Geochronology Discuss., author comment AC1
https://doi.org/10.5194/gchron-2021-19-AC1, 2021

Reply on RC1

Douglas P. Steen et al.

Author comment on "Paleomagnetic secular variation for a 21,000-year sediment sequence from Cascade Lake, north-central Brooks Range, Arctic Alaska" by Douglas P. Steen et al., Geochronology Discuss., https://doi.org/10.5194/gchron-2021-19-AC1, 2021

We thank the reviewer for their helpful and constructive comments. Our responses and proposed revisions are in **bold** font below excerpts of the reviewer's verbatim comments.

Summary

… the Cascade Lake paleomagnetic record has no reliable age model with the measured radiocarbon dates, possibly affected by old carbon.

While we do present evidence that the radiocarbon dates have been influenced by old carbon, we also present evidence for a reliable age model based on independent evidence using tephra ages (from Davies et al. companion paper) and constraints from other regional paleomagnetic secular variation (PSV) records.

However, the evidence is weak because the correlation [among PSV records] is flexible…

We will improve the objectivity and quantification of correlations between PSV records by using: (1) an established tie-point identification algorithm, such as QAnalySeries, to detect points of correlation between records, and (2) Pearson correlation coefficients to evaluate the strength of alternative tie-point correlations. This procedure has been used in similar studies, including recently (Li et al., 2021).

… and the possibility of downward-shifted recording of paleomagnetic field by authigenic iron-sulfide ferrimagnets is remained.

Although it is a remote possibility, there is no evidence for authigenic Fe-S (greigite) as a dominant magnetic mineral within this assemblage, and we doubt that it is present. Because authigenic greigite is a diagenetic product of sulphate reduction (Roberts et al., 2011; Roberts, 2015), it is most often found in strongly reducing marine deposits, or in lake sediments that transitioned from marine settings (e.g., Loch Lomond, Snowball and Thompson, 1990), or vice versa (e.g., Black Sea, Nowacyzk et al., 2012). When present in lake sediments, it is typically characterized by highly variable intensities often at centimeter scale (Stockhausen and Zolitschka, 1999; Frank, 2007), and by poor quality natural

remanent magnetization. Evidence for Greigite is often associated with a gyro remanent magnetization (Stephenson and Snowball, 2001; Snowball, 1997; Roberts et al., 2011) and extremely high SIRM/k or IRM/k ratios (Snowball et al., 1991; Nowaczyk et al., 2012, 2020). Instead, the consistency of the Holocene assemblage at Cascade Lake, including its AF demagnetization behavior and remanence records, is reminiscent of data from Scandinavian lakes where high-quality magnetization is associated with a magnetite-dominated magnetic assemblage, likely produced by microbes (e.g., Snowball et al., 2013; Haltia-Hovi et al., 2011). Although we cannot prove that the assemblage is a result of biogenic magnetite, the data are consistent with this interpretation, and more importantly, they afford a high-quality magnetization record by a fine-grained ferrimagnetic component, with no evidence for greigite.

… additional magnetic experiments, e.g. progressive thermal demagnetizations of NRMs, thermomagnetic analyses (Js-T), and/or FORC experiments, are necessary to estimate magnetic carriers/particle sizes.

We agree that extensive additional analyses would be needed to prove the magnetic mineralogy of the sediments, but such an undertaking would be beyond the scope of this paper. More importantly, our use of AF demagnetization is commonly used across many (hundreds?) of high-quality paleomagnetic studies of lake sediments, especially for Holocene sediments, which typically preserve well-defined NRM. Furthermore, the thermal demagnetization suggested by the reviewer can be problematic when working with wet lake sediments because: i) additional subsampling disturbs the soft sediment and can alter the paleomagnetic signal; ii) desiccation during heating can alter the directional record; iii) combusting organic-rich lake sediment in a restricted environment (magnetically shielded) can be hazardous; iv) thermal sample alteration can generate new magnetic minerals; and v) after heating, the sediment can no longer be used for paleointensity or environmental magnetic studies.

Individual comments

(1) P. 4, lines 125-126. The authors calibrated the 14C dates of this study using the IntCal 13 calibration curve (Reimer et al., 2013). Is the curve consistently used in the calibrations for other SV records in and around Alaska, and the global SV models (Figs. 9 and 11)? We have the IntCal20 calibration curve, now (Reimer et al., 2020).

