Does the Paleoproterozoic Animikie Basin record the sulfidic ocean transition? REPLY

REPLY: doi:10.1130/G32187Y.1

Peir K. Pufahl[1]*, Eric E. Hiatt[2], and T. Kurtis Kyser[3]
[1]*Department of Earth and Environmental Science, Acadia University, Wolfville, Nova Scotia B4P 2R6, Canada*
[2]*Department of Geology, University of Wisconsin–Oshkosh, Oshkosh, Wisconsin 54901, USA*
[3]*Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario K7L 3N6, Canada*

Fralick et al. (2011) question our interpretation that the Paleoproterozoic Animikie Basin was a restricted marginal sea for at least part of its evolution and should not be used as a global ocean analog (Pufahl et al., 2010). This is in contrast with Poulton et al. (2004, 2010) and Johnston et al. (2006), who suggest unrestricted flow and chemistries reflective of the open ocean. Fralick et al. disagree that a landmass existed in the southern Animikie Basin as a barrier to mixing. The presence of such a barrier is central to the argument whether the Animikie Basin is an appropriate benchmark for understanding the sulfidic ocean transition. When geochemical data are viewed in the context of accepted published tectonic, sedimentologic, and paleoceanographic models, the interpreted "global" transition to euxinic deep oceans corresponds with the onset of restricted circulation associated with foreland basin development in a marginal sea (Pufahl et al., 2010), and may not represent a global change. Inconsistencies and problems with the "open ocean" model of Fralick et al. are summarized below.

1. Most problematic is that Fralick et al.'s (2011, and references therein) tectonic model has not been peer-reviewed. The sedimentologic and stratigraphic model they present is largely based on unpublished conference proceedings, field trip guidebooks, and theses (see Johnston et al., 2006). The scientific merit of such sources is impossible to evaluate. Our interpretation is rooted in the peer-reviewed literature (e.g., Hoffman, 1987; Hemming et al., 1995; Van Wyck and Johnson, 1997; Ojakangas et al., 2001; Schneider et al., 2002), and is supported by data from correlative sedimentary rocks in the southern Animikie Basin that indicate a southerly landmass (Morey, 1973; Ojakangas, 1994; Ojakangas et al., 2001; Nelson et al., 2010).

2. The ubiquity of north-flowing paleocurrents along the southern shore of the Animikie Basin during the foreland phase of basin development is unequivocal evidence of a southern source terrain (Morey, 1973; Ojakangas, 1994; Ojakangas et al., 2001; Nelson et al., 2010). These uplifted island arc–related rocks, Archean mini-plates, and older Paleoproterozoic sedimentary units were accreted to the continental margin during the Penokean orogeny (e.g., Ojakangas et al., 2001, and references therein). What is baffling is that Fralick et al. cite Morey (1973) as supporting their "open ocean" model. Morey (1973) not only presents evidence of transport from the north, but also from a landmass to the south. In addition, Morey (1973) and Morey and Ojakangas (1970) provide evidence of shore-parallel currents in deep-water environments, which likely represent axial flow within a trough-like basin rimmed by landmasses. Recent work supports Morey's (1973) paleocurrent data and demonstrates that foreland fill in the south was derived first from the south and then later from the north (Nelson et al., 2010). Although the upper portion of the succession is predominantly composed of sediment originating from the Trans-Hudson orogen, paleocurrent data also indicate continued derivation of sediment from accreted terranes to the south (Nelson et al., 2010).

3. To question the existence of a thick, basal succession of laterally extensive peritidal sedimentary rocks in the southern Animikie Basin based on a transect hundreds of kilometers away is dubious, especially given the abundant evidence for such deposits (Pufahl et al., 2007; Nelson et al., 2010). The regional trend that Fralick et al. cite as evidence for progressive deepening occurs in a section trending oblique to the paleoshoreline. Our study area is due south of their most nearshore section, and is marked by an ~120-m-thick unit of interbedded flaser, lenticular, and crossbedded sandstones resting unconformably on uplifted Archean gneisses (Ojakangas, 1994; Ojakangas et al., 2001; Nelson et al., 2010). These deposits are not a condensed facies as suggested by Fralick et al., but were deposited on expansive intertidal flats (Nelson et al., 2010).

4. The assertion that a barrier to mixing did not exist because Penokean-related uplift only occurred after deposition ended in the southern Animikie Basin is inconsistent with what is known about the timing of the Penokean orogeny. The age of sedimentary rocks in the south is well constrained at 1850 Ma by the Sudbury impact ejecta, a chronostratigraphic marker that blankets the Animikie Basin (Nelson et al., 2010). Deformation and magmatism during the Penokean orogeny is also well constrained between 1875 and 1835 Ma (e.g., Schneider et al., 2002), indicating that accreted terranes underwent periodic uplift prior to and contemporaneous with deposition.

