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A rapid lake-shallowing event terminated preservation of the Miocene Clarkia Fossil *Konservat-Lagerstätte* (Idaho, USA)

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ABSTRACT

The world-renowned middle Miocene Clarkia lacustrine deposits (15.4–16.0 Ma) in northern Idaho, United States, known as Fossil *Lagerstätten*, yield extraordinary fossils that preserve *in situ* ancient biomolecules and organic biomarkers. The sudden formation of the Clarkia Lake basin by means of the Columbia River Basalt damming the proto–St. Maries River is well documented, but less is known about the tempo and mode of the lake environmental succession which impacted on the preservation of these Fossil *Lagerstätten*. Here, we present evidence for a previously unrecognized, geologically instantaneous drop in the Clarkia Lake water level, using tetraether-based water-depth proxies from a continuous sedimentary sequence at the classic P-33 site. Terrestrial hydrological conditions inferred from compound-specific hydrogen isotope compositions (δD) and tetraether-derived temperature estimates from the same sequence show that the rapid shallowing by >10 m was independent of regional climatic changes. We hypothesize that a volcanic-related geological event was primarily responsible for the rapid reduction of Clarkia Lake water depth—an event that played a decisive role in switching depositional conditions for Clarkia Fossil *Lagerstätten* from a conservation deposit to a concentration deposit.

INTRODUCTION

The Clarkia lacustrine deposits (15.4–16.0 Ma; Ladderud et al., 2015), formed during the Middle Miocene Climatic Optimum in northern Idaho, United States, are well known for the extraordinary preservation of a diverse terrestrial fossil biota (Fossil *Lagerstätten*) (Smiley et al., 1975; Smiley and Rember, 1985, and references therein). The excellent preservation of fossil leaves and insects from the lower unoxidized stratigraphic horizons of the type locality P-33 site is exhibited by original coloration, leaf ultrastructures, and a suite of ancient biomolecules such as flavonoids, lignin, polysaccharides, terpenoids, lipids, and possible DNA and amino acids (Yang and Huang, 2003, and references therein). The upper oxidized section preserves a lower-quality fossil assemblage, but abundant fossil impressions still retain detailed morphological characters (Smiley et al., 1975). Environmental controls for the preservation of lacustrine Fossil *Lagerstätten* are insufficiently understood, but the Clarkia P-33 sequence presents a unique opportunity to examine environmental changes for the two major categories of Fossil *Lagerstätte*, the conservation deposit (*Konservat-Lagerstätte*) and the concentration deposit (*Konzentrat-Lagerstätte*), under a single sedimentary setting.

The damming of the proto–St. Maries River by lava flows of the Columbia River Basalt created the long and narrow Miocene Clarkia Lake along the former river valley (Smiley and Rember, 1985). Subsurface lithological evidence shows that the transition from fluvial to lacustrine phases was abrupt (Yang et al., 1995). Paleobiological and sedimentological analyses (Smiley et al., 1975; Smiley and Rember, 1985) suggested that the P-33 section represents a gradual filling up of the lake, changing its physical and chemical conditions which impacted on fossil taphonomy. However, the timing, scale, and possible mechanism for this critical lake environmental shift remain poorly constrained.

Since the discovery of the Clarkia Fossil *Lagerstätten* in the 1970s, many cutting-edge technologies, such as the polymerase chain reaction, amino racemization, and compound-specific carbon and hydrogen isotope analyses (Yang and Huang, 2003, and references therein), have been initially applied to Clarkia materials to demonstrate the feasibility of these novel technologies. Recent advances in high-performance liquid chromatography–mass spectrometry technique have enabled the identification and quantification of glycerol dialkyl glycerol tetraethers (GDGTs), a range of microbial lipid biomarkers, in modern and ancient environments (Hopmans et al., 2004; Schouten et al., 2013). Here, we present the first sequential GDGT data set from the P-33 site. In combining this with compound-specific hydrogen isotope (δD) analysis of leaf-wax *n*-alkanes from the same sequence, we show a rapid shallowing of Clarkia Lake under a stable climatic condition. We believe that this event triggered a series of physical, chemical, and biological changes leading to the change of the lacustrine Fossil *Lagerstätten* from a conservation deposit to a concentration deposit.

