

Greenhouse and icehouse epochs: overridden by global CO₂ evolution and mass extinctions

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Criteria used to infer primary mineralogy

The following criteria are used to infer the primary mineralogy of fossilized skeletons (shells, tests, sclerites, spicules, teeth, etc.) and abiotic precipitates (oids, marine synsedimentary cements):

- (1) Detection of original element concentrations either from fluid inclusions in precipitates or from skeletal material (magnesium – for low- or high-Mg calcite; strontium – for aragonite).
- (2) Preservation of specific skeletal fabrics either in calcite or in phosphate minerals' and silica replicas (e.g., foliated and prismatic microstructure – low Mg-calcite; microgranular microstructure – high-Mg calcite; nacreous and lamello-fibrillar microstructures – aragonite).
- (3) Relative quality of preservation of different precipitates in the same sample: fabric preserved – low-Mg calcite; fabric preserved and spar-filled molds with microdolomite – high-Mg calcite; coarse spar mosaic-filled molds, generally irregularly cross-cutting original structure – aragonite.
- (4) Epitaxial synsedimentary marine cements developing in optical continuity with skeletal elements (skeletons only): bladed equant calcite – low-Mg calcite; fibrous calcite – high Mg-calcite; botryoids of acicular crystals – aragonite.
- (5) Phylogenetic application of skeletal mineralogies in extant groups to their probable fossil relatives.
- (6) Relative stable isotope composition ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) of different precipitates in the same sample with less altered signatures characterizing low-Mg calcite fabrics.

Table DR1. Inferred primary mineralogy of Upper Ediacaran–Cambrian carbonate skeletal taxa. FAD – first appearance datum: E – Upper Ediacaran, IND – lower Nemakit-Daldynian, uND – upper Nemakit-Daldynian, IT – lower Tommotian, mT – middle Tommotian, uT – upper Tommotian, IA – lower Atdabanian, uA – upper Atdabanian, B – Botoman, MC – Middle Cambrian (Cambrian Series 3), UC – Upper Cambrian (Furongian); A – aragonite, HMC – high Mg-calcite, LMC – low Mg-calcite.

Taxon	FAD	Inferred mineralogy	Criteria	Comments and references
<i>Cloudina</i> -group	E	HMC	2-4	Grant (1990); Fedorov & Zhuravlev (1993); Zhuravlev et al. (2007)
<i>Namapoikia</i>	E	A	3	Wood et al. (2002)
<i>Namacalathus</i> -group	E	HMC	2-4	Grotzinger et al. (2000); Zhuravlev et al. (2007)
<i>Sinotubilites</i>	E	A	2	Chen et al. (2007)
Anabaritida	IND	A	2, 3	Conway Morris & Chen (1989); Kouchinski & Bengtson (2002); FAD - Khomentovsky & Karlova (2005)
Orthothecimorpha	uND	A	2, 3	Kouchinsky (2000b); Feng et al. (2001);

				FAD – Khomentovsky & Karlova (2005)
Helcionelliformes	uND	A	2, 3	Runnegar (1985, 1989); Bengtson et al. (1990); Kouchinsky (2000a); Feng & Sun (2003); FAD - Khomentovsky & Karlova (2005)
Paragastropoda	uND	A	2, 3	Runnegar (1985, 1989); Bengtson et al. (1990); Kouchinsky (2000a); FAD - Khomentovsky & Karlova (2005)
Coelosclerophora	uND	A	2, 3	Including chancelloriids Bengtson et al. (1990); Mehl (1996); Kouchinsky (2000a); Porter (2004); FAD - Khomentovsky & Karlova (2005)
Cambroclavida	IT	A		Bengtson et al. (1990); Conway Morris et al. (1997); FAD – Li et al. (2007)
Paracarinachitidae	IT	A	2, 3	Conway Morris & Chen (1991)
Rostroconchia	IT	A	2, 3	Pojeta & Runnegar (1976); Runnegar (1996); Kouchinsky (2000a); Rogalla et al. (2003); FAD - Khomentovsky & Karlova (2005)
Bivalvia	IT	A	2, 3	Runnegar & Bentley (1983); Runnegar (1985); Berg-Madsen (1987); Kouchinsky (1999)
Archaeocyatha	IT	HMC	1-6	James & Klappa (1983); Brasier et al. (1994); Kruse et al. (1995); Zhuravlev & Wood (2008); FAD - Rozanov & Zhuravlev (1992)
Cribrycyatha	mT	HMC	2, 3	Zhuravlev & Wood (2008); FAD - Rozanov & Zhuravlev (1992)
Hyolithomorpha	IT	A?	2, 3	Martí Mus & Bergström (2007); FAD - Rozanov & Zhuravlev (1992)
Coleoloida	IT	A	2, 3	Landing et al. (2002); FAD - Rozanov & Zhuravlev (1992)
Obolellata	mT	HMC	2, 3, 5	Ushatinskay & Zhuravlev (1994); Williams et al. (2000)
Calcaronea	mT	HMC	2, 3, 5	Jones (1979); James & Klappa (1983); FAD – Kruse et al. (1995)
Khasakiidae	mT	HMC	1-4, 6	Zhuravlev et al. (1993); Brasier et al. (1994); Zhuravlev & Wood (2008)
Radiocyatha	mT	A	3, 4	Wood et al. (1993); FAD - Rozanov & Zhuravlev (1992)
Tabulaconida	B	A	1-4, 6	modular species only Zhuravlev et al. (1993); Hicks (2006); Fuller & Jenkins (2007)
Hydroconozoa	uT	LMC	1-4, 6	Lafuste et al. (1990); Brasier et al. (1994)
Stenothecoida	1A	LMC	2, 3	Ushatinskay & Zhuravlev (1994); FAD - Rozanov & Zhuravlev (1992)
Trilobita	1A	LMC	1-4, 6	James & Klappa (1983); Lowenstam & Weiner (1989); Wilmot & Fallick (1989); Gaines & Droser (2003); Brand (2004); Lee et al. (2007); FAD - Rozanov & Zhuravlev (1992)

