Ali, G.A.H., Lin, K., Hemming, S.R., Cox, S.E., Ruprecht, P., Zimmerman, S.R.H., Stine, S., and Wang, X., 2021, Emergence of wet conditions in the Mono Basin of the Western USA coincident with inception of the Last Glaciation: GSA Bulletin, https://doi.org/10.1130/B36084.1.

Supplemental Material

Text. Assessment of Ash 19 age data

Figure S1. Measured section at the Tufa site of Lower Wilson Creek (38.02986°N, 119.12459°W; ~1,987 m). We measured the section about ~1 m to the east (left in the photo in Fig. 6) of Tufas 1 and 2. Normal typeface represents observations. Italicized typeface shows interpretations. Since we observed that the fluvial gravel is overlain by lacustrine silt, we interpret the section to show a lake transgressive sequence. We reason that the lag deposit we find between the lacustrine silt and fluvial gravel highlights a flooding surface of Mono Lake. The elevation of the flooding surface in this exposure is ~1,987 m.

Figure S2. Our measured section of IV D of Brideport Creek (38.08968°N, 119.04885°W; ~2,006 m). Normal typeface represents observations. Italicized typeface shows interpretations. The section shows fluvial sand and gravel overlain by lacustrine sand, which is then overlain by lacustrine silt. The silt is intercalated with Ash 19. This sequence was interpreted by Lajoie (1968) to represent a lake transgressive sequence, and we agree with this interpretation. We infer the contact between the lacustrine silt and the fluvial gravel is a flooding surface that correlates with the other flooding surfaces we observed at the Tufa site of lower Wilson Creek (see Fig. S1) and the Between site of Bridgeport Creek (see Fig. S3). At IV D, the flooding surface is at an elevation of ~2,006 m. Bedding-parallel carbonate beds cross-cut the lacustrine silt (and an obscure layer of very fine sand) that overlies Ash 19. These carbonate beds may correspond to the “platy lithoid tufa” shown in the measured section of IV D in the dissertation of Lajoie (1968).

Figure S3. Measured section at the Between site of Bridgeport Creek (38.09056°N, 119.04985°W; ~2,010 m). Regular typeface represents observations. Italicized typeface shows interpretations. The section shows a fining-upward sequence of fluvial gravels that are overlain by a sedimentary unit that largely consists of lacustrine silts. We reason this fining-upward sequence constitutes a lake transgressive sequence, and we therefore suggest the contact between the fluvial gravel and lacustrine silt is a flooding surface that marks the rise of Mono Lake. Ash 19 is found within the silt, and the base of Ash 19 is two cm above the flooding surface, making the depositional age of the tephra a credible approximation of the rise of Mono Lake to an elevation of ~2,010 m. Note: The ~2,010 m flooding surface at this section correlates with the ~2,006 m flooding surface at IV D of Bridgeport Creek and the ~1,987 m flooding surface observed at the Tufa site of lower Wilson Creek.

ASSESSMENT OF ASH 19 AGE DATA

Age Models Supported by Radiometric and Paleomagnetic Data

Seven different studies attempted to date the depositional age of Ash 19 using direct radiometric measurements or indirect age-model estimates (Lajoie, 1968; Benson et al., 1990; Benson et al., 1998; Kent et al., 2002; Zimmerman et al., 2006; Cassata et al., 2010; Vazquez and Lidzbarski, 2012; Fig. 5). The methods used for these estimates included lacustrine carbonate ^{14}C, sanidine $^{40}Ar/^{39}Ar$, and allanite-zircon U-Th, with the absolute ages derived from some of these data used to uphold paleomagnetic correlations to marine records and stacks. Since the uncertainties that limit these disparate methods and data have not been discussed together before, we describe the full set of work in this section with sufficient detail to make clear the authority held by each age determination.

Efforts to estimate the age of Ash 19 began with the ca. 27 ka date reported in Lajoie (1968). Lajoie estimated this date using an age model of the Wilson Creek Formation, which was based on a linear regression of two beta-counted ^{14}C measurements on ostracodes that were sampled from the upper and middle thirds of the type section. The reliability of this approach and the accuracy of the age model supporting the ca. 27 ka date rested on two premises. One is an assumption of constant rates of sediment deposition at the type section. The second is an assumption of the intrinsic validity of the ostracode ^{14}C dates. Lajoie acknowledged that evidence for a 1.8 ^{14}C k.y. radiocarbon reservoir in contemporary Mono Lake waters (after Broecker and Walton, 1959) posed a challenge to the second assumption, but without a means to quantify the reservoir effect, Lajoie accepted that evaluating the reliability of the second assumption was impossible. This left the accuracy of the Wilson Creek Formation age model and the ca. 27 ka Ash 19 date open to question.

