Geomorphological Evolution of the Hengshixi Anticline of The Three Gorges Area Through Isobases: A Model of Yangtze River Capture

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Abstract **— The evolution of Yangtze drainage system and the Three Gorges has aroused great interest for many years. In the "Three Gorges", the Wu Gorge is formed by the Yangtze cuts through the Hengshixi Anticline, and the Wushan Mountain is the highest mountain in the "Three Gorges". The Wu Gorge is also the shortest gorge, which also formed in the simplest geological background. So we choose Hengshixi anticline in our study in order to find out the fluvial and geomorphic evolution process of it. Isobase maps of second-third and third-fourth order streams and vertical dissection maps was made for two drainage of the Hengshixi anticline to reconstruct the former geomorphological surface of the area in order to understand the processes that are responsible of the genesis of the gorges in the area. The gorges were firstly identified and their morphometric parameters were analyzed. The results show that the former models that explain the genesis of those gorges (antecedence, superimposition, underground rivers top collapse) cannot be backed up by the evidence gathered. The gorges, as it appears on the data gathered, are the result of river piracy by headwater erosion in an asymmetric folds environment characterized by the development of strike stream, dip streams and antidip streams. The birth of the current Yangtze River by the piracy of the Chuanjiang and the Xiajiang were by such processes. The piracy disorganized the drainage system of the area, some beheaded rivers just formed lakes that by overflow are responsible of some later gorges the chronology of that river piracy is still need more studies.**

Keywords - Yangtze, isobase map; Three Gorges; evolution of drainage system

I. INTRODUCTION

From west to east, the Yangtze River flows through the Sichuan Basin, and then enters a mountainous area constituted by a succession of anticlines and synclines oriented SW-NE. It flows quite perpendicular to the anticlines through steep gorges, well known as the Three Gorges named respectively from West to East as the Qutang Gorge, The Wu Gorge and the Xiling Gorge. In addition to those Three Gorges, many other gorges exist in the area built by the tributaries of the Yangtze River. Those tributaries flow in a North-South direction in the left side of the Yangtze and SW-NE in the right side. The gorges in the Three Gorges area have driven the attention of Geomorphologists since the beginning of the 20th century [1-7]. All those authors have tried to answer two main questions:How and when the Yangtze River made its course through those Gorges. Different hypotheses have been formulated: antecedence [8], superimposition [2, 9], complex combination of headwater erosion, underground rivers collapse triggered by an earthquake [10] , river piracy [11, 12]. These hypotheses based on the study of river terraces [13], planation surfaces [4] , and the analysis of the sediment deposit in the Jianghan Plain [14, 15] show that there is still no consensus on the origin of the gorges. The problem became more complex as it has been found that the area used to be the drainage divide of two paleo-rivers (the Chuanjiang flowing west and the Xiajiang flowing east) and that one of the gorge is the place where the river piracy took place [10, 16, 17]. This paper aims to evaluate those hypotheses by using isobase maps built from digital elevation model and to propose a model for the genesis of these gorges. Isobase maps also called base level maps express a relationship between valley order and topography [18] . They draw erosional surfaces hence isobase surfaces are related to erosional cycles [19-22]. As isobase maps can reconstruct different erosional stages of a drainage basin [23], they were used to reconstruct the different changes of the gorges on the anticline so to find out the processes that built them.

The Hengshixi anticline, a branch of the Compound Qiyaoshan Anticline, located in the middle part of the Three Gorges area (well known in China as Wushan: Wu Mountains) bears the most important number of gorges, this could be seen in Fig. (1). Beside the Wu Gorge which is the most important of the three gorges, this anticline counts another eight gorges. Thus, it offers the geological and geomorphological conditions to evaluate those hypotheses.

II. METHODS

Different authors described the steps to build isobase maps [19-21]. Isobase maps are built through three different steps: stream order definition, superimposition of stream order on topographical relief, then isobase construction. In this paper, we used ASTER GDEM 30m resolution images. They were processed using GRASS GIS software on a Linux environment.

The river networks of the area was first extracted using the r.watershed command using a threshold of 50 to get a more detailed stream network; the MDF (Multi-directional

Flow) was used. The resulting stream raster was used to get the stream order using a GRASS add-ons script called r.stream.order developed by Jarek Jasiewicz who computed the Horton, Strahler, Shreeve and Hack stream orders [24]. In this research only the Strahler order results were used [25, 26] . The drainage basins were delineated using an overlay of the stream order and the elevation raster maps.