The other PSV records to which we are correlating were calibrated using earlier versions of IntCal, so we are hesitant use a different version. More importantly, the differences are relatively small within the timeframe of the Cascade Lake record.

(2) P. 6 to 7, "4.2 S-ratios and kARM/klf" The authors interpret as the increasing up-core trends of the S-ratio and kARM/klf reflect the progressive addition of a separate fine-grained ferromagnetic component to the magnetic assemblage dominated by high-coercivity particles in the lower part. This interpretation would be correct. However, we should note that a similar up-core increasing trend lies in the organic material content (OM), while up-core decreasing trends are present in the magnetic susceptibility (klf) and IRM (Fig. 2). These trends must be discussed, together with the trends in the proxies of soft-component (S-ratio) and magnetic grain size (kARM/klf), which can be associated with the gradually increased anoxic environments that cause dissolution of fine magnetites, and formation of super-fine authigenic ferrimagnets, e.g., greigites.

Both susceptibility (k) and IRM decrease subtly up core, reflecting an increase in

an extremely fine-grained ferrimagnetic assemblage that is not present in the older part of the sequence. This component increases up core, as indicated by a decrease in k and IRM, relative to ARM that is biased toward fine magnetite (Banerjee et al., 1981). We interpret this fine-grained ferrimagnetic component as biogenic magnetite, which is consistent with the expected evolution of the lake and its catchment toward increasing productivity following the last ice age. Biogenic magnetite also explains the well- defined, high-quality magnetization record, and the coercivity of the magnetization. Alternatively, the fine-grained magnetite might be dust. Dust seems to be present in lake sediment in the region (Burial Lake, Dorfman et al., 2015); however, the dust is most abundant in the Pleistocene sediment. The up-core increase inferred biogenic magnetite is consistent with the corresponding increase in organic matter associated with warmer climates of the Holocene, as found at other high-latitude lakes (e.g., Snowball et al., 2013; Haltia-Hovi et al., 2011). As explained above, there is no evidence for the presence of greigite: poor quality magnetization, gyro remanent magnetization typically between 50 and 80 mT (Ron et al., 2007; Nowacyzk et al., 2020), high IRM/k, coercivity lower than hematite as indicated by the S-ratio.

(3) P.7, "4.3 Hysteresis, magnetic grain size and mineralogy" The sediments contain a high coercivity mineral of hematite (or goethite), in addition to a low coercivity ferrimagnet (magnetite?). Further, the possibility of containing iron-sulfide ferrimagnets is still remained. Thus, the authors need to reconsider the interpretation of the domain states with the Day diagram, which is originally for titanomagnetite (Fig. 3B). FORC diagram may be suitable for a mixture of magnetic minerals to estimate domain state (Roberts et al., 2017, JGR, 123, 2618–2644).

Production of FORC diagram would further document a complex magnetic mineral assemblage (again, however, there is no evidence for Fe-S greigite), but would do little to address the primary question much further than the evidence already provided. Additionally, a full accounting of the magnetic mineralogy is not the goal of this study and would entail an exceptional amount of work with equipment not readily available.

(4) P.8, "4.4 Characteristic remanent magnetization" The ChRM determined with a small MAD value is a strong point of this study. However, the orthogonal projections of demagnetization data seem to show that the magnetization vector does not decay toward the origin. Doesn't this result indicate the presence of a higher coercivity component except hematite/goethite? A PDRM component by detrital hematite/ goethite particles should have a component with a similar direction with that of detrital magnetite particles.

Small deviations in directions at high field strengths are commonly observed and generally considered to reflect increased noise relative to signal in that part of the demagnetization diagram, with many potential causes including general measurement noise. While it is possible that detrital hematite or goethite might contribute to the signal following the demagnetization of magnetite, and while we appreciate the suggestion, it is difficult to know where to take this because neither mineral is considered to carry a quality magnetic signal in Holocene lake sediments.

(5) P.10, "4.5 Normalized remanence (relative paleointensity)" The main magnetic carriers of Cascade Lake sediments comprise a high-coercivity mineral (probably hematite) and a low-coercivity mineral (possibly magnetite/greigite). I consider the NRM20-70mT/ARM20-70mT and NRM20-70mT/IRM20-70mT are better RPI proxies, because they are less affected by high-coercivity components. Unfortunately, no curves of normalizers ARM20-70mTand IRM20-70mT are shown in Fig. 7, so that we cannot

evaluate the correlation between the RPI and normalizers ("R" is not helpful). The kLF, ARM45mT, and IRM45mT in Fig. 7 include both mineral components, and in addition the contributions of high-coercivity particles increased in the ARM45mT and IRM45mT , compared with those before AFD.