Agmata	B	LMC	2, 3	James & Klappa (1983); FAD - Voronova et al. (1987)
Rhynchonelliformea	lA	LMC	2, 3, 5, 6	Williams et al. (2000); Ushatinskaya & Malakhovskaya (2006); Pérez-Huerta et al. (2008)
Kutorginata	uT	LMC	2, 3	Ushatinskaya & Malakhovskaya (2006)
Echinodermata	uA	HMC	1-5	James & Klappa (1983); Dickson (2004); FAD - Rozanov & Zhuravlev (1992)
Plectonocerida, Protactinocerida	UC	A	5	Crick (1981); Chen & Qi (1982); Teichert (1988)
Polyplacophora	UC	A	5	Haas (1972); Lowenstam & Weiner (1989); Carter and Hall (1990); FAD - Stinchcomb & Darrough (1995)

Table DR2. Inferred primary mineralogy of Ordovician–Quaternary carbonate skeletal taxa listed in Sepkoski's (2002) compendium. Systems: C – Carboniferous, J – Jurassic, K – Cretaceous, P – Permian, S – Silurian, Tr - Triassic; series and stages: Anis – Anisian, Apti – Aptian, Aren – Arenigian, Ashg – Ashgillian, Bajo – Bajocian, Bath – Bathonian, Berr – Berriasian, Camp – Campanian, Cara – Caradocian, Carn – Carnian, Eife – Eifelian, Emsi – Emsian, Eoc – Eocene, Fame – Famennian, Give – Givetian, Guad – Guadalupian, Hett – Hettangian, Indu – Induan, Ladi – Ladinian, Leon – Leonardian, Llvi – Llanvirnian, Loch – Lochkovian, Ludl – Ludlovian, Maas – Massstrichtian, Mi – Miocene, Mosc – Moscovian, Nori – Norian, Olen – Olenekian, Oxfo – Oxfordian, Plie – Pliocene, Prag – Pragian, Prid – Pridolian, Rhae - Rhaetian, Sakm – Sakmarian, Step – Stephanian, Tatr – Tatarian, Than – Thanetian, Tith – Tithonian, Tour – Tournaisian, Trem – Tremadocian, Vala – Valanginian, Wenl – Wenlockian; 1 – lower, m – middle, u – upper¹.

