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Abandonment of ancient cities near the Salawusu River valley, China, triggered by stream capture

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Several cities in the Salawusu River basin in the western Mu Su Desert of China were abandoned after the Yuan Dynasty (1271 to 1368 CE). Incisions of rivers caused by earth uplift coupled with a drier climate after the Yuan Dynasty have previously been attributed to such irreversible abandonments. Here we use geomorphological analyses, coupled with hydrological reconstructions to investigate the ancient stream patterns in the period leading up to the abandonments. We find that the abandonment of wells, the thermoluminescence age of which is about 640 years before present, in these cities coincided with a stream capture event that led to rapid river valley incision of up to 95 mm/year. We suggest that this stream piracy event lowered the water table in the area and triggered the abandonment of settlements, rather than a change to a drier climate as previously believed. We conclude that when considering environmental influences on archaeological records, geographic events must be considered in addition to climatic change.

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anchahe City is an abandoned ancient city on the southeastern margin of the Mu Us Desert on the Ordos Plateau, China (Fig. 1a and Supplementary Fig. 10a). The unearthed urban relics indicate that the city was built after the annihilation of the Western Xia (1038–1227 CE) by the Yuan dynasty (1271 to 1368 CE)[1]. A large amount of ancient coins and rubble covered an area of about one million square meters around the city before, during, and after this period[2], indicating a former scale of human activity around the city. A moat of about 20 m wide immediately outside the city walls, which has now been filled with rolling sand[1], also displays the city's former prosperity and adequate water supply. A wall brick found in the city was dated with TL (thermoluminescence) to 705 ± 84 a BP (1316 CE), denoting the time of the city's construction, while the AMS (Accelerator Mass Spectrometry) ^{14}C age of two samples collected from the artificial earth fill or cultural layer of the city was 852 ± 51 cal a BP (1089 CE) and 841 ± 73 cal a BP (1110 CE), respectively (median calibrated years before 1950), indicating the settlement of people in the area prior to the establishment of the city.

A derelict well built in an artificial earth fill was found on the western margin of the city. The lateral extension of the slope of the Salawusu River valley destroyed part of the western wall of the city, resulting in the exposure of the well (Fig. 1b, c and Supplementary Fig. 10a). The base of the well is located at an altitude of 1275.8 m, which denotes the level of ancient groundwater tables, but the Salawusu River bed is now at least 61 m lower than the base of the well (Fig. 1c and Supplementary Fig. 10a). Two well bricks (Supplementary Fig. 1) are dated in different laboratories with TL to 669 ± 82 a BP and 600 ± 99 a BP, respectively, with a mean value of 640 ± 91 a BP (1381 CE), representing the building time of the well. The AMS ^{14}C age of charred material next to the well was 647 cal a BP, equivalent to approximately 718 ± 22 a BP (1303 CE) and are broadly consistent with the TL ages of the well bricks, indicating human activities around the time of well construction (Fig. 1b, Supplementary Tables 1 and 3). This allows us to precisely estimate the incision rate of the Salawusu River, which has reached an average of at least 95 mm/year over the last 640 years.

River incision is mainly caused by an increase in the stream power of a river, which may result from an increase in riverbed gradients due to base level lowering or tectonic uplift, or an increase in the water-sediment supply ratio due to climate change[3–6]. The present Salawusu River was originally developed over the Dagouwan Formation, which is a lacustrine deposit of about 1–2 m thick above the Odors Plateau surface, with a base age of about 11,000 years (11 ka BP)[7]. Thus, it is generally accepted that the Salawusu River is decreasing at a very fast rate, although this has been reported differently in different studies[7–9]. However, all previous studies attribute this rapid incision to tectonic uplift[7–10]. If the authors' findings are true, then the speed of the uplift that caused the incision is much faster than in the Himalayan areas where the incision rate of the Indus River is only 2–12 mm/year, which has already been referred to as "extremely high rates"[11]. Geological engineering investigations have shown that the inner area of the Ordos block, where the Salawusu River is located, is tectonically stable even it is surrounded by active deformation zones with frequent earthquakes (Supplementary Fig. 2)[12]. During the Cenozoic era, the Ordos block has been in a state of slow uplift with an amount of 160 m since 1.4 Ma BP, and geodetic deformation surveys show that the Ordos block is still rising at a rate of 1~2.8 mm/year[13], which is about 35 (34.93) times slower than that of the Salawusu River. On the other hand, if the rapid decline is attributed to climate change, then an increase in precipitation is required[14,15]. Nevertheless, dry conditions prevailed in the Salawusu River area during the last 3 ka[16]. The time of abandonment of this city after 1381 CE was broadly

contemporaneous with the Little Ice Age[17], during which annual precipitation in China decreased[18]. Thus, questions concerning the factors controlling the rapid incision remain unanswered. On the other hand, the attention of recent studies has been drawn to the irreversible environmental degradation and the abandonment of local cities due to the rapid incision and the drier climate, which was considered to have destroyed the basic conditions for maintaining the original vegetation of the Mu Us Desert[8,9]. However, destinies of ancient cities built along river banks different from those on lake coasts in Mu Us Desert region after the Yun Dynasty (see late) suggest that it seems questionable.

Results and discussion

The capture of the Salawusu River by the Wuding River. The Salawusu valley is a deeply incised meandering valley, while the Wuding River valley is similar in depth but straighter and wider (Figs. 1a and 2). The meanders that are developed in a stream channel are not 'random' either in their size or occurrence, so meanders are generally a more obvious feature of the lower part of a valley, whereas they are poorly developed towards the source of the stream[19]. As shown in Fig. 2a, even though the Wuding River meanders in its lowest reach before flowing into the Yellow River, the meander ratio in this section (1.65) is still much lower than that of the Salawusu River (2.27). Meander formation provides a way to "mark time" in a long-term erosional setting[20]; therefore, a stream with meanders is referred to as an aged stream[19]. As one of the first-order tributaries of the Yellow River, the Wuding River has a much longer history than the Salawusu River[21], which was only a small creek meandering on the plateau surface in the Middle and Late Holocene[10]. Only the processes of stream capture can explain the phenomenon of an ancient river having an upstream section with an even older channel planform.

