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Supplemental Material

Spreadsheet. Sample locations and full detrital zircon U-Pb isotopic ratios and age results

Text. Detailed detrital zircon U-Pb results description

Figure S1. Ariel Photographs of Missouri River downstream from the Ft. Peck Dam

Figure S2. River Steepness Index (Ksn) values for Upper Missouri River

Figure S3. Multidimensional scaling (MDS) of detrital zircon U-Pb data

RESULTS

Detailed Results Description

Missouri River Detrital Zircon U-Pb results

U-Pb analysis for the uppermost Missouri River sample (18MR-01) yielded individual ages from 143 grains, the detrital zircon U-Pb age distribution is dominated by Archean (32.9%, >2500 Ma) grains, with subordinate proportions of Late Cretaceous Cordilleran (14%, 60–100 Ma), Grenville (11.2%, 975–1200 Ma), and Wopmay-Trans-Hudson (11.2%, 1.8–2.5 Ga) grains, all other grain ages constituting less than 10% of the total U-Pb age distribution (Fig. 6). Downstream, sample 18MR-02 yielded 177 U-Pb ages, with a detrital zircon U-Pb age distribution dominated by Late Cretaceous Cordilleran (37.2%) grains, Archean (20.9%), Yavapai-Mazatzal (15%, 1.5–1.8 Ga), and Wopmay-Trans-Hudson (10.7%) grains, all other U-Pb age components are less than 10% of the age distribution (Fig. 6). Sample 18MR-03 yielded 140 ages, with 27.9% Late Cretaceous Cordilleran, 25.6% Archean, 15.7% Yavapai-Mazatzal, and all other age components being <10% respectively (Fig. 6). Sample 18MR-04 yielded 148 ages, with 28.4% Late Cretaceous Cordilleran, 16.9% Yavapai-Mazatzal, 16.2% Archean, 11.5% Wopmay-Tans-Hudson grains, and all other components being <10% respectively (Fig. 6). Sample 18MR-05 yielded 128 grains with 32.8% Late Cretaceous Cordilleran, 28.1% Archean, 12.5% Yavapai-Mazatzal, and all other age components making up <10% of the age distribution respectively (Fig. 6). Sample 18MR-07 yielded 146 grains with 19.9% Wopmay-Trans-Hudson, 18.5% Yavapai-Mazatzal, 15.1% Late Cretaceous Cordilleran, 15.1% Archean, 11.5% Grenville grains, and all other age components making up <10% respectively (Fig. 6). Sample 18MR-08 yielded 137 grains with 32.8% Late Cretaceous Cordilleran, 14.6% Yavapai-Mazatzal grains and all other grain ages making up less than 10% of the age distributions respectively (Fig. 6). Sample 18MR-10 yielded 141 grains with 36.9% Late Cretaceous Cordilleran, 18.5% Yavapai-Mazatzal grains, and all other age components having less than 10% each (Fig. 6). Two samples (18MR-11A, 18MR-11B) from the 18MR-11 sample locality are grouped into a single composite sample for that locality yielding 358 ages with 34.1% Late Cretaceous Cordilleran grains, 23.5% Yavapai-Mazatzal, and 11.2% Wopmay-Trans-Hudson grains, with all other age components

being <10% each (Fig. 6). Two samples (18MR-12A, 18MR-12B) from the 18MR-12 sample locality are grouped into a single composite sample yielding 332 ages with 26.8% Late Cretaceous Cordilleran, 23.2% Yavapai-Mazatzal, and 10.2% Wopmay-Tans-Hudson grains, with all other age component being <10% each (Fig. 6).