The first challenge to the ca. 27 ka date of Lajoie (1968) was the estimate derived from the ^{14}C-based age model reported in Benson et al. (1990). This interpretation was underpinned by the same methods and assumptions employed in Lajoie (1968), albeit with many more lacustrine carbonate ^{14}C measurements spaced across the entire formation. It suggested that the depositional age of Ash 19 was between 40 and 41 ka. However, the validity of the ^{14}C data underpinning this interpretation was questioned by Benson et al. (1990). First, the authors raised concerns about the potential for significant and variable radiocarbon reservoir of lake waters, for their analyses of modern to historical lacustrine carbonates implied a reservoir of 1.1–5.3 ^{14}C k.y. Further complicating the matter was their observation of an unusual dispersion of ^{14}C ages that increased with depth through the section. They suspected that the age dispersion showed sample contamination with young carbon.

Benson et al. (1998) attempted to strengthen the age model of Benson et al. (1990) by reinterpreting its supporting data set. The reinterpretation began with an exclusion of ^{14}C ages from deposits that were deemed to be too young (on the suspicion of modern carbon contamination), reworked (based on the stratigraphic context), or, in one case, too old (based on the interpretation that a 39.6 ± 1.0 ^{14}C kyr B.P. date was infinite). With these data excluded, the newly derived interpretation suggested the depositional age of Ash 19 was ca. 41 ka; however, the accuracy of this new age was unknown because the uncertainty concerning young or old carbon contamination in the remaining samples could not be eliminated. To circumvent this hurdle, the authors employed an indirect approach, gauging how well their ^{14}C-dated time series of Wilson Creek Formation paleomagnetic variations corresponded with those measured in marine sedimentary records. The comparison revealed that the Wilson Creek Formation paleomagnetic time series lagged those shown in the marine sedimentary records for the stratigraphic interval spanning the oldest five ash beds (Ashes 15–19). Benson et al. (1998) interpreted this evidence to show that their model was likely too young for the Ash 15–19 interval. By their estimation, a correction for this bias suggested that Ash 19 was >43 ka (see explanation in caption of Table 1 of Benson et al., 1998). The cause of the age bias, they hypothesized, was most likely contamination by a young carbon source that was equivalent to 0.3% modern carbon.

The hypothesis for modern carbon contamination in Benson et al. (1998) agreed with the results of two- and three-step dissolution experiments on Wilson Creek Formation ostracodes and tufa nodules presented in Kent et al. (2002). The sequential dissolution of these Wilson Creek Formation carbonates revealed progressively older radiocarbon ages, which were measured via accelerator mass spectrometry. Kent et al. (2002) suggested that the sequence of increasing age in each sample was consistent with the stepwise removal of a young carbon contaminant, but the full removal of this young contaminant, they reasoned, was not achieved because they found no age plateau in their three-step dissolution experiment. They therefore argued that the apparent ^{14}C age measured in the final dissolution step was likely younger than the true ^{14}C age of the sample. Accordingly, Kent et al. (2002) asserted that the most prudent interpretation of the data is that the ^{14}C ages of the final dissolution steps are minimum age constraints. The authors of the study, then, used these minimum age ^{14}C constraints—along with a reservoir correction of 1.0 $^{+2.5}/_{-0.8}$ ^{14}C kyr that was adjusted to the calendar calibration available at that time—to derive a model with the youngest age interpretation of the Wilson Creek Formation. They termed this interpretation Model 1. It asserted that Ash 19 must be ≥48 ka, with an uncertainty no greater than 2.5 ^{14}C k.y. (the maximum age disparity observed on paired wood-tufa ^{14}C ages reported in Broecker et al., 1988).

