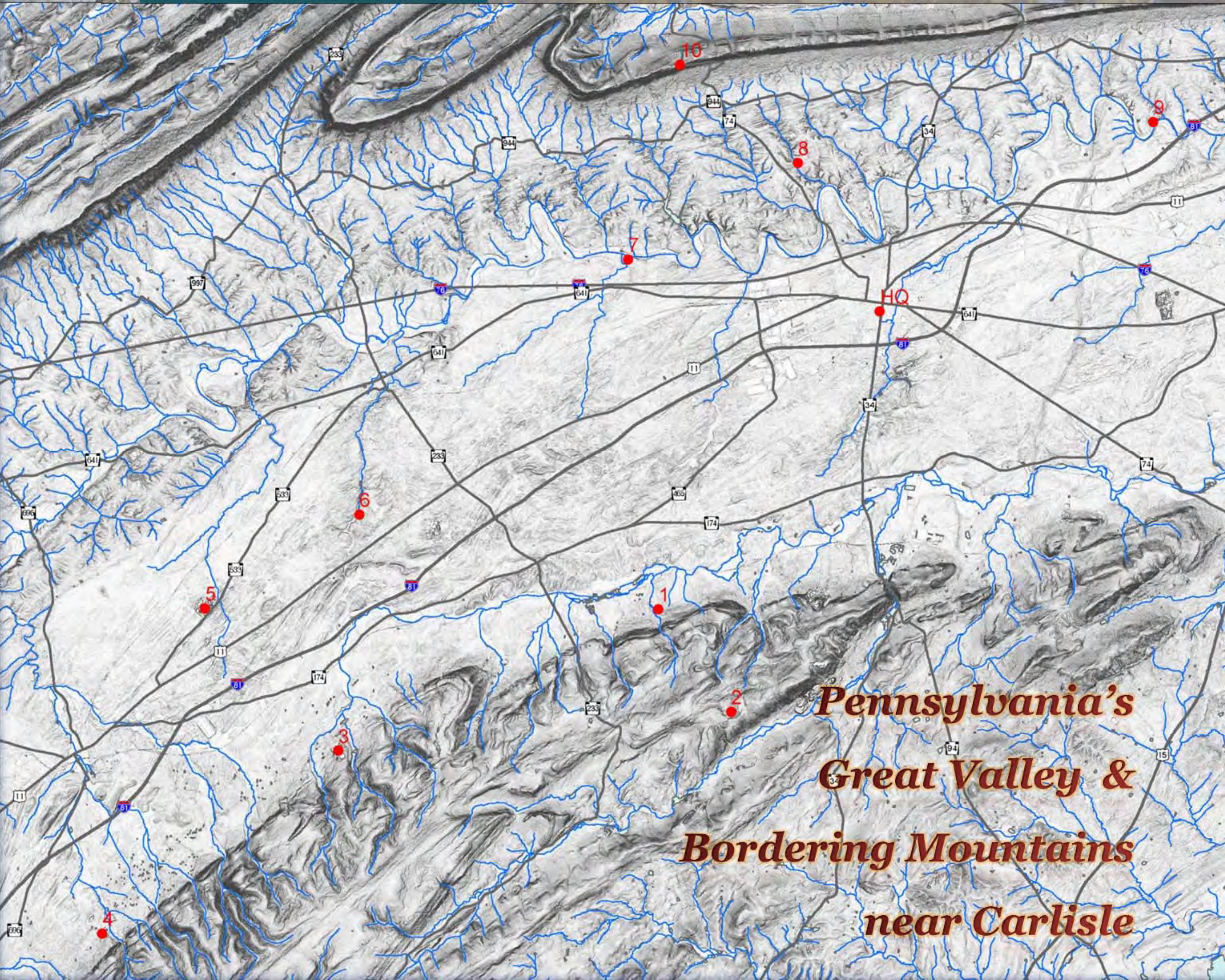
October 16th-18th, 2014

HOSTS:
PENNSYLVANIA GEOLOGICAL SURVEY &
DICKINSON COLLEGE

79TH ANNUAL FIELD CONFERENCE OF PENNSYLVANIA GEOLOGISTS



Pennsylvania's Great Valley & Bordering Mountains near Carlisle

Guidebook for the

79th ANNUAL FIELD CONFERENCE OF PENNSYLVANIA GEOLOGISTS

October 16 — 18, 2014

PENNSYLVANIA'S GREAT VALLEY & BORDERING MOUNTAINS NEAR CARLISLE

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SKOLITHOS IN THE LOWER CAMBRIAN ANTIETAM FORMATION AT SOUTH MOUNTAIN, PENNSYLVANIA

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The naming of *Skolithos*

Skolithos is one of the best known, globally distributed trace fossils, but it was first described from south central Pennsylvania. It was originally defined as an ichnogenus by Samuel Stehman Haldeman in 1840. He grew up in Bainbridge, PA, 15 km upstream from Chickies Rock where he studied *Skolithos*. In the middle of the Susquehanna River across from Bainbridge today is Haldeman Island which was named for him. Haldeman was a Dickinson College student from the class of 1831. After college he worked in his family sawmill and iron forge, but he was drawn to be a naturalist. He even corresponded with Charles Darwin. In 1836, Henry Darwin Rogers, a former professor of Haldeman's at Dickinson, asked him to take over the geology field operations in New Jersey that Rogers had to abandon on his being appointed the state geologist of Pennsylvania. Haldeman served in New Jersey for one year and, in 1837, came back to Pennsylvania to assist on the state survey here. It was then that he lived at the north end of Chickies Rock where he excavated a Native American archeological site and described *Skolithos* (Dickinson College Archives, 2005; Haldeman Mansion Preservation Society, 2011; Scharnberger et al., 2014). Soon after Haldeman's 1840 publication, there was confusion over the spelling of the genus. A GeoRef search on 6 May 2014 returned the following number of hits for the various spellings of *Skolithos* (999): *Scolithus* (38), *Skolithus* (6), and *Scolithos* (4). Based on the taxonomic nomenclatural principle of priority, the proper spelling is *Skolithos* (Häntzschel, 1975; Scharnberger et al., 2014) which is used here.

