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Leaving no stone unturned: the feedback between increased biotic diversity and early diagenesis during the Ordovician

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(Abstract)

Ordovician change in the nature of seafloor carbonates saw rapid decline of previously widespread flat pebble conglomerates and the Palaeozoic peak abundance of hardgrounds. The effective disappearance of flat pebble conglomerates, widely attributed to physical disruption of substrate by bioturbation, is re-interpreted as reflecting increased depth of carbonate precipitation below the Taphonomically Active Zone such that early lithified carbonates were less frequently reworked by scour. With deeper, more stable zones of cementation, exhumed limestones formed hardgrounds, whose mid Ordovician acme supported rapid increase in epizoan diversity. Further deepening of cementation to below normal scour accompanied post-Ordovician decline in submarine hardgrounds.

Supplementary material: database for Figure 1 is available at http://www.geolsoc.org.uk/SUP----

The early Palaeozoic evolutionary and ecological development of benthic metazoans was strongly affected by changes to the nature of the sea floor environment such as increased burrowing activity (e.g. Cambrian Substrate Revolution, Bottjer *et al.* 2000) and widespread development of shallow marine hard substrates (Great Ordovician Biodiversification Event (GOBE); Harper 2006). How did those changes impact upon, and relate to, carbonate systems and shallow sediment diagenesis? Here we consider two characteristic carbonate facies of early Palaeozoic shelf seas: flat pebble conglomerates (FPC) and submarine hardgrounds (carbonate cemented sea floors). Both peak in abundance before rapid decline, the former most widespread in the late Cambrian–early Ordovician, while the latter reach their Palaeozoic acme in the Mid-Late Ordovician (e.g. Taylor 2008, fig. 2).

Flat pebble conglomerates (locally breccias) with carbonate intraclasts (rudstones, floatstones) are a striking feature of Late Proterozoic to early Ordovician shallow marine carbonate successions. They were mostly deposited in subtidal, typically offshore settings reflecting storm or tsunami reworking of shallow cemented limestone beds (Mount & Kidder 1993; Pratt 2002; Myrow *et al.* 2004; Pratt & Bordonaro 2007). The FPCs are variable in bed geometry and thickness, matrix or clast supported texture, but typically have tabular, thin (<20mm) pebble to cobble sized clasts of fine grainstone to calcimudstone (e.g. Myrow *et al.* 2004). This distinctive lithofacies effectively disappears from the stratigraphic record in offshore settings after the Early Ordovician (Sepkoski 1982; Sepkoski *et al.* 1991; Liu & Zhan 2009). The accepted view (e.g. Sepkoski *et al.* 1991) has been that with an Ordovician increase in the extent and depth of burrowing (Droser & Bottjer 1989; Bottjer *et al.* 2000), biotic mixing of the sediment would have prevented early cementation and the formation of thin lithified zones, removing the source for FPCs after scouring by storms or tsunamis.

In the Ordovician, submarine hardgrounds become widely developed in shallow seas, colonised by an expanding diversity of encrusting and boring epizoans (e.g. Brett & Brookfield 1984) that form specialized new communities in the GOBE. They have been interpreted as indicating seafloor calcite precipitation and aragonite dissolution in ‘calcite seas’ (Taylor & Wilson 2003; Palmer & Wilson 2004; Harper 2006; Taylor 2008).

The aim of this paper is to provide a single, geochemical explanation for both the decline of subtidal FPC lithofacies and the peak abundance of hardgrounds during the Ordovician.

Sea floor diagenesis and changes in sea floor shallow geochemical profiles during the early Palaeozoic

The diagenetic processes for mobilization of calcium carbonate during shallow burial have been appreciated for some time (e.g. Sanders 2003; Berkeley *et al.* 2008; Cherns *et al.* 2011). Calcium carbonate, especially the more soluble aragonite, is dissolved in the uppermost sediment layer largely as a result of acidity caused by the oxidation of H_2S, and while most back-fluxes to the water column, some is re-precipitated as calcite in the sediment column in areas of increased alkalinity such as depths where sulfate reduction takes place (e.g. Sanders 2003, 2004; Fig. 1). This oxidized zone, effectively the Taphonomically Active Zone (TAZ), will be controlled by diffusion from the overlying water column, if oxygenated, and by mixing caused by bio-irrigation (mainly burrowing; e.g. Aller 1982; Aller & Aller 1998). Organic matter accumulated more among finer grained sediment sources the microbially mediated decay processes that drive skeletal carbonate dissolution and re-precipitation (e.g. Walter & Burton 1990; Walter *et al.* 1993; Hendry 1993). The importance of such processes linked to the mobilization of labile carbonates in the very shallow sediment column forms the basis for understanding the limestone-marl alternations that form a widely developed facies in Phanerozoic epeiric sea settings (Munnecke & Samtleben 1996; Westphal & Munnecke 2003; Munnecke & Westphal 2005).