Two other model interpretations of Ash 19 were shown in Kent et al. (2002): Model 2 and Model 3. Model 2 included a regression of the minimum sanidine $^{40}Ar/^{39}Ar$ age populations they measured on Ash 16, 51.4 ± 1.0 ka, and two $^{40}Ar/^{39}Ar$ data published in Chen et al. (1996): 23.1 ± 1.2 ka on Ash 5; and 35.4 ± 2.8 ka on Ash 12. With the interpretation that the youngest population of $^{40}Ar/^{39}Ar$ dates constrain the maximum age of deposition of a tephra bed, interpolation of the three $^{40}Ar/^{39}Ar$ age constraints suggested the deposition of Ash 19 was no older than ~55 ka, assuming a constant rate of sediment deposition. Model 3 was underpinned by an interpolation of $^{40}Ar/^{39}Ar$ and ^{14}C data that included an assumption that the rates of sediment deposition varied. In this interpretation, the $^{40}Ar/^{39}Ar$ and ^{14}C data are maximum and minimum age constraints, respectively. Model 3 suggested that Ash 19 was deposited at 55.4 ka. This estimate is more than 5 k.y. older than the estimates derived from or based entirely on lacustrine carbonates ^{14}C ages, giving further support to the argument of Kent et al. (2002): that ^{14}C ages of Wilson Creek Formation lacustrine carbonates are best interpreted as minimum constraints owing to modern carbon contamination.

Zimmerman et al. (2006) suggested that Ash 19 was deposited 66.0 ± 3.6 ka. This age determination of the authors was based on a correlation of their geomagnetic paleointensity time series from the Wilson Creek Formation to GLOPIS (Global Paleointensity Stack), a near-global stack of paleointensity time series that was tied to the Greenland Ice Sheet Project 2 age model (Laj et al., 2000, 2004). They began the correlation by using closely agreeing lacustrine carbonate ^{14}C and sanidine $^{40}Ar/^{39}Ar$ ages to constrain the time spanning Ashes 7 and 12. The sedimentation rate implied by this portion of the record was then extrapolated to calculate the ages of the strata below Ash 12. The resulting age model produced a correlation to GLOPIS that showed an r^2 value of 0.639 and an age of c. 65 ka for the base of the section (Ash 19). The addition of tie points derived from geologic inferences and inflections in the Wilson Creek Formation paleointensity time series improved the correlation with GLOPIS (r^2 of 0.815) and suggested that Ash 19 was deposited 66.0 ± 3.6 ka. This age determination suggested that the age of Ash 19 was beyond the range of the radiocarbon method, and it implied that the bulk ^{14}C ages measured at or near the level of Ash 19, such as those used in the age model of Benson et al. (1990), likely reflected post-depositional carbon addition (see e.g., Figure S3 of Zimmerman et al. 2006). Zimmerman et al. (2006) suggested the disparity between their age model and the unleached ^{14}C ages used by Benson et al. (1990, 1998) could be reconciled if the ^{14}C ages were contaminated with 1.5% modern carbon. The suggestion was consistent with the amount of modern carbon contamination of Wilson Creek Formation carbonates revealed from the dissolution experiments reported in Kent et al. (2002) and Hajdas et al. (2004). This agreement strengthened the Ash 19 age determination of 66.0 ± 3.6 ka reported by Zimmerman et al. (2006).

Cassata et al. (2010) presented two alternative correlations of the Zimmerman et al. (2006) Wilson Creek Formation paleointensity time series to GLOPIS. These alternative correlations were termed Model A and Model B. Model A agreed with prior $^{40}Ar/^{39}Ar$ and ^{14}C age constraint, and though Model A suggested younger ages for the middle third of the Wilson Creek Formation compared to the Zimmerman et al. (2006) interpretation, both interpretations yielded similar ages for the bottom and upper third of the sequence. While the model of Zimmerman et al. (2006) arrived at a ~66 ka date for the deposition of Ash 19, Model A arrived at a 70 ka date. Model B, on the other hand, suggested a much younger age of 40 ka. This model was described by the authors to be largely based on the paleomagnetic interpretation of Benson et al., (1998).