MATERIALS AND METHODS

A total of 20 sedimentary samples were collected from unit 2d to unit 5c of Smiley and Rember (1985) at the P-33 site outcrop (Fig. 1; Table DR1 in the GSA Data Repository[1]), with the lower (L) sample series being from unit 2d and unit 3 below the volcanic ash layer unit 4 and the upper (U) series being from unit 5a to unit 5c above unit 4. The distributions of GDGTs were used to infer changes in lake water depth (Wang et al., 2014, 2016), water pH, and mean annual temperature (MAT) (Sun et al., 2011). We apply the method of Sun et al. (2011) for pH and MAT calculations because it was established based upon a global lacustrine data set. Regional hydrological changes were inferred using δD values of long-chain (n-C_{27}, n-C_{29}, and n-C_{31}) leaf-wax *n*-alkanes (Castañeda and Schouten, 2011) from 11 lacustrine sediments (see the Data Repository for details).

GDGTS AS PROXIES FOR LAKE WATER DEPTH

Recent investigations showed that the lacustrine Thaumarchaeota prefers living in stratified waters with a deep mixed layer (Pouliot et al., 2009; Buckles et al., 2013), where ammonium availability near the oxycline is high and competition with photoautotrophs is low (Tierney et al., 2010). Consequently, if the lake is deep enough, crenarchaeol (the diagnostic GDGT for Thaumarchaeota) production would be high, but if the lake is too shallow, low crenarchaeol production is expected. Thus, the relative amount of crenarchaeol normalized to total archaeal isoprenoid GDGTs (isoGDGTs) (%cren) can be used as a bimodal proxy for lake depth (Wang

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[1]GSA Data Repository item 2017062, extended method and supplemental figures and tables, is available online at www.geosociety.org/datarepository/2017 or on request from editing@geosociety.org.

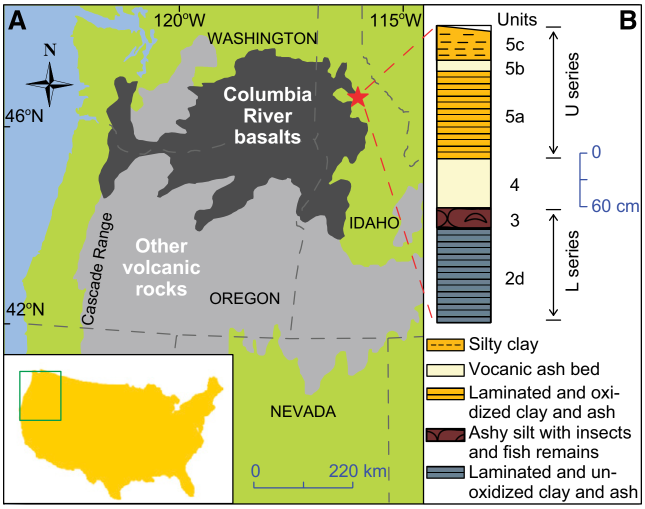

Figure 1. A: Map showing geographic location of Miocene Clarkia fossil site P-33 (star) in relation to Miocene Columbia River Basalts in northern Idaho, USA. B. Stratigraphy of P-33 section illustrates the two sample series (U—upper; L—lower) used in this study in relation to lithological units of Smiley and Rember (1985).

et al., 2014). The branched and isoprenoid tetraether (BIT) index, which represents the relative abundance of three major branched GDGTs (brGDGTs) to crenarchaeol, was initially defined as a proxy for tracing terrestrial organic matter, based on the premise that brGDGTs are produced by soil bacteria (Hopmans et al., 2004). However, recent studies have demonstrated that brGDGTs in lakes can be predominantly produced *in situ* (Sinninghe Damsté et al., 2012; Hu et al., 2015). We also detected the lake-specific hexamethylated brGDGT (Weber et al., 2015) in our samples (Table DR2), further attesting to the *in situ* production of brGDGTs in Clarkia Lake. On the other hand, variation in BIT values appears to be mainly controlled by the crenarchaeol concentration, which strongly depends on lake depth, rather than brGDGT concentration (Sinninghe Damsté et al., 2012; Wang et al., 2016), which is not sensitive to the variation in lake water depth (Tierney et al., 2010). Significant negative relationships between BIT values and lake water depth were found in both surface and downcore sediments in Lake Qinghai and in surface sediments across a full gradient of global modern lake environments (Wang et al., 2016), supporting the use of BIT index as an indicator for lake water depth.

