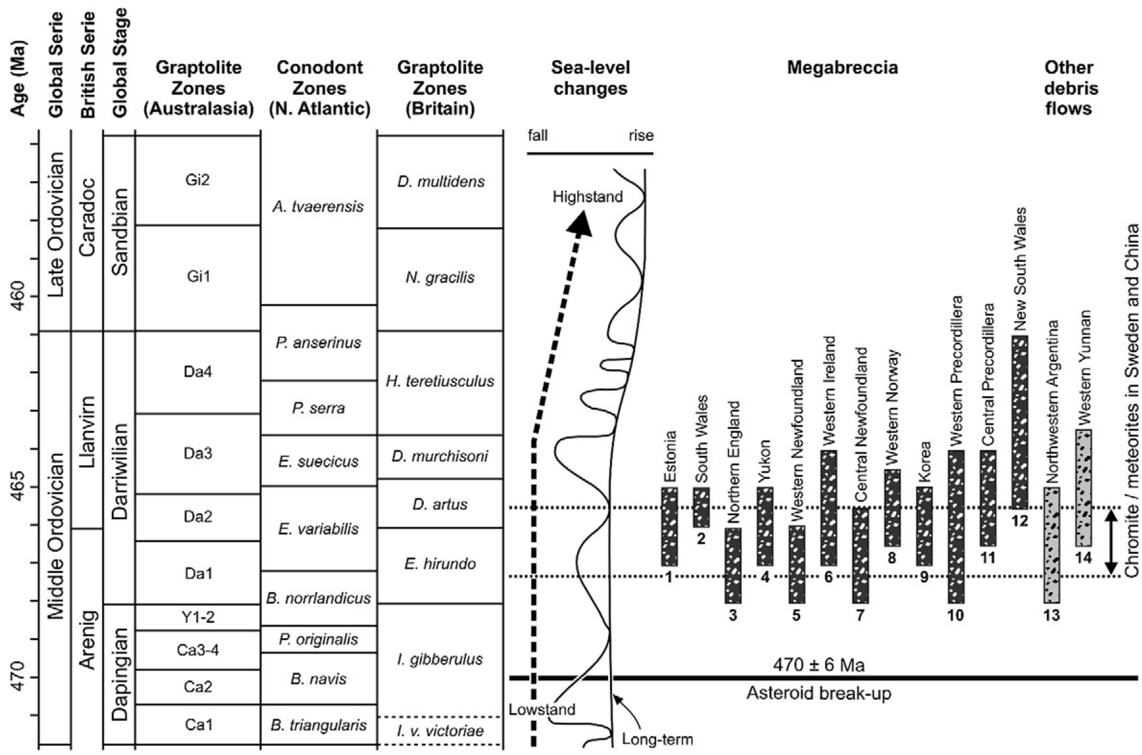

Fig. 2. Age range of megabreccias and other debris flow deposits during the Middle Ordovician (modified from Parnell, 2009). See Section 6 of the current paper for brief descriptions of the mass wasting sites. Conodont and graptolite zone fossils, respectively, are *Baltoniodus triangularis*, *Baltoniodus navis*, *Paroistodus originalis*, *Baltoniodus norrlandicus*, *Eoplacognathus variabilis*, *Eoplacognathus suecicus*, *Pygodus serra*, *Pygodus anserinus*, *Amorphognathus tvaerensis*, *Isograptus victoriae victoriae*, *Isograptus gibberulus*, *Expansograptus hirundo*, *Didymograptus artus*, *Didymograptus murchisoni*, *Hustedograptus teretiusculus*, *Nemagraptus gracilis and Diplograptus multidens*. The time scale of Gradstein et al. (2004) was used. Curves showing sea level changes are according to Haq and Schutter (2008). Note that the asteroid break-up occurred at 470 ± 6 Ma based on high-precision ^{40}Ar–^{39}Ar dating of L chondrites (Korochantseva et al., 2007) and not at 468 ± 2 Ma, as shown by Parnell (2009, his Fig. 2).

erosion, volcanoes, gas and gas hydrates release, groundwater seepage and diapirism (e.g., Bugge et al., 1987; Einsele, 1993; Hampton et al., 1996; Weaver et al., 2000; Locat and Lee, 2005; Maslin et al., 2004; Lee, 2009). Interestingly, glacial and interglacial phases have a major influence on the stability of submarine slopes (e.g., Maslin et al., 2004; Lee, 2009). They can cause or hinder the development of large submarine slides (Lee, 2009), with periods of glaciations producing more mass wasting than do non-glacial periods, as exemplarily shown for the submarine slides on the southeastern Canadian margin (Piper et al., 2003).