Cassata et al. (2010) compared the strength of their two interpretations (Models A and B) to the Zimmerman et al. (2006) model by first quantifying which correlated more strongly to GLOPIS. This comparison revealed that the Zimmerman et al. (2006) age model represented the highest coefficient of correlation to GLOPIS (r^2 = 0.815). A close second was Model A (r^2 = 0.715). Model B showed the lowest strength of correlation to GLOPIS (r^2 = 0.482). However, they argued that the correlation method they used for these quantifications was biased, affording more value to low-frequency paleomagnetic variations than those marked by abrupt changes, which they stressed were also necessary to accurately correlate paleomagnetic time series. To resolve this bias, they offered visual matching as a qualitative aid in the correlation of the more abrupt changes in the paleointensity data (following the recommendation of Paillard et al., 1996). When both high- and low-frequency variability data were used to assess the best match to GLOPIS, they found a different result: that Model A was a better match to GLOPIS than the solution put forward in Zimmerman et al. (2006). This finding advanced the 70 ka date of Model A as the most suitable age for the deposition of Ash 19.

Direct Radiometric Ages on Volcanic Phases from Ash 19

There are only two analytical efforts to directly date mineral phases of Ash 19. The first comprised $^{40}Ar/^{39}Ar$ analyses reported by Cassata et al. (2010), which included 12 fusion analyses of single, HF-leached, sanidine crystals. The weighted mean of 10 of these analyses suggested a date of 90.0 ± 2.0 ka, but the large age dispersion (26 k.y.) of the 10 analyses and disagreement with ^{14}C data caused the authors to deem the date was inaccurate. Instead, they interpreted the 90 ka estimate to reflect a maximum depositional age for Ash 19.

The second direct radiometric date on Ash 19 is shown in Vazquez and Lidzbarski (2012). The authors collected Ash 19 from the South Shore section of Lajoie (1968), which shows abundant soft-sediment deformation in the part of the section that includes Ash 19. Their study used the U-Th method to date the crystallization ages of allanite and zircon crystals in the sampled ash. An isochron approach yielded a date of 61.7 ± 1.9 ka, but since this date is supported by crystallization age data, the ~62 ka date may be equal to or older than the eruption or depositional age of the sampled ash.

REFERENCES CITED

Benson, L.V., Currey, D.R., Dorn, R.I., Lajoie, K.R., Oviatt, C.G., Robinson, S.W., Smith, G.I., and Stine, S., 1990, Chronology of expansion and contraction of four great Basin lake systems during the past 35,000 years: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 78, p. 241–286, https://doi.org/10.1016/0031-0182(90)90217-U.

Benson, L.V., Lund, S.P., Burdett, J.W., Kashgarian, M., Rose, T.P., Smoot, J.P., and Schwartz, M., 1998, Correlation of late-Pleistocene lake-level oscillations in Mono Lake, California, with North Atlantic climate events: Quaternary Research, v. 49, p. 1–10, https://doi.org/10.1006/qres.1997.1940.

Broecker, W.S., and Walton, A., 1959, The geochemistry of C_{14} in fresh-water systems: Geochimica et Cosmochimica Acta, v. 16, p. 15–38, https://doi.org/10.1016/0016-7037(59)90044-4.

Broecker, W.S., Wanninkhof, R., Mathieu, G., Peng, T.H., Stine, S., Robinson, S., Herczeg, A., and Stuiver, M., 1988, The radiocarbon budget for Mono Lake: An unsolved mystery: Earth and Planetary Science Letters, v. 88, p. 16–26, https://doi.org/10.1016/0012-821X(88)90042-8.

Cassata, W.S., Singer, B.S., Liddicoat, J.C., and Coe, R.S., 2010, Reconciling discrepant chronologies for the geomagnetic excursion in the Mono Basin, California: Insights from new $^{40}Ar/^{39}Ar$ dating experiments and a revised relative paleointensity correlation: Quaternary Geochronology, v. 5, p. 533–543, https://doi.org/10.1016/j.quageo.2010.02.001.

Chen, Y., Smith, P.E., Evensen, N.M., York, D., and Lajoie, K.R., 1996, The edge of time: Dating young volcanic ash layers with the ^{40}Ar- ^{39}Ar laser probe: Science, v. 274, p. 1176–1178, https://doi.org/10.1126/science.274.5290.1176.

Hajdas, I., Bonani, G., Zimmerman, S.H., Mendelson, M., and Hemming, S., 2004, ^{14}C ages of ostracodes from Pleistocene lake sediments of the western Great Basin, USA—Results of progressive acid leaching: Radiocarbon, v. 46, p. 189–200, https://doi.org/10.1017/S0033822200039515.