Skolithos morphology

Skolithos is one of the simplest trace fossils. It normally consists of a single, vertical, long, thin, unbranched, straight cylinder, with or without a funnel top, that is perpendicular to bedding and never crosses adjacent tubes (Haldeman, 1840; Hallam and Swett, 1966; Alpert, 1974; Häntzschel, 1975; Schlirf and Uchman, 2005). Less commonly they are sub-cylindrical or prismatic when in contact, inclined to bedding, slightly curved, but these may simply be artifacts of tectonic deformation (see below). The burrow walls can be distinct/lined or indistinct/unlined, rough or smooth, and possibly annulated. *Skolithos* is so distinct that it has even furnished the name of a formal stratigraphic unit (i.e., *Skolithos* Sandstone of the Lower Cambrian of Sweden (Häntzschel, 1975)).

The tubes are typically filled with non-laminated, finer-grained sediment which are casts of the original burrow (Alpert, 1974; Goodwin and Anderson, 1974; Häntzschel, 1975; Schlirf and Uchman, 2005). The vertical continuity of the tubes as well as the textural and compositional differences between the cast and the surrounding matrix suggests there originally was a permanent mucous-cemented burrow (Goodwin and Anderson, 1974). They occasionally weather out so the tubes become free from their surrounding matrix (Howell, 1943). This has been attributed to slightly reduced sericite content in the sediment infilling relative to the rock matrix (Hallam and Swett, 1966). Wise (2010) attributed this at Chickies Rock to sericite micro-slickenlines "coating" the tubes in the plane of cleavage.

Funnel-topped (a.k.a., trumpet pipe) forms were originally assigned to a different ichnogenus, *Monocraterion* (Torell, 1870; Westergård, 1931). More recently as part of the single organism hypothesis, *Monocraterion* has been interpreted as simply the completely preserved top of the *Skolithos* tube (Howell, 1943; Hallam and Swett, 1966; Goodwin and Anderson, 1974; Barwis, 1985; Schlirf and Uchman, 2005). Environments with lower sedimentation rates and more frequent scour generally only preserve the bottom of the burrow (i.e., *Skolithos*), whereas environments with higher sedimentation rates and less frequent scour generally preserve the entire burrow (i.e., *Monocraterion*) (Hallam and Swett, 1966; Goodwin and Anderson, 1974; Bromley, 1990). Deep permanent vertical burrows dominate shallow water environments for two reasons. First, they protect the animal from desiccation and fluctuating water temperatures and salinities (Rhoads, 1967; Crimes, 1975). Second, they provide protection from erosion in environments with rapid shifts in the vertical position of the sediment-water interface (Seilacher, 1967). Deep, permanent, vertical burrows are characteristic of Seilacher's (1967) classic shallow water *Skolithos* ichnofacies. An ichnofacies is a sedimentary deposit defined by the preserved patterns (i.e., trace fossils) of the organisms that lived there (Miller, 2007).

Maximum *Skolithos* tube lengths are typically reported in the 1-2 m range (Alpert, 1974; Goodwin and Anderson, 1974; Schlirf and Uchman, 2005), but this is hard to measure to due erosional truncation of the tube tops. *Skolithos* tube diameters range from 1-30 mm (Alpert, 1974; Häntzschel, 1975; Schlirf and Uchman, 2005). The larger diameters reflect the apertural upper *Monocraterion* end of the tube. Most diameters in the local Cambrian quartzites are 2-6 mm (Goodwin and Anderson, 1974; Gourley and Key, 1996; Key, 2014).

What made the *Skolithos* trace fossil?

Polychaete annelids living today in shallow marine environments produce permanent mucous-lined dwellings that are *Monocraterion-Skolithos* shaped as the animal feeds on suspended food particles above or on the sediment-water interface (Schäfer, 1972).

