Heavy–mineral analysis and provenance of Yellow River sediments around the China Loess Plateau

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Abstract:

In its upper–middle reaches the Yellow River has high sand contents after traversing through large areas of desert and the China Loess Plateau. Understanding riverbed sediment composition in the channel is critical for the interpretation of the potential provenance, aeolian sand transport and the linkage between the Loess Plateau and the Yellow River. To address these issues, we collected 52 samples from the modern riverbed, proximal deserts, and major tributaries and used analyses of grain size, grain morphology, and heavy–mineral compositions, to establish the spatial distribution and characteristics of source regions and riverbed sediments. The heavy–mineral assemblages demonstrate significant variations for the different sections of the Yellow River. The riverbed samples from the upper reach are dominated by opaque minerals (limonite and magnetite), amphibole and epidote, with minor zircon, tourmaline and rutile. Riverbed sediments from the middle reach are garnet–rich, reflecting the widespread distribution of Mesozoic sandstones. This variability closely reflects the source regions. Our data show that seasonal tributaries (the “Ten Great Gullies”) carrying detritus from the Ordos Plateau may account for the localized high garnet concentrations in the Inner Mongolia section of the upper reach. Scanning electron microscope (SEM) imaging of quartz grains show that the river sediments are characterized by composite microtextures acquired in both fluvial and eolian environments of the Hedong, Ulan Buh and Kubuq Deserts. The mineralogical composition in the upper reach (Lanzhou–Yinchuan) is similar to that of sediments in the Loess Plateau and Northeast Tibet Plateau (Western Lanzhou). However, the composition differs markedly from that in the Inner Mongolia section of the upper and middle reaches. This variation indicates that in the upper reach the Northeast Tibet Plateau contributes significant volumes of sediment to the Yellow River and Loess Plateau, but compositions change across the Inner Mongolia section of the upper and middle reaches owing to local sediment supply from arid desert areas and seasonal tributaries.

Keywords: Heavy minerals; Quartz grain morphology; Provenance; Yellow River (Huang He);

1. Introduction

Fluvial sediments are derived from a variety of parent rocks, and their composition is affected by several environmental processes, including chemical weathering, selective physical break-down, and hydrodynamic sorting during transport and deposition. Tracing studies using river sediments can provide a fingerprint of an area's geological setting and geomorphologic evolution (Milliman and Syvitski, 1992; Heroy et al., 2003; Roddaz et al., 2005; Piper et al., 2006; Yang et al., 2009; Garzanti et al., 2007a, 2010a, 2015).

The Yellow River (Huang He), originating from the Tibetan Plateau, has an annual sediment load of about one billion tons ($\sim 1.1 \times 10^9$; Milliman, 1983), which is the highest of all rivers on Earth. A very large volume of sediment is deposited in the channel, resulting in the “hanging river” phenomenon of the Inner Mongolia and lower reaches (Yao et al., 2011; Wang et al., 2012). As Earth's largest accumulation of dust, the China Loess Plateau is bordered by the big bend of the Yellow River (Figure 1). Because of its high erodibility the Loess Plateau is currently a major source to riverbed sediments (Milliman, 1987). In addition, a huge volume of sediments eroded from the northeast Tibetan Plateau was carried by the Yellow River, but this was not directly delivered to the lower reach. Instead, this sediment has been stored in the Loess Plateau and the western Mu Us desert since at least the Middle Pleistocene (Nie et al., 2015). The dust deposition rate of the Loess Plateau is potentially influenced by the uplift and erosion of the northern Tibetan Plateau and the dynamics of the Yellow River system (Stevens et al., 2013). Although the total contribution of the Yellow River to the loess accumulation has not thus far been conclusively assessed (Stevens et al., 2013), fluvial transportation is required in the sequence of events leading to the formation of a loess deposit (Smalley et al., 1972, 2009). Rivers are efficient transporting agents, and may feed vast accumulations of aeolian sediment, as documented by the formation of sand seas (Yang et al., 2011b; Rittner et al., 2016).