Table 1

Impact structures of Ordovician age, including those with an age overlapping within error with the Late Ordovician. Note that palynological investigations by Wallin (2005) suggest an age around the Volkhov–Kunda boundary for the Hummeln structure (cf. Lindström et al., 1999). Zhang (1998) identified the Volkhov–Kunda boundary between the *Lenodus antivariabilis* Zone and the *L. variabilis* Zone in the lower part of the Kunda Stage in the Hällekis section in Västergötland and in the Grötlingbo-1 drill core from southern Gotland. In the Gillberga section on Öland, the lower boundary of the *L. variabilis* Zone lies slightly above the base of the Kunda Stage (Löfgren, 2000a,b), which corresponds to an age of about 467 Ma, according to Webby et al. (2004).

Country	Structure name	Diameter (km)	Age (Ma)	Reference
Canada	La Moinerie	8	400 ± 50	Spray (2009)
Canada	Couture	8	430 ± 25	Spray (2009)
Canada	Pilot	6	445 ± 2	Spray (2009)
Canada	Slate Islands	30	~450	Spray (2009)
USA	Calvin	8.5	450 ± 10	Spray (2009)
Sweden	Tvären	2	~458	Grahn et al. (1996)
Estonia	Kärdla	4	~458	Grahn et al. (1996)
Sweden	Lockne	7.5	~458	Grahn et al. (1996)
Sweden	Granby	4	~466	Grahn et al. (1996)
USA	Ames	16	~466	Repetski (1997)
Sweden	Hummeln	1.2	~467	Wallin (2005)

It is worth mentioning that the Earth's geological record shows that many mass wasting deposits were generated in the late Pleistocene and Holocene along the north-west African, west European and North American continental margins (e.g., Bugge et al., 1987; Weaver et al., 2000; Maslin et al., 2004; Lee, 2009, and references therein). Slope failure causing this mass wasting was triggered by terrestrial processes (e.g., seismic events, sea level lowering, gas hydrate release) most active during glacial times (e.g., Weaver et al., 2000; Piper et al., 2003; Maslin et al., 2004; Lee, 2009) and unrelated to extraterrestrial influx.

3. Earth's extraterrestrial influx

The Earth has suffered meteorite bombardment ever since its formation with fluctuating intensity but only under certain circumstances has it been recorded (e.g., Peucker-Ehrenbrink and Schmitz, 2001; Schmitz et al., 2001; Dypvik and Jansa, 2003; Lindström, 2003; Spray, 2009; French and Koeberl, 2010). About 40,000 tonnes of extraterrestrial material fall to the Earth each year (Brownlee, 2001). For example, about 14,000 meteorite fragments have been collected from a ~2500 km^2 large area of the Antarctic ice shield over the past decades (Cassidy et al., 1992). Although this is a single example only, it clearly demonstrates the background sedimentation of extraterrestrial material to the Earth, in that particular case, during the Quaternary.

Having a look further back into the Earth's geological record reveals that also during the early Palaeozoic the Earth has suffered meteorite bombardment. For example, Middle Ordovician limestones from southern Sweden, northwestern Estonia and central China (Schmitz et al., 2001, 2003, 2008; Alwmark et al., 2010) record the Earth's extraterrestrial influx for a time period of less than 2 Ma during the Darriwilian. At that time, the meteorite influx was one to two orders of magnitude higher than today (Schmitz et al., 2001). Meteorites accumulated in epicontinental seas and were preserved throughout the Phanerozoic, although they have been completely pseudomorphosed primarily by calcite, barite and phyllosilicates; with chrome spinel being the only relic phase (Schmitz et al., 2001). Thus, chasing ancient meteorites in the Earth's sedimentary record is quite a challenge for geological research and certainly warrants further studies (see French and Koeberl, 2010). Other epochs of enhanced meteorite influx to the Earth may have been unrecognised so far. Note that preserved meteorite fragments or relict minerals (e.g., chromite: Schmitz et al., 2001, 2003, 2008; Alwmark et al., 2010) do not necessarily indicate that an impact event occurred since there is a continued flux of meteorites onto the Earth unrelated to large impact events (French and Koeberl, 2010). Furthermore, like for any other heavy mineral, the possibility of polyphase recycling has to be kept in mind.