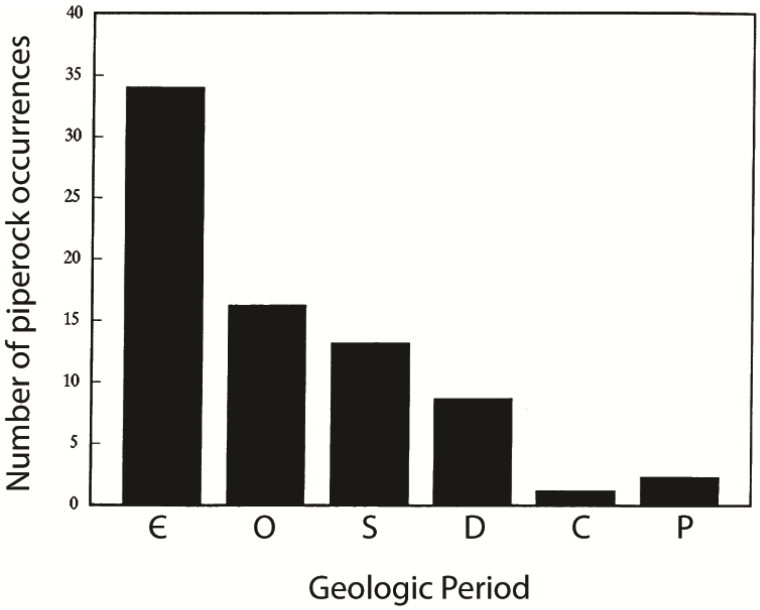
Skolithos, like their modern analog polychaetes, are opportunistic colonizers following storm depopulation (Vossler and Pemberton, 1988). But this isn't the only possible candidate for the *Skolithos* trace maker. Hypotheses for the agent responsible for making the *Skolithos* trace were initially wide ranging, including plants, sponges, annelids, brachiopods, and phoronids (Häntzschel, 1975) or even inorganic (Högbom, 1915; Hofmann, 1971). Though most *Skolithos* are marine, some are terrestrial, and those have been attributed to insects, spiders, or plants (Schlirf and Uchman, 2005; Gregory et al., 2006; Netto, 2007). Marine forms are now thought to have been made by a burrowing, soft-bodied, worm-like polychaete annelid or phoronid lophophorate (Alpert, 1974; Pemberton and Frey, 1984; Barwis, 1985; Skoog et al., 1994; Schlirf and Uchman, 2005). Regardless of what made the *Skolithos* trace, it is important the keep in mind that trace fossil taxa are defined on their morphology, regardless of their origin (Häntzschel, 1975; Miller, 2007), so different trace-makers may produce identical structures when behaving similarly (Bromley, 1990). With a stratigraphic range spanning the Phanerozoic (see below), numerous different animals are undoubtedly responsible for making *Skolithos*, especially considering they form in both marine and terrestrial environments.

Skolithos geographic and stratigraphic range

Skolithos is globally distributed (Alpert, 1974; Häntzschel, 1975; Behrensmeyer and Turner, 2013). Though *Skolithos* has a stratigraphic range from the Ediacaran to Recent, it is most common in the Paleozoic (Alpert, 1974; Häntzschel, 1975; Fillion and Pickerill, 1990; Droser, 1991; Ekdale and Lewis, 1991; Crimes, 1994; Behrensmeyer and Turner, 2013). As a result of its >600 Myr stratigraphic range, *Skolithos* is useless as a biostratigraphic index fossil. Regardless, the relative abundance of *Skolithos* can be used for lithostratigraphic correlation. They have been used for understanding the stratigraphy of and exploring for Cambro-Ordovician petroleum reservoirs in North Africa, the Middle East, and Australia (McIlroy and Garton, 2004).

Skolithos are especially common in Cambrian sedimentary rocks, even after correcting for relative geologic map area and period durations (Figure 1). During the Early Cambrian an abrupt increase in the diversity of bioturbators as well as the degree and depth of bioturbation occurred in conjunction with the rapid radiation of metazoans (McMenamin and Schulte-McMenamin, 1990; McIlroy and Logan, 1999). This has been termed the Cambrian Substrate Revolution (Bottjer et al., 2000). Major components of this ecological revolution include the first appearance of vertical burrows and the development of tiered endobenthic communities (McIlroy and Logan, 1999). This may have been associated with the extraordinarily large amounts of sand on Cambrian continental shelves due to the lack of land plants before the Ordovician that favored the development of extensive coastal subaerial dune fields and braided fluvial systems (MacNaughton et al., 1997; Desjardins et al., 2010).

Transgressive episodes in the Early Cambrian contributed to the flux of sediment from the coast to the shelf by flooding and ravinement of preexisting sandy coastal deposits (Simpson and Eriksson, 1990; Desjardins et al., 2010). The post-Cambrian decrease in *Skolithos* has been attributed to a temporal decrease in nearshore sandstones as well as the Great Ordovician Biodiversification event. This event involved a radiation in the biodiversity of predators and an increase in competition for infaunal ecospace previously dominated by the *Skolithos* tracemakers (Bottjer et al., 2000; Droser, 1991; McIlroy and Garton, 2004; Webby et al., 2004; Desjardins et al., 2010) including the advent of "biological bulldozers" (Thayer, 1979).



In Pennsylvania, *Skolithos* has long been known from numerous Cambrian formations (Table 1). It has also been reported in the Silurian Tuscarora Formation (Cotter, 1982, 1983; Droser and Bottjer, 1989; Sanabria and Thompson, 1997) and the Devonian Catskill Formation (Bridge and Droser, 1985). Further south in Maryland and Virginia, it occurs in the Antietam (Howell, 1943; Simpson and Sundberg, 1987; Simpson and Eriksson, 1990; Simpson, 1991; Skoog et al., 1994) and Harpers (Brezinski, 2004). In the southern Appalachians, *Skolithos* is found in the Chilhowee's Weisner and Wilson Ridge Formations, the latter correlative with the Antietam (Tull et al., 2010) as well as the Hampton (stratigraphic equivalent of the Harpers Formation) and Erwin (stratigraphic equivalent of the Antietam) Formations (Simpson and Sundberg, 1987; Simpson and Eriksson, 1990; Smoot and Southworth, 2014).