Both past and present dispersal patterns and source areas for Yellow River sediments are controversial. Different lines of evidence suggest that diverse sandy deserts adjacent to the banks of the upper Yellow River may act as sources of coarse sediment to the river because of dune transport by wind (Xu, 2003; Ta et al., 2003; 2008; Yu et al., 2014). Sediment cores demonstrate that the contributions of sand amounted to 6.06×10^8 t for the Ulan Buh Desert and to 5.85×10^8 t for the Kubuq Desert between 1954 and 2000 (Yang et al., 2004). Other studies have highlighted the additional contributions from seasonal tributaries in the upper reach (e.g., Zuli, Qingshui Rivers) that carry large volumes of sediments from the Loess Plateau to the modern channel (Zhao et al., 1999). In addition to the complexity of transport mechanisms, no consensus exists as to the major sediment sources for the middle reach. Some studies argue that the loess transported by Yellow River tributaries (e.g., Wuding, Huangpu Rivers) represent a very significant source of sediment to the middle reach (Milliman et al., 1987), accounting for ~73% of the sediment flux in the whole drainage basin (Xu et al., 2010). Feng et al. (1992) argued that in the headwaters of the tributaries aeolian sand from the Mu Us and Kubuq Deserts is funnelled into the channel by wind during the dry season, and subsequently supplied to the Yellow River during the flood season.

Previous studies used grain size, geochemical and mineralogical data to assess potential sand provenance in the upper reach (Yang, 2004; Yao et al., 2011; Jia et al., 2011; Wang et al., 2012; Ta et al., 2013; Pan et al., 2015), and middle reaches (Xu, 2003). However, the upper–middle reaches of the Yellow River have received conclusive studies of spatial changes of the source and distribution characteristics for the river sediments.

Heavy–mineral analysis is one of the most widely used techniques for provenance determination (Morton and Hallsworth, 1999; Svendsen and Hartley, 2002; Garzanti et al., 2008; Nie et al., 2012). Although most river sediments derived from orogenic sources yield similar amphibole–epidote–garnet assemblages (Garzanti and Andò 2007a), the spectrum of comparatively stable species commonly present in sediments is so wide that their mineralogical, geochemical or

100 isotopically fingerprints may be directly linked to specific source rocks exposed in the river
101 catchment (Morton et al., 2002; Heroy et al., 2003; Sevastjanova et al., 2012; Garzanti et al., 2015).
102 Furthermore, scanning electron microscope (SEM) analyses of detrital grains (especially quartz) can
103 reveal peculiar morphologies that may be associated with specific sedimentary processes or
104 provenance (Cardona et al., 2005; Krinsley and Donahue, 1968; Mahaney, 2002), thus helping to
105 discriminate among different depositional environments (Damiani et al., 2006).

106 In this study, we use heavy-mineral analyses coupled with grain-surface textural analysis to
107 carry out a detailed investigation of riverbed sediments in the upper-middle reaches of the Yellow
108 River, along the big bend and in adjacent source areas. This research serves the purpose of providing
109 insight into the relationship between the Yellow River, Loess Plateau and peripheral deserts, which is
110 useful for determining controlling factors and discriminating among the major additional sediment
111 source areas, thereby improving understanding of the distribution features of coarse sediments in the
112 upper-middle alluvial reaches.

113

114 **2. Study Area and setting**

115

116 The Yellow River, with a total length of 5464 km and a total relief of 4830 m, has been
117 traditionally divided into upper, middle and lower reaches. The study area is located in the
118 upper-middle Yellow River, starting from Lanzhou and ending at Sanmen Gorge (Fig. 1). The upper
119 reach of the Yellow River is characterized by a low gradient, loose riverbed materials, and
120 desert-gully tributaries. The Qingtong Gorge separates a canyon portion from a depositional
121 alluvial-plain portion. Downstream of the Qingtong Gorge, the Yellow River flows over the wide
122 Yinchuan Plain, characterized by sediment deposition with a low gradient (0.236‰). Nearly 87 km
123 of channel runs adjacent to the Hedong Desert (Yao et al., 2011). Farther downstream, the Yellow
124 River enters the Inner Mongolia section, which is a desert reach with a low gradient (0.234‰). The

125 Ulan Buh Desert extends along the northern and western sides of the Yellow River channel. The
126 alluvial plain is covered with both active and semi-fixed sand dunes. The Kubuq Desert extends
127 along the southern bank, where the dunes are mainly semi-fixed.