Kent, D.V., Hemming, S.R., and Turrin, B.D., 2002, Laschamp excursion at Mono Lake?: Earth and Planetary Science Letters, v. 197, p. 151–164, https://doi.org/10.1016/S0012-821X(02)00474-0.

Laj, C., Kissel, C., Mazaud, A., Channell, J.E.T., and Beer, J., 2000, North Atlantic palaeointensity stack since 75 ka (NAPIS-75) and the duration of the Laschamp event: Philosophical Transactions - Royal Society. Mathematical, Physical, and Engineering Sciences, v. 358, p. 1009–1025, https://doi.org/10.1098/rsta.2000.0571.

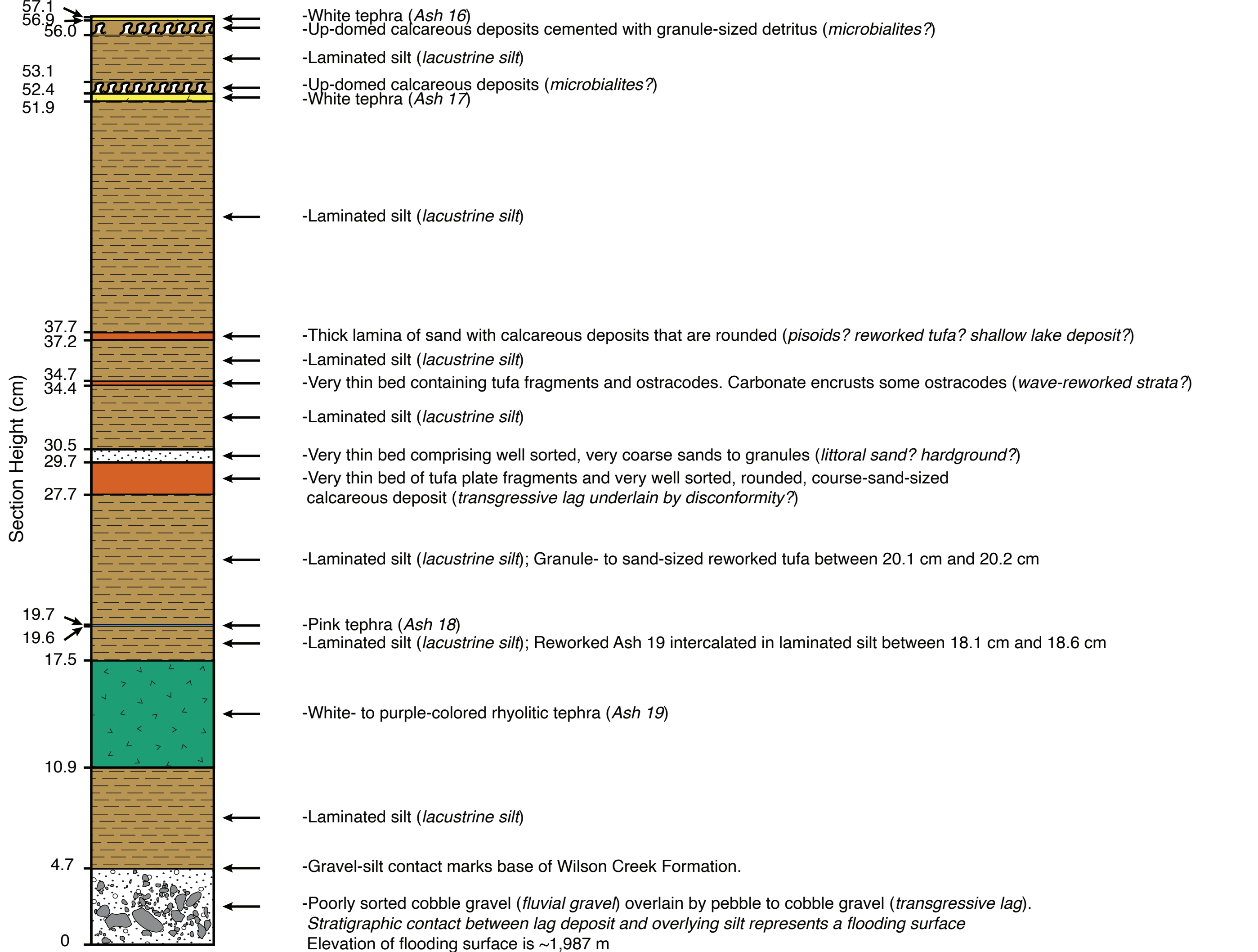
Laj, C., Kissel, C., and Beer, J., 2004, High Resolution Global Paleointensity Stack since 75 kyr (GLOPIS-75) Calibrated to Absolute Values: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 145, p. 255–265,, https://doi.org/10.1029/145GM19.