Among the drainage basin 2 drainages basins crosses the Hengshixi anticlines. Those two drainages were used for further analysis.

The Strahler order raster image was converted into a vector map and the second and third order streams were extracted. A 40 meters Contour lines map was made for those two drainage basins, then superimposed to the second and third order streams vector map. Wherever a contour line crosses a second or third order streams a vector point was made. Those points were then converted into a raster map and an isobase surface was made by surface generation using the spline methods. The same methods were used for the coupled third and fourth, fourth and fifth stream orders. Three elevation profiles were made: a profile of the current elevation raster map, of the second and third order isobase maps and of the third and fourth order image isobase map to compare the erosional surface.

Concomitantly some morphometric analysis was made. The vector contour maps was converted to 3D vector map and overlaid to the elevation image. That gave a 3D view of the anticline and the gorges. The gorges were identified, measured and classified as V, from 1 to 9, from south to north. The slope maps of the area was made then reclassified into three classes for better readability: 0-10 degrees slopes, 10 to 30 degrees and 30 degrees slope and above. This slope map was made to assess the symmetry of the anticline that is to find out if the two sides of the anticline have the same slope.

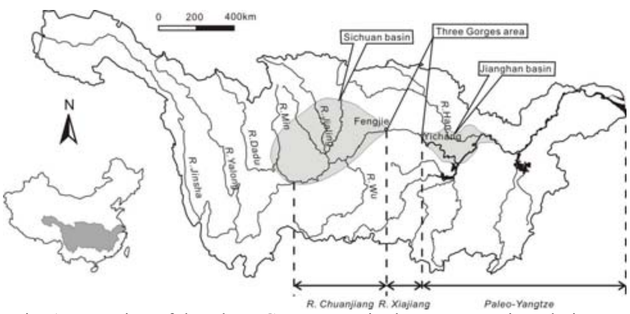

Fig. 1. Location of the Three Gorges area in the Yangtze River drainage basin.

III. REGIONAL SETTING

Located at the middle reaches of the Yangtze River, the Three Gorges region is the mountainous area that separates the Sichuan Basin in the west from the Jianghan Basin in the east. The geology of the area is mainly composed of sedimentary rocks, which span a very long time range; from Quaternary colluviums and alluvium to Sinian carbonate rocks. The sedimentary rocks lay on some places on Archean metamorphic rocks of the Kongling Group, the oldest rocks in Yangtze Craton. According to the rock types and ages, the Three Gorges region can be classified into three geological regions.

The first region, from Fengjie to Badong, shows interbedded Triassic limestone, shale and dolomite; the second, from Badong to Zigui, is a Jurassic basin, called Zigui basin; the eastern area, from Zigui to Yichang, is a granitic area which constitutes the core of the Huangling Anticline, where the Xiling Gorge and the Three Gorges dam are located. The northern part of Huangling anticline is composed of pre-Sinian metamorphic and some ultrabasic rocks referring to Fig. 2.

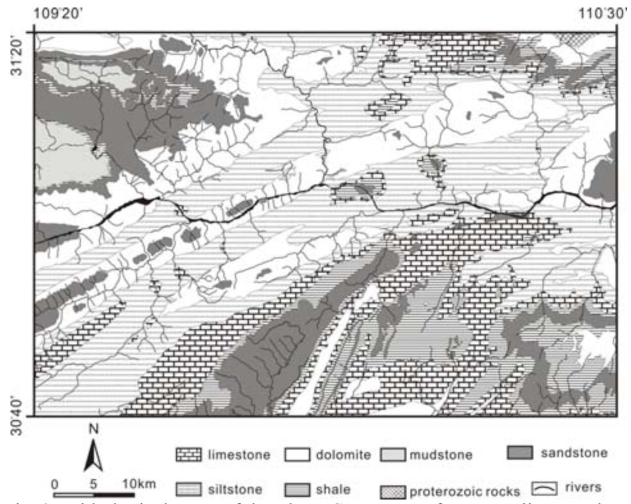

Fig. 2. Lithological maps of the Three Gorges area from Fengjie to Badong area.