Brasier *et al.* (2011) proposed that changes in the position, relative to the sea floor, of the depth of the redox boundary during the Ediacaran–early Cambrian affected the zones of early lithification in the shallow sediment column. Late Proterozoic precipitation of calcium carbonate took place at or very close (<1cm) to the sea floor (also Peters & Gaines 2012), and though the early Cambrian advent of metazoan burrowing and biomineralization depressed the zone of cementation it remained very shallow (early-mid Cambrian subtidal burrow depth <3 cm, typically mm scale: Tarhan *et al.* 2015; Droser & Bottjer 1988). The depth of subtidal bioturbation, and by inference the zone of cementation, remained <6 cm through to the mid Ordovician, before both bioturbation depth (<30 cm) and intensity increased significantly in the Late Ordovician (Droser & Bottjer 1989).

Abundance of flat pebble conglomerates and hardgrounds

Subtidal FPCs are most common in the late Cambrian–Early Ordovician, before rapid decline, and notably while the TAZ remained very shallow (Fig. 2). Their temporal record, using publications by formation as a proxy for abundance, provides a direct comparison with published data for submarine hardgrounds (Fig. 2; Taylor 2008). A peak FPC distributional map illustrates the extensive occurrence (with a latitudinal control), and suggests any bias from availability of rock formations is likely not significant (Fig. 3). In shallow carbonate epeiric seas of the North China Plate, the subsequent decline of FPCs corresponds to the decrease also in subtidal microbialites and increasing intensity of bioturbation as the shallow sea floor character changed in the late Early Ordovician (early Floian) (Liu 2009; Liu & Zhan 2009). Notably, in post-Ordovician times, minor occurrences of subtidal FPCs (Fig. 2) correspond to post-extinction events, when suppression of bioturbation would have led to shallowing of the TAZ (e.g. Wignall & Twitchett 1999; Calner 2005).

For submarine hardgrounds (carbonate cemented sea floors) the Palaeozoic peak of abundance is in the Ordovician (Taylor & Wilson 2003; Palmer & Wilson 2004; Harper 2006; Taylor 2008; Fig. 2). Early, encrusting hardground faunas are described from surfaces of cemented FPC in the late Cambrian (Brett *et al.* 1983). By the mid Ordovician hard substrate morphologies are variable, some largely comprising reworked, encrusted limestone nodules but others forming beds with complex hummocky and undercut surfaces; hardground biotas are notably more diverse (Brett & Liddell 1978; Brett & Brookfield 1984; Wilson et al. 1992). Taylor and Wilson (2003, p. 44) suggested that the "Ordovician was a golden age for epizoans on hard substrates" due in part to increased hard substrate availability. The appearance of encrusters makes hardgrounds more recognizable after the early Ordovician (Brett & Liddell 1978) and likely reflects the availability of more stable substrates as compared with the fragmented cemented layers characteristic earlier in the Palaeozoic.

Previously the abundance of hardgrounds had been explained by local calcite cementation sourced from carbonate released by sea-floor dissolution of aragonite in undersaturated (with respect to aragonite) Ordovician 'calcite seas' (Wilson et al. 1992; Taylor & Wilson 2003; Palmer & Wilson 2004; Harper 2006). Recent experimental data, however, indicate that aragonite precipitation continued alongside calcite during 'calcite seas' in warm water environments (Balthasar & Cusack 2015). In a study of Ordovician hardgrounds from eastern North America, Kenyon-Roberts (1995) found no direct evidence for sea floor dissolution, but did note petrographic evidence of hardground formation in shallow sub-oxic conditions below the TAZ. Cherns & Wright (2011), when comparing the taphonomy of skeletal lagerstätten between 'aragonite' and 'calcite seas', found no differences, suggesting that 'calcite seas' did not increase aragonitic shell dissolution.