Table 1. Published reports of *Skolithos* trace fossils in Cambrian formations of Pennsylvania

Stratigraphic Formation	**Reference(s)**
Weverton	Smoot and Southworth, 2014
Chickies	Haldeman, 1840; Hunt, 1878; Stose and Jonas, 1939; Howell, 1943; Wise, 1960, 2010; Goodwin and Anderson, 1974; Kauffman, 1999; Scharnberger et al., 2014
Harpers	Stose, 1906, 1909; Freedman, 1967; Fauth, 1968; Root, 1968; Key, 1991; Gourley and Key, 1996
Antietam	Stose, 1906, 1909; Howell, 1945; Freedman, 1967, 1968; Fauth, 1968; Root, 1968; Key, 1991; Key and Sims, 1991; Sevon and Van Scyoc, 1991; Kauffman, 1999
Hardyston which is stratigraphically equivalent to the Antietam (Berg et al., 1983)	Leidy, 1882; Lyman, 1909; Howell, 1943, 1944; Aaron, 1969; Kauffman, 1999; Simpson et al., 2002
Setters which is stratigraphically equivalent to the Chilhowee Group (Berg et al., 1983)	Rand, 1900
Potsdam	Hunt, 1878; Bjerstedt and Erickson, 1989

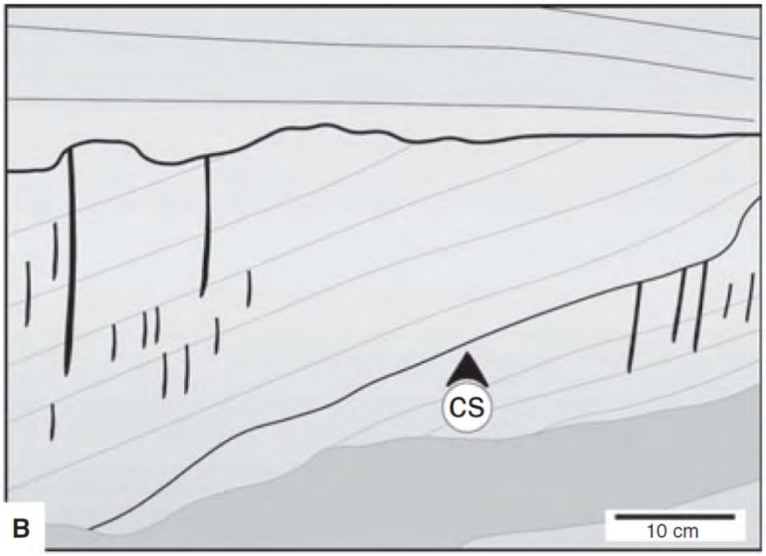
Deformed *Skolithos*

Cylindrical *Skolithos* tubes have long been used to calculate strain (Wise, 1960, 2010; Brace, 1961; Sylvester and Christie, 1968; McLeish, 1971; Wilkinson et al., 1975; Allison, 1979). Deformation of *Skolithos* burrows has been noted in Cambrian quartzites locally (Key and Sims, 1991; Gourley and Key, 1996; Wise, 1960, 2010; Key, 2014). This is typically reflected by the normally circular transverse cross-sectional shape of the burrow being distorted into an ellipse (Häntzschel, 1975). Wise (2010) attributed this in the Blue Ridge anticlinorium to layer-parallel shortening that flattened the *Skolithos* tubes in the plane of cleavage resulting from the Appalachian orogenies, especially the Alleghanian. Key (2014) measured the long (L) and short (W) axes of *Skolithos* tubes from the Antietam

Formation near Shippensburg and calculated the L/W (i.e., Rf strain) ratio as 1.9. This is more than the 1.6 that Key and Sims (1991) measured in the Antietam Formation exposed in the Mt. Holly Pennsy Supply quarry as well as the 1.3 value reported by Kilby and Connors (2002) in the Antietam of Virginia. Gourley and Key (1996) measured the same ratio in the underlying Montalto Member of the Harpers Formation outcropping at Pole Steeple and reported a ratio of 1.5. *Skolithos* tubes can also refract into a sigmoid shape along with cleavage in response to flexural slip (Allison, 1979; Wise, 2010). This has been reported elsewhere in a Devonian *Skolithos*-bearing quartzite (Richter, 1920) and the Antietam Quartzite at Bender's quarry (Freedman, 1967, 1968), now Pennsy Supply's Mt. Holly quarry (Key and Sims, 1991).