The regional geological structures dominantly trend NE–SW, and are associated with the major anticline–syncline fold systems. The most significant one is the Compound Qiyaoshan Anticline, which has two branches named respectively from west to east the Qiyaoshan Anticline and the Hengshixi anticline. These two anticlines are separated by the Wushan Syncline. The Yangtze River in its journey to the east cut these anticlines quite perpendicular to their trend by forming magnificent gorges. The river crosses the Qiyaoshan Anticline (also called Qiyueshan Mountains) through the Qutang Gorge. It crosses the Hengshixi anticline through the Wu Gorge. The Hengshixi Anticline consists mainly of middle Triassic limestone of the Badong formation, and of Early Triassic dolomite of the Jialingjiang formation. As stated before, the Hengshixi anticline is also cut by many other tributaries of the Yangtze River always through deep gorges. In some of the gorges of the Hengshixi Anticline, the rivers have incised down into the Ordovician sandstone and Permian shale, this was shown in Fig. 3.

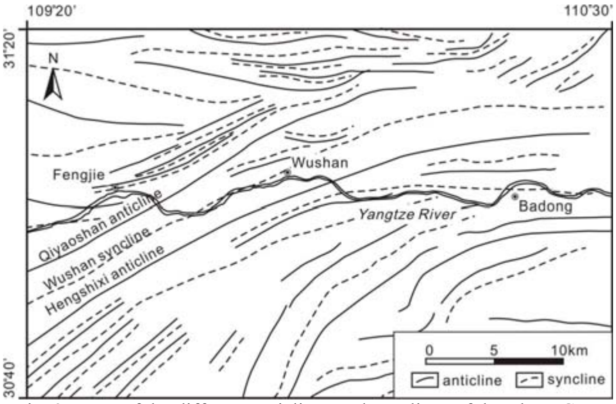

Fig. 3. Map of the different anticlines and synclines of the Three Gorges area.

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IV. RESULTS

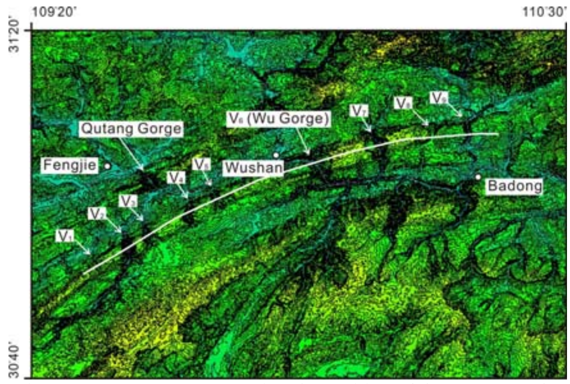

Fig. 4. 3D DEM map presenting the position of the gorges on the Hengshixi Anticline and the line used for longitudinal profile along the anticline.

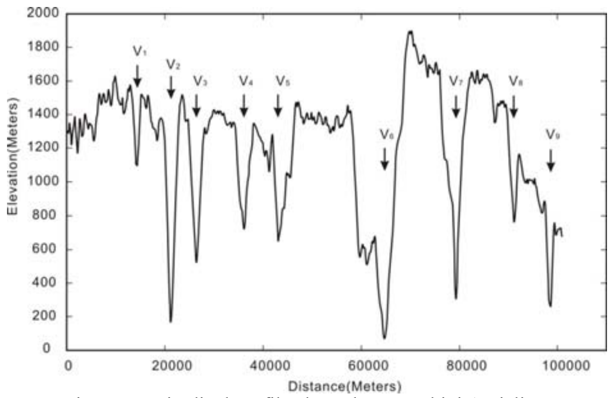

Fig. 5. Longitudinal profile along the Hengshixi Anticline.

The Hengshixi anticline is about 100km long oriented SW-NE (bearing 65 degrees). A gorge is found wherever a river crosses the anticline. 9 gorges were identified in Fig. (4). In Fig. (5), longitudinal profile was made along the Hengshixi Anticline, and the characteristics of 9 gorges are presented here. The results were listed in Table 1.

TAB. 1. THE CHARACTERISTICS OF THE NINE GORGES IN THE HENGSHIXI ANTICLINE

Gorges	Length meters)	Bearing (degrees)	Stream order
V_1	4786	154	1
V_2	3846	158	5
V_3	5504	131	5
V_4	4829	167	3
V_5	4997	148	3
V_6	11998	135	6
V_7	8678	160	5
V_8	3623	199	2
V_9	5076	174	5

Table 1 show that the gorges are quite large. The longest (V_6) correspond to the Wu Gorge, which is the most important gorge in the area and belongs to the Yangtze River's channel. The other gorges belong to different tributaries of the Yangtze. V_1 to V_5 belong to the southern tributaries while V_7 to V_9 belong to the northern tributaries. The bearings show that the Gorges cut the anticline quite perpendicularly in an N-S direction or a NW-SE direction. Those tributaries have different stream orders, thus different importance in length and drainage area. V_6 belonging to the Yangtze River has the highest stream number. 4 gorges are occupied by rivers of 5^{th} order, 2 of 3^{rd}order, 1 of 1^{st} and 2^{nd}. The elevation of the gorges valley walls appears in a table below, and the results were shown in Table 2.