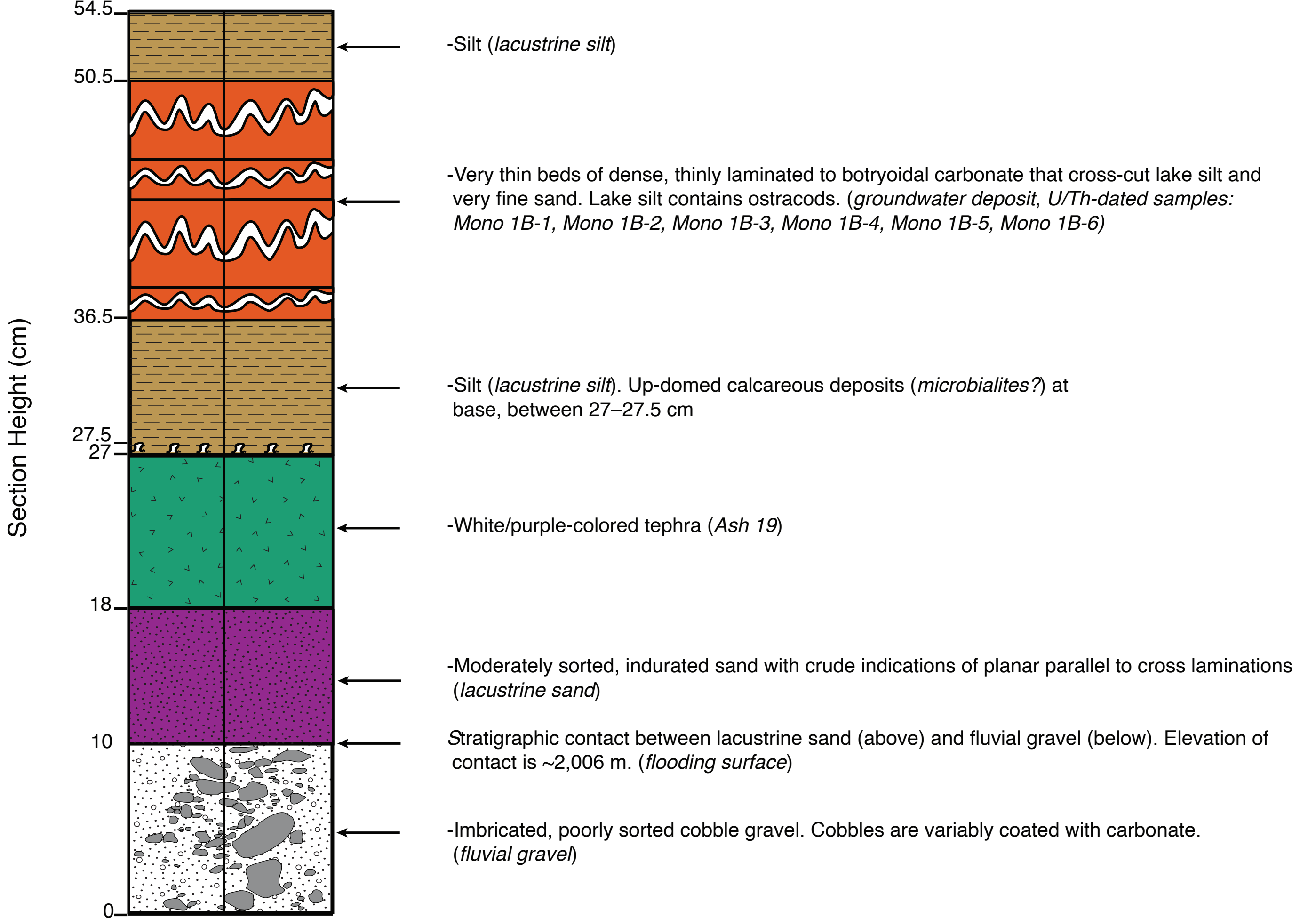
Lajoie, K.R., 1968, Late Quaternary stratigraphic and geologic history of Mono Basin, eastern California [Ph.D. thesis]: Berkeley, California, USA, University of California, 271 p.