Diagenetic model for Early Palaeozoic subtidal settings (Fig. 4)

As the depth and intensity of burrowing increased through the early Palaeozoic, the TAZ thickened and the depth at which secondary carbonate re-precipitated also deepened. This reduced the probability that lithified carbonate would be exhumed by erosional reworking caused by wave scour. The FPCs in shallow subtidal settings formed only while the TAZ was very thin, and hence the zone of cementation was close to the sediment-water interface allowing even relatively small and frequent scour events (storms or tsunamis) to exhume the cemented horizons (Late Precambrian–late Early Ordovician; Figs 2, 4). As the TAZ thickened and the depth of carbonate precipitation increased, these horizons were less likely to be reworked by scouring. The FPC facies was replaced in shallow subtidal settings by less frequently exhumed, and hence more developed and thicker, cemented horizons, which when eventually exposed by scour formed reworked concretions and hardgrounds on which hard substrate biotas expanded (Mid–Late Ordovician; Figs. 2, 4). Development of these carbonate horizons may have been facilitated by increased skeletal input through diversification and faunal expansion during this interval (Porter 2010). In more offshore settings rarely affected by wave-related erosion, the secondary carbonate could accumulate uninterrupted to produce the nodular, diagenetic bedding of limestone-marl alternations. As the TAZ deepened through the later Ordovician the cementation zone was displaced to deeper levels where reduced likelihood of exhumation led to decline in hardground abundance and more widespread development of diagenetic bedding (Late Ordovician; Fig. 3; Westphal 2006, fig. 2). An implication is that diagenetic bedding would have been preserved in shallower areas than previously, assuming that shallower sea floors were more susceptible to periodic reworking than deeper ones (Peters & Loss 2012). This hypothesis is testable if it can be demonstrated that diagenetic bedding is found in shallower settings by the Late Ordovician.

Discussion

This model proposes that a single trend, namely the deepening of the zone of cementation below the TAZ, can explain the rapid decline of FPCs, and the peak abundance of hardgrounds during the Ordovician, before their subsequent decline. That progressive change was ultimately a consequence of the previously documented increased depth and intensity of bio-irrigation. Rather than destroying the potential for rapid shallow cementation (Sepkoski 1982; Sepkoski et al. 1991), lowering of the TAZ decreased the likelihood of erosional exhumation of thin cemented carbonate layers by wave scour.

Many variables affected early diagenesis during the early Palaeozoic, including increased nutrient-rich organic matter and oxygen levels in sea floor sediments as a result of metazoan evolution (McIlroy & Logan 1999; Bottjer *et al.* 2000, Dornbos *et al.* 2005). The amount of labile aragonite from skeletal carbonate dissolution also likely increased with biomineralization, although the skeletal contribution to carbonate deposition remained limited up to mid Ordovician times (e.g. Pruss *et al.* 2010, fig. 8). Could the thinness of limestone beds ripped up to form FPCs from latest Proterozoic to Early Ordovician be explained by lower flux of carbonate from skeletal dissolution before the GOBE rather than reflecting frequency of exhumation at shallow burial depths? Although the intensity of bio-irrigation increased markedly in the Early Cambrian, bioturbation depth (<6 cm) remained shallow through to the Late Ordovician, when both depth (<30 cm) and average ichnofabric index increased substantially (Droser & Bottjer 1989; Tarhan *et al.* 2015). If changes in the biogeochemical environment of the upper sediment layers were a consequence of that deeper and more intense bio-irrigation, accompanied by increased oxygenation of the seas and oversaturation (Pruss *et al.* 2010) that affected diagenetic carbonate precipitation, what other effects took place in terms of carbonate behaviour? The biogenically reworked mixed layer increased only slowly, from 0.2 cm in the early-mid Cambrian to 1.5 cm in the Ordovian-

Silurian (Tarhan *et al.* 2015). Could the presence of a thin TAZ potentially result in higher levels of acidity through sulfide oxidation and a greater degree of undersaturation with respect to aragonite, compared with today's thicker TAZ?