4. Ordovician mass wasting localities

Parnell (2009) described 12 megabreccia localities from various sites along the margins of the Iapetus Ocean and other parts of the Middle Ordovician globe (Figs 1, 2). In addition, debris flow deposits from NW Argentina and Western Yunnan were mentioned. Some of these breccias and debris flows belong to carbonate platforms, which were deposited during relative sea level lowstand (Fig. 2). In general, the megabreccias contain clasts up to kilometre size embedded in a fine-grained siliciclastic matrix and were interpreted as subaqueous debris flows triggered by earthquakes and tsunamis (Parnell, 2009). The age of these megabreccia deposits is based on biostratigraphy (see Parnell, 2009). The onset and extend of the Middle Ordovician megabreccias varies in time over 7 million years (Fig. 2). The depositional settings of these megabreccias and debris flows are described in Section 6 of this paper.

Parnell (2009) showed the global distribution of the megabreccias sites on a palaeogeographic reconstruction, unfortunately without an illustration of important plate-tectonic features such as subduction zones. It has been correctly noted that some of the sites “reveal a 540 km along-strike record of mass wasting along the Avalonian margin” (Parnell, 2009, p. 57) and “some may nevertheless be unrelated to the meteorite flux” (Parnell, 2009, p. 58). Although these points are important for the mass wasting story, they were not discussed further. Therefore, we had a closer look at the palaeo-localities of these megabreccia sites. This revealed that a number of megabreccias were deposited in tectonically unstable areas, e.g., around active volcanic arcs, around collapsing orogens and in continental rift zones, or at least in their proximity. Such a coincidence is very intriguing and needs further discussion with focus on Ordovician plate tectonics (Fig. 1).

5. Alternative causes for Middle Ordovician mass wasting

5.1. Plate tectonics

Throughout the Ordovician period, magmatism, terrane accretion and back-arc rifting, related to subduction of oceanic lithosphere, chiefly of the Iapetus Ocean, occurred along the margins of Avalonia, Ganderia, Laurentia and Gondwana (e.g., Bird and Dewey, 1970; Dewey and Mange, 1999; Friedrich et al., 1999; Soper et al., 1999; Cocks, 2001; Stampfli and Borel, 2004; Thomas and Astini, 2003; Clift et al., 2004; Valverde-Vaquero et al., 2006; Ryan, 2008; von Raumer and Stampfli, 2008; Fergusson, 2009; Voldman et al., 2009; Murphy et al., 2010; Nance et al., 2010, Nance, 2010 and references therein). Volcanic arcs have accompanied active margins. Subaerial and submarine volcanism has been widespread. Various orogenic events are recognised worldwide during the Ordovician (mainly Middle Ordovician), for example, the Famatinian orogeny in South America (e.g., Thomas and Astini, 2003; Voldman et al., 2009), the Humberian orogeny in Newfoundland and the Taconic orogeny in western New England (e.g., Bird and Dewey, 1970); the Taconic orogeny corresponds to the Grampian orogeny in western Ireland and Scotland (e.g., Dewey and Mange, 1999; Friedrich et al., 1999; Soper et al., 1999; Clift et al., 2004; Ryan, 2008). Geochronological data suggest that the Grampian orogeny occurred between ca. 475 and 460 Ma (Dewey and Mange, 1999; Friedrich et al., 1999; Soper et al., 1999), which overlaps in time with the mass wasting discussed in the present paper.