TAXON	FAD	INFERRED MINERALOGY	CRITERIA	COMMENTS AND REFERENCES
Buliminacea	mJ	HMC	5	Van de Poel & Schlager (1994)
Carterinacea	Eoc	LMC	5	Van de Poel & Schlager (1994)
Cassidulinacea	lK	LMC	5	Van de Poel & Schlager (1994)
Ceratobulinalinacea	Plie	A	5	Van de Poel & Schlager (1994)
Discorbacea	lJ	LMC	5	Van de Poel & Schlager (1994)
Duostominacea	Anis	A	2, 3	Van de Poel & Schlager (1994)
Endothyracea	lS	LMC	3	Van de Poel & Schlager (1994)
Globogerinacea	mJ	LMC	5	Van de Poel & Schlager (1994)
Involutinacea	Leon	A	2, 3, 5	Van de Poel & Schlager (1994)
Lituoliacea	lC	LMC	3, 5	Van de Poel & Schlager (1994)
Miliolacea	lC	HMC	2, 3, 5	Van de Poel & Schlager (1994)
Nodosariacea	mC	LMC	1-3, 5	Van de Poel & Schlager (1994)
Orbitoidacea	lK	LMC	5	Van de Poel & Schlager (1994)
Robertinacea	Than	A	2, 3, 5	Van de Poel & Schlager (1994)
Rotaliacea	lK	LMC	2, 3, 5	Van de Poel & Schlager (1994)
Spirillinacea	Carn	HMC	5	Van de Poel & Schlager (1994)
HETERACTINIDA	uA	HMC?		Botting & Butterfield (2005); FAD - Rozanov & Zhuravlev (1992)
PHARETONIDA	Mosc	HMC	2, 3, 5	Hooper & Van Soest (2002)

VERTICILLITIDA	Leon	A	1-3, 5	Cuif & Gautret (1991)
Cassianothalamidae	Carn	HMC	1-3	Cuif & Gautret (1991)
Stromatoporoidea s.s. ²	Aren	HMC	2, 3	Rush & Chafetz (1991); Yoo & Lee (1993)
GUADALUPIIDA	Sakm	A?		
Actinostromarianinidae	Oxfo	LMC?	2, 3	Wood (1987)
Actinostromariidae	Oxfo	LMC?	2, 3	Wood (1987)
Burgundiidae	Oxfo	LMC?	2, 3	Wood (1987)
Disjectoporidae	Guad	A	2, 3	Van de Poel & Schlager (1994)
Milleporellidae	Nori/J/	LMC	2, 3	Wood (1987); FAD - Cuif & Gautret (1991)
Sphaeractinidae	Step			
Spongiomorphidae	Tatr	A	2, 3	Van de Poel & Schlager (1994)
Acanthochaetidae	Oxfo	HMC	1-3, 5	Wood (1987); Cuif & Gautret (1991)
Ceratoporellidae	Anis	A	2, 3, 5	Wood (1987); Cuif & Gautret (1991)
Chaetetidae s.s. ²	Ashg	LMC?	2, 3, 5	Cuif & Gautret (1991)
Desmidoporidae	Ashg			
Favosichaetidae	lC			
Tabulospongiidae ³				
Tiverinidae	Wenl			
PERMSOPHINCTA ⁴	Cara	A (P-Tr)	2, 3	Hooper & Van Soest (2002)
Sphaerocoeliidae	uP	LMC (J)	2, 3	Wendt (1990)
Alpinothalamidae	Ladi	HMC	2, 3	Hooper & Van Soest (2002)
Ceotinelliidae	Ladi	HMC	2, 3	Hooper & Van Soest (2002)
MILLEPORINA	Nori	A	2, 3, 5	Wendt (1990)
STYLASTERINA	Maas	A	5	Van de Poel & Schlager (1994)
STOLONIFERA	Mi	HMC	5	Van de Poel & Schlager (1994)
HELIOPORACEA	Berr	A	2, 3, 5	Van de Poel & Schlager (1994)
GORGONIDA	Berr	HMC, A	2, 3, 5	Wendt (1990)
PENNATULACEA	Rhae	HMC	2, 3, 5	Wendt (1990)
TABULATA	Trem	LMC	2, 3	Wendt (1990); Scrutton (1997)
Numidiaphyllidae	Tatr	A	2, 3	Wendt (1990)
other RUGOSA	Llde	LMC	2, 3	Wendt (1990); Scrutton (1997)
HETEROCORALLIA	Eife	LMC	2, 3	Scrutton (1997)
SCLERACTINIA	Anis	A ⁵	1-5	Wendt (1990); Stanley (2003)
KILBUCHOPHYLLIDA	Cara	A	3	Scrutton et al. (1998)
MACHAERIDIA	Trem	LMC?	3	Dzik (1986); Adrain (1992)
Cornulitidae	Cara	LMC?	2, 3	Vinn & Mutvei (2005)
Ancientidae	Cara	LMC?	2, 3	Vinn & Mutvei (2005)
CYRTONELLIDA	Trem ⁶	?		
BELLEROPHONTIDA	Trem ⁶	LMC, A	2, 3	Van de Poel & Schlager (1994)
PATELLOGASTROPODA	Llvi ⁶	LMC, A	2, 3, 5	Van de Poel & Schlager (1994)
other GASTROPODA	Trem ⁶	A	2, 3, 5	Van de Poel & Schlager (1994)
ELLESMEROOCERIDA	Trem ⁶	A	2, 3	Hewitt & Stait (1985)
ORTHOUCERIDA	Trem	A	1-3	Dauphin (1981, 1989a); Hewitt & Stait (1985)
ASCOCERIDA	Llvi			
INTEJOUCERIDA	Trem			
ACTINOCERIDA	Aren			