Organisms with more labile, aragonitic shells (primarily molluscs) are diverse in the early Cambrian radiation although their fossils are relatively sparse in the trilobite dominated Cambrian–Lower Ordovician skeletal record (Porter 2007; Porter *et al.* 2010). From the mid Ordovician, skeletal material was a major contributor to carbonate sediment; limestone shell beds, most commonly brachiopod-rich, increase in proportion, thickness and abundance in shallow marine settings (Kidwell and Brenchley 1994; Li & Droser 1997, 1999; Pruss *et al.* 2010). Molluscs are dominant in some storm beds, most commonly representing local reworking of concentrations of dead gastropod shells accumulated in the upper sediment layers (Li & Droser 1999; Harper 2006, fig. 9). Did a thicker TAZ later in the Ordovician result in less intense sulfide oxidation, less dissolution and a longer survival time of aragonite shells in the TAZ?

The Palaeozoic decrease in abundance of hardgrounds after the Ordovician (Fig. 2) is here interpreted as reflecting the lowering of the TAZ and cementation zone to depths in the sediment column affected less frequently by wave (storm or tsunami) reworking. It might also imply that such reworking later rarely affected sediments much below the TAZ at 30cm. Mesozoic peaks of hardground occurrence (Fig. 2) may in part reflect large outcrop areas of marine sediments (Smith and McGowan 2007), such as the Cretaceous Chalk. The extensive hardgrounds of the middle Jurassic are hosted predominantly in very shallow, oolitic facies and are of much more diverse origins than those of the Ordovician (Kenyon-Roberts 1995).

Conclusions

The decline of flat pebble conglomerates and the peak abundance of submarine hardgrounds in the Ordovician are interpreted as reflecting the progressive deepening of the zone of carbonate precipitation below the TAZ, resulting in less frequent reworking of the upper part of the sediment column by scour. The deepening was a consequence of increased depth and intensity of bioturbation and bio-irrigation. This shift also created a range of more lithified substrates in subtidal settings, promoting a rapid expansion in epizoan diversity. Thus, changes in bioturbation affected carbonate diagenesis and the composition of the sea floor carbonates, and provided new niches for invertebrates.

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Figure Captions

Figure 1. Shallow burial diagenetic environment and calcium carbonate precipitation. A, labile aragonite shells (molluscs), more susceptible to early dissolution in the oxic upper sediment layers of the Taphonomically Active Zone (TAZ), release carbonate and leave moulds that are readily destroyed through bioturbation. B, calcitic shells more likely to survive early dissolution, and more rarely steinkerns of aragonitic shells; diffused carbonate precipitates in a zone of cementation in the sulfate reduction zone.

Figure 2. Abundance (using publications by formation as proxy) of subtidal flat pebble conglomerates (pale, points; supplemental information available online at www.geolsoc.org.uk/SUP0xxxx) and submarine hardgrounds (dark, histogram; based on Taylor 2008 and http://markwilson.voices.wooster.edu/bioerosion-bibliography/). Note: revision of Cambrian stratigraphy into four series is ongoing; divisions into Lower, Middle and Upper series follow standard usage in literature.

Figure 3. Palaeogeographic reconstruction for 485 Ma (Bugplates IGCP503; T.H. Torsvik 2009) showing late Cambrian–early Ordovician extent of flat pebble conglomerate facies (black stars).

Figure 4. Diagenetic model for carbonate precipitation in subtidal Palaeozoic settings, showing early Cambrian through Ordovician changes in the depth of the Taphonomically Active Zone (TAZ) and zone of cementation, susceptibility of lithified limestone layers to scouring, and distribution of flat pebble conglomerates, submarine hardgrounds and the diagenetic nodular bedding of limestone-marl alternations. SWI sediment-water interface.

Figure 1.