Missouri River Tributaries Detrital Zircon U-Pb results

The Jefferson River sample (18JR-02) yielded 131 ages, with 32.1% Late Cretaceous Cordilleran, 22.9% Yavapai-Mazatzal, and 13.7% Wopmay-Tans-Hudson, and 15.3% Archean grains, all other age components being <10% each (Fig. 6). The Madison River (18MaR-02) yielded 135 ages with 43.7% Archean, 15.6% Late Cretaceous Cordilleran, 11.9% Yavapai-Mazatzal grains, and all other age components being less than 10% each (Fig. 6). The Gallatin River (18GR-02) yielded 136 grains with 37.5% Archean, 15.4% Late Cretaceous Cordilleran grains, and all other age components being less than 10% each of the age distribution (Fig. 6). The Smith River (18SmR-01) yielded 95 grains with 16.8% Grenville, 15.8% Wopmay-Trans-Hudson, 13.7% Yavapai-Mazatzal, 13.7% Mesoproterozoic granitoids, and all other U-Pb age components being <10% each of the age distribution (Fig. 6). The Sun River (18SuR-01) yielded 88 grains with 28.4% Late Cretaceous Cordilleran, 25% Yavapai-Mazatzal, and all other U-Pb age component making up less than 10% of the sample distribution each (Fig. 6). The Teton River (18TR-01) yielded 112 ages with 26.8% Late Cretaceous Cordilleran, 25.9% Yavapai-Mazatzal, 17% Wopmay-Trans-Hudson, 10.7% Archean grains with all other U-Pb age component being <10% each (Fig. 6). The Marias River (18MsR-01) yielded 119 ages with 43.7% Late Cretaceous Cordilleran, 16.8% Yavapai-Mazatzal, 10.9% Wopmay-Trans-Hudson grains, and all other age component <10% each (Fig. 6). The Judith River (18JuR-01) yielded 154 grains with 18.2% Early Cretaceous Cordilleran, 14.9% Late Cretaceous Cordilleran, 11.7% Grenville, 11% Yavapai-Mazatzal, 10.4% Appalachian, 10.4% Wopmay-Trans-Hudson grains, and all other age components being <10% of the total age distribution each (Fig. 6). The Musselshell River (18MuR-01) yielded 137 ages with 31.4% Late Cretaceous Cordilleran, 17.5% Yavapai-Mazatzal, 10.9% Mesoproterozoic Granitoid grains, and all other age components being <10% of the age distribution each (Fig. 6). The Milk River (18Mir-01) yielded 79 ages with 39.2% Late Cretaceous Cordilleran, 22.8% Yavapai-Mazatzal, 11.4% Triassic-Jurassic Cordilleran, 10.1% Wopmay-Trans-Hudson grains, and all other U-Pb age components making up less than 10% of the total age distribution each (Fig. 6)

Yellowstone River Detrital Zircon U-Pb Results

Detrital zircon U-Pb analysis for the uppermost Yellowstone River sample (18YR-01), yielded 174 grains, the detrital zircon U-Pb age distributions is dominated by Archean basement (28.2%, >2500 Ma), with secondary proportions of the Yellowstone Volcanic fields (19%, <15 MA), Early Cenozoic volcanic rocks (13.2%, 15–60 Ma), and Late Cretaceous Cordilleran (10.9%, 60–100 Ma) grains, all other age components make up less than 10% for the total age distribution (Fig. 7). Sample 18YR-02 yielded 139 ages with 30.9% Late Cretaceous Cordilleran, 18% Yavapai-Mazatzal, 15.1% Archean grains, and all other age components making up less than 10% of the age distribution each (Fig. 7). Sample 18YR-03 yielded 150 ages with 26.7% Late Cretaceous Cordilleran, 18% Yavapai-Mazatzal, 14.7% Archean, and 10.7% Grenville grains, with all other age components being <10% of the sample distribution each (Fig. 7). Sample 18YR-04 yielded 134 ages with 27.6% Late Cretaceous Cordilleran, 23.1% Yavapai-Mazatzal, 13.4% Archean Grains, with all other age components being <10% of the age

distribution each (Fig. 7). Sample 18YR-05 yielded 147 ages with 25.2% Late Cretaceous Cordilleran, 19.7% Yavapai-Mazatzal, 10.9% Mesoproterozoic Granitoids, 10.2% Wopmay-Trans-Hudson grains, with all other age components being <10% of the sample distribution each (Fig. 7). Sample 18YR-06 yielded 141 ages with 27% Late Cretaceous Cordilleran, 21.3% Yavapai-Mazatzal grains, with all other age components being <10% of the sample distribution each (Fig. 7). Sample 18YR-07 yielded 149 ages with 25.5% Yavapai-Mazatzal, 16.8% Late Cretaceous Cordilleran, 13.4% Early Cretaceous Cordilleran, 13.4% Wopmay-Trans-Hudson grains, with all other age components being <10% of the sample distribution each (Fig. 7). Two samples (18YR-09A, 18YR-09) collected from the sample location were grouped into a composite sample 18YR-09 which yielded 348 grains with 22.4% Late Cretaceous Cordilleran, 19% Yavapai-Mazatzal, 10.1% Mesoproterozoic Granitoid, and 10.1% Wopmay-Trans-Hudson grains, with all other age components being <10% of the sample distribution each (Fig. 7).