Subduction of oceanic lithosphere under continental margins, terrane accretion and rifting are commonly connected with seismic activity causing earthquakes, which might affect directly or indirectly (tsunami) even continental margins at several thousands of kilometres of distance. Using a recent example, the 26 December 2004 Sumatra–Andaman earthquake was related to fault displacement under the sea, which triggered a widespread tsunami in the Indian Ocean (Lay et al., 2005). Large submarine slides may also trigger a tsunami, as happened by the Storegga slide off the coast of Norway about 7250 yr BP (e.g., Lee, 2009, and references therein). Of course, a tsunami may also occur due to flank collapse of volcanic islands, e.g., Canaries Islands (Ward and Day, 2001), without a tectonically (seismically) active margin. In general, tsunami deposits are more likely on the inner shelf with massive reworking but not at the continental margin and slope.

Seismically induced release of pore-water overpressure can destabilise carbonate platforms and can generate megabreccias along the platform margins (e.g., Hine et al., 1992; Spence and Tucker, 1997).

Based on an evaluation of potential alternatives, we suggest that down slope movement of sediment and rock at continental margins on a global scale during the Middle Ordovician can be explained by earthquakes related to subduction of ocean lithosphere, accompanied by terrane accretion and rifting processes (Fig. 1), as discussed in Section 6 of this paper.

5.2. Sea level changes

Another important fact is the coincidence of the time period of megabreccia formation with sea level drops during global sea level lowstand (Fig. 2), which has already been noticed by previous studies (e.g., Keller et al., 1993; Keller, 1999; Ryu et al., 2005). Linking relative sea level falls with carbonate megabreccia formation is a generally accepted model because of pore-water overpressure in hydrologically confined horizons (e.g., Einsele, 1993; Spence and Tucker, 1997), although carbonate megabreccia may also occur during sea level highstand because of overstepping as a result of rapid reef growth (Einsele, 1993). Nonetheless, we suggest that some of the mass wasting described by Parnell (2009) was probably caused by release of pore-water overpressure promoting instability of sediment due to sea level drops during the Middle Ordovician (Fig. 2), which of course could have overlapped with seismic-induced release of pore-water overpressure due to earthquakes. Furthermore, as outlined by Maslin et al. (2004), lowering sea level reduces the hydrostatic pressure and thus will lead to gas hydrate release, causing destabilisation of sediment at the continental margin and finally leads to mass wasting.

6. Summary of alternative explanations for the mass wasting sites

As outlined above, most of the mass wasting during the Middle Ordovician can simply be explained by seismic-induced slope instability related to plate-tectonic processes. Global sea level changes (in particular sea level falls) may have also had a significant influence. Possible explanations for the formation of the mass wasting on different palaeo-continents during the Middle Ordovician are given below, whereby the numbers in brackets refer to the mass wasting localities discussed, as shown in Figs. 1 and 2.

6.1. Baltica

Limestone breccias from northwestern Estonia, Osmussaar breccia (1), contain clasts and blocks ranging in size from tens of centimetres to tens of metres in a mainly sandy matrix and were formed on an inner-middle carbonate ramp (Ainsaar et al., 2007). Based on their relative proximity to the limestone of Sweden with enhanced extraterrestrial material (Schmitz et al., 2001, 2003, 2008) and their unique formation, they may be real impact-related breccias of Middle Ordovician age (Ainsaar et al., 2007). Alwmark et al. (2010) found detrital chrome spinel of extraterrestrial origin in a sample from the Osmussaar breccia, which seems to support an impact-related origin.

6.2. Avalonia

Darriwilian mass wasting in Northern England (3) belongs to the Skiddaw Group (e.g., Webb and Cooper, 1988). A similar succession is found on the Isle of Man in the Irish Sea. Both were deposited at the northern margin of Avalonia. The latest Arenig regression (see, e.g., sea level curves in Molyneux, 2009) might have been the trigger for their formation but here more likely is tectonic instability due to beginning rifting, which just predates the onset of back-arc volcanism in the Welsh Basin (Woodcock and Morris, 1999). It may represent rifting of either Avalonia from the Gondwana mainland (Woodcock and Morris, 1999) or more likely Ganderia from Avalonia. The same may apply for debris flows and breccias in southwestern and southeastern Ireland, which are correlated with the Skiddaw Group (Todd et al., 2000). In southern Wales (2), early Llanvirn debris flows were disrupted by intrusion of rhyolite at least at some localities; explosive felsic volcanism has also occurred (Kokelaar et al., 1985). Here, mass wasting was likely caused by the contemporaneous tectonism and volcanism. Mass wasting in western Ireland (6) can be linked to an arc–continent collision environment (Dewey and Mange, 1999; Clift et al., 2004; Ryan, 2008).