ENDOCERIDA	Trem			
DISCOSORIDA	Llvi			
ONCOCERIDA	Aren	A	2, 3	Stridsberg (1985)
NAUTILIDA	Wenl	A	1-3, 5	Zakharov & Khudolozhkin (1969); Dauphin (2006)
TARPHYCERIDA	Trem	A	2, 3	Mutvei (2002)
BARRANDEOCERIDA	Llvi			
ANARCESTIDA	Prag			
CLYMENIIDA	Fame			
GONIATITIDA	Give	A	1-3	Kulicki et al. (2002)
PROLECANTIDA	Tour			
CERATITIDA	Leon	A	1-3	Zakharov & Khudolozhkin (1969)
PHYLLOCERIDA	Olen			
AMMONOIDEA	Hett	A	1-3	Dauphin (1989b, 2002); Dauphin & Denis (1990)
BELEMNITIDA	Carn	LMC, A	1-3, 6	Dauphin et al. (2007)
SEPIIDA	Apti /Step	A	2, 3, 5	Dauphin (1976, 1986a, b); Doguzhaeva (2000)
PHRAGMOTHEUTIDA	Guad	A	1-3	Hall & Kennedy (1967)
BOLETZKYIDA	Emsi			
AULACOCERIDA	Emsi	A	1-3	Zakharov & Khudolozhkin (1969); Dauphin (1988)
SOLEMYOIDA	Aren	A	2, 3, 5	Van de Poel & Schlager (1994)
NUCULOIDA	Trem	A	2, 3, 5	Van de Poel & Schlager (1994); Cope (2003)
PRAECARDIOIDA	Llde	A	2, 3	Yancey & Heaney (2000)
MYTILOIDA	Aren	LMC, A	2, 3, 5	Harper et al. (1997)
ARCOIDA	Aren	A	2, 3, 5	Van de Poel & Schlager (1994)
Ambonychiidae	Llde	LMC	2, 3	Cope (2003)
Anomiidae	Bath	LMC	2, 3, 5	Harper et al. (1997); Checa et al. (2007)
Buchiidae	Olen	A, LMC (J-K)	2, 3	Hautmann (2006)
Deltopectinidae	Step	LMC	2, 3	Esteban-Delgado et al. (2008)
Gryphaeidae	Carn	A, LMC (J-K)	2, 3, 5	Harper et al. (1997); Hautmann (2006); Checa et al. (2007)
Inoceramidae	Sakm	LMC (J-K)	2, 3	Harper et al. (1997); Hautmann (2006)
Limidae	Cara	LMC (J-K)	2, 3, 5	Harper et al. (1997); Checa et al. (2007)
Malleidae	Bajo	LMC	2, 3, 5	Esteban-Delgado et al. (2008)
Ostreidae	Guad	A, LMC (J-K)	2, 3, 5	Harper et al. (1997); Hautmann (2006); Checa et al. (2007)
Pectinidae	Tatr	LMC (J-K)	2, 3, 5	Harper et al. (1997); Hautmann (2006); Checa et al. (2007)
Placunidae	lEoc	LMC	2, 3, 5	Harper et al. (1997); Checa et al. (2007)
Plicatulidae	Anis	A, LMC (J-K)	2, 3, 5	Harper et al. (1997); Checa et al. (2007)
Spondylidae	Ladi	LMC (J-K)	2, 3, 5	Harper et al. (1997); Checa et al. (2007)