TAB. 2. THE ELEVATION OF THE GORGE VALLEY WALLS.

Gorges	Left(meters)	Right(meters)
V_1	1540	1530
V_2	1300	1420
V_3	1350	1350
V_4	1350	1350
V_5	1225	1190
V_6	1300	1890
V_7	1750	1625
V_8	1295	1260
V_9	930	870

Except for V3 and V4 there seems to be a difference in the valley side elevation of all the other gorges. The following figure gives a better view of those differences we can see them in Fig. (5). V6 and V_7 can be seen to be at the highest elevation of the anticline. The elevation decreases in both directions from V_6 and V_7. The elevation from V_1 to V_5 is quite regular, while from V_7 to the North there is a rapid drop in elevation. From the curve it appears that the left walls of V_7 asymmetrically divide the anticline into two sides.

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Isobase surfaces of second-third, third-fourth, fourth-fifth order streams were made for two drainage basins, which flow through those gorges. The first drainage basin and its tributaries flow to the Yangtze River between the Wu and the Qutang Gorges crossing the Hengshixi anticline through V_1, V_2, and V_3. The second drainage basin coming from the North reaches the Yangtze River just before the Wu Gorge; it crosses the anticline through V_7. Those drainage basins can be used to reconstruct the erosional surfaces of the anticlines and can help understand the processes that are responsible for the genesis of the gorges.

The comparison of those two drainage basin shows that they are quite different in many ways. The southern basin is longer more developed. It is quite 4 times longer than the northern basin, and its drainage basin is more than 5 times bigger. The results were shown in Table 3.

TAB. 3. THE DRAINAGE PROPERTIES OF NORTHERN AND SOUTHERN BASINS IN THE STUDY AREA.

Drainage properties	Northern basin	Southern basin
Max order	6	7
Stream number	1215	5746
Stream length (km)	697.1	3313.4
Total area(km^2)	258	1233.7
Bifurcation ratio	4.003	4.33
Drainage density (km/km^2)	2.7	2.69
Stream frequency	4.7	4.65
Circularity ratio	0.65	0.56

Questions just arise: why such long river passes only through small gorges in the southern part of the anticline while the northern river, which is shorter, flows through the second gorge of the area (V7)? How the northern drainage basin built up its drainage basin and gets the strength to cut than V_7? The analysis of the isobase should give more evidence to answer those two questions.

The different isobase maps of second-third, third-fourth, fourth-fifth order streams are presented in the following figures.

The isobase maps show a change in base levels through time. Between the geomorphic stage of the second-third order stream and that of the third-fourth order stream the base level was lowered from 144 meters to 96 as the result of landscape degradation through normal erosion. From the second-third order isobase to nowadays the base level have risen. The reason could be the effect of uplift but the non-availability of uplift data for the three gorges area makes it difficult to confirm such hypothesis, but as it appears from this analysis the base level have risen by 1 meters since the stage of the second and third order stream. The maps also show that at the beginning there was an internal depression inside the drainage area between the upper stream of the river and the Gorge. Such depression was filled with water and a lake was formed there. If one continues to build the isobase map for higher stream order, the gorge V_7 just closes up and the presence of the internal depression is expressed with more evidence. This process is shown in Fig. 6. A lake used to exist in the center of the drainage basin and later the streams of the right side of the anticline by headwater erosion connected to the lake which by overflow built such magnificent gorge in a quite short time. A lake spilling across the limestone anticline will be able to cut down in a short amount of time that large and deep gorge [27]. This process was shown in the sketch map in Fig. 7. That gorge (V_7) was then the result of an overflow process.