128 “Ten Great Gullies” (*Shi Da Kongdui* in Chinese) drain the Ordos Plateau and flow from south
129 to north to join the Yellow River in the Zhonghexi–Tuoketuo section. The length of the gullies varies
130 from 29 to 111 km, with an average gradient ranging from 0.267% to 0.525%. These gullies are
131 ephemeral, with water flow during the flood period in June–September.

132 The middle reach of the Yellow River is 1206 km-long, with a very low gradient (0.234‰).
133 The river incises deeply into bedrock and flows southward through the Ordos Block along the
134 western front of the Luliang Mountains, carving the ca. 700 km-long and ca. 200 m-deep Jinshan
135 Gorge between Tuoketuo and Yumenkou. Thereafter the river flows into the Fen Wei basin from
136 Yumenkou to Sanmen Gorge, with a wider and frequently migrating channel. Due to rapid erosion,
137 these reaches are characterized by hyperconcentrated flows, with maximum suspended-sediment
138 concentration up to 1700 kg/m³ (Xu et al., 1998). The climate of this reach is semi-arid to arid, with
139 unevenly distributed annual precipitation. Approximately 75% of the rainfall occurs from July to
140 September. Sandy storms occur in the spring, and the maximum wind speed can reach 25–30 m/s
141 (Yang et al. 2004). Sediments accumulated by winds are carried into the river during the rainy
142 season.

143

144 **Fig. 1.** Map of the Yellow River, showing major deserts, tributaries and the locations mentioned
145 in the text. The black oblique line indicates the boundary of the upper, middle and lower reaches of
146 the Yellow River. The Inner Mongolia section extends from Shizuishan to Tuoketuo.

147

148 Geologically, the Yellow River drains diverse lithological units, including Archean
149 metamorphic rocks, Paleozoic carbonate rocks, Mesozoic–Cenozoic clastic rocks, and Quaternary

150 detrital covers (Fig. 2)., Sourced in the Tibetan block, the Yellow River cuts across the Qilian Fold
151 belt and flows in the Yinchuan–Hetao Graben in its upper reach. This region, framed by the Ordos
152 and Alxa Blocks, has recorded tectonic activity throughout the Quaternary and is characterized by
153 intermittent subsidence with an average deposition rate of 2–3 mm/y (Yang et al., 2004). The 165
154 km–long and 42–60 km–wide Yinchuan Basin, framed by the Helan Mountains to the west and by
155 the western margin of the Loess Plateau to the east (Tong et al., 1998), includes a mainly Cretaceous
156 to Quaternary succession with lacustrine, fluvial, glaciofluvial and aeolian deposits. Mesozoic
157 sandstones are widely exposed in the southeast of the Yinchuan Basin, with local outcrops of
158 Paleozoic granite. The 480 km–long and 40–80 km–wide Hetao Basin lies to the north of the Ordos
159 Basin, and to the south of the Yinshan Mountains. It is characterized by thick lacustrine deposits. In
160 the middle reach, the Loess Plateau, located to the east of the river, is underlain by Mesozoic
161 –Cenozoic clastic rocks. In particular, Jurassic and Cretaceous sandy mudstone and sandstone crop
162 out widely in the region (Zhang et al., 2009). Quaternary silt, sand and gravel are widely distributed
163 in the alluvial plains.

164

165 **Fig. 2.** Geological sketch map of the upper–middle reaches of the Yellow River with sampling sites.

166

167 **3. Sampling and methods**

168

169 We collected 33 riverbed sediment samples along the upper–middle reaches of the Yellow
170 River (Table. 1; Fig. 2). All of the sediments were collected from recently deposited, unaltered sand
171 bars of the main channel. We employed a dragger sampler, ~15 m away from the riverbank to reduce
172 the influence of human activities. A similar setup was used to collect sediments from the Qingshui
173 River and the “Ten Great Gullies” samples were collected by digging about 20 cm below the

174 riverbed. We also collected dune sediments from the adjacent Hedong, Ulan Buh, and Kubuq Deserts
175 (Table. 1).