Yellowstone River Tributaries Detrital Zircon U-Pb Results

Detrital zircon U-Pb analysis for the Clarks Fork on the Yellowstone River sample (18CfR-01), yielded 136 ages, with 26.5% Yavapai-Mazatzal, 22.1% Late Cretaceous Cordilleran, 11% Mesoproterozoic Granitoid, and 10.3% Grenville grains, and all other age components making up less than 10% of the age distribution each (Fig. 7). The Bighorn River (18BhR-01) yielded 142 ages with 31.7% Late Cretaceous Cordilleran, 17.6% Yavapai-Mazatzal, 10.6% Grenville, 10.6% Mesoproterozoic granitoid grains, with all other age components being <10% of the sample distribution each (Fig. 7). The Tongue River (18ToR-01) yielded 83 ages with 30.1% Late Cretaceous Cordilleran, 21.7% Yavapai-Mazatzal grains, and all other age components being <10% of the sample distribution each (Fig. 7). The Powder River (18PR-01) yielded 145 ages with 31% Yavapai-Mazatzal, 16.6% Late Cretaceous Cordilleran, with all other age components being <10% of the sample distribution each (Fig. 7).

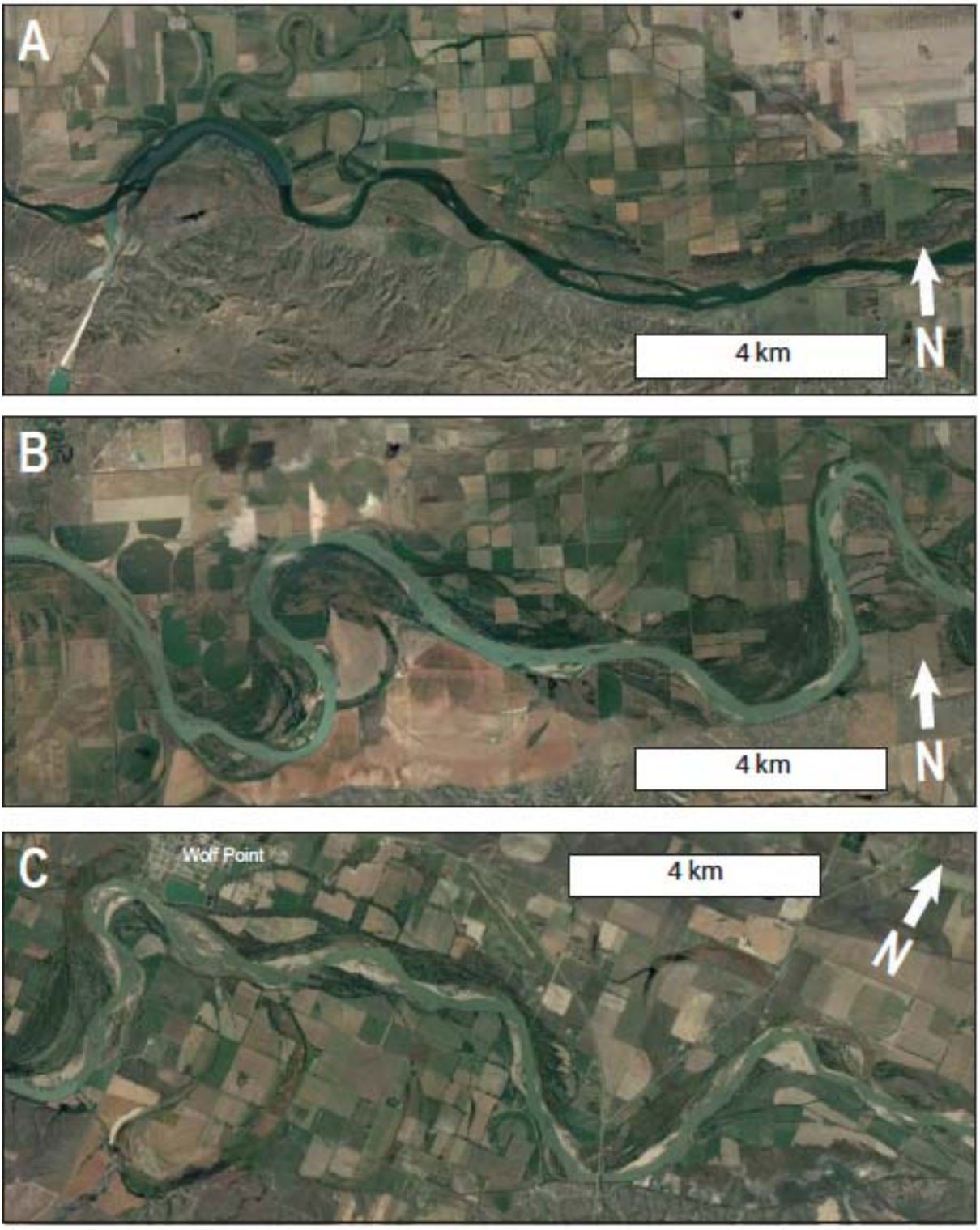

Figure S1. Google Earth satellite images of the Missouri River beneath Ft. Peck. Flow is toward the right in all photos. (A) Immediately downstream of Ft. Peck Dam with the emergency spillway and confluence of the Missouri and Milk rivers present. The channel margins of Missouri River lack loose sediment or sandy bar forms due to the removal of fine grained

sediments. (B) ~20 km downstream from the Ft. Peck Dam, sandy bars are beginning to appear on the margins of the channel and on point bars. (C) ~60 km downstream of Ft. Peck Dam near the town of Wolf Point, sandy barforms bank all sides of the Missouri River.