A col and a misfit on the north bank of Batuwan Reservoir (Fig. 3a, b) provide supporting evidence for capture. It is the only valley with an inland slope along the bank of the reservoir; all other valleys along the bank are inclined toward the reservoir, obviously resulting from gully headcut retreat (Supplementary Fig. 6). Although no river exists at all in this area today, a layer of fluvial sand coupled with channel-lag deposits dated with OSL (optically stimulated luminescence) to 6610 ± 510 a BP (4589 BCE) were found to occupy the col floor (Fig. 4, Supplementary Table 2). The fluvial sand was overlain by eolian sand with an OSL age of 4350 ± 680 a BP (2329 BCE) (Supplementary Table 2). Consequently, if there are no reasons to believe that the inward-sloping valley is also a gully formed on reservoir side slopes by headcuts, then its former occupation by a stream is virtually indisputable. A GIS-based hydrological model directly confirms this, with all of the ancient streams in the south shore area of the reservoir flowing to the north shore area of the reservoir before being captured, and the old Salawusu River flowing through the place from southwest to northeast, where the col is located (Figs. 3c-1). Comparing between the old and modern streams identified by the model in Figs. 3c-1, it was found that after capture, or after the formation of the channel that now occupies the Batuwan Reservoir, all the streams in the north shore area disappeared, suggesting a rerouting of all the old rivers towards the Wuding River via the Batuwan Reservoir. If the model is valid, a question arises: where does the old stream flow to? It can be easily argued that the paleo-streams eventually flowed to the lakes in the north shore area of the reservoir before being captured, since the area had large and small lakes and marshes 1600 years ago, although these lakes cannot be found today[22]. It is confirmed that the locals called the lake "Hai", which is the English equivalent of 'sea'[22], and many places named after "sea", "beach", "bay", etc. are still preserved in the Google Earth map of this area (Figs. 3c-2).
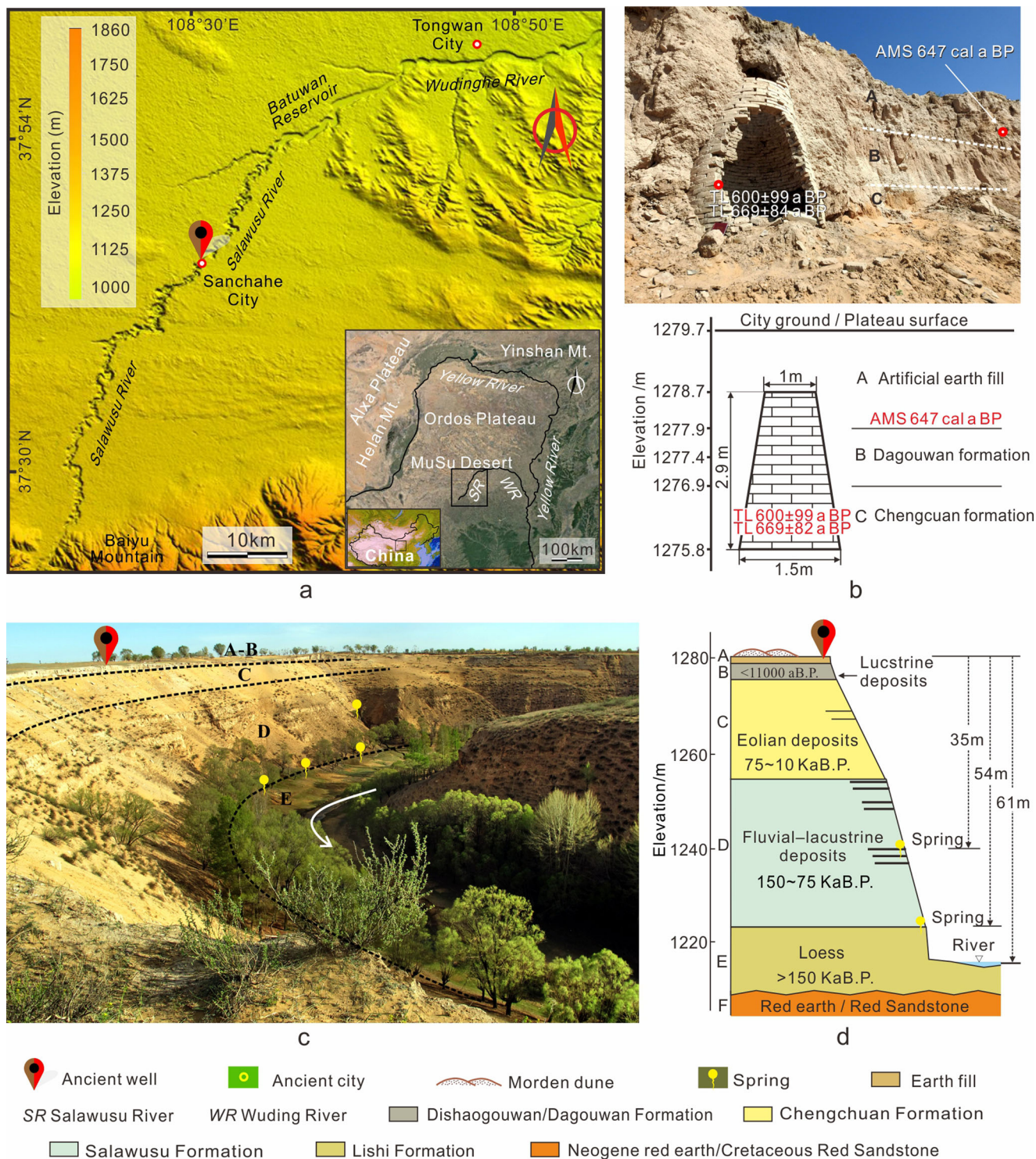
Fig. 1 Location of the abandoned well and Sanchahe City and the strata of the study area. a Map showing locations of the Salawusu River, Wuding River, and Sanchahe City in the Mu Us Desert. **b** Field photograph of the abandoned well and diagram showing altitudes of the abandoned well and the strata next to the well coupled with the TL ages of the well bricks and the AMS median calibrated age of the charred dust in the artificial earth-fill above strata. **c** Field photograph of the Salawusu Valley and location of the ancient well. **d** Diagram showing vertical distance from the well to the valley bed and strata present on the side of the valley.

The Wuding River, as one of the first tributaries of the Yellow River, extended westward and then southward through headward erosion, providing an extremely low base level that promoted extreme incision of the Salawusu River, which originally flowed on the plateau surface, during capture. Fall in the base levels of the older Salawusu River due to capture resulted in the formation of deeply incised meandering valleys, which were manifested by a rapid change in stream valley cross-sections, varying abruptly from V shapes in the Salawusu River course to wide U shapes in the Wuding River course (Fig. 3d). However, the cutting depths of the rivers, including the Salawusu and Wuding Rivers, were controlled by the occasional
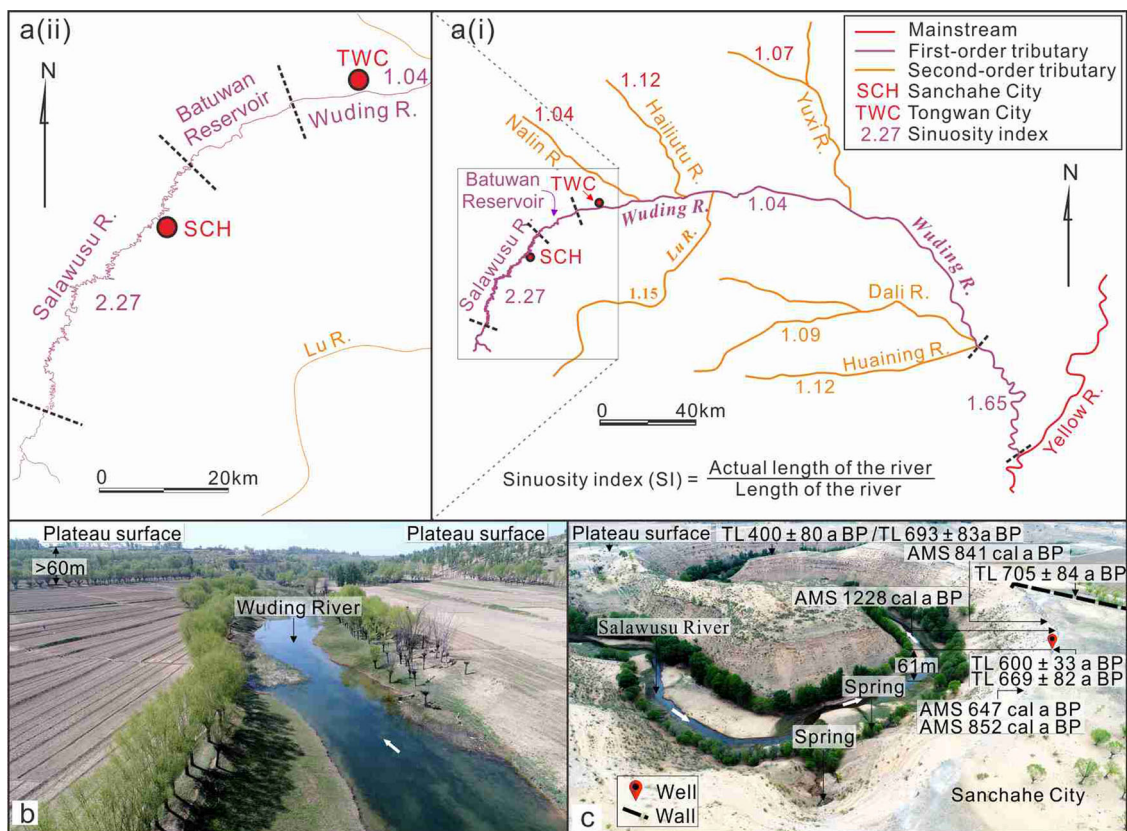
Fig. 2 The sinuosity of the Salawusu River and the Wuding River. a (i) The present-day Wuding River, with the Salawusu River as its upstream river, flows from southwest to southeast turning half a circle before flowing into the Yellow River, and the Salawusu River section has the highest sinuosity. **a** (ii)-2 Detailed section of the Salawusu River meanders. **b** Field photograph showing the wide and straight Wuding River channel that deeply incises into the Ordos Plateau. **c** Field photograph showing the narrow and deep meanders of the Salawusu River and the location of the dating samples (AMS cal a BP = median of AMS calibration year calculated from 1950).