We applaud Fralick et al. for recognizing the importance of multiple data sets to understand seawater stratification within the Animikie Basin. Although Poulton et al. (2010) attempt such an approach to investigate stratification in the Animikie Basin, they largely ignore the connection between stratigraphy and alteration. The most pronounced changes in $\delta^{34}S$ values occur at the transition from a backarc to foreland basin. When these trends are considered in context with published literature, as well as data presented herein and in Pufahl et al. (2010), an even stronger case exists for restricted circulation in the Animikie Basin. Data are also extremely variable (~50‰ $\delta^{34}S$ variation; Poulton et al., 2010), suggesting that postdepositional fluid movement along facies contacts altered and obscured the primary geochemical signature (e.g., Kyser and Hiatt, 2003). Basing "global" oceanographic models on such data, especially without careful consideration of their relationship to sedimentology, stratigraphy, and alteration is problematic. In addition to the evidence for restricted circulation and alteration by postdepositional fluids, the predominance of deltaic deposits in the upper portion of Animikie Basin stratigraphy (Nelson et al., 2010; Pufahl et al., 2010; Poulton et al., 2010) indicates that the water chemistry would have been strongly affected by river input, further suggesting that this marginal sea was an unreliable analog for global ocean conditions.

REFERENCES CITED

Fralick, P.W., Poulton, S.W., and Canfield, D.E., 2011, Does the Paleoproterozoic Animikie Basin record the sulfidic ocean transition?: Comment: Geology, doi:10.1130/G31747C.1.

Hemming, S.R., McLennan, S.M., and Hanson, G.N., 1995, Geochemical and Nd/Pb isotopic evidence for the provenance of the Early Proterozoic Virginia Formation, Minnesota. Implications for the tectonic setting of the Animikie Basin: The Journal of Geology, v. 103, p. 147–168.

Hoffman, P.F., 1987, Early Proterzoic foredeeps, foredeep magmatism and Superior-type iron-formations of the Canadian Shield, *in* Kroner, A., ed., Proterozoic lithospheric evolution: American Geophysical Union, v. 17, p. 85–98.

Johnston, D.T., Poulton, S.W., Fralick, P.W., Wing, B.A., Canfield, D.E., and Farquhar, J., 2006, Evolution of the oceanic sulfur cycle at the end of the Paleoproterozoic: Geochimica et Cosmochimica Acta, v. 70, p. 5723–5739, doi:10.1016/j.gca.2006.08.001.

Kyser, T.K., and Hiatt, E.E., 2003, Fluids in sedimentary basins: An introduction: Journal of Geochemical Exploration, v. 80, no. 2–3, p. 139–149, doi:10.1016/S0375-6742(03)00188-2.

Morey, G.B., 1973, Stratigraphic framework of Middle Proterozoic rocks in Minnesota, *in* Young, G.M., ed., Huronian Stratigraphy and Sedimentation: Geological Association of Canada Special Paper 12, p. 211–249.

Morey, G.B., and Ojakangas, R.W., 1970, Sedimentology of the middle Precambrian Thomson Formation, east-central Minnesota: Minnesota Geological Survey Report 13, 32 p.

Nelson, G.J., Pufahl, P.K., and Hiatt, E.E., 2010, Paleoceanographic constraints on Precambrian phosphorite accumulation, Baraga Group, Michigan, USA: Sedimentary Geology, v. 226, p. 9–21, doi:10.1016/j.sedgeo.2010.02.001.

Ojakangas, R.W., 1994, Sedimentology and provenance of the early Proterozoic Michigamme Formation and Goodrich Quartzite, northern Michigan—Regional stratigraphic implications and suggested correlations: United States Geological Survey Bulletin 1904-R, 31 p.

Ojakangas, R.W., Morey, G.B., and Southwick, D.L., 2001, Paleoproterozoic basin development and sedimentation in the Lake Superior region, North America: Sedimentary Geology, v. 141–142, p. 319–341, doi:10.1016/S0037-0738(01)00081-1.

Poulton, S.W., Fralick, P.W., and Canfield, D.E., 2004, The transition to a sulfidic ocean ~1.84 billion years ago: Nature, v. 431, p. 173–177, doi:10.1038/nature02912.

Poulton, S.W., Fralick, P.W., and Canfield, D.E., 2010, Spatial variability in oceanic redox structure 1.8 billion years ago: Nature Geoscience, v. 3, p. 486–490.

Pufahl, P.K., Hiatt, E.E., Stanley, C.R., Morrow, J.R., Nelson, G.J., and Edwards, C.T., 2007, Physical and chemical evidence of the 1850 Ma Sudbury impact event: Geology, v. 35, p. 827–830, doi:10.1130/G23751A.1.

Pufahl, P.K., Hiatt, E.E., and Kyser, T.K., 2010, Does the Paleoproterozoic Animikie Basin record the sulfidic ocean transition?: Geology, v. 38, p. 659–662, doi:10.1130/G30747.1.

Schneider, D.A., Bickford, M.E., Cannon, W.F., Schulz, K.J., and Hamilton, M.A., 2002, Age of volcanic rocks and syndepositional iron formations, Marquette Range Supergroup: Implications for the tectonic setting of Paleoproterozoic iron formations of the Lake Superior Region: Canadian Journal of Earth Sciences, v. 39, p. 999–1012, doi:10.1139/e02-016.

Van Wyck, N., and Johnson, C.M., 1997, Common lead, Sm-Nd, and U-Pb constraints on petrogenesis, crustal architecture, and tectonic setting of the Penokean orogeny (Paleoproterozoic) Wisconsin: Geological Society of America Bulletin, v. 109, p. 799–808, doi:10.1130/0016-7606(1997)109<0799:CLSNAU>2.3.CO;2.