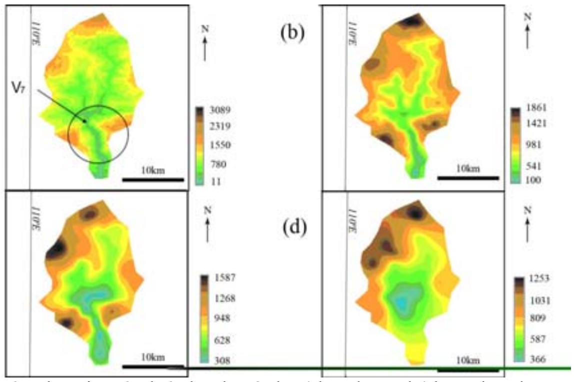

Fig. 6. Elevation, 2nd -3rd order, 3rd – 4th order and 4th – 5th order streams isobases maps of the northern drainage basin

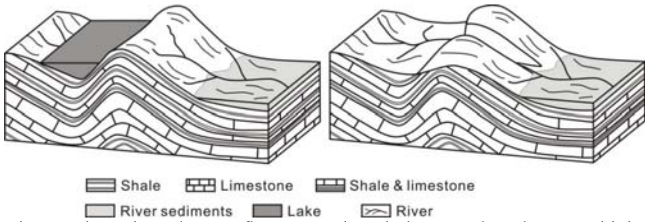

Fig. 7. River piracy by overflow as we thought happened on the Hengshixi Anticline.

In Fig. 8, a north-south profile of the drainage basin shows a disruption or a disturbance between the third-fourth order isobase surface and the second-third isobase and the current elevation. The analyses of the profile show that the current surface is the dissected surface of the second-third order stream isobase surface for all along the profile. The third-fourth order surface is synchronous with the other surfaces from the drainage divide to the gorge. After the Gorge, the third-fourth order surface is just the inversion of the other two surface profiles. The reason of such change should be found in a drainage reorganization of the lower drainage area especially where the river connects to the Yangtze River. What causes this disturbance is still unknown. One can think of an earthquake or may be it is at that period that the two rivers captured to form the Yangtze.

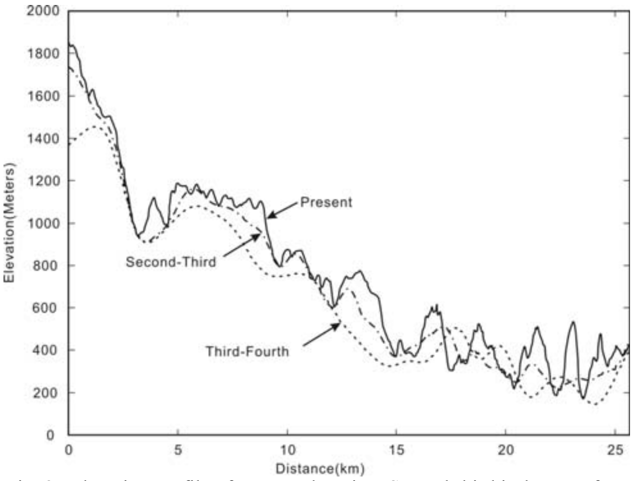

Fig. 8. Elevation profile of current elevation, Second-third isobase surface, and Third-fourth isobase surface.

In contrast with the northern basin the southern one is well developed. In Fig. 10, the isobase maps of different order show differences of the shape and extent of the gorges at different geomorphological or erosional stage. The Gorge V_1, the smallest gorge on the Hengshixi anticline, well visible on the current elevation map, became separated into 2 streams flowing on both side of the anticline on the second and third order isobase map. In the third-fourth order stream isobase map the gorge V_1 disappears completely. The other gorges V_2 and V_3 also change in shape and length on the three isobase maps becoming smaller in size and extent. It appears that in southern basin riverhead erosion and river piracy was the preeminent process that built the gorges. Two streams on the two side of the anticline erode headward, get connected and the lower stream just absorb the higher one.

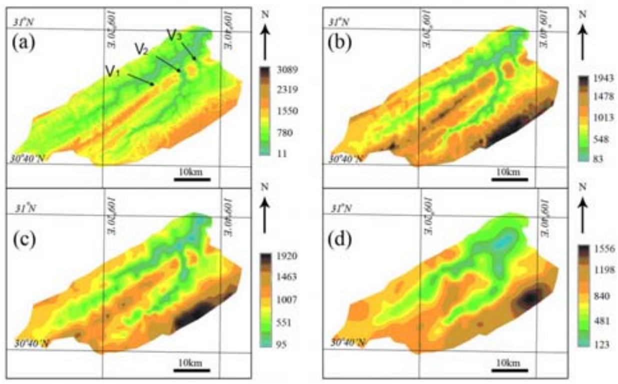

Fig. 9. Elevation, 2nd -3rd order, 3rd – 4th order and 4th – 5th order streams isobases maps of the southern drainage basin.