occurrence of Cretaceous red sandstones along the river courses (Fig. 5 and Supplementary Fig. 5). The red rock was resistant to erosion and served as local base levels for downcutting and headward erosion. The rivers cut deeper only when the rock was cut through. The present base level of the Salawusu River is located at the junction between the Wuding River and the Batuwan Reservoir, where the river penetrates deep into the red sandstone and forms a knickpoint indicating the headward erosion of the Wuding River (Fig. 5 and Supplementary Fig. 5a).

An elbow of diversion, which is a sharp change in channel direction, may or may not be expected in a stream capture process, while elbows and wind gaps are features of stream diversion, but may not always be the result of river piracy[19,23]. Although no typical capture elbow is seen in this area, it is worth considering the change in course of the present-day Wuding River, with the Salawusu River as its upstream reach, flowing half a turn from southwest to southeast before entering the Yellow River (Fig. 2a). A river is unlikely to have operated in this manner in a tectonically quiescent setting without being adjusted by geological factors, such as rectangular faults or joints, unless the Salawusu River once emerged as a south-bank tributary of the Wuding River. However, with the exception of the Salawusu River, all tributaries of the Wuding River are relatively straight (Fig. 2a), and there is no evidence that the Salawusu or Wuding Rivers flow through rectangular faults or joints (Supplementary Fig. 2), which suggests that no particular relief or geological conditions have caused the Wuding River to produce a tributary with well-developed meanders during its development.

Ancient fluvial deposits in the col. Three trial pits at a depth of about 1 m were dug on the floor of the col and misfit (Fig. 4a–c) and each pit contains a layer of sand with an increased mean particle size (medium-sized sand) (Fig. 4b and Supplementary Table 4). The coarser-grained materials were not only coarser than sand samples taken from different layers of the gully strata (Fig. 4g–4), the same as at the nearby col, but also coarser than the ancient city strata where the ancient well was built (Figs. 4g–5). The grain size of the coarser-grained materials was even slightly coarser than that of the present-day Salawusu River floor below the ancient city (Figs. 4g–5). The resulting grain sizes of the samples collected from the gully strata and the older city indicate that the old strata in the study area do not provide grain particles coarser than the coarser-grained materials deposited in the col and, more importantly, that there are no streams flowing along the north shore of the present-day Batuwan Reservoir. Needless to say, the coarser-grained grains in each pit are not the materials derived from the old strata or the present river, but rather the old stream residues present after the deposition of the old strata. In addition, a thin layer of even coarser sand lay on an unconformity surface beneath the coarse-grained sand layer in Pit 2 (Figs. 4b–2) denoting channel lag deposits with a sedimentation of erosional surface[24], which provides further evidence to support the former existence of a river.

Since the old strata in this area do not provide gravel and pebble-sized grains, the channel lag deposits here fail to develop into gravels and pebbles, which are generally thin and discontinuous lower gravel layers overlying an equivalent eroding surface to the maximum depth of effective flood scour, representing the lowest
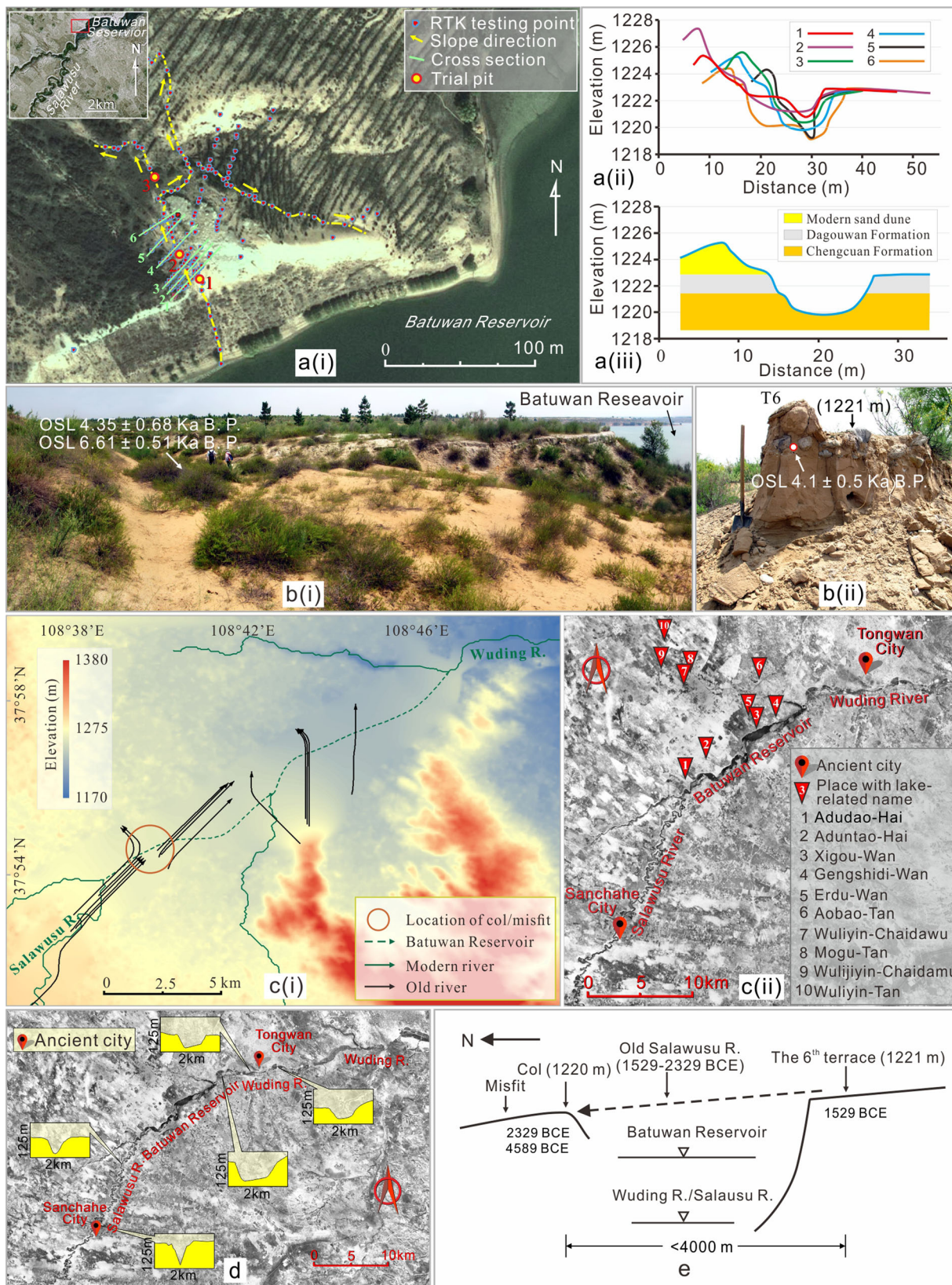
part of a channel[24]. At time when the Salawusu River was just a small creek meandering on the plateau surface in the Middle and Late Holocene[10], even mud blocks or pebbles that derived from dried lacustrine deposits (Dagouwan Formation) could not be easily formed due to the fact that the lakes did not completely dry up. In such a case, it is not surprising to find that the channel lag deposits are only a thin layer of coarser sand grains lying on the erosion surface in trial Pit-2 (Figs. 4b–2).