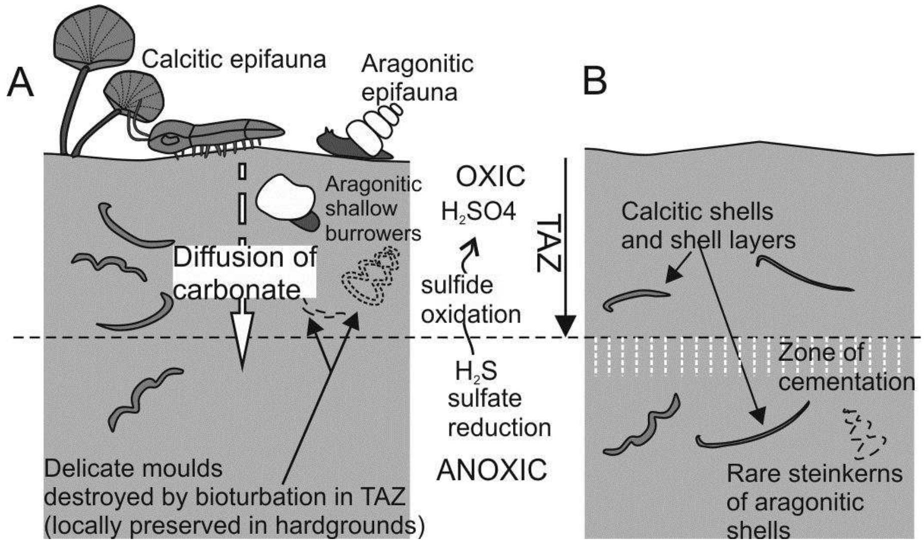
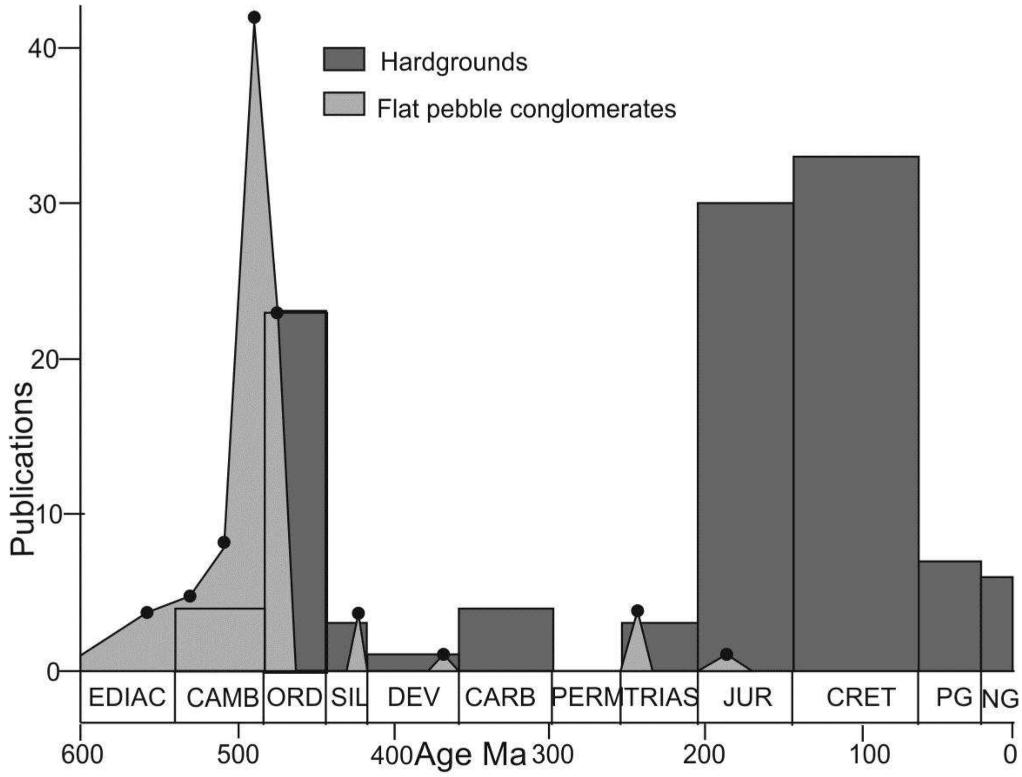


Figure 2.