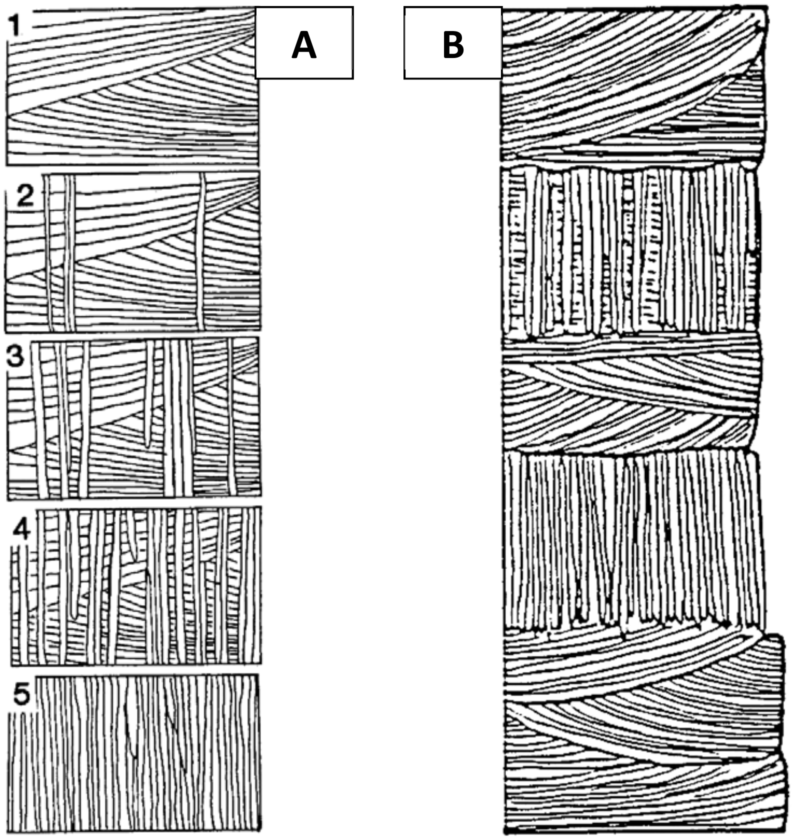
Skolithos tube spacing

Much research has been done on the spacing of *Skolithos* tubes as a paleoenvironmental indicator. This is because the preserved burrow density on a bedding plane is more closely related (i.e., inversely) to sedimentation rate than original animal density (Desjardins et al., 2010). *Skolithos* spacing is a function of both original animal density and contemporaneity of the burrows. The former is controlled by size of the animal's food-catching apparatus and the current velocity-regulated food density (Dodd and Stanton, 1981). The latter is controlled by the time available for colonization of the substrate, sedimentation rate, and burrow depth. Because all burrows are equally preservable, contemporaneity is virtually impossible to determine in the rock record (Figure 2) (Frey and Seilacher, 1980). That is one reason why *Skolithos* densities are at least one order of magnitude greater in fossils than with extant organisms (Skoog et al., 1994). In addition to spacing, work has been done on random versus clustered packing of *Skolithos* (e.g., Skoog et al., 1994; Gourley and Key, 1996).



Skolithos ichnofabric indices

Droser and Bottjer (1989) developed a *Skolithos* ichnofabric index that ranges from 1 (*Skolithos* absent) to 5 (complete bioturbation of the original bedding by *Skolithos*) (Figure 3A). Sandstone with a higher density of *Skolithos* is called piperock. The term piperock was coined by Peach and Horne (1884) to describe the dense assemblage of *Skolithos* in the so-named Pipe Rock Member of the Lower Cambrian Eriboll Sandstone of Scotland (McIlroy and Garton, 2004; Netto, 2007). Piperock has an ichnofabric index of 3-5 (Droser and Bottjer, 1989; Droser, 1991). This can produce a type of biostratification in response to non-bioturbated strata alternating with piperock (Figure 3B).



Depositional environment of shallow marine *Skolithos*

Unlike conventional body fossils which are typically preserved in time averaged death assemblages which may be far from where the organism lived, trace fossils are preserved in situ as they cannot normally be transported without being destroyed (Häntzschel, 1975; Bromley, 1990; Miller, 2007). This is why they are effective tools for interpreting depositional environments. Though *Skolithos* also occurs in a variety of terrestrial (Netto, 2007), subtidal shelf (Vossler and Pemberton, 1988), and deep marine environments (Ekdale, 1977), here we focus on the more ubiquitous shallow marine *Skolithos*. Seilacher (1967) originally named his shallowest marine ichnofacies after *Skolithos* for the littoral environment with frequent sediment transport and little net deposition due to episodic erosion and deposition. Based on characteristics of the surrounding sediment and sedimentary structures, shallow marine *Skolithos* have been interpreted to form in a variety of high energy, mature, siliciclastic, nearshore environments including tidal flats, tidal channels, beach shorefaces, and offshore sand bars (Frey and Pemberton, 1985; Simpson and Eriksson, 1990; Droser, 1991; Skoog et al., 1994). *Skolithos* achieves its greatest density in conditions with more consistent, higher velocity, wave/tidal currents near the low tide line, whereas *Monocraterion* is most common where there are inconsistent, lower velocity, wave/tidal currents near the high tide line (Goodwin and Anderson, 1974). *Skolithos* densities are highest near the low tide line due the longer duration and more favorable submerged feeding conditions.

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References

Aaron, J. M. 1969. Petrology and origin of the Hardyston Quartzite (Lower Cambrian) in eastern Pennsylvania and western New Jersey. Pp. 21-34. In: S. Subitzky (ed.). Geology of selected area in New Jersey and eastern Pennsylvania and guide book. Rutgers University Press, New Brunswick.

Allison, I. 1979. Variations of strain and microstructure in folded Pipe Rock in the Moine Thrust Zone at Loch Eriboll and their bearing on the deformational history. Scott. J. Geol. 15, (4), 263-269.

Alpert, S. P. 1974. Systematic review of the genus *Skolithos*. Journal of Paleontology, 48: 661-669.

Alpert, S.P., 1975, Planolites and Skolithos from the Upper Precambrian-Lower Cambrian, White-Inyo Mountains, California: Journal of Paleontology, v. 49, p. 508-521.

Barwis, J. H. 1985. Tubes of the modern polychaete *Diopatra cuprea* as current velocity indicators and as analogs for *Skolithos-Monocraterion*. Pp. 225 – 235, In: Biogenic structures: their use in interpreting depositional environments / edited by H. Allen Curran. SEPM Special Publication 35

Berg, T.M., McInerney, M.K., Way, J.H., and MacLachlan, D.B. 1983. Stratigraphic correlation chart of Pennsylvania. Pennsylvania Geological Survey, General Geology Report 75.

Behrensmeyer, A. K., and A. Turner. 2013. Taxonomic occurrences of *Olenellus* recorded in the Paleobiology Database. Fossilworks. http://fossilworks.org. search 23 June 2014.

Bjerstedt, T.W. & Erickson, J.M. 1989: Trace fossils and bioturbation in peritidal facies of the Potsdam–Theresa formations (Cambrian–Ordovician), northwest Adirondacks. Palaios 4, 203–224.