Timing constraints for the capture process. An estimate of the timing constraints for the capture process can be outlined based

Fig. 3 Evidence of the capture. a (i) The location and slope direction of the col and misfit, and the location of three trial pits for sediment analysis along the col and misfit shown in Google Earth satellite image; (**a**) (ii) cross sections of the col and misfit; (**a**) (iii) stratigraphy of the col and misfit. **b** (i) Field photograph of the col on the north bank of the reservoir; **b** (ii) sixth terrace on the south bank of the reservoir. **c** (i) A GIS-based paleochannel flow model illustrating old streams before and after the capture event around the Batuwan Reservoir area; (**c**) (ii) places with names after "sea", "beach", "bay", etc. shown in Google Earth satellite image. In Chinese, "Hai" means sea, "Wan" means bays andary "Tan" means beaches, and "Chaidamu" means salt marshes in Mongolian. **d** Changes in cross-sectional shape of the Salawusu and Wuding Rivers shown in Google Earth satellite image. **e** Extrapolation of the old Salawusu stream profile using age and elevation data from sampling sites. The old stream has a 0.25% fall to the north. Google Earth Maps data: Image @2022 CNES/Image @2022 Maxar Technologies.
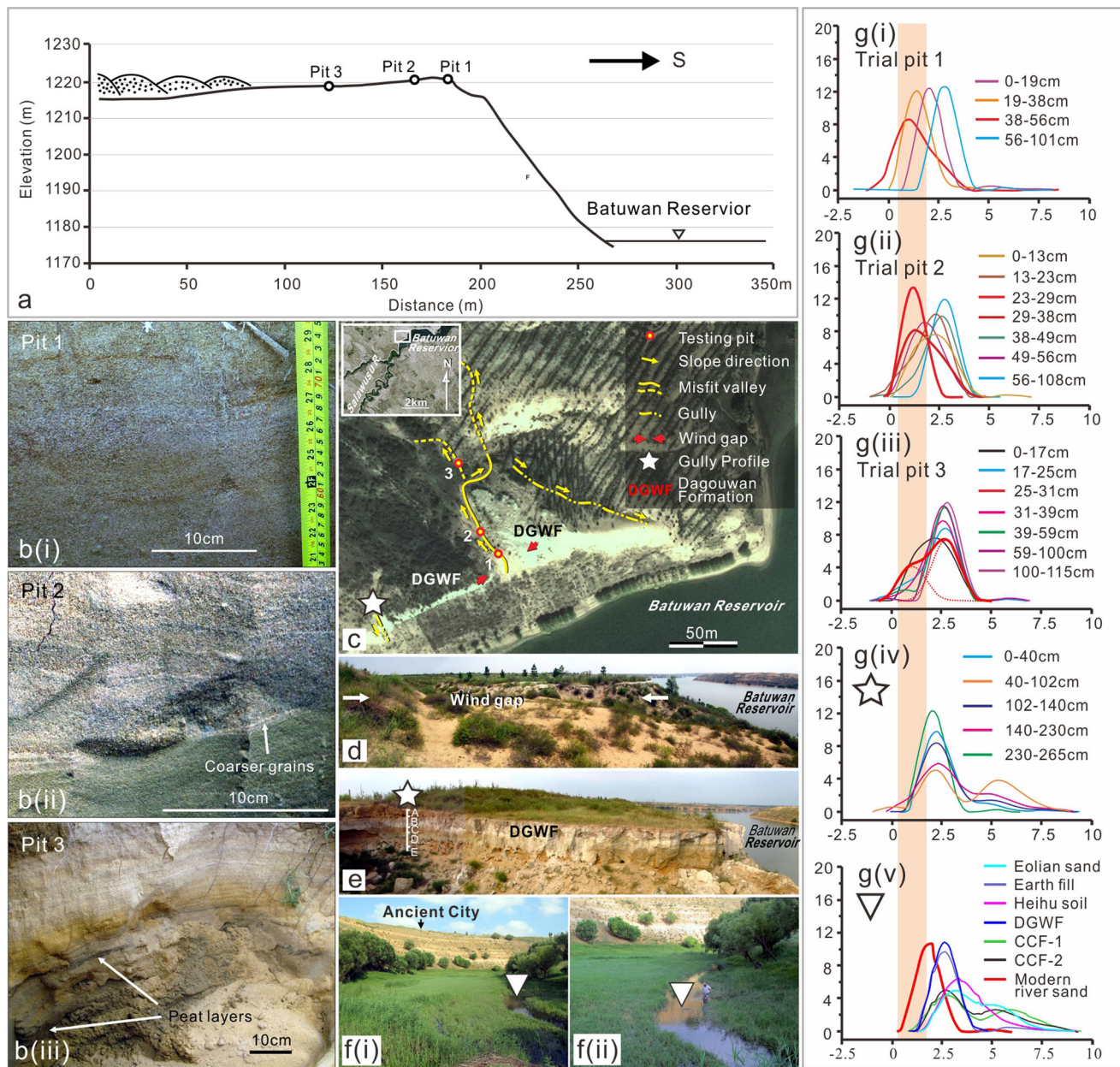