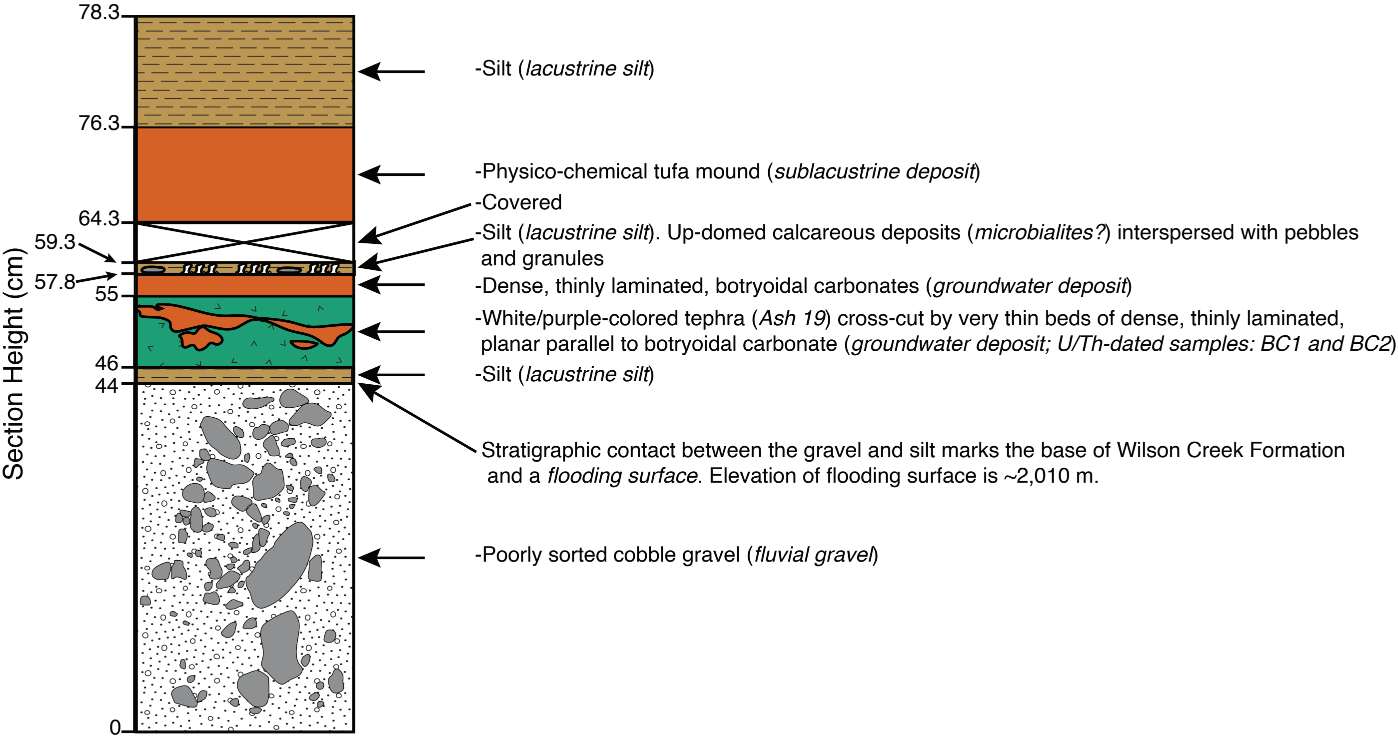
Paillard, D., Labeyrie, L., and Yiou, P., 1996, Macintosh Program performs time-series analysis: Eos (Transactions, American Geophysical Union), v. 77, p. 379–379, https://doi.org/10.1029/96EO00259.

Vazquez, J.A., and Lidzbarski, M.I., 2012, High-resolution tephrochronology of the Wilson Creek Formation (Mono Lake, California) and Laschamp event using ^{238}U–^{230}Th SIMS dating of accessory mineral rims: Earth and Planetary Science Letters, v. 357–358, p. 54–67, https://doi.org/10.1016/j.epsl.2012.09.013.