Bottjer, D.J., Hagadon, J.W. & Dornbos, S.Q. 2000: The Cambrian substrate revolution. GSA Today 10, 2–7.

Brace, W. F. 1961. Mohr construction in the analysis of large geologic strain, Geol. Soc. America, Bull., 72:1059-1080.

Bridge, J. S., and M. L. Droser. 1985. Unusual marginal-marine lithofacies from the Upper Devonian Catskill clastic wedge. Geological Society of America Special Paper 201.

Bromley, R. G. 1990. Trace fossils: biology and taphonomy. Unwin Hyman, 280 p.

Cotter, E. 1982. Tuscarora Formation of Pennsylvania. Guidebook for the Society of Economic Paleontologists and Mineralogists, Eastern Section field trip. Lewisburg, PA. 105 p.

Cotter, E. 1983. Shelf, paralic, and fluvial environments and eustatic sea-level fluctuations in the origin of the Tuscarora Formation (Lower Silurian) of central Pennsylvania. Journal of Sedimentary Petrology, 53 (1): 25-49.

Crimes, T. P. 1975. The stratigraphical significance of trace fossils. Pp. 109-130. In: R. W. Frey (ed.). The Study of Trace Fossils. Springer-Verlag, New York.

Crimes, T. P. 1994. The period of early evolutionary failure and the dawn of evolutionary success: the record of biotic changes across the Precambrian–Cambrian boundary, in Donovan, S.K., ed., The Paleobiology of Trace Fossils: Baltimore, The John Hopkins University Press, p. 105–133.

Desjardins, P.R., Mángano, M.G., Buatois, L.A. and Pratt, B.R. 2010. *Skolithos* pipe rock and associated ichnofabrics from the southern Rocky Mountains, Canada: colonization trends and environmental controls in an early Cambrian sand-sheet complex. Lethaia, 43: 507–528.

Dickinson College Archives. 2005. Samuel Stehman Haldeman (1812-1880). http://archives.dickinson.edu/people/samuel-stehman-haldeman-1812-1880. Accessed 23 June 2014.

Dodd, J. R., and Stanton, R. J., Jr. 1981. Paleoecology, Concepts and Applications: New York, Wiley, 559 p.

Droser, M.L., 1991, Ichnofabric of the Paleozoic Skolithos ichnofacies and the nature and distribution of Skolithos piperock: Palaios, v. 6, p. 316-325.

Droser, M.L., and Bottjer, D.J., 1989. Ichnofabric of sandstones deposited in high-energy nearshore environments: Measurement and utilization: Palaios, v. 4, p. 598-604.

Ekdale, A. A. 1977. Abyssal trace fossils in worldwide Deep Sea Drilling Project cores: in Crimes, T. P., and Harper, J. C., eds., Trace Fossils 2: Geological Journal Special Issue No. 9, Seel House Press, p. 163-182.

Ekdale, A. A. & Lewis, D. W. 1991, Trace fossils and paleoenvironmental control of ichnofacies in a late Quaternary gravel and loess fan delta complex, New Zealand: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 81, p. 253-279.

Fauth, J. L. 1968. Geology of the Caledonia Park Quadrangle Area, South Mountain, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Atlas 129a, 133 p.

Fillion, D. and R. K. Pickerill. 1990. Ichnology of the Upper Cambrian? to Lower Ordovician Bell Island and Wabana groups of eastern Newfoundland, Canada. Palaeontographica Canadiana, 7: 1- 119.

Frey, R. W., and Pemberton, S. G. 1985. Biogenic structures in outcrops and cores: I: Approaches to ichnology. Bulletin of Canadian Petroleum Geologists, 33:72-115.

Frey, R. W. and Seilacher, A. 1980. Uniformity in marine invertebrate ichnology. Lethaia, 13: 183-207.

Goodwin, P. W., and Anderson, E. J. 1974. Associated physical and biogenic structures in environmental subdivision of a Cambrian tidal sand body: Journal of Geology, v. 82, p. 779-794.

Gourley, J. R., and M. M. Key, Jr. 1996. Analysis of the *Skolithos* ichnofacies from the Cambrian Montalto Quartzite Member of the Harpers Formation in south central Pennsylvania. Pp. 152. *In*: J. E. Repetski (ed.). North American Paleontological Convention Abstracts of Papers. Paleontological Society, Special Publication, No. 8.

Haldeman, S. S. 1840. Supplement to number one of "A monograph of the *Limniades*, and other freshwater univalve shells of North America" containing new descriptions of apparently new animals in different classes, and the names and characters of the subgenera *Paludina* and *Anculosa*. Philadelphia. 3 p.

Haldeman Mansion Preservation Society. 2011. Samuel Steman Haldeman. http://www.haldeman-mansion.org/samuelstemanhaldeman.htm. Accessed 24 June 2014.

Hallam, A., and Swett, K. 1966. Trace fossils from the Lower Cambrian Pipe Rock of the north-west Highlands. Scottish Journal of Geology, 2: 101-106.

Häntzschel, W. 1975. Miscellanea: supplement 1: trace fossils and problematica. Treatise on Invertebrate Paleontology, Part W. Geological Society of America, Boulder Colorado, 269 p.

Hofmann, H. J. 1971. Precambrian fossils, pseudofossils, and problematica in Canada. Geol. Surv. Canada, Bull. 189, 146 p.

Högbom, A.G. 1915. Zur Deutung der Scolithus-Sandsteine und "Pipe Rocks". Bull. geol. Instn. Univ. Upsala, 13: 45-60.