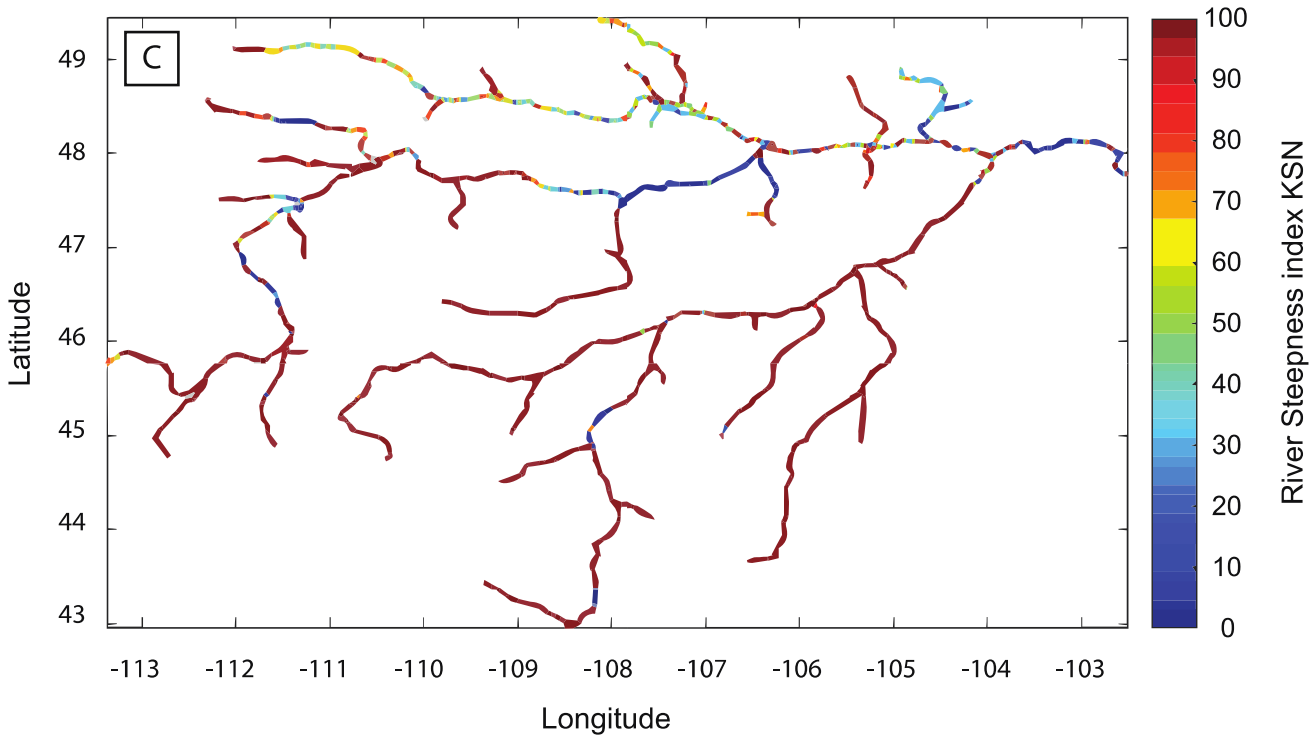

Figure S2. River steepness index (Ksn) along the rivers of the Upper Missouri Catchment. Plot constructed with TopoToolbox for Matlab from 30-arc second (~1km) GMTED2010 DEM (Danielson and Gesch, 2011; Schwanghart and Scherler, 2014). Normalized river steepness (Ksn) index is based upon the stream power model and is calculated with

$$K_{sn} = \frac{S}{A^{-\theta}}$$

Where S is slope, A is upslope area, and θ is channel concavity (Schwanghart and Scherler, 2014).

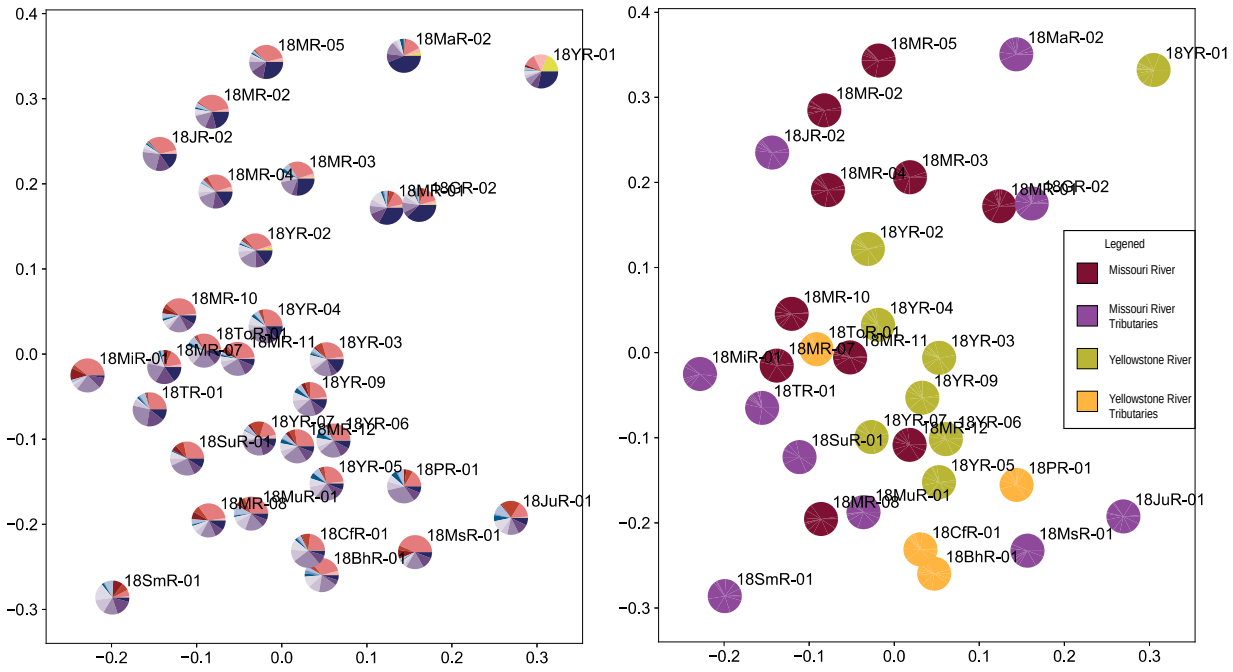

Figure S3. Multidimensional Scaling (MDS) plot based upon the V-value comparison statistic. (A) shows samples as pie diagrams in terms of the relative proportions of U-Pb age components. (B)shows the samples in groups organized by sample locations. Detrital zircon MDS shows the clustering of samples by the collection location of samples; both the tributary samples of the Upper Missouri River and the Yellowstone River cluster around the edges of the MDS point cloud with the Missouri River and Yellowstone River samples progressively moving toward the center of the MDS cluster as the further downstream samples reflect a more mixed age distribution.

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