Zimmerman, S.H., Hemming, S.R., Kent, D.V., and Searle, S.Y., 2006, Revised chronology for late Pleistocene Mono Lake sediments based on paleointensity correlation to the global reference curve: Earth and Planetary Science Letters, v. 252, p. 94–106, https://doi.org/10.1016/j.epsl.2006.09.030.


Section Height (cm)
57.1
56.9
56.0
53.1
52.4
51.9
37.7
37.2
34.7
34.4
30.5
29.7
27.7
19.7
19.6
17.5
10.9
4.7
0
-White tephra (*Ash 16*)
-Up-domed calcareous deposits cemented with granule-sized detritus (*microbialites?*)
-Laminated silt (*lacustrine silt*)
-Up-domed calcareous deposits (*microbialites?*)
-White tephra (*Ash 17*)
-Laminated silt (*lacustrine silt*)
-Thick lamina of sand with calcareous deposits that are rounded (*pisoids? reworked tufa? shallow lake deposit?*)
-Laminated silt (*lacustrine silt*)
-Very thin bed containing tufa fragments and ostracodes. Carbonate encrusts some ostracodes (*wave-reworked strata?*)
-Laminated silt (*lacustrine silt*)
-Very thin bed comprising well sorted, very coarse sands to granules (*littoral sand? hardground?*)
-Very thin bed of tufa plate fragments and very well sorted, rounded, course-sand-sized calcareous deposit (*transgressive lag underlain by disconformity?*)
-Laminated silt (*lacustrine silt*); Granule- to sand-sized reworked tufa between 20.1 cm and 20.2 cm
-Pink tephra (*Ash 18*)
-Laminated silt (*lacustrine silt*); Reworked Ash 19 intercalated in laminated silt between 18.1 cm and 18.6 cm
-White- to purple-colored rhyolitic tephra (*Ash 19*)
-Laminated silt (*lacustrine silt*)
-Gravel-silt contact marks base of Wilson Creek Formation.
-Poorly sorted cobble gravel (*fluvial gravel*) overlain by pebble to cobble gravel (*transgressive lag*).
Stratigraphic contact between lag deposit and overlying silt represents a flooding surface
Elevation of flooding surface is ~1,987 m


Section Height (cm)
54.5
50.5
36.5
27.5
27
18
10
0
-Silt (*lacustrine silt*)
-Very thin beds of dense, thinly laminated to botryoidal carbonate that cross-cut lake silt and very fine sand. Lake silt contains ostracods. (*groundwater deposit*, *U/Th-dated samples: Mono 1B-1, Mono 1B-2, Mono 1B-3, Mono 1B-4, Mono 1B-5, Mono 1B-6)*
-Silt (*lacustrine silt*). Up-domed calcareous deposits (*microbialites?*) at base, between 27–27.5 cm
-White/purple-colored tephra (*Ash 19*)
-Moderately sorted, indurated sand with crude indications of planar parallel to cross laminations (*lacustrine sand*)
Stratigraphic contact between lacustrine sand (above) and fluvial gravel (below). Elevation of contact is ~2,006 m. (*flooding surface*)
-Imbricated, poorly sorted cobble gravel. Cobbles are variably coated with carbonate. (*fluvial gravel*)


Section Height (cm)
78.3
76.3
64.3
59.3
57.8
55
46
44
0
-Silt (*lacustrine silt*)
-Physico-chemical tufa mound (*sublacustrine deposit*)
-Covered
-Silt (*lacustrine silt*). Up-domed calcareous deposits (*microbialites?*) interspersed with pebbles and granules
-Dense, thinly laminated, botryoidal carbonates (*groundwater deposit*)
-White/purple-colored tephra (*Ash 19*) cross-cut by very thin beds of dense, thinly laminated, planar parallel to botryoidal carbonate (*groundwater deposit; U/Th-dated samples: BC1 and BC2*)
-Silt (*lacustrine silt*)
Stratigraphic contact between the gravel and silt marks the base of Wilson Creek Formation and a *flooding surface*. Elevation of flooding surface is ~2,010 m.
-Poorly sorted cobble gravel (*fluvial gravel*)