Howell, B. F. 1943. Burrows of *Skolithos* and *Planolites* in the Cambrian Hardyston Sandstone at Reading, Pennsylvania. Bulletin of the Wagner Free Institute of Sciences of Philadelphia. 3:1-33.

Howell, B. F. 1944. A new *Skolithos* from the Cambrian Hardyston Formation of Pennsylvania. Bulletin of the Wagner Free Institute of Sciences of Philadelphia, 19 (4): 41-46.

Howell, B. J. 1945. *Skolithos*, *Diplocraterion*, and *Sabellidites* in the Cambrian Antietam Sandstone of Maryland. Bulletin of the Wagner Free Institute of Sciences of Philadelphia, 20: 33-42.

Hunt, T. S. 1878. Special report on the trap dykes and azoic rocks of southeastern Pennsylvania. Part 1. Historical introduction. Second Geological Survey of Pennsylvania, E: 1-253.

Kauffman, M. E. 1999. Eocambrian, Cambrian, and transition to Ordovician. Pp. 58-73, In: The geology of Pennsylvania. Shultz, C. H. (ed.). Special Publication - Geological Survey of Pennsylvania, Harrisburg.

Key, M. M., Jr. 1991. The Lower Cambrian Clastics of South Mountain, Pennsylvania. Pp. 21-27. *In*: W. D. Sevon and N. Potter, Jr. (eds.). Guidebook for the 56th Annual Field Conference of Pennsylvania Geologists. Field Conference of Pennsylvania Geologists. Harrisburg, PA.

Key, M. M., Jr. 2014. *Skolithos* in the Lower Cambrian Antietam Formation at South Mountain, Pennsylvania. Pp. 13-26. In: D. Hoskins and N. Potter, Jr. (eds.). Guidebook for the 79th Annual Field Conference of Pennsylvania Geologists. Field Conference of Pennsylvania Geologists. Harrisburg, PA.

Key, M. M., Jr. and S. J. Sims. 1991. Geology of the Pennsy Supply Quarry, Mt. Holly, Pennsylvania. Pp. 220-225. *In*: W. D. Sevon and N. Potter, Jr. (eds.). Guidebook for the 56th Annual Field Conference of Pennsylvania Geologists. Field Conference of Pennsylvania Geologists. Harrisburg, PA.

Kilby, R. E., and C. D. Connors. 2002. Preliminary strain analysis of the Antietam Fm., southern Central Appalachians, Virginia. Geological Society of America, Abstracts with Programs 34 (6): 439.

Leidy, J. 1882. Remarks on some rock specimens. Proceedings of the Academy of Natural Sciences of Philadelphia. 1882: 10-12.

Lyman, B. S. 1909. *Scolithus linearis* burrows with the orifice complete. Proceedings of the Academy of Natural Sciences of Philadelphia. 1909: 296-297.

MacNaughton, R.B., Dalrymple, R.W. & Narbonne, G.M. 1997: Early Cambrian braid-delta deposits, Mackenzie Mountains, north-western Canada. Sedimentology 44, 587–609.

McIlroy, D. & Garton, M. 2004: A worm's eye view of the early Paleozoic sea floor. Geology Today 20, 224–230.

McIlroy, D. & Logan, G. 1999: The impact of bioturbation on infaunal ecology and evolution during the Proterozoic–Cambrian transition. Palaios 14, 58–72.

McLeish, A. J. 1971. Strain analysis of deformed pipe rock in the Moine Thrust Zone, northwest Scotland. Tectonophysics 12, 469-503.

McMenamin, M.A.S., and Schulte-McMenamin, D.L., 1990. The Emergence of Animals: The Cambrian Breakthrough. Columbia University Press, New York, 217 p..

Miller, W. C. 2007. Trace fossils: concepts, problems, prospects. Elsevier, 611 p.

Netto, R. G. 2007. *Skolithos*-dominated piperock in nonmarine environments: An example from the Triassic Caturrita Formation, southern Brazil. Pp. 107-121, In: Sediment-Organism Interactions: Multifaceted Ichnology, Edited by R. G. Bromley, L. A. Buatois, G. Mángano, J. F. Genise, and R. N. Melchor. SEPM Special Publication No. 88.

Peach, B.N., and Horne, J. 1884. Report on the geology of the north-west of Sutherland. Nature, 31: 31–34.

Pemberton, S.G., and Frey, R.W., 1984, Quantitative methods in ichnology: Spatial distribution among populations. Lethaia, v. 17, p. 33-49.

Rand, T. D. 1900. Notes of the geology of southeastern Pennsylvania. Proceedings of the Academy of Natural Sciences of Philadelphia. 1909: 160-338.

Rhoads, D. C., 1967, Biogenic reworking of intertidal and subtidal sediments in Barnstable Harbor and Buzzards Bay, Massachusetts. Journal of Geology, 75: 461-476.

Richter, R. 1920. Ein devonischern 'Pfeifenquarzit' verglichen mit der heutigen "Sandkoralle" (*Sabellaria*, Annelida). Senckenbergiana, 2: 215-235.

Root, S. I. 1968. Geology and mineral resources of Southeastern Franklin County, Pennsylvania Geological Survey, 4th Ser., Atlas 119cd, 118 p.

Sanabria, D. I., and A. M. Thompson. 1997. Stratigraphic relations of the Juniata-Tuscarora contact in central Pennsylvania. Pennsylvania Geological Survey, 4th Series, Open-Fire Report 97-01, Harrisburg. 30 p.

Schäfer, W. 1972. Ecology and Palaeoecology of Marine Environments. University of Chicago Press, Chicago, Illinois, 568 p.