390 Figure 3.

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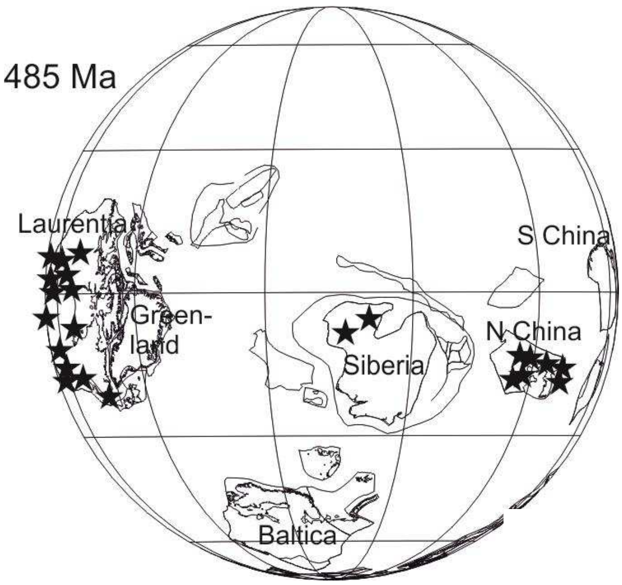
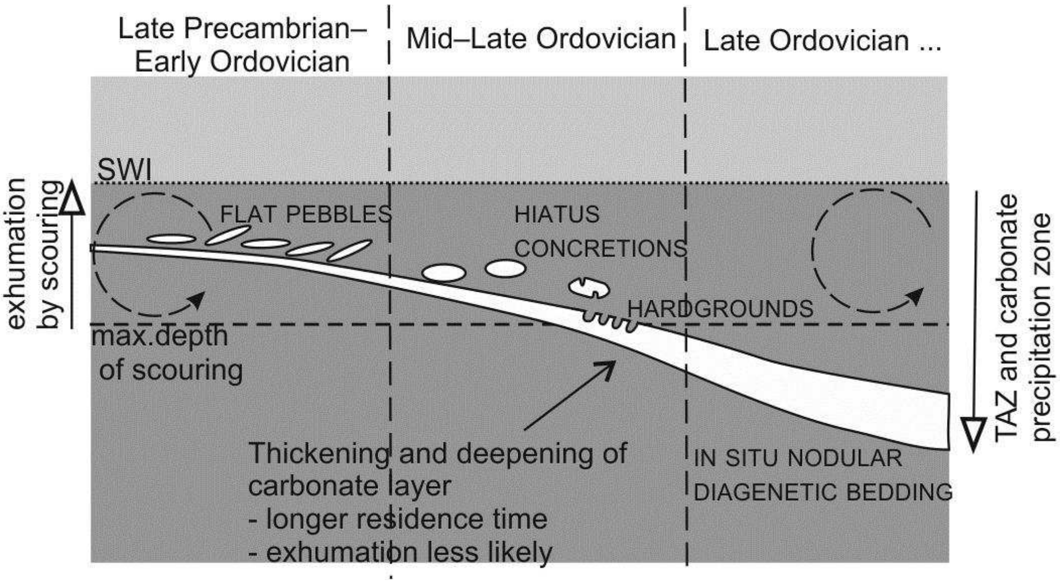


401 Figure 4.



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Wright and Cherns Supplementary Data

Flat pebble conglomerates from subtidal settings (Fig. 2)

AGE	LOCATION	FORMATION	SHELF SETTING	PROPOSED PROCESS	AUTHOR(S)
Mesoproterozoic	China, Hebei Province	Gaoyuzhuang Formation	Subtidal within storm wave base	storms	Luo *et al.* 2014
Proterozoic, Pre-Marinoan glaciation	NW Canada, Mackenzie Mountains	Keele Fm	mid to outer ramp	storms	Day *et al.* 2004
Vendian	Gourma, West Africa		slope	bottom currents'	Bertrand-Sarfati & Moussine-Pouchkine 1983
Ediacaran	South Africa	Swartpunt Fm	Low energy deeper ramp	storm	Narbonne *et al.* 1997
Ediacaran	Canadian Arctic	Gametrail Fm	subtidal ramp	storms	MacNaughton *et al.* 2008
Ediacaran	Kazakhstan	Kyrshabakty Formation	shallow carbonate platform	high energy events	Heubeck *et al.* 2013
Ediacaran - Lower Cambrian	Oman	Ara Group	carbonate platform		Grotzinger & Al-Rawahi 2014
Lower Cambrian	South Australia	Sellick Hill Formation	subtidal	storms	Mount & Kidder 1993
Lower Cambrian	W Mongolia	Bayan Gol Fm, Zavkhan Basin	shallow subtidal	storms	Kruse *et al.* 1996
Lower Cambrian	South China	Shuijingtuo Fm	subtidal		Ishikawa *et al.* 2008
Middle Cambrian	Canadian Arctic		ramp		Dewing & Nowlan 2012
Middle Cambrian	British Columbia, Canada	Jubilee Fm			Pope 1990