The profiles of Clarkia *n*-alkanes show strong odd-even predominance throughout the P-33 section in units 2d, 3, and 5, with carbon preference index (CPI, a typical maturity index; Bray and Evans, 1961) varying from 4.1 to 5.5, suggesting minimal thermal alteration of organic biomarkers. GDGTs are relatively resistant to degradation because of their strong ether linkages (Hren et al., 2010), and their distributions tend to be less affected in immature sediments (Schouten et al., 2013). GDGTs are quite abundant in all of our samples (Table DR1), with the concentrations higher than those in surface sediments of modern lakes (Fig. DR1 in the Data Repository). Additionally, no significant difference in the concentration of brGDGTs or individual isoGDGTs (except for crenarchaeol) was observed between unit 2d, unit 3, and unit 5 (Fig. DR2). This is consistent with the high total organic carbon (TOC) content across the three units (4.6%, 3.4%, and 3.6% for samples L1, L10, and U1, respectively). Therefore, we believe that little post-depositional diagenesis of all GDGTs has occurred throughout our profile, and thus GDGT paleolimnological proxies are applicable for the Clarkia lacustrine deposits. Moreover, a previous study has demonstrated that the diagenetic alteration of primary δD signals of carbon-bound hydrogen in leaf wax *n*-alkanes is small in unit 2 sediments (Yang and Huang, 2003). Although this is the first time that molecular δD values are reported from sediments in units 3 and 5, given the stable structure of *n*-alkanes and carbon-bound hydrogen as well as reports of primary *n*-alkane δD values dated back to Paleozoic sediments (Dawson et al., 2004), we have the confidence to apply lipid δD values as a climate proxy for the immature Clarkia sedimentary profile.

RAPID SHALLOWING OF CLARKIA LAKE

The P-33 sequence was believed by previous researchers to represent a complete lake cycle with progressive filling up from a deep (unit 2) to a shallow (unit 5) environment based upon sedimentological and paleobiological inferences (Smiley and Rember, 1985). In our study, we obtained values of 39.4 ± 3.9 %cren in unit 2d and 3.7 ± 0.5 %cren in unit 5, while the BIT values are 0.68 ± 0.06 and 0.99 ± 0.00 in unit 2d and unit 5, respectively. These values indicate a deep lake during unit 2d and a shallow phase during unit 5 (Fig. 2), independently confirming