176

177 **Table 1**

178 Location, name and type of samples from the Yellow River, adjacent deserts and tributaries.

179

180 Grain size was measured using a Malvern Mastersizer 2000 grain size analyzer in the Key
181 Laboratory of Western China's Environmental Systems, Lanzhou University. Prior to measurement,
182 organic matter and carbonates were removed from the samples using 30% H₂O₂ and 10% HCl. Then,
183 100 ml of deionized water was added to the samples and the supernatant was siphoned after letting
184 the samples stand for 24 h. Clay-rich samples rich in organic matter were treated with an ultrasonic
185 disperser to further separate detrital minerals from clay.

186 Heavy-mineral analyses were performed on the 0.63–0.25 μm fraction of each sample, dried at
187 60°C and placed in a settling tube with bromoform (2.89 g/cm³). After frequent stirring, heavy
188 minerals were allowed to separate via gravity. The heavy fraction was thinly spread on a glass plate
189 and an Nd-Fe-B magnet was used to remove all magnetic minerals. Finally, heavy-mineral
190 assemblages were determined based on counts of 400–500 grains using the “area method” (Mange
191 and Maurer, 1992).

192 Preparation for grain-morphology analyses involved boiling for 20 min in 10% HCl to remove
193 carbonates and iron oxides. The samples were then washed with deionized water until the decant
194 water was clear. Then, the samples were boiled for 10 min in 30% H₂O₂ to remove clay and organic
195 matter. Next, they were washed at least three times with deionized water. Approximately fifteen to
196 thirty quartz grains were randomly selected with a binocular microscope. In addition, an ion plating
197 machine (EIKOIB-3/ IB-5) was used to spray gold film and ensure electrical conductivity (Krinsley

and Doornkamp, 1973). The samples were sputter coated for 30 s, and studied by a TESCAN MIRA 3 SEM at the Physical Science and Technology College, Lanzhou University.

4. Results

4.1. Heavy-mineral assemblages in the Yellow River

The results of heavy-mineral analyses are illustrated in Fig. 3 and provided in full in Appendix A. The dominant transparent minerals are predominantly dark-green, green and brown amphibole (from 2% to 48%) and sub-angular to rounded and mainly pink garnet (from 6% to 60%). Other mineral species include epidote (0.4%–28%), zircon (0.6%–19%), apatite (0.04%–3%), pyroxene (0–5%), titanite ($\leq 3\%$), rutile ($\leq 4\%$), tourmaline ($\leq 3\%$), monazite ($\leq 0.2\%$) and even rarer staurolite and glaucophane (Fig. 3). Significant mineralogical changes are observed along the channel. The samples from Lanzhou (sample 1) and western Yinchuan (samples 2–6) are dominated by amphibole and epidote; garnet increases in the eastern Yinchuan (samples 7–8) and Inner Mongolia reach (samples 9–29). Sample 30 from the middle reach is markedly distinct by the abundance of garnet (60%). Amphibole may show an abrupt increase close to tributary confluences.

4.2. Heavy-mineral assemblages in tributaries and adjacent deserts

Heavy minerals in Qingshui River sand (Fig. 3 and Appendix A) are dominated by opaque minerals, amphibole and garnet, with minor amounts of epidote, zircon, pyroxene, titanite, apatite and rutile. This assemblage is similar to that observed in western Yinchuan samples 5–6, whereas samples from the Hedong Desert yielded mainly garnet and amphibole, associated with epidote and minor zircon, similar to eastern Yinchuan samples 7–9. Ulan Buh Desert sands display significantly

223 higher epidote contents. Samples from the Ten Great Gullies are mineralogically similar to the
224 Kubuq Desert samples, both having higher garnet proportion. “Ten Great Gully” samples yielded
225 less opaque minerals (limonite).

226 The ZTR index (sum of zircon, tourmaline and rutile over total transparent heavy minerals;
227 Hubert, 1962), defining the “mineralogical durability” of the assemblage, ranges between as low as
228 0.6 to 22, with particularly low values in the middle reach (Fig. 3). More stable minerals reach a
229 maximum in sample 30 of the middle reach, and a minimum at tributary confluences where
230 amphibole is most abundant.