In Fig. 10, the analysis of the isobase profiles compared to the profile of the current elevation shows no great change in the profile of the three elevation maps. They are synchronous during all the period with only small changes as it appears on the Fig. (10), even if one can note an important downward dissection of the Gorges.

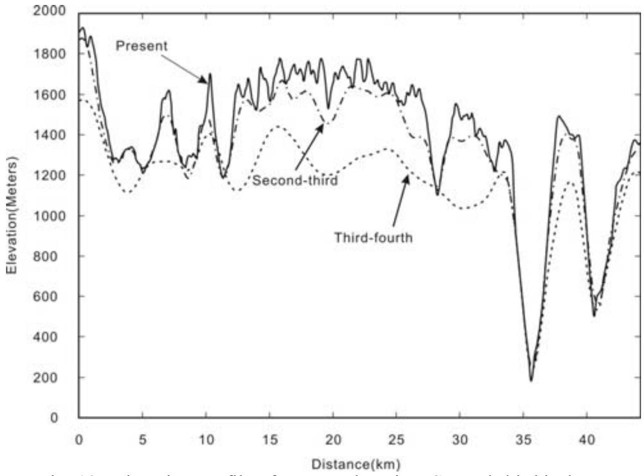

Fig. 10. Elevation profile of current elevation, Second-third isobase surface, and Third-fourth isobase surface.

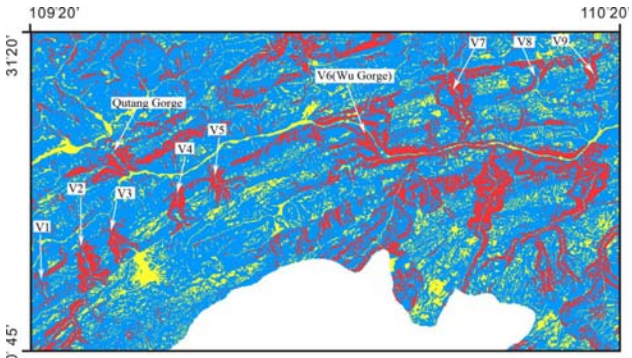

Fig. 11. Slope map of the Hengshixi: yellow (0- 10°), blue (10°- 30°), Red (above 30°).

The Red seems to appear more along the left side of the anticline showing its asymmetry with the left side characterized by steep slopes and the right side by quasi flat slopes as is confirmed by the figure below.

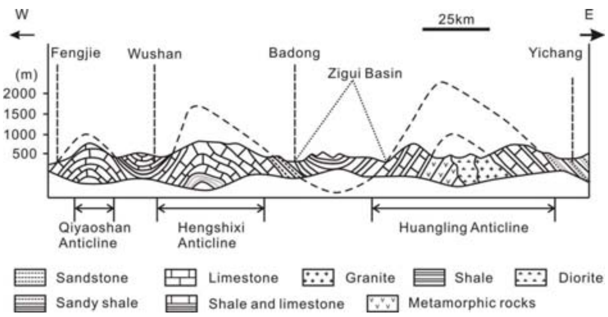

Fig. 12. Asymmetry of the Hengshixi Anticline.

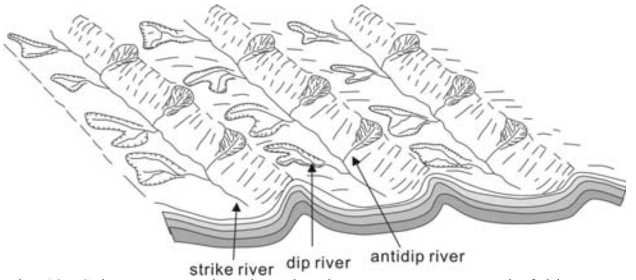

Fig. 13. Scheme presenting river development on asymmetric folds system such as the Hengshixi Anticline

These results are very significant to the formation of the Yangtze River in this area, which flow through the Wu Gorge. It can be believed that the capture of the Chuanjiang flowing west and the Xiajiang flowing east happened in three steps.