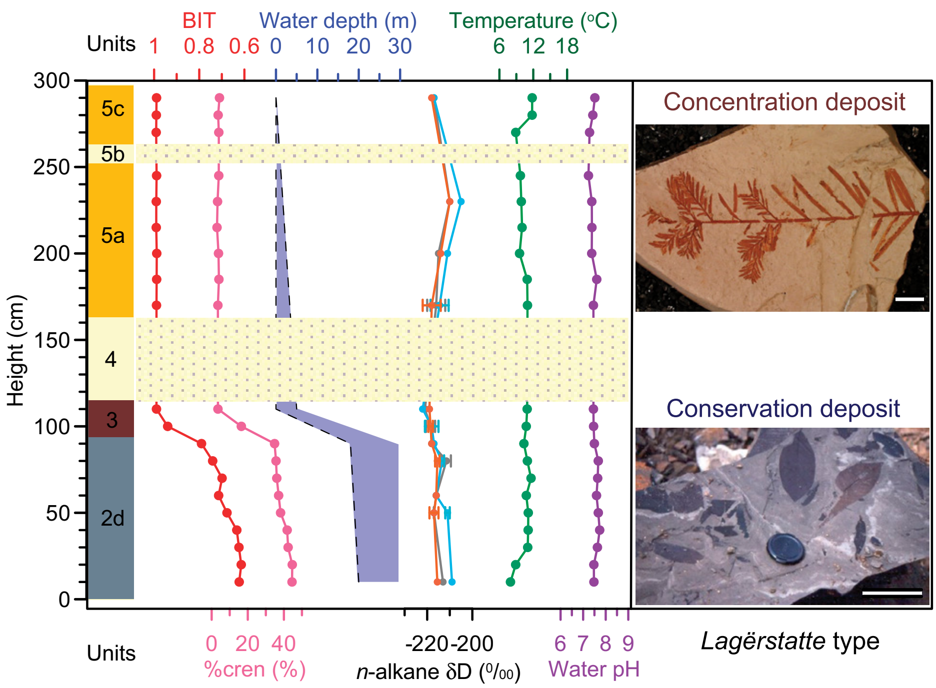

Figure 2. Stratigraphic units, lake-level proxies (branched and isoprenoid tetraether [BIT] index in red dots; relative amount of crenarchaeol [%cren] in pink dots), schematic lake level (blue area), hydrogen isotope composition (δD) of long-chain *n*-alkanes (*n*-C$_{27}$, *n*-C$_{29}$, and *n*-C$_{31}$ in gray, orange, and blue, respectively), and tetraether-inferred temperature and pH (in green and purple dots, respectively) at Clarkia P-33 section, northern Idaho, USA. Schematic lake depth curve is inferred from proxy data and sedimentology, with dashed lines indicating lower and upper limits. Two photographs on right illustrate lithology and quality of fossil preservation before (*Konservat-Lagerstätte*, conservation deposit) and after (*Konzentrat-Lagerstätte*, concentration deposit) sudden shallowing of Clarkia Lake water. Upper: *Taxodium* impressions (scale bar = 1 cm) from light-colored siltstone of unit 5 deposited in oxidized shallow lake water. Lower: *Magnolia* compressions (scale bar = 10 cm) preserved in dark-colored siltstone deposited in anoxic deep-lake phase of unit 2.

the two lacustrine phases inferred by Smiley and Rember (1981, 1985). However, rather than a gradual change as previously proposed, we detected a rapid shallowing event that served as the turning point for the lake water environment change. This event is indicated by a drop of 30 %cren and a BIT increase of 0.2 within the 30 cm transitional unit 3 (Fig. 2). According to the BIT–water depth relationship established from over 120 globally distributed modern lakes, a water depth of 18 m seems to be a threshold value for BIT values to be <0.8 (Wang et al., 2016) (Fig. DR3). The BIT values of unit 2d (<0.8) may thus indicate a lake depth of no less than 18 m at the P-33 site during the deep-water phase. This is in general agreement with Smith and Elder (1985) who inferred that the water was 8–12 m deep or more based upon fossil fish preservation. For the upper shallow-water phase, we estimate its depth to be 5 m or less based upon the following evidence. First, if the shallowing of the lake was mainly due to the infilling of the lake, given the ~2 m combined thickness of units 3, 4, and 5 and the 2:1 compaction ratio (Smiley and Rember, 1985), the lake should have remained <5 m deep for unit 5. Second, the fossil flora of unit 5 represents a *Taxodium*-dominated swamp association (Smiley and Rember, 1981), similar to modern bald cypress swamps of southeastern North America which can sustain in a water depth no more than ~3.66 m (12 ft) (Kurz and Demaree, 1934). Consequently, the lake water depth may have been reduced by over 10 m during this event. Based upon estimated average sedimentation rates of 1–15 cm/yr for the Clarkia section (Smiley and Rember, 1981, 1985), the drop in lake level at the P-33 site during the deposition of unit 3 occurred in 2–30 yr. It should be pointed out, however, that the sedimentation rate in unit 3 may have been even higher than the average of P-33 section, making the drop in lake level at unit 3 even more abrupt.

CAUSES OF THE RAPID SHALLOWING

Regional climatic factors are important in influencing lake-level fluctuations. However, our combined analysis of *n*-alkane δD values and GDGTs suggests that the rapid shallowing of Clarkia Lake was not accompanied by major hydrological/thermal shifts, thus unlikely to reflect a climatic event. In the transitional unit 3 where %cren and BIT values showed rapid changes, the δD values of individual long-chain *n*-alkanes exhibited little change from the uppermost unit 2d through unit 3 to unit 5 (Fig. 2). For example, δD values of n-C_{29} are −218‰ (L9), −219‰ (L10), −219‰ (L11), and −218‰ (U1), indicating a relatively stable hydrological condition during the abrupt lake-shallowing event. The brGDGT-inferred MAT varied within 0.6 °C across the rapid shallowing event (Fig. 2), suggesting no abnormal regional temperature fluctuation during the time of this shallowing event.