231

232 **Fig. 3. Heavy minerals in modern Yellow River sediments and potential sources (deserts and**
233 **tributaries).** Opaque minerals include limonite, magnetite, ilmenite, anatase and leucoxene. ZTR=
234 Zircon + Tourmaline + Rutile (Hubert et al., 1962). More stable minerals include zircon, tourmaline,
235 rutile, garnet, monazite and titanite. Less stable minerals include epidote, amphibole and pyroxene
236 (Zuffa et al., 2007). The black straight line denotes the main wind direction, whereas the black dotted
237 line denotes the minor wind direction.

238

239 4.3. Grain size and quartz grain morphology

240

241 Sand contents are highest in the Inner Mongolia section of the upper reach (Table. 1). The grain
242 size distribution for aeolian sand typically displays a sharp kurtosis with a dominant mode at about
243 220 μm . In bed sediment sample 11 the mode is finer-grained and the skewness is more positive.
244 Sediment sample 18 shows a polymodal grain-size distribution with a dominant modal size at about
245 55 μm (Fig. 4). This relatively fine grain size suggests that the riverbed sediments reflect a only
246 weak downstream influence from the local aeolian sand transport of the Ulan Buh or Kubuq Deserts.

247 The surface textures of quartz grains can provide crucial information to identify the associated
248 transport mode, particularly in distinguishing aeolian from fluvial depositional environments
249 (Mahaney et al., 2001). Microstructure studies in different sedimentary environments have found that
250 quartz grains in aqueous environments exhibit V-shaped percussion cracks, conchoidal fractures,
251 irregular craters or depressions, straight-curved grooves and large gaps. Aeolian environments, in
252 contrast, are characterized by sheets, butterfly pits and parallel ridges (Mahaney and Kalm, 2000;
253 Mahaney, 2002; Vos et al., 2014).

254 Differences among quartz grains in the Ulan Buh and Kubuq Deserts are subtle (Fig. 4), with
255 both regions displaying rounded to sub-rounded and butterfly-shaped pits typical of aeolian
256 environments (Fig. 5A, B). However, DLGKD (Fig. 5C) and XLGKD (Fig. 5D) are seasonal
257 tributaries of the Yellow River with a high proportion of V-shaped pits, conchoidal fractures and
258 ground surfaces, with no butterfly-shaped pits (Fig. 4), indicating both fluvial and
259 chemical-dissolution processes.

260

261 **Fig. 4.** Grain frequency for genetic types of quartz-grain surface textures and grain-size distribution
262 of typical samples for the upper reach of the Yellow River.

263

264 **Fig. 5.** Typical surface microstructures for quartz grains under a scanning electron microscope
265 (SEM). A. Rounded grain from the Ulan Buh Desert; B. Rounded grain from the Kubuq Desert; C.
266 Grain from the “Ten Great Gullies” (DLGKD), displaying irregular surface and v-shaped pits; D.
267 Grain from the “Ten Great Gullies” (XLGKD) showing composite V-shaped pits and scratches; E.
268 Angular grain with cleavage surface (sample 5); F. Butterfly-shaped pits and ground surfaces
269 (sample 11).