				al. (2007)
Pterineidae	Llvi	A	2, 3, 5	Cope (1996)
other PTERIOIDA	Fran	A	2, 3, 5	Harper et al. (1997)
UNIONOIDA	Indu	A	2, 3, 5	Van de Poel & Schlager (1994)
TRIGONIOIDA	Loch	A	2, 3, 5	Van de Poel & Schlager (1994)
Veneridae	Vala	LMC, A	5	Harper et al. (1997)
other VENEROIDA	Llde	A	5	Van de Poel & Schlager (1994)
MYOIDA	Guad	A	5	Van de Poel & Schlager (1994)
Megalodontidae	mO	A	2, 3	Crick et al. (1998)
other HIPPURITOIDA	Oxfo	LMC	2, 3	Harper et al. (1997)
MODIOMORPHOIDA	Trem	A	2, 3	Cope (2003)
PHOLADOMYOIDA	Aren	A	5	Van de Poel & Schlager (1994)
SCAPHPOPODA	Cara	A	1-3, 6	Hall & Kennedy (1967); Lowenstam & Weiner (1989)
CRICOCONARIDA	Trem	LMC?	2, 3	Larsson (1979); Yochelson & Lindemann (1986)
Sabellidae	J ⁷	A	2, 3, 5	Vinn et al. (2008)
Serpulidae	Anis ⁷	HMC, A	2, 3, 5	Wilbur & Simkiss (1979); Vinn (2005)
OSTRACODA ⁸	Aren	LMC	2, 3, 5	Lowenstam & Weiner (1989); Gabbott et al. (2003); Vann et al. (2004)
CIRRIPEDIA	Prid	LMC	5	Lowenstam & Weiner (1989); Rodríguez-Navarro et al. (2006)
DECAPODA	Fame	HMC, LMC, A	5	Roer & Dillaman (1984); Lowenstam & Weiner (1989); Plotnick (1990); Becker et al. (2005)
CYCLOSTOMATA	Aren	LMC	1-3, 5	Taylor & Weedon (2000); Smith et al. (2006); Xiao et al. (2007)
CYSTOPORATA	Trem	LMC	1-3	Smith et al. (2006)
TREPOSTOMATA	Trem	LMC	1-3	Smith et al. (2006); Xiao et al. (2007)
Dianulitidae	Aren	HMC	2	Taylor & Wilson (1999)
CRYPTOSTOMATA	Aren	LMC	1-3	Smith et al. (2006)
FENESTRATA	Aren	LMC	1-3	Smith et al. (2006)
CHEILOSTOMATA	Tith	HMC, A	1-3, 5	Smith et al. (2006)
CRANIIDA	uJ	HMC	2, 3, 5	Williams et al. (1999); Cusack et al. (2008)
CRANIOPSIDA	Cara	HMC	2, 3, 5	Williams et al. (1999); Cusack et al. (2008)
TRIMERELLIDA	Aren	HMC	2, 3, 5	Williams et al. (1999); Cusack et al. (2008)
TUNICATA	Leon	A	5	Lambert et al. (1990)
TELEOSTEI ⁹	Carn	A	1, 5, 6	Ivany et al. (2000); Söllner et al. (2003)

Notes:

1 – Stratigraphic intervals and fossil ranges are given in accordance with Sepkoski (2002); some corrections are listed below.

- 2 – The Stromatoporoidea *s.s.* and the Chatetidae *s.s.* include Palaeozoic, but Cambrian, genera only.
- 3 – The Tabulospongiidae are synonymised with the Acanthochaetidae (Hooper and Van Soest, 2002).
- 4 – Cambrian shinctozoan-like sponges are not included in the Permosphincta.
- 5 – Some Cretaceous and Palaeogene scleractinians display features of primary LMC skeletal composition (Wendt, 1990; Stoliarski et al., 2007).
- 6 – Cambrian molluscs are not included in the orders Cytonellida, Bellerophontida, Patellogastropoda, Archaeogastropoda, and Ellesmerocerida.
- 7 – Authentic calcareous annelid tubes (Serpulidae and Sabellidae) are restricted to Mesozoic and Cenozoic strata only, while Palaeozoic calcareous tubicolous fossils belong to different extinct groups (Vinn et al., 2008).
- 8 – The Ostracoda do not include the Archaeocopida and the Leperditicopida possessing mostly phosphatic carapaces.
- 9 – The Teleostei include the orders Pachycormiformes, Osteoglossiformes, Elopiformes, Megaliformes, Anguilliformes, Crossognathiformes, Clupeiformes, Gonorynchiformes, Siluriformes, Osmeriformis, Salmoniformes, Stomiiformes, Alepsauriformes, Aulopiformes, “Ctenothrissiformes”, Myctophiformes, Polymixiiformes, Ophidiiformes, Batrachoidiformes, Lophiiformes, Gadiformes, Atheriniformes, Beloniformes, Beryciformis, Lampridiformes, Zeiformes, Gasterosteiformes, Dactylopteriformes, Scorphaeniformes, Perciformes, Pleuronectiformes, and Tetraodontiformes of Sepkoski (2002).

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