We agree that NRM20-70mT/ARM20-70mT and NRM20-70mT/IRM20-70mT are better RPI proxies, but not "because they are less affected by high-coercivity components", but rather because k is not a remanence carrier and influenced by other things. However, the main point is that the similarity between all three normalizers lends confidence to the record of geomagnetic intensity. Plotting ARM, IRM as a stack or from a single demagnetization step makes little practical difference, but this can be changed and addressed.

(6) P. 13, "5.1 Magnetic assemblage". The authors indicate that the fine grained and low-coercivity ferromagnetic component is carried by (titano)magnetite. As mentioned in (2), greigite is also a candidate. Authigenic greigite particles are fine, with coercivity ranges similar to magnetite. Therefore, it is difficult to separate the components of magnetite and greigite by AF demagnetization. To reject the possibility of the presence of greigite, the authors should show evidence with thermal experiments, e.g. progressive thermal demagnetizations of NRMs, thermos-magnetic analysis (Js-T), and so on.

We would agree with this if there was evidence for greigite (gyro remanence, high SIRM/k, magnetic dissolution, detection hydrogen sulfides during coring or splitting, oxidative changes in magnetic properties or coloring, sulfidic lake, down core increase in greigite indicators, etc.). Again, a full accounting of the magnetic mineralogy is not the goal of this study and would entail an exceptional amount of work with equipment not readily available.

(7) P. 13, line 330. I do not agree the reason of the linear depth-age relation over the past 17 ka for the Burial Lake 14C age model's being more realistic than the Cascade Lake 14C age model.

We will omit the phrase, "… and because the sedimentation rate at Burial Lake is rather linear over the past ~ 17 kyr."

(8) P. 15, Figure 9. The correlation of inclination features between Cascade Lake and Burial Lake seems to be generally good (Fig. 9). But I do not agree with the correlation with the global SV models. Many tie-points between I3 and I8 are flexible. For example, the oldest part of the pfm9k.1b Inc-GAD may not reach the inclination feature I7 of the Burial Lake inc-GAD, and the I6-I8 of the pfm9k.1b may correlate in phase to around I4 of the Burial Lake. The correlations in Fig. 9 are not robust, and thus the authors must be careful with using the tie-point ages for age models and others.

We will improve the objectivity and quantification of correlations between PSV records by using: (1) an established tie-point identification algorithm, such as QAnalySeries, to detect points of correlation between records, and (2) Pearson correlation coefficients to evaluate the strength of alternative tie-point correlations. This procedure has been used in similar studies, including recently (Li et al., 2021).

(9) P. 16, "5.3 Age model discrepancy". For the age model discrepancy, the authors discussed two possible causes; the old carbon of aquatic organic materials and the lock-in depth of PDRM. If the authors do not show evidence for the absence of authigenic greigite, readers would concern the effect of it. Large downward shifts of paleomanetic signals in the record carried by greigites are likely (e.g., Robert et al. (2005) GRL).

See our responses above regarding the lack of evidence for greigite.

The authors mention that four tephra ages published in the companion paper by Davies et al. provide strong evidence for the discrepancy. If they clearly show the discrepancy without help of PSV data, the authors can construct a new age model with selected measured 14C dates and the tephra ages for the Cascade Lake SV curve. In this case, they should not mention the old carbon effect in the conclusion. In place, they would have a merit of making a type SV curve in Alaska by stacking the Cascade Lake and Burial Lake SV data, both of which have independent age models.

We understand this alternative approach and appreciate the suggestion. However, the primary goal of the study is generating a reliable age model for Cascade Lake, and not improving the regional PSV curve.

(10) P. 17, lines 414-415. The authors mention that high-amplitude inclination shifts at this time are contemporaneous with low relative paleointensity estimates (Fig. 11). However, the relative paleointensity curve plotted in Fig. 11 is after 15.3 ka, which does not show paleointensity values around 17 ka. Readers may want to see the global VADM values plotted until about 20 ka.