6.3. Laurentia

Darriwilian extensional tectonism might have been the trigger for the formation of carbonate conglomerate-breccias in the Road River Group of Yukon, NW Canada (4), since equivalent successions in British Columbia were deposited due to steepening of the shelf margin which coincides with a period of extensional tectonism (Pyle and Barnes, 2000). However, the onset of this mass wasting also coincides with the latest Arenig regression. Megabreccias of the Cow Head Group in Western Newfoundland (5) formed as slides and debris flows on the upper continental slope (Bird and Dewey, 1970; Lock, 1973; Hiscott and James, 1985) and represent a collapsed carbonate platform by extensional faulting due to flexural bulge of the Taconic foreland basin (Knight et al., 1991; Cooper et al., 2001).

6.4. Island arcs within Iapetus Ocean

Middle Ordovician mass wasting of Central Newfoundland (7) includes debris flows comprising megablocks of volcanic rocks. Its formation can be attributed to rifting and opening of the Exploits back-arc basin on the Ganderian margin (Valverde-Vaquero et al., 2006). Limestone of the Hølonda area from Norway (8) was deposited on an island arc in the Iapetus Ocean near Laurentia (Cocks and Torsvik, 2005). Its brecciation is likely related to tectonism and volcanism because the limestone occurs in close association with porphyrite (Grenne and Roberts, 1998).

6.5. North China

Darriwilian carbonate breccias in the Okcheon belt of South Korea (9) have two types of origin. The Yemi carbonate breccia was deposited along a platform fault scarp, which formed by initial rifting of the basin during the early Middle Ordovician whereas breccias in the upper Maggol Limestone are palaeokarst solution-collapse breccias formed during regression (Ryu et al., 2005).

6.6. Precordillera

The gravitational collapse of the Middle Ordovician carbonate platform in the Central and Eastern Precordillera (10, 11) producing megabreccias coincides with a major relative sea level drop in connection with rifting (Keller et al., 1993, 1998; Keller, 1999). Voldman et al. (2009) recently noted that the Middle Ordovician succession of the Argentine Precordillera records an important event of palaeotectonic rearrangement (see also Thomas and Astini, 2003). Debris flows from the Famatina terrane in northwestern Argentina (13) were related to deposition in a retro-arc basin (Zimmermann and Bahlburg, 2003).

6.7. Southeast Gondwana

In New South Wales, Australia (12), limestone blocks in the Oakdale Formation were deposited on an unstable outer shelf edge (Zhen and Percival, 2004) during a time of widespread arc volcanism in the surrounding area (Fergusson, 2009), which was probably associated with earthquakes due to tectonism causing instability of the carbonate platform. Debris flows from the Ammania terrane in western Yunnan, China (14), are likely related to small-scale fluctuations in sea level.

7. Conclusions

Although meteorite impacts caused modifications of the Earth's surface ever since its formation, in the case of the mass wasting during the Middle Ordovician, they may have had only regional impact rather than global. Furthermore, preserved meteorite fragments or relict minerals (e.g., chromite: Schmitz et al., 2001, 2003, 2008) in Middle Ordovician shallow marine limestone of southern Sweden and in central China do not necessarily indicate that an impact event occurred (cf. Parnell, 2009) since there is a continues flux of meteorites onto the Earth unrelated to large impact events (French and Koeberl, 2010).

We have highlighted that a number of mass wasting sites were located at active continental margins or belong to rift basins (passive margins). This suggests that at these sites, the formation of megabreccias was probably triggered by earthquakes, which were related to processes such as subduction, accretion and uplift or rifting due to plate tectonics. Global sea level falls may be another cause. Overall, our alternative hypothesis is a simple explanation since it "only" relies on plate-tectonic processes and global sea level changes. We do not see any need to search for extraterrestrial support to explain the global mass wasting during the Middle Ordovician.

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