Alternatively, we propose that the sudden and irreversible release of lake water was likely due to a physical geologic event that altered the configuration of the lake basin drainage. During the time of Clarkia Lake deposition, the Columbia River Basalt eruptions dominated geologic activities in the region and the nearby Yellowstone hotspot and the Cascades arc remained active, as indicated by thick basalt flows in the vicinity and numerous volcanic ash layers imbedded in the Clarkia sediments (Smiley and Rember, 1985; Ladderud et al., 2015). Importantly, unit 3 was directly overlain by a volcanic ash bed (unit 4) as much as ~50 cm thick, implying strong regional volcanic activities during the period of the sudden lake shallowing. Modern observations and historical records have shown that volcanic eruptions are generally preceded by earthquakes and usually associated with surface deformations such as landslides, faulting, ground fissure, and regional tilting (Cioni et al., 2000; White and McCausland, 2016). We hypothesize that a sudden break in the original "basalt lava dam" downstream of the Miocene Clarkia Lake or a sudden damming and diversion of the main river drainages upstream would have caused the rapid fall of the Clarkia Lake water level.

IMPLICATIONS FOR CLARKIA FOSSIL *LAGERSTÄTTEN*

Sedimentary environments leading to the occurrence and preservation of plant Fossil *Lagerstätten* have been viewed differently from those of soft-bodied animals (Briggs, 2003). Factors such as temperature, pH, oxidation-reduction potential (Eh), rapid burial, and lake stratification have been proposed to control the formation of Clarkia Fossil *Lagerstätten*, but their relative importance is poorly understood (Smiley and Rember, 1985; Briggs et al., 2000, and references therein). Our new data suggest that, rather than water temperature or pH, the rapid change of lake water depth acted as the first order of environmental controls for the quality of Clarkia fossils. The most direct impact of the rapid shallowing is the disturbance of Clarkia lake stratification, which changed water Eh and associated microbial communities that are critical to balance decay and preservation of organic remains. During the deep-lake phase (unit 2), the stratified lake column maintained an anoxic hypolimnion that facilitated an active methane cycle by methanotrophic bacteria (Huang et al., 1995) and excluded metazoan grazers (Smiley and Rember, 1985), stabilizing plant tissues and biomolecules for long-term preservation. The abrupt shallowing of lake water by >10 m permanently destroyed lake water stratification, causing a mass mortality of fish, which is recorded in the transitional unit 3 (Smiley et al., 1975; Smith and Elder, 1985). The unstratified and oxygenated shallow water column of unit 5 sustained benthic organisms (Smiley and Rember, 1985; Taylor, 1985) and, more importantly, nurtured a different microbial community that facilitated organic decay. However, the stable climate conditions in the area maintained a dense vegetation which continued to supply abundant plant material to the shallow lake, as indicated by TOC values. Instead of transforming organic remains for long-term preservation, microbial mats under oxygenic conditions could have generated microenvironments around plant remains to provide templates for the formation of high-fidelity impressions, a *Konzentrat-Lagerstätte,* before the completion of tissue decay in unit 5. Thus, the geologically instantaneous drop of Clarkia Lake water level played a decisive role in terminating the sedimentary environments that favored the preservation of a high-quality *Konservat-Lagerstätte* and replacing it with a high-quantity *Konzentrat-Lagerstätte*. This interpretation reconciles previous paleontologic, sedimentologic, and geochemical evidence at the P-33 site and points toward the critical role of different microbial communities in mediating the formation of Fossil *Lagerstätten*, drawing parallels to the microbial involvement during the fossilization of soft-bodied animals as demonstrated by recent experimental decay analyses (Briggs and McMahon, 2016).

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REFERENCES CITED

Bray, E.E., and Evans, E.D., 1961, Distribution of *n*-paraffins as a clue to recognition of source beds: Geochimica et Cosmochimica Acta, v. 22, p. 2–15, doi:10.1016/0016-7037(61)90069-2.

Briggs, D.E.G., 2003, The role of decay and mineralization in the preservation of soft-bodied fossils: Annual Review of Earth and Planetary Sciences, v. 31, p. 275–301, doi:10.1146/annurev.earth.31.100901.144746.

Briggs, D.E.G., and McMahon, S., 2016, The role of experiments in investigating the taphonomy of exceptional preservation: Palaeontology, v. 59, p. 1–11, doi:10.1111/pala.12219.