Fig. 4 Results of sedimentary analysis. a Profile of col and misfit with 3 trial pits about 1 m deep. **b** (i)–(iii) Vertical profiles of the 3 trial pits, each containing a layer of coarser grained sand (medium-sized sand, refer to grain size distributions in g1-g3). **c** The slope directions of col and misfit, and a gully (marked with a white star) next to col shown in Google Earth satellite image. **d** Field photograph of the col valley that slopes inland. **e** Field photograph of the gully, sloping towards the reservoir, with its stratigraphic profile. The gully is marked with a white star in the Google image and has the same strata as the col and misfit. **f** Field photograph of a modern river below the ancient city. The white triangle marks the sampling point. **g** The grain size distribution of the samples taken from the study area: **g** (i)–(iii) the grain size distribution of the samples taken at different depths from the 3 trial pits. The grain size of coarse sand in each pit is indicated by the vertical red-orange band or red distribution curves in the plots; (**g**) (iv) the grain size distribution of samples taken from different layers of the stratigraphic profile of the gully (marked with a white star in Fig. 4c and 4e) next to the col and misfit; (**g**) (v) the grain size distribution of sedimentary samples taken from the strata of the ancient city (see Fig. 1b) and the modern river below the city (marked with a white triangle in Fig. 4f). Google Earth Maps data: Image @2022 CNES/Image @2022 Maxar Technologies.
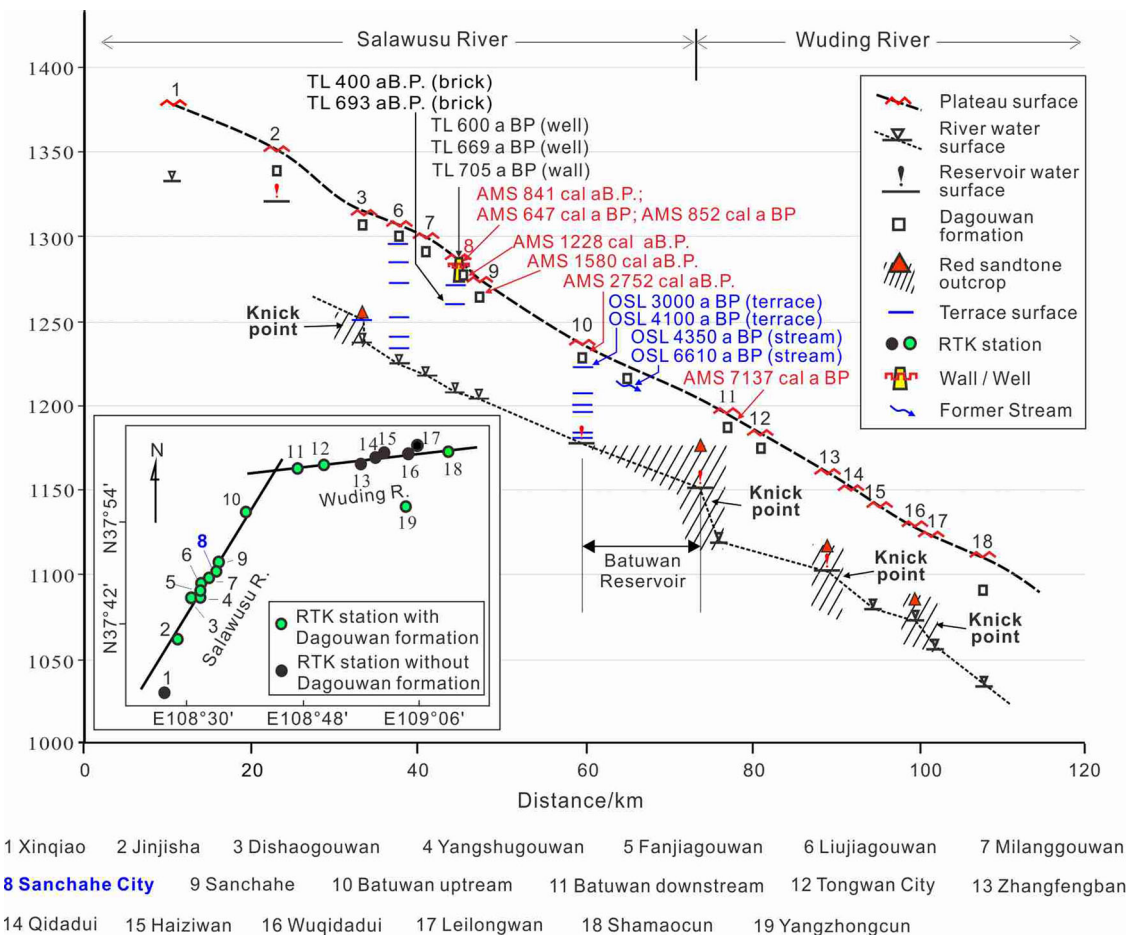
Fig. 5 Sequential and longitudinal profiles of the Salawusu and Wuding Rivers. Knickpoints formed in Cretaceous red sandstone, chronological dating, the Dagouwan formations and stream terraces along the longitudinal profile of the Salawusu and Wuding Rivers.

on the chronological data from this study. The base age of the Dagouwan Formation (about 11 ka BP) indicates the beginning time of the lake environment[7,25–28], which suggests that prior to capture, the areas around Salawusu and parts of the Wuding River are occupied by lakes. However, the end time of the lake environment varies from place to place (Fig. 5 and Supplementary Fig. 4). The superficial age of the Dagouwan Formation was dated with ^{14}C to 7137 ± 42 cal a BP (5187 BCE) 3 km downstream of Batuwan Reservoir and 2752 ± 29 cal a BP (802 BCE) near the upstream end of the reservoir, respectively, while the average OSL age of the Salawusu River's 6th terrace located at the upstream end of the reservoir was 3550 ± 30 a BP (1592 BCE) (Fig. 5, Supplementary Figs. 4 and 8, Supplementary Tables 1 and 2). This indicates that at the time of 5187 BCE, the lakes in the downstream region of the reservoir dried up due to being cut off by headward erosion of the Wuding River (see later); however, its headwaters had not yet reached the Salawusu basin and, by the time of 1529 BCE, the Wuding River had captured the Salawusu River, which began incising to form terraces that subsequently dried up the nearby lakes (in BCE 802). On the other hand, the northward gradient of the old Salawusu River between the col and the terrace was 0.25% (Fig. 3e). With reference to the above-mentioned ages of the fluvial and eolian sands of the col, it is indicative that by 4589 BCE, the old Salawusu River was still meandering on the plateau surface and the section of the river on the north shore area did not dry up until 2329 BCE. In other words, the capture occurred during the years 3550–4350 (1529–2329 BCE) when the rivers in the north shore area were

beheaded. As the result, eolian sands filled the channel. The old Salawusu stream profile was extrapolated, as shown in Fig. 3e.

Terraces, acting as abandoned formerly active river beds, can be used to deduce the timing and external causes of abandonment[29]. Six levels of terraces were identified somewhere in the Salawusu River valley, although they may not always have a one-to-one correspondence (Fig. 5 and Supplementary Figs. 7–9). Two terraces were found at about 400 m on the downstream side of the ancient city, with elevations of 1264 m and 1274 m above sea level, respectively, equivalent to the uppermost (5th and 6th) terraces in the Salawusu River drainage area (Fig. 5 and Supplementary Fig. 9). The elevation of the 6th terrace near Sanchahe City was close to the base of the well (Fig. 1b), indicating that the river water flowing through the river floor, namely the 6th terrace, is sufficiently large to provide ground water for the well. Then, it can be inferred that the 6th terrace near the city is of the same age as the well bricks (1381 -CE). On the other hand, the age of the 5th terrace near the city should be equal to or older than 400 years, since the two brick fragments in the terrace are dated with TL to 400 ± 80 a BP (1621 CE) and 693 ± 83 a BP (1328 CE), respectively (Fig. 5, Supplementary Fig. 1 and Supplementary Table 3). If the terrace surface is taken as the floor of a former river[29], then it would take about 2910 years for the river channel (6th terrace) to extend from the upstream end of the reservoir to the vicinity of the ancient city (3550−640 = 2910) and 240 years for the Salawusu River to cut from the 6th terrace to the 5th one (640−400 = 240). When the 5th terrace was formed, the well could not be utilized due to its

great depth (10 m) from the terrace, indicating the abandonment of the city. In other words, the groundwater level remained high until the 5th terrace was formed. The river subsequently incised down to a depth of 51 m at an extremely high rate (about 130 mm/year) for the remaining 400 years (51,000 mm/400 years = 127.5 mm/year).

Cause for the quick incision. The Salawusu drainage basin has been in a climatic transition area from wet to dry zones over the last 150 ka, and the local depositional environment in this area is sensitively responsive to alternating wet/dry or cold/warm climate changes, which are linked to glacial and interglacial fluctuations during the Late Pleistocene[7,25–28]. As a result, a sequence of sediments was formed, which were deposited in eolian, fluvial or lacustrine environments and exposed on the sides of the Salawusu River valley due to river incision (Fig. 1c and Supplementary Fig. 10a).