270

271 The quartz grain morphologies of the riverbed sediments include microtextures produced by
272 mechanical impacts, by chemical precipitation (Fig. 5E), or by both processes combined (Fig. 5F).
273 River sediments include both angular to sub-angular grains with slightly blunt edges with medium to
274 low relief, and subordinate rounded grains. V-shaped percussion cracks and small concoidal
275 fractures commonly occur (Fig. 3). Sample 5 exhibits the highest frequency of cleaved surfaces (Fig.
276 3); most grains are angular with sharp edges and irregular shapes with medium-high relief,
277 overprinted by fresh V-shaped percussion cracks (Figs. 6A and 6B). These microtextural
278 assemblages suggest that the sand may have formed originally in a high-energy environment
279 characterized by strong grain-grain collisions. In contrast, samples (7 and 11) are characterized by
280 common V-shaped percussion cracks (Fig. 6C) and more abundant rounded quartz grains (Fig. 3).
281 Older butterfly-shaped pits have been overprinted by scratches (Fig. 6E). Other composite structures,
282 such as pitted surfaces, siliceous precipitations, upturned plates and V-shaped percussion cracks (Fig.
283 6D) are common. Because butterfly-shaped pits and upturned plates are the representative
284 microtextures for modern aeolian sand, we infer that dunes have moved into the mainstream under
285 the influence of predominant NWN wind, causing large volumes of sand to experience renewed
286 fluvial abrasion. Sample 18 displays a high proportion of angular, medium-relief ridge and abrasion
287 edges, with V-shaped percussion cracks distributed over the grain surfaces (Fig. 6F) and small to
288 medium concoidal fractures along grain edges (Fig. 6H). Lower-energy discharge conditions are
289 inferred from chemical-precipitation and chemical-dissolution features preserved on quartz-grain
290 surfaces (Figs. 6I and 6J).

291

292 **Fig. 6.** SEM micrographs of surface textures in quartz grains showing: angular shapes, breakage and
293 cleavage fractures (A and B); V-shaped fractures (C); upturned plates revealing silica dissolution
294 and precipitation (D); rounded grains with dish-shaped concavity and shallow scouring (E);

295 concoidal fractures produced in high-energy subaqueous environments (F); larger V-shaped
296 fractures with high relief (H); silica precipitation and chemical etching (I); and solution lines (J).

297

298 **5. Discussion**

299

300 ***5.1. Provenance discrimination using heavy minerals***

301

302 Heavy-mineral assemblages in fluvial sediments are controlled by source-rock lithology,
303 hydraulic sorting and chemical weathering (Morton, 1999; Frihy, 2007; Garzanti, 2007b, 2013a). In
304 the upper-middle reaches of the Yellow River, sediment fluxes, desert sand supply, and tributary
305 contributions result in distinctive characteristics. Sediment accumulation occurs in the Yinchuan-
306 Hetao plain of the upper reach (Yang et al., 2004; Ta et al., 2008; Pan et al., 2015), whereas erosion
307 is dominant in the middle reach (Lin et al., 2011). In the upper reach (upstream of Lanzhou),
308 amphibole content is higher than in the middle reach (Fig. 7). This region is predominantly located in
309 a tectonically active area where bedrock is exposed to weathering. Garnet increases downstream
310 from Lanzhou to Tuoketuo, which indicates a significant addition of detritus from local sources,
311 especially the Mesozoic clastic deposits widely exposed in the Ordos Basin. Our data suggest that
312 Cretaceous sandstones may represent a very significant source of sediment (Nie et al., 2015). In the
313 lower Yellow River, sediments are relatively enriched in unstable minerals (Wang et al., 2010) (Fig.
314 7), and assemblages resemble those of the upper reach, owing to supply from tributaries draining the
315 Qinling Mountain, as suggested by the U-Pb age distributions of detrital zircons (Nie et al., 2015).

316

317 **Fig. 7.** Comparison of heavy minerals in different reaches of the Yellow River. The upper reach data
318 (upstream of Lanzhou) are after Nie et al. (2015), the lower reach data after Wang et al. (2010).

319

5.2. Sediment supply from the Loess Plateau

The Yellow River transports a large volume of sediment from the northern Tibetan Plateau to the Yinchuan–Hetuo Graben. Similar zircon U–Pb age data and heavy–mineral assemblages in sediments from the Yellow River and Loess Plateau indicate that the Yellow River has likely represented a major sediment source for the Plateau since at least 1.8 Ma (Stevens et al., 2013; Bird et al., 2015). Samples from the Loess Plateau and the modern western Mu Us desert are dominated by amphibole and epidote (Stevens et al., 2013, Bird et al., 2015), which is consistent with modern upper Yellow River samples 1–4 and samples of Western Lanzhou (Figs. 3 and Fig.7).