Middle Cambrian	Argentina	La Laja Fm	subtidal shelf	tsunamis	Pratt & Bordonaro 2007
Middle Cambrian	Australia	Ranken Lst	low energy shallow subtidal	storms	Kruse 1996
Middle Cambrian	Wyoming, USA	Upper Gros Ventre Shale			Csonka 2009
upper Middle Cambrian	W Utah, USA	upper Wheeler, Marjum fms	middle carbonate belt - subtidal shelf		Robison 1964
Middle-Upper Cambrian	NW China		Supratidal to subtidal fpc	storms	Liang *et al.* 1993
Middle Cambrian - Lower Ordovician	Siberia	Ust'-Brus,Labaz, Orakta, Kulyumbe, Ujgur and Iltyk fms			Kouchinsky *et al.* 2008
Upper Cambrian	NW Siberia	Chopko Fm, Chopka River	carbonate platform, turbidites	submarine landslides	Varlamov *et al.* 2006
Upper Cambrian	N China	Gushan, Chanshang formations	subtidal shelf	storms	Ding *et al.* 2008; Meng *et al.* 1997
Upper Cambrian	China, Shandong Province	Chaomidian Formation (Furongian)	shallow subtidal		Lee *et al.* 2010; Chen 2014; Chen *et al.* 2009, Chen *et al.* 2010; Van Loon *et al.* 2013
Upper Cambrian	S Korea	Hwajeol Formation	subtidal, relatively deep		Kim & Lee 2000
U Cambrian	Western USA		Outer detrital belt (subtidal lagoon)	Storms	Sepkoski 1982
Upper Cambrian	Rocky Mts USA	Snowy Range Fm (Sunwaptan-L Skullrockian)	Inner detrital belt, subtidal	Storms (leading to slope failure)	Brett *et al.* 1983; Myrow *et al.* 2004; Myrow *et al.* 2012
Upper Cambrian	Montana USA	Deadwood Fm	subtidal shelf	tsunamis	Pratt 2002

Upper Cambrian	Wyoming, USA	Snowy Range Fm - Upper Deadwood Formation	subtidal intrashelf basin	storms	Saltzman 1999; Myrow *et al.* 2004
Upper Cambrian	Wyoming, USA			fpc produced by dewatering	Wiison 1985; Kozub 1997
Upper Cambrian	Virginia, USA	Nolichucky Formation	shallow subtidal basin facies	storms	Markello & Read 1981, 1982
Upper Cambrian	Nevada and Utah, USA	SPICE interval	Intrashelf basin	storms	Saltzman *et al.* 1998
Upper Cambrian	Montana USA	Grove Creek, Snowy Range, Maurice formations			Dorf & Lochman 1940
Upper Cambrian	Maryland, USA	Conococheague Limestone	sand shoal environments		Demicco 1985; Demicco *et al.* 1991
Upper Cambrian	Virginia, USA	Conococheague Limestone, Copper Ridge Dolomite	Group I outer shelf	storms	Whisonant 1987
Upper Cambrian	Tennessee, USA	Maynardsville Fm, Conosauga Group	subtidal		Glumac and Walker 1997
Upper Cambrian	Wisconsin and Minnesota, USA	Tunnel City Group	shallow subtidal	storms	Eoff 2014
Upper Cambrian	California, USA	Nopah Fm (Sunwaptan); also Desert Valley Formation, Whipple Cave Formation, Notch Peak Formation, Ajax Dolomite	shallow subtidal	storms	Shapiro & Awramik 2006
Upper Cambrian	S Alberta, Canada	Bison Creek and Mistaya formations	shallow subtidal shelf	storms	Westrop 1989