The Dagouwan Formation, which is overlain by the artificial earth fill in the areas around Sanchahe City (Fig. 1b), serves as a water-resisting layer (confining stratum) to maintain the lake and stream water cover due to its extremely low permeability (Supplementary Fig. 3). The Dagouwan Formation also serves as a protective layer for the underlying deposits, which are unconsolidated sediments that are not resistant to river incision[7,25–28]. When the lakes were cut through by the headward erosion of rivers, the lake water seeped into the underlying sediment and flowed downstream, causing the lakes to dry up. Previous study showed that the Wuding River extended westward through headward erosion in the Late Pleistocene but did not provide exact age data[30]. The end time of the lakes is represented by the superficial ages of the Dagouwan formation, which decrease from about 7137 ± 42 cal a BP (5187 BCE) in the downstream area of the Batuwan Reservoir to about 2752 ± 29 cal a BP (802 BEC) near the upstream end of the reservoir, 1580 ± 30 cal a BP (370 CE) at Sanchahe (the Sanchahe River) located 2.5 km north of the city and 1228 ± 57 cal a BP (722 CE) in the nearby areas of the city, respectively (Fig. 5 and Supplementary Fig. 4). The sequence of lake drying indicates that the headward erosion of the Wuding River extended first to the west and then to the south, and more importantly, the lake environment around the city was maintained at least until about 722 CE, and the city was built about 600 (594) years later (1316 −722 = 594).

The sediments below the Dagouwan Formation are the Changchun, Salawusu, and Lishi Formations, which are eolian sand, fluvial–lacustrine, and loess deposits, respectively (Fig. 1c)[7,25–28]. The first two formations are the main aquifers in the Salawusu River drainage area[31]. As shown in Fig. 1b, the base of the well is lower than the bed of the Dagouwan Formation and reaches the upper portion of the Changchun Formation, which indicates a high groundwater level at the time of well construction (640 years ago) still up to the upper portion of the Changchun Formation, serving as an aquifer for the well. Alternatively, the lakes around the city had dried up at that time, and the Salawusu River was shallow and meandered near the city, providing a suitable environment for people to build wells.

Ultimate result of the capture. Even though the Salawusu River area has been experiencing dry conditions prevailed for the past 3 ka[16], the annual precipitation in the study area today is 420 mm/year[31]. Previous studies have been trying to demonstrate that drought variability in the region is part of the overall variability of the MU SU desert influenced by climate change[7]. Plants in the surrounding areas are mostly xerophytes, whose growth depends on atmospheric precipitation and soil water systems, but are independent of groundwater[31]. However, in the river valley beds and central part of the lowlands, where groundwater tables were shallowly buried, plants are mainly hygrophytes and mesophytes (Fig. 2c and Supplementary Fig. 10a)[31]. This strongly suggests that the surface landscape of the Salawusu region should not have been as dry as it is today if the groundwater remained as high as the level of the abandoned well. The 20 m wide moat immediately outside the city walls[1] indicates an adequate water supply at the time when the city was built.

Stream bank water storage was confined to a narrow zone adjacent to the channel[32], and a reduction in the groundwater level of the river may result in a "riparian hydrological drought", which is a hydrological disconnection of the riparian groundwater level from the river floodplain due to stream incision[33]. Assuming that the underlying rock layers are invariant with constant saturation depth and uniform recharge, and ignoring the presence of the seepage face on the downstream face between the groundwater level and the downstream water level, a simplified model based on the Dupuit–Forchheimer theory and Darcy's Law[34] shows that the riparian depth to groundwater (D_{gw}) increases with stream incision depth and enlarges the drought region (Fig. 6). The groundwater surface at 3 km away from the stream channel decreases by 25 m when the valley is cut to a depth of 60 m (Fig. 6).

Living close to natural water sources such as rivers and lakes was the most convenient option for ancient people[30]. Groundwater is an important part of water supply for ancient cities in Ordos Plateau, where people built cities in the Mu Us Desert in ancient times in two ways: building cities on the coast of a lake and building cities along the banks of a river[2]. The Sanchahe City belongs to the latter. Except for the Sanchahe City, six other ancient cities were built along the banks of the Salawusu River. All of these cities were established during the period of the Song (960–1279 CE) and the Western Xia Dynasty (1038–1227 CE), but were all abandoned after the Yuan Dynasty (1271–1368 CE), and there were no human relics in the subsequent historical period (after the Yuan Dynasty) of the areas on both banks of the Salawusu River[8]. Due to the low groundwater level, today's agricultural production in these areas mainly relies on deep wells for irrigation[8]. In contrast, the ancient ruined cities found on the lake coast in the southwestern part of the Mu Us Desert still have ground water levels that are only 2–8 m lower than the present land surface[2]. These cities were first settled during the Tang Dynasty (618 to 906 CE) and were abandoned and reused repeatedly. The abandonment was more due to political or military reasons than climatic ones, and some of the cities were still in use during the Ming (1368–1644 CE) and Qing (1644–1901 CE) Dynasties[2]. Conversely, cities built along banks of rivers were not so fortunate, suggesting that hydrological droughts due to stream capture events are limited only to areas on either side of the river where the underlying strata are thick and soft enough for rapid and deep river incisions to occur.

Abandonment of societies or cities due to stream capture are not uncommon in other parts of the world, including China[35,36]. Taking a cue from the movement of Sanchahe City through time and space toward its end, striking similarities were observed in the abandonment of the famous Tongwan City, which is located 35 km northeast of Sanchahe City, on the north bank of the Wuding River. Tongwan City was originally built about 1600 years ago (419 CE), but is now buried by modern sand dunes and was 30–50 m higher than the Wuding River bed (Supplementary Fig. 10b)[22,37]. The difference in height between the Wuding River and Tongwan City prior to its construction was not that large, and the river was probably one of the important water sources for
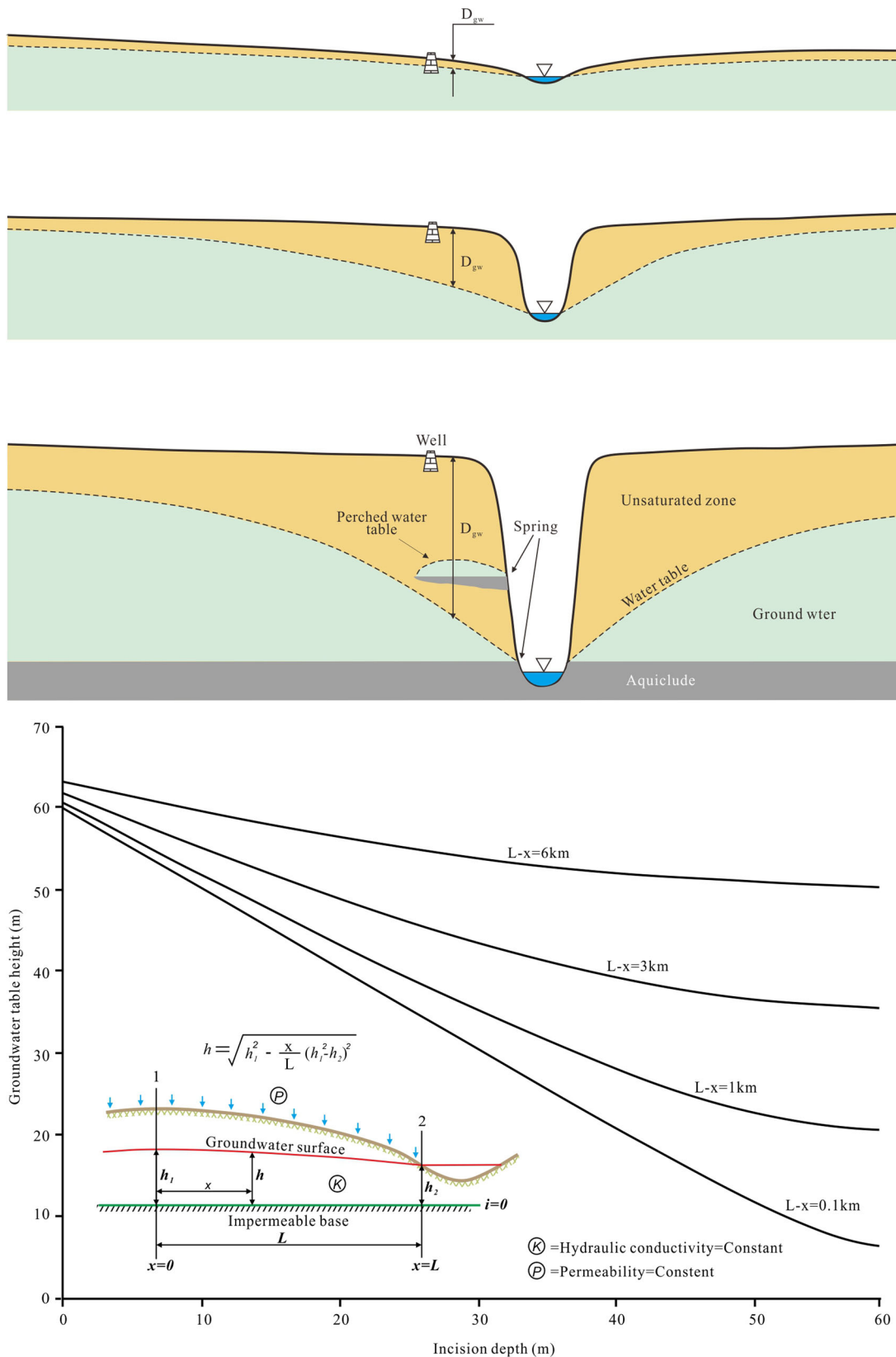
Fig. 6 Model-based estimation of ground water drops due to river incision. Groundwater drops depending on the degree of incision. D_{gw} (the riparian depth to groundwater) is greatest near the stream channel and shallower in more distal floodplain regions.