Our research further confirms the correlation between the Yellow River, the Northern Tibetan Plateau and the Loess Plateau (Nie et al., 2015). The Qingshui River, a major tributary draining the Loess Plateau shows high amphibole content, similar to the Loess Plateau sediments. The Qingshui River assemblage is a close match to samples 5–6 from the modern riverbed, suggesting that the Qingshui River is a potentially significant remover of sediment from the Loess Plateau.

Tributaries deeply incise into Cretaceous sandstone bedrock and erodible overlying strata during the rainy season in the middle reach of the Yellow River (Xu et al., 2003). We estimate that as much as 10^6 to 10^7 kg /m² of sediment from the Loess Plateau is carried to the Yellow River every year, which might account for as much as 90% of the sediment flux into the Bohai Sea (Zhang et al., 1990).

Zircon U–Pb age spectra of samples from the middle reach, Cretaceous sandstones and eastern Mu Us desert are dominated by a single peak at ~250 Ma, a notable difference relative to the upper reach (Nie et al., 2015). This suggests that, in addition to the loess sources, riverbed sediments in the middle reach may be derived largely from bedrock. Zircon U–Pb age spectra and heavy mineral assemblages change again in the lower reach, becoming similar as in the upper reach, which was suggested to be related to supply from the Qingling mountains via tributaries (Nie et al., 2015) as well

345 as to contributions from the Loess Plateau via the Wei river and other tributaries. Sand petrography
346 confirms the similarity of detrital modes (e.g., feldspar/lithic ratio) between upper–reach and
347 lower–reach sediments, and their significant difference from middle reach sediments (Wang et al.,
348 2007).

349

350 *5.3. Sediment supply from adjacent deserts and tributaries*

351

352 Downstream of the Qingtong Gorge, the river becomes braided, in a relatively low–relief
353 floodplain (Wang et al., 2012). Riverbed samples display a high garnet/amphibole ratio, which
354 maybe ascribed to contribution from the Hedong Desert. This is confirmed by the surface textures of
355 quartz grains, which display a high frequency of butterfly–shaped pits and rounded edges in sample 7.
356 The annual amount of sediment input from the Hedong Desert is estimated at about 0.15×10^8 tons
357 (Yang et al., 1988).

358 Yellow River sediments in the Inner Mongolia section exhibit a notable variability in
359 heavy–mineral assemblages ascribed to significant contributions from local deserts. Under the
360 influence of northwesterly winds, a large number of Ulan Buh Desert sand dunes encroach onto the
361 floodplain and into the channel (Yang et al., 2004; Ta et al., 2008; Pan et al., 2015). This is
362 confirmed by the appearance of quartz grains with surface morphologies dominated by composite
363 V–shaped percussion cracks and butterfly pits (Fig. 6). After aeolian sand reaches the riverbed,
364 rounded grains will undergo abrasion associated with hydraulic flow, and a series of new distinct
365 microstructures will form. Aeolian sand from the Kubuq Desert is blown into the gullies during the
366 windy season, and reaches the channel in the rainy season (Pan et al., 2015). The channel bed
367 elevation has risen by an average of about 0.73 m during the past 20 years (Ta et al., 2008). As
368 observed in Fig. 8, the “Ten Great Gullies” samples and Ulan Buh Desert samples can
369 bedifferentiated by the higher amphibole and epidote content in the former. Kubuq Desert samples

plot closer to the “Ten Great Gullies” samples, although minor differences exist in the opaque minerals limonite and magnetite (Fig. 3 and Appendix A). Indeed, the sample KBQ02 lies close to the “Ten Great Gullies” samples on the principal component map, reinforcing the hypothesis that the gullies store aeolian sand from the Kubuq Desert (Fig. 8). The high garnet content in the riverbed samples points to provenance from Cretaceous sandstones via seasonal tributaries draining the Ordos Plateau (Fig. 3). Fluvial transport is temporary and seasonal, which may account for some of the variability observed along the mainstream (samples 15–29) (Fig. 3).

377

Fig. 8. Principal component plot of the studied samples.