We will attempt to extend the field intensity curve in Figure 11, as suggested.

(11) P. 17, lines 434-435. "Magnetic grain-size estimation (Fig. 3 and 4) suggests fine PSD magnetites". As mentioned in (3), we cannot estimate grain sizes (domain states) with a Day plot of magnetic mineral assemblages of low-coercivity ferrimagnets and hematites, which are suggested by the relatively small S-ratio values ranging from 0.5 to 0.88 throughout the sequence.

We agree, at least as a strict grain-size indicator. However, hysteresis data provide information on the magnetic assemblage and our Day plots suggest that fine-grained ferrimagnetic minerals are a substantial component.

References cited in authors' replies

Banerjee, S.K., King, J. Marvin, J., 1981. A rapid method for magnetic granulometry with applications to environmental studies. Geophysical Research Letters, 8, 333-336.

Dorfman, J.M., J.S. Stoner, M.S. Finkenbinder, M.B. Abbott, C. Xuan, & G. St-Onge 2015: A 37,000-year Environmental Magnetic Record of Aeolian Dust Deposition from Burial Lake, Arctic Alaska. Quaternary Science Reviews, 128, 81-97.

Frank, U. 2007, Palaeomagnetic investigations on lake sediments from NE China: a new record of geomagnetic secular variations for the last 37 ka. Geophys. J. Int. (2007) 169, 29–40

Haltia-Hovi, E., Nowaczyk N., Saarinena T., 2011. Environmental influence on relative palaeointensity estimates from Holocene varved lake sediments in Finland. Physics of the Earth and Planetary Interiors 185, 20–28

Li, C.G., Zheng, Y., Wang, M., Sun, Z., Jin, C., and Hou, J., 2021. Refined dating using palaeomagnetic secular variations on a lake sediment core from Guozha Co, northwestern Tibetan Plateau. *Quaternary Geochronology*, *62*, 101146.

Nowaczyk, N.R., Arz, H.W., Frank, U., Kind, J.& Plessen, B., 2012. Dynamics of the Laschamp geomagnetic excursion from Black Sea sediments, Earth Planet.

Sci. Lett., 351–352, 54–69.

Nowaczyk N.R., Liu, J. Arz, H.W., 2020 Records of the Laschamps geomagnetic polarity excursion from Black Sea sediments: magnetite versus greigite, discrete sample versus U-channel data. Geophys. J. Int. (2021) 224, 1079–1095

Roberts, A.P., 2015. Magnetic mineral diagenesis. Earth-Science Reviews, 151 1–47.

Roberts, A.P., Chang, L., Rowan, C.J., Horng, C.S., Florindo, F., 2011. Magnetic properties of sedimentary greigite (Fe3S4): an update. Rev. Geophys. 49, RG1002.

Ron, H., Nowaczyk, N.R., Frank, U., Schwab, M.J., Naumann, R., Striewski, B. & Agnon, A., 2007. Greigite detected as dominating remanence carrier in Late Pleistocene sediments, Lisan formation, from Lake Kinneret (Sea of Galilee), Israel, Geophys. J. Int., 170, 117–131.

Snowball, I.F., 1997. Gyroremanent magnetization and the magnetic properties of greigite-bearing clays in southern Sweden, Geophys. J. Int., 129, 624–636.

Snowball, I.F., Thompson, R., 1990. A mineral magnetic study of Holocene sediment yields and deposition patterns in the Llyn Geirionydd catchment, north Wales. The Holocene 2, 238–248.

Snowball, I.F., 1991. Magnetic hysteresis properties of greigite (Fe3S4) and a new occurrence in Holocene sediments from Swedish Lappland. Phys. Earth Planet. Inter. 68, 32–40

Snowball, I., Mellström, A., Ahlstrand, E., Haltia, E., Nilsson, A., Ning, W., Muscheler, R., Brauer, A., 2013. An estimate of post-depositional remanent magnetization lock-in depth in organic rich varved lake sediments. Glob. Planet. Change 110, 264–277.

Stephson and Snowball, A large gyromagnetic effect in griegite. (2001) Geophys. J. Int. 145, 570–575.

Stockhausen, H., Zolitschka, B., 1999. Environmental changes since 13,000 cal. BP reflected in magnetic and sedimentological properties of sediments from Lake Holzmaar (Germany). Quat. Sci. Rev. 18, 913–925.