the city and, more importantly, there were large and small lakes and marshes in the area west of the city at that time, including the northern shore area of Batuwan Reservoir (refer to Figs. 3c-2)[22]. Despite the historical, political, military, and economic value of the area around Tongwan City[37], the city fell out of use after it was abandoned in 1227 CE[38]. Previous studies also tried to link the collapse of Tongwan City to climate changes[39]. However, as mentioned above, the lake environment around Sanchahe City was maintained until around 722 CE. Sanchahe City was built in 1316 CE, about 89 years after the abandonment of Tongwan City, and was abandoned in 1621 CE, about 394 years after the abandonment of Tongwan City. This means that the area around Tongwan City had already suffered from irreversible environmental degradation at the time when the conditions in the area around Sanchahe City were available for urban construction. The distance between the two cities is 35 km, which is too small for systematic changes in climate to produce such a great environmental difference in such a small area. On the other hand, the building and abandonment sequences of the two cities showed again that the headward erosion of the Wuding River first extended westward and then southward to capture the Salawusu River, resulting in rapid incision of the Salawusu River and suggesting that river incision has also played a dominant role in the abandonment of Tongwan City, but was not triggered by stream capture.

Conclusions

Since the discovery of "Ordos Man" in Salawusu region by E. Licent and Teilhard de Chardin during the period 1922–1928[7], extensive geological surveys and studies have been carried out over the last 100 years. In these studies, people are more likely to ask whether Salawusu has been so dry for tens of thousands of years or it is the result of climate change. Did people change the surrounding living organisms and environment? Or did changes in climate and environment cause people to change? Or did they influence each other[40]? Our study addresses all the questions asked and differs from previously published studies in two ways. First, we propose that the rapid incision of the Salawusu River is only due to a stream capture event rather than a rapid uplift of the Earth's movement which was long accepted by the public. Second, we suggest that the irreversible environmental degradation is caused only by riparian hydrological drought due to river incision rather than by systematic climate changes, and is therefore only limited to the river bank area rather than the entire Mu Us Desert. In addition, this study links the abandonment of Tongwan City with that of Sanchahe City, despite the fact that the reason for the abandonment of Tongwan City is still a matter of great debate in China. Even though the prevailing topic of interest now is the wet/dry or cold/warm shift governed by global climate variations that lead to desertification, our findings showed that geographic events must be considered in addition to climatic change when considering the causes of environmental influences on the archaeological record.

Methods

Mapping, field topographic surveying and sampling. Google images and images generated using ASTER data with Global Mapper software were used to observe channel patterns and calculate the sinuosity index of the river (Fig. 2a). To calculate the sinuosity index (SI), the formula of Brice (1964) was used (SI = length of channel/length of meander belt axis)[41]. An unmanned aerial vehicle (DJI Phantom 4) was used to taked field photographs.

Real-Time Kinematic (RTK) GPS (Supplementary Figs. 11a-11c) was used to obtain horizontal positions and vertical levels (altitudes) of abandoned wells, river terraces, river water surfaces, springs, sampling points, strata profiles (stratum), and modern and ancient river valley profiles and cross-sections (Supplementary Data 1).

Three trial pits of a depth of about 1 m were dug along the col and misfit areas that were found on the north bank of Batuwan Reservoir (Figs. 4a–c and 4g-1–4g-3),

and sand samples at different depths from each pit were collected for grain size analysis (Figs. 4g-1- 4g-3); sediment samples from the strata of Sanchahe City, including modern eolian sands, earth fills, heilu soils, the Dagouwan and Changchun formations, and modern rivers beneath the ancient city (Figs. 4g-5), were collected for grain size analysis and determination of sample permeability (Supplementary Fig. 3); sediment samples from different layers (strata) of a gully at about 100 m west of the col and the misfit on the north bank of Batuwan Reservoir (Figs. 4c and 4g-4) were collected for grain size analysis. 7 samples were taken for AMS ^{14}C tests, 4 for OSL tests, and 5 (2 well bricks, 1 city wall brick, and 2 brick fragments) for TL test.

Grain size analysis. All samples were analyzed to determine their grain-size distributions (GSDs) using a Mastersizer 2000M laser diffraction instrument (Malvern Instruments, Malvern, U.K.) at the Sediment Analysis Laboratory, School of Geography, South China Normal University, China. Both metric and Phi (Φ) scales were used for the analysis. Phi values are expressed as $Phi\ (\Phi) = -log2\ d$[42], where d is the grain diameter in millimeters. The graphical computational method of Folk and Ward (1957) was used to calculate the grain size statistical parameters: Mean (M_z), Sorting (σ_1), Skewness (Sk_1) and Kurtosis (K_g)[43] (Supplementary Table 4).

Building a hydrological model with ArcGIS to produce ancient stream channels. Digital Elevation Model (EDM) has been effectively used to reconstruct topography in studying stream capture events[44]. ArcGIS 10.2 (ESRI, 2013) was used to vectorize the area around Batuwan Reservoir in a 30 m resolution DEM provided by ASTER GDEM V 3 (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model Version 3), which then converted the vector into raster data, and then extracted the DEM without the river valleys using the Con Function from the map algebra available in ArcGIS. Afterwards, the DEM was converted into point elements, and then the gaps between the points were compared and interpolated using the inverse distance weighting method of ArcGIS to finally obtain a new DEM in which modern stream channels were filled up.