Briggs, D.E.G., Evershed, R.P., and Lockheart, M.J., 2000, The biomolecular paleontology of continental fossils: Paleobiology, v. 26, p. 169–193, doi:

10.1666/0094-8373(2000)26[169:TBPOCF]2.0.CO;2.
Buckles, L.K., Villanueva, L., Weijers, J.W.H., Verschuren, D., and Sinninghe Damsté, J.S., 2013, Linking isoprenoidal GDGT membrane lipid distributions with gene abundances of ammonia-oxidizing Thaumarchaeota and uncultured crenarchaeotal groups in the water column of a tropical lake (Lake Challa, East Africa): Environmental Microbiology, v. 15, p. 2445–2462, doi:10.1111/1462-2920.12118.
Castañeda, I.S., and Schouten, S., 2011, A review of molecular organic proxies for examining modern and ancient lacustrine environments: Quaternary Science Reviews, v. 30, p. 2851–2891, doi:10.1016/j.quascirev.2011.07.009 (erratum available at http://dx.doi.org/10.1016/j.quascirev.2015.07.020).
Cioni, R., Gurioli, L., Sbrana, A., and Vougioukalakis, G., 2000, Precursors to the Plinian eruptions of Thera (Late Bronze Age) and Vesuvius (AD 79): Data from archaeological areas: Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy, v. 25, p. 719–724, doi:10.1016/S1464-1895(00)00111-3.
Dawson, D., Grice, K., Wang, S., Alexander, R., and Radke, J., 2004, Stable hydrogen isotopic composition of hydrocarbons in torbanites (Late Carboniferous to Late Permian) deposited under various climatic conditions: Organic Geochemistry, v. 35, p. 189–197, doi:10.1016/j.orggeochem.2003.09.004.
Hopmans, E.C., Weijers, J.W.H., Schefuss, E., Herfort, L., Sinninghe Damsté, J.S., and Schouten, S., 2004, A novel proxy for terrestrial organic matter in sediments based on branched and isoprenoid tetraether lipids: Earth and Planetary Science Letters, v. 224, p. 107–116, doi:10.1016/j.epsl.2004.05.012.
Hren, M.T., Pagani, M., Erwin, D.M., and Brandon, M., 2010, Biomarker reconstruction of the early Eocene paleotopography and paleoclimate of the northern Sierra Nevada: Geology, v. 38, p. 7–10, doi:10.1130/G30215.1.
Hu, J., Zhou, H., Peng, P., Yang, X., Spiro, B., Jia, G., Wei, G., and Ouyang, T., 2015, Reconstruction of a paleotemperature record from 0.3–3.7 ka for subtropical South China using lacustrine branched GDGTs from Huguangyan Maar: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 435, p. 167–176, doi:10.1016/j.palaeo.2015.06.014.
Huang, Y., Lockheart, M.J., Collister, J.W., and Eglinton, G., 1995, Molecular and isotopic biogeochemistry of the Miocene Clarkia Formation: Hydrocarbons and alcohols: Organic Geochemistry, v. 23, p. 785–801, doi:10.1016/0146-6380(95)80001-8.
Kurz, H., and Demaree, D., 1934, Cypress buttresses and knees in relation to water and air: Ecology, v. 15, p. 36–41, doi:10.2307/1931384.
Ladderud, J.A., Wolff, J.A., Rember, W.C., and Brueseke, M.E., 2015, Volcanic ash layers in the Miocene Lake Clarkia beds: Geochemistry, regional correlation, and age of the Clarkia flora: Northwest Science, v. 89, p. 309–323, doi:10.3955/046.089.0402.
Pouliot, J., Galand, P.E., Lovejoy, C., and Vincent, W.F., 2009, Vertical structure of archaeal communities and the distribution of ammonia monooxygenase A gene variants in two meromictic High Arctic lakes: Environmental Microbiology, v. 11, p. 687–699, doi:10.1111/j.1462-2920.2008.01846.x.
Schouten, S., Hopmans, E.C., and Sinninghe Damsté, J.S., 2013, The organic geochemistry of glycerol dialkyl glycerol tetraether lipids: A review: Organic Geochemistry, v. 54, p. 19–61, doi:10.1016/j.orggeochem.2012.09.006.
Sinninghe Damsté, J.S., Ossebaar, J., Schouten, S., and Verschuren, D., 2012, Distribution of tetraether lipids in the 25-ka sedimentary record of Lake Challa: Extracting reliable TEX_{86} and MBT/CBT palaeotemperatures from an equatorial African lake: Quaternary Science Reviews, v. 50, p. 43–54, doi:10.1016/j.quascirev.2012.07.001.