Scharnberger, C., E. Simpson, J. Jones, and J. Smoot. 2014. Stratigraphy and structure of the Chilhowee Group in Lancaster and York Counties. Pp. 53-72. In: de Wet, A. P. (ed.). Field Trip Guide, Northeastern Section of the Geological Society of America, Lancaster.

Schlirf, M., and Uchman, A. 2005, Revision of the ichnogenus *Sabellarifex* Richter, 1921 and its relationship to *Skolithos* Haldeman 1840 and *Polykladichnus* Fürsich, 1981: Journal of Systematic Palaeontology, v. 3, p. 115-131.

Schwab, F. L., 1972, The Chilhowee Group and the late Precambrian-early Paleozoic sedimentary framework in the Central and Southern Appalachians, in Lessing, P., et al, eds., Appalachian Structures: Origin, Evolution, and Possible Potential for New Exploration Frontiers; A Seminar: Morgantown, West Virginia University and West Virginia Geological and Economic Survey, p. 59-101.

Seilacher, A. 1967. Bathymetry of trace fossils. Marine Geology, 5: 413-428.

Sevon, W. D., and R. L. Van Scyoc. 1991. Mount Cydonia Quarry, Valley Quarries, Inc. Pp. 168-176. In: W. D. Sevon and N. Potter, Jr. (eds.). Guidebook for the 56th Annual Field Conference of Pennsylvania Geologists. Field Conference of Pennsylvania Geologists. Harrisburg, PA.

Simpson, E. L., 1991, An exhumed Lower Cambrian tidal flat: the Antietam Formation , central Virginia, U.S.A., Pp. 123-134. In: Smith, D.G., Reinson, G.E. Zaitlin, B.A., and Rahmani, R.A., Eds., Clastic Tidal Sedimentology: Canadian Society of Petroleum Geologists Memoir No. 16.

Simpson, E.L., Dilliard, K.A., Rowell, B.F. & Higgins, D. 2002: The fluvial to marine transition within the post-rift Lower Cambrian Hardyston Formation, eastern Pennsylvania, USA. Sedimentary Geology 147, 127–142.

Simpson, E.L., and Eriksson, K.A., 1990, Early Cambrian progradational and transgressive sedimentation patterns in Virginia: An example of the early history of a passive margin: Journal of Sedimentary Petrology, 60: 84-100.

Simpson, E. L., and Sundberg, F. A. 1987. Early Cambrian age for synrift deposits of the Chilhowee Group of southwestern Virginia. Geology, 15 (2): 123-126.

Skoog, S.Y., Venn, C., and Simpson, E.L., 1994, Distribution of *Diopatra cuprea* across modern tidal flats: Implications for the Skolithos: Palaios, v. 9, p. 188-201.

Smoot, J.P., and Southworth, S. 2014. Volcanic rift margin model for the rift-to-drift setting of the late Neoproterozoic-early Cambrian eastern margin of Laurentia:

Chilhowee Group of the Appalachian Blue Ridge: Geological Society of America Bulletin, v. 126, p. 201-218.

Stose, G. W. 1906. The sedimentary rocks of South Mountain, Pennsylvania. Journal of Geology, 14: 201-220.

Stose, G. W. 1909. Mercersburg-Chambersburg folio. U.S. Geological Survey Geologic Atlas, Folio No. 170, 19 p.

Stose, G. W., and A. I. Jonas. 1939. Geology and mineral resources of York County, Pennsylvania. Pennsylvania Geological Survey, 4th Series, Bulletin C67.

Sylvester, A. G., and J. M. Christie. 1968. The origin of crossed-girdle orientations of optic axes in deformed quartzites. Journal of Geology 76: 571-580.

Thayer, C. W. 1979. Biological bulldozers and the evolution of marine benthic communities. Science, 203: 458–461.

Torell, 0. 1870. Petrificata suecana formationis Cambricae. Lunds Universitets ars. Volume 6, Avdel. 2, No. VIII: 1-14.

Tull, J.F., Allison, D.T., Whiting, S.E., and John, N.L., 2010, Southern Appalachian Laurentian margin initial driftfacies sequences: Implications for margin evolution, in Tollo, R.P., Bartholomew, M.J., Hibbard, J.P. , and Karabinos, P.M., eds., From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir 206, p. 935-956.

Vossler, S.M., and Pemberton, S.G., 1988, *Skolithos* in the Upper Cretaceous Cardium Formation: An ichnofossil example of opportunistic ecology: Lethia, v. 21, p. 351-362.

Webby, B. D., F. Paris, M. L. Droser, I. G. Percival. 2004. The great Ordovician biodiversification event. Columbia University Press, 484 p.

Westergård, A. H. 1931. *Diplocraterion*, *Monocraterion*, and *Scolithus* from the Lower Cambrian of Sweden. Sveriges Geologiska Undersökning. C372: 1-25.

Wilkinson, P., Soper, N. J., Bell, A. M. 1975. *Skolithos* pipes as strain markers in mylonites. Tectonophysics, 28 (3): 143-157.

Wise, D. U. 1960. Stop #8: Chickies Rock, in Wise, D. U and M. E. Kauffman, eds., Some Tectonic and Structural Problems of the Appalachian Piedmont along the Susquehanna River, 25th Annual Field Conference of Pennsylvania Geologists, Lancaster, PA, p. 68-75.

Wise, D. U. 2010. Stop #5: Structural geology at Chickies Rock, in Wise, D. U and Gary M Fleeger, eds., Tectonics of the Pennsylvania Piedmont along the Susquehanna River, 75th Annual Field Conference of Pennsylvania Geologists, Lancaster, PA, p. 49-57.