The sink filling in Hydrology toolset of ArcGIS is used to remove small anomalous values in the DEM that has no modern rivers, and then Flow Direction Analysis is carried out to create a raster of flow direction from each cell to its steepest downslope neighbor, and then Flow Accumulation Analysis is performed to create a raster of accumulated flow into each cell. With the help of ArcGIS, the confluence accumulation is reclassified. According to the resulting reclassification, the Stream to Feature tool is used for vectorization of the raster linear network around the area of Batwuwan Reservoir for which directionality is known. The flow direction of the old streams is symbolized in ArcGIS producing a GIS based hydrological modeling for ancient streams that flowed before the capture event. Figures 3c-1 illustrates the old streams before the capture event around the area of Batuwan Reservoir. In Figs. 3c-1, streams that are too short are omitted.

Modern streams were obtained directly from the 30 m resolution DEM using the same approach without filling the present river valleys. The map obtained by this way were superimposed on the map of old streams for the purpose of identifying the relationship between old and current streams (Figs. 3c-1).

Chronological dating. The distribution of the samples for chronological analysis is shown in Fig. 4 and Fig. S6. All ages are also reported in the BCE/CE system to allow a better comparison ^{14}C and TL/OSL ages.

AMS 14 C dating. The ages of 4 superficial deposit samples (bulk sediments) of the Dagouwan Formation along the banks of the Salawusu and Wuding Rivers, 2 artificial earth fill samples of the Dagouwan Formation in the Sanchahe City area, and 1 charcoal dust sample in one of the artificial earth fill samples next to the well were determined, respectively, at the Beta Analytic Radiocarbon Dating Laboratory, USA, using standard pretreatment procedures (Beta Analytic, 2022). All ^{14}C ages were calibrated to calendar years with a precision of ± 2σ by CALIB (version 8.2) using the IntCal20 database[45]. All AMS conventional and calibrated median ages are listed in Supplementary Table 1.

Measurements of radiocarbon (^{14}C) in lake samples are complicated by a "reservoir effect" due to the fact that the apparent age of the source reservoir differs from the contemporary atmospheric surface ^{14}C value[46]. The reservoir effect then certainly affects the preciseness of the carbon ages of the Dagouwan Formation. Some past studies in the Mu Us Desert have not made any corrections; whereas others have assumed that reservoir effects are constant over time[47,48] by dating living vegetation. In light of the spatial and temporal variations in carbonate content, the assumption of constancy seems unlikely to be valid. As a result, no reservoir correction was applied in this study. On the other hand, in most cases, radiocarbon dates on macroscopic charcoal may provide a reasonably accurate estimate of burning time because charcoal produced from the combustion of terrestrial biomass through photosynthetic fixation of atmospheric CO_2 is not subject to an inherent reservoir effect unless the burning species have slow growth rates and slow decay rates[49]. Therefore, charred dust (SCH-GC-AMS2*) may provide an AMS 14 C age that is not affected by the reservoir effect.

OSL dating. The ages of 2 sand samples from the coarse sand layer (at depths of 23–38 cm) and the overlying eolian sand (at depths of 12–23 cm) of trial Pit 2 in the floor of the col on the north bank of Batuwan Reservoir were dated using the OSL method by the OSL Dating Laboratory of South China Normal University in China in 2020. Two sand samples from the coarse sediments at the bottom of the 6th terrace dual structure at the upstream end of Batuwan Reservoir (Supplementary Fig. 8) were dated using the OSL method by Zhejiang Zhongke Institute of Luminescence Testing Technology, China, in 2017. All OSL ages obtained using the Central Age Model (CAM) and the Minimum Age Model (MAM) are listed in Supplementary Table 2.

Incomplete resetting of the OSL signal due to inadequate light exposure in the fluvial environment can result in age overestimation, especially for relatively young samples[50], and does not even guarantee that eolian transport was well bleached at the time of deposition[51]. As a result, both fluvial and eolian sediments in the study area are suspected to be poorly bleached. The use of a Central Age Model (CAM) may yield larger palaeodoses and optical ages; therefore, the minimum age model (MAM) is a suitable model that can be used to provide ages for incompletely bleached samples[52].

TL dating. Two well bricks taken from an abandoned well, two brick fragments obtained from the river deposits of the 5th terrace at about 400 m on the downstream side of Sanchahe City, and one city wall brick taken from within the city, all of which are fired materials, were dated by the TL method in the laboratories of Ralf Kotalla in Germany and the Shanghai Museum in China, respectively (Fig. S1). All TL ages are listed in Supplementary Table 3.

Permeability determination and hydrological calculations. The relationships between the permeability and grain size distribution indexes of the unconsolidated sediment of the strata and the present deposits are shown in Supplementary Fig. 3. Groundwater drops due to river incision based on the hydrological calculations is shown in Fig. 6.

Permeability determination. Hazen (1892) developed an empirical equation for predicting permeability from grain size distribution indexes[53]. Hazen's formula is most frequently found in the literature and is the empirical relationship commonly used to determine permeability:

$$K = C(D_{10})^2 \tag{1}$$

where K is the coefficient of permeability (cm/s), C is a constant ranging from 0.4 to 1.2, usually assumed to be 1.0, and D_{10} is the grain size corresponding to 10% by weight passing, also referred to as the effective size (mm)[53].

hydrological calculations. For unconfined aquifers where the saturated thickness is a function of the unknown groundwater head, approximate solutions can be obtained using the Dupuit–Forchheimer approach[54]. In Fig. 5, the parameter h (which must be measured from an impermeable base) represents both the groundwater head in the element and the height of the section through which flow occurs. In terms of continuity, the inflow plus the recharge Q_{in} must equal the outflow Q_{out} (which can be expressed as the inflow plus the rate of change of the inflow multiplied by the length of the element dx).

$$Q_{in} + qdx = Q_{out} = Q_{in} + \left(\frac{dQ_{in}}{dx}\right)dx \tag{2}$$

where q is the vertical recharge, hence

$$\frac{dQ_{in}}{dx} = q.$$

From Darcy's Law

$$v_x = -K_x \frac{dh}{dx} \tag{3}$$

where v_x is the Darcy velocity in the x direction and K_x is the hydraulic conductivity, and

$$Q_{in} = -K\frac{dh}{dx}h\,(\text{hydraulic conductivity} \times \text{head gradient} \times \text{saturated depth})\,\text{thus}$$

$$\frac{d}{dx}\left(K\frac{dh}{dx}h\right) = -q \tag{4}$$

From the differentiation of products

$$\frac{d[h \cdot h]}{dx} = h\frac{dh}{dx} + \frac{dh}{dx}h,$$

Equation (4) becomes

$$\frac{d}{dx}\left(\frac{dh^2}{dx}\right) = -\frac{2q}{K} \tag{5}$$

where K is a constant.

By integrating Eq. (5), the Dupuit–Forchheimer equation, twice and substituting the conditions that at $x = 0$, $h = $ h1 and at $x = $ L, $h = $ h2, in Fig. 6, the following equation for the variation in groundwater head (and hence the water table elevation) is obtained (see Fig. 6),

$$h^2 = h_1^2 - \frac{h_1^2 - h_2^2}{L}x \tag{6}$$

Data availability

The data that supports the findings of this study, including the supplementary figures of field photographs, the supplementary tables of age dating and grain size parameters, are included in Supplementary information. Source data for RTK leveling and grain size analysis are available at https://doi.org/10.6084/m9.figshare.21652352.

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Author contributions

W.W. conceived the ideas and interpretations. The manuscript was written and prepared by W.W. Relevant data were contributed by W.W., B.S.L. and X.H.W. L.B.X. contributed to OSL dating. W.W., B.S.L., X.H.W., R.H.H. and J.F. conducted field work. J.F. performed experiments. M.Q.Q. contributed to GIS analysis. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information