Smiley, C.J., and Rember, W.C., 1981, Paleoecology of the Miocene Clarkia Lake (northern Idaho) and its environs, *in* Gray, J., et al., eds., Communities of the Past: Stroudsburg, Pennsylvania, Hutchinson and Ross, p. 551–590.
Smiley, C.J., and Rember, W.C., 1985, Physical setting of the Miocene Clarkia fossil beds, northern Idaho, *in* Smiley, C.J., ed., Late Cenozoic History of the Pacific Northwest: San Francisco, Pacific Division of the American Association for the Advancement of Science, p. 11–31.
Smiley, C.J., Gray, J., and Huggins, L.M., 1975, Preservation of Miocene fossils in unoxidized lake deposits, Clarkia, Idaho: Journal of Paleontology, v. 49, p. 833–844.
Smith, G.R., and Elder, R.L., 1985, Environmental interpretation of burial and preservation of Clarkia fishes, *in* Smiley, C.J., ed., Late Cenozoic History of the Pacific Northwest: San Francisco, Pacific Division of the American Association for the Advancement of Science, p. 85–93.
Sun, Q., Chu, G., Liu, M., Xie, M., Li, S., Ling, Y., Wang, X., Shi, L., Jia, G., and Lü, H., 2011, Distributions and temperature dependence of branched glycerol dialkyl glycerol tetraethers in recent lacustrine sediments from China and Nepal: Journal of Geophysical Research, v. 116, G01008, doi:10.1029/2010JG001365 (errata available at http://dx.doi.org/10.1029/2011JG001753).
Taylor, D.W., 1985, Miocene freshwater mollusks from the Clarkia fossil site, Idaho, *in* Smiley, C.J., ed., Late Cenozoic History of the Pacific Northwest: San Francisco, Pacific Division of the American Association for the Advancement of Science, p. 73–74.
Tierney, J.E., Russell, J.M., Eggermont, H., Hopmans, E.C., Verschuren, D., and Sinninghe Damsté, J.S., 2010, Environmental controls on branched tetraether lipid distributions in tropical East African lake sediments: Geochimica et Cosmochimica Acta, v. 74, p. 4902–4918, doi:10.1016/j.gca.2010.06.002.
Wang, H., Dong, H., Zhang, C.L., Jiang, H., Zhao, M., Liu, Z., Lai, Z., and Liu, W., 2014, Water depth affecting thaumarchaeol production in Lake Qinghai, northeastern Qinghai-Tibetan plateau: Implications for paleo lake levels and paleoclimate: Chemical Geology, v. 368, p. 76–84, doi:10.1016/j.chemgeo.2014.01.009.
Wang, H., Dong, H., Zhang, C., Jiang, H., and Liu, W., 2016, A 12-kyr record of microbial branched and isoprenoid tetraether index in Lake Qinghai, northeastern Qinghai-Tibet Plateau: Implications for paleoclimate reconstruction: Science China: Earth Sciences, v. 59, p. 951–960, doi:10.1007/s11430-015-5213-4.
Weber, Y., De Jonge, C., Rijpstra, W.I.C., Hopmans, E.C., Stadnitskaia, A., Schubert, C.J., Lehmann, M.F., Sinninghe Damsté, J.S., and Niemann, H., 2015, Identification and carbon isotope composition of a novel branched GDGT isomer in lake sediments: Evidence for lacustrine branched GDGT production: Geochimica et Cosmochimica Acta, v. 154, p. 118–129, doi:10.1016/j.gca.2015.01.032.
White, R., and McCausland, W., 2016, Volcano-tectonic earthquakes: A new tool for estimating intrusive volumes and forecasting eruptions: Journal of Volcanology and Geothermal Research, v. 309, p. 139–155, doi:10.1016/j.jvolgeores.2015.10.020.
Yang, H., and Huang, Y., 2003, Preservation of lipid hydrogen isotope ratios in Miocene lacustrine sediments and fossils at Clarkia, northern Idaho, USA: Organic Geochemistry, v. 34, p. 413–423, doi:10.1016/S0146-6380(02)00212-7.
Yang, H., Smiley, C.J., Sprenke, K.F., Rember, W.C., and Knowles, C.R., 1995, Subsurface evidence for a rapid formation of the Clarkia Miocene lake in northern Idaho: Northwest Science, v. 69, p. 52–59.

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