Upper Cambrian - Lower Ordovician	Alberta , Canada	Survey Peak Fm; Ibexian-Tremadoc			Ji & Barnes 1996
Upper Cambrian - Lower Ordovician	Mexico	Ti˜nu Fm	subtidal dysoxic shelf	debris flows	Landing *et al.* 2007
Upper Cambrian - Lower Ordovician	N China	Fengshan Formation - Yeli Formation	subtidal shelf		Yang *et al.* 2002
Upper Cambrian - Lower Ordovician	China, Jilin Province	candidate GSSP Xiaoyangqiao	subtidal	storms	Chen *et al.* 1988
Upper Cambrian - Lower Ordovician	Utah, USA; Nevada USA	Notch Peak and House Limestone fms; Whipple Cove and House Limestone fms	shoals on shallow carbonate shelf		Popov *et al.* 2002; Cook & Taylor 1975, 1977
Upper Cambrian - Lower Ordovician	Colorado, USA	Dotsero Fm, Manitou Fm			Berg 1960
Lower and Upper Cambrian, Lower Ordovician	Appalachians, USA	Dunham Fm; Pine Plains Fm; Ogdenburg and Tribes Hill fms		storms	Friedman 1994
Upper Cambrian - Lower Ordovician	Siberia	Nya sequence	shallow carbonate platform		Dronov *et al.* 2009
Upper Cambrian - Lower Ordovician	Mid-East Korea	Choson Supergroup	subtidal	storm, diagenetic lsts	Kwon *et al.* 2002
Lower Ordovician	Newfound-land	Watt's Bight and Boat harbour fms	deep subtidal to peritidal	storms	Pruss *et al.* 2010

Lower Ordovician	Utah, USA	Pogonip Group - Notch Peak Formation, House Limestone, Fillmore Formation, and Wah Wah Limestone	shallow subtidal to peritidal		Pruss *et al.* 2010
Lower Ordovician	S Korea	Dumugol Fm	shallow to deep ramp	storms	Lee & Kim 1992
Lower Ordovician	Korea	Mungok Fm	subtidal shelf	storms	Kim and Lee 1995; Choi, Kim & Lee 1993
Lower Ordovician	NY, USA	Tribes Hill Fm	intertidal to supratidal	desiccation and high energy events (seismic /storm /tsunami?)	Braun & Friedman 1969
Lower Ordovician (Tremadoc)	Pingquan, Hebei Province, N China		shallow subtidal to shaly basinal		Liu & Zhan 2009
Lower Ordovician	Pingquan, Hebei Province, N China and Xingshan, Hubei Province, S China		Lower Tremadoc shallow subtidal, Upper Tremadoc shallow to deep subtidal		Liu 2009
Lower Ordovician	NW Hubei	Nantsinkian-lower Dawan fms; Tremadoc - early Floian	shallow marine carbonate platform; shallow to deeper subtidal		Liu *et al.* 2011
Lower Ordovician	Nevada, USA	Ninemile Shale	within storm wave base	storms	Sprinkle & Guensburg 1995

Lower Ordovician	Utah and Nevada, USA	Kanosh Shale	Intrashelf basin	storms	Wilson *et al.* 1992
Lower Ordovician	Utah	Fillmore Formation	storm dominated shelf	storms	Sprinkle & Guensburg 1995; Dattilo 1993; Benner *et al.* 2004
Upper Silurian	Gotland, Sweden	upper Hemse-Eke fms	subtidal to very shallow, microbial shoals	anachronistic facies - suppressed burrowing	Cherns 1982, 1983; Calner 2005
Upper Silurian	Somerset Is., Arctic Canada	Reach Bay Fm	Subtidal within storm wave base	storms	Jones & Dixon 1976
Upper Devonian (Frasnian)	Holy Cross Mts, Poland		Shallow subtidal	storms or tsunamis	Kazmierczak & Goldring 1978
Lower Triassic	S Turkey	Dienerian Fm	storms affecting shallow shelf	anachronistic facies - suppressed burrowing	Pruss *et al.* 2006
Lower Triassic	South China; North Italy		storm-dominated shelf to deep basin; mid ramp carbonates	anachronistic facies - suppressed burrowing	Wignall & Twitchett 1999
Lower Triassic	SW USA	Moenkopi - Union Wash formations	subtidal to deep	anachronistic facies - suppressed burrowing	Pruss *et al.* 2005; Woods 2009
Lower Jurassic	Portugal	Achada Dolomites and Limestones	Subtidal	dip-slip movements causing tsunamis	Kullberg *et al.* 2001

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