379

5.4. *Tentative sediment budget*

381

Fluvial sediments are mixtures of detritus derived from different geological units (Garzanti et al, 2007a). If the end-member signatures are all known, we can estimate sediment contributions from each end-member source using a linear model (Weltje, 1997). Such a basic mixing-model principle requires a sufficient number of control samples in order to characterize adequately the entire basin. The study area is a semi-arid region, where river sediment is transported from source to sink with minimal influences from chemical weathering. Apart from local hydrodynamic effects, heavy-mineral assemblages in Yellow River sediments can thus be assumed to faithfully reflect the lithology of their source rocks. Sixteen sequential riverbed sediment samples—collected from critical points located at the boundary between main geological units and close to tributary confluences – and seventeen major heavy-mineral parameters were used to estimate the relative contributions from the different end-members, expressed by a value ranging from 0 to 1. We selected results with the smallest sum of residuals, using the corresponding standard deviation and fitting error as validation criteria.

394

The contribution of the upper Yellow River reach is estimated to range from 0% to 51%, and that from the Ulan Buh Desert also varies widely from 0% to 63%. Even larger is the variability of contribution from the Kubuq Desert (from 0% to 95%) (Fig. 9). Much of the coarse-grained sediment derived from the Ulan Buh and Kubuq Deserts is estimated to be gradually deposited in the river channel, and only a part of this material is transported downstream. Conversely, fine-grained floodplain sediments exposed to deflation after the flood pulse receded may feed the dunes. The relative average contribution from the “Ten Great Gullies” also varies widely, from 2% to 87%. Those seasonal tributaries contribute to hyper-concentrated floods resulting in coarser sediments aggrading in the river channel (Pan et al., 2015). The spatial pattern of changing sources proves that the river system is very dynamic, with notable changes in provenance over short intervals. This suggests that the compositional signature of river sediments in the lower reach may not reflect the signal generated in the upper reach, as has been commonly argued in the literature and used to infer information on the river system’s evolution (Yang et al., 2009; Zheng et al., 2013).

Fig. 9. Relative contributions of main end-members to riverbed sediments in the Inner Mongolia section of the upper Yellow River.

6. Conclusions

Heavy mineral assemblages in the upper-middle reaches of the Yellow River are primarily composed of opaque minerals (e.g., limonite, magnetite), amphibole, garnet, epidote, and zircon. Apatite, pyroxene, titanite, rutile, tourmaline and monazite occur in minor amounts. Heavy-mineral analysis coupled with quartz-grain morphology suggests that there is a significant spatial variation in the composition and sediment supply of riverbed sediments. In the upper reach (between Lanzhou and Yinchuan), the riverbed sediments are dominated by amphibole and epidote, thereby showing

similarity to the Loess Plateau and the Northeastern Tibetan Plateau. The low ZTR index indicates very little chemical weathering for Yellow River sediments. Trunk–river sediments from Yinchuan to Tuoketuo display a notable increase in garnet, suggesting a significant sediment supply from the adjacent Ulan Buh Desert, Kubuq Desert and the “Ten Great Gullies.” The greatest abundance in garnet is observed in sediments of the middle reach, reflecting erosion of Cretaceous sandstone bedrock. The surface morphology of quartz grains consistently suggests that the riverbed sediments comprise a mixture from multiple sources. A simple mixing model indicates that the adjacent Ulan Buh and Kubuq Deserts may provide a very significant amount of sediment to the Yellow River channel. However, our estimates are poorly constrained, ranging from 0% to 63% and from 0% to 95%, respectively. The “Ten Great Gullies” act as an additional sediment source, with a contribution also estimated to vary widely from 2% to 87%. Aeolian dunes and tributaries may represent a significant source of sediment in Inner Mongolia, especially during the hyper–concentrated floods of the rainy season when detritus is transported rapidly into the Yellow River and siltation in the channel occurs.

Acknowledgments

This research was supported by the National Basic Research Program of China (No. 2011CB403301), the National Science Foundation of China (No. 91125008, 41471008 and 41571003) and the Fundamental Research Funds for the Central Universities (lzujbky–2014–262; lzujbky–2014–255; lzujbky–2014–272). We thank Editor-in chief Mei-Fu Zhou, Michel Faure, and two anonymous reviewers for their constructive comments. We are also grateful to the professional editing service (Elsevier Language Editing Services) and Prof. Victor R. Baker for improving the language of our manuscript.

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