- Firstly, because of the morphotectonic structure of the three gorges constituted by a succession of anticlines and synclines, strike streams started to develop and extend on the synclines as it happens in such area [28, 31-33]. This stage was shown in Fig. 14A.
- Secondly, headwater erosion started to develop on the side of the different anticlines. Because of the difference of sloping between the two sides of the anticlines, dip streams formed on the right side while anti-dip streams developed on the right side. The Fig. 13 explains why the right side stream has cut very deep valley as it can be seen on the 3D surface map. This stage was shown in Fig. 14B.
- Finally, an anti-dip stream captured one of the dip stream's head and the two rivers started to flow east. The capture site just lowered down under the forces of riverbed erosion to give the steep Wu Gorge (V_6) as seen today. This stage was shown in Fig. 14C.The beheaded rivers disappeared or organized into an internal drainage with lakes that also later gave birth to gorges in the area by overflow as for V_7.

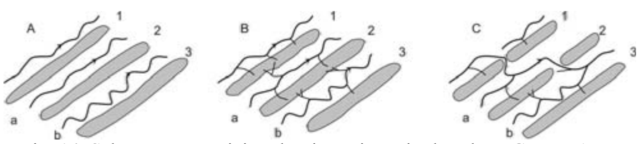

Fig. 14 Scheme summarizing the river piracy in the Three Gorges Area that gave birth to the current Yangtze River.

The result also shows that the Gorges of the river are not of antecedence nor superimposition origin but are the result of headwater erosion and river piracy in an asymmetric fold context. The third hypothesis that combined headwater erosion, underground rivers collapse triggered by an earthquake seems also not evident because there is currently no evidence to back it up. We can then at the light of the result obtained here said with high probability that the Gorges are the result of river piracy by headwater erosion and for some of them like V_7, the result of overflow even if the processes of genesis of V_7 seems to be an exception in the area..

V. CONCLUSION

The former models that explain the genesis of those gorges (antecedence, superimposition, underground rivers top collapse) cannot be backed up by the evidence gathered. The gorges, as it appears on the data gathered, are the result of river piracy by headwater erosion in an asymmetric folds environment characterized by the development of strike stream, dip streams and antidip streams. The modern Yangtze River was form via river piracy. The piracy disorganized the drainage system of the area, some beheaded rivers just formed lakes that by overflow are responsible of some later gorges the chronology of that river piracy is still need more studies.

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REFERENCES

[1] Barbour G B. "Physiographic history of the Yangtze," T*he Geographical Journal*, vol. 87, pp. 17-34,1936.

[2] J. S. Lee Y T C. " Geology of the gorge district of the Yangtze (from Ichange to Tzekuei) with special reference to the development of the gorges," *Bulletin of the Geological Society of China*, vol. 3, no.3-4, pp.351–92, 1924.

[3] Lee C Y. "The development of the upper Yangtze valley," *Bulletin of the Geological Society of China*, vol. 13, no.1, pp.107-18(in Chinese) , 1934,.

[4] Li J J, Xie S Y, Kuang M S. "Geomorphic evolution of the Yangtze Gorges and the time of their formation," *Geomorphology*, vol. 41, no.2-3, pp. 125-35, 2001.

[5] Yang D Y. "Origin and evolution of the Yangtze Gorges," *Journal of Nanjing University*, *Natural Sciences*, vol. 24, no.3, pp. 466-73, 1988.

[6] Yei L F, Xie, J.R., "Geological structure and physiographic developing history of the Yangtze River," *Geological Report*, vol. 7, pp.22-30, 1925.

[7] Zhang Y F, Li C A, WANG Q L, et al. "Magnetism parameters characteristics of drilling deposits in Jianghan Plain and indication for forming of the Yangtze River Three Gorges," *Chinese Science Bulletin*, vol. 53, no.4, pp. 584-90, 2008.

[8] Lee C Y. The development of the upper Yangtze Valley. *Bulletin of the Geological Society of China*, vol. 3, pp. 107-17, 1933.

[9] Ye L F, Xie J R. Structural geology and geological history of the Yangtze eastward from Wushan. *Geological Report*, no.7, pp. 69-70, 1925.

[10] Liu C Z. Geo-hazard initiation and assessment in the Three Gorges Reservoir," in *Landslide Disaster Mitigation in Three Gorges Reservoir, China*. Springer. pp. 607, 2009.

[11] Clark M K, Schoenbohm L M, Royden L H, et al. Surface uplift, tectonics, and erosion of eastern Tibet from large-scale drainage patterns. Tectonics, vol. 23, no.1, 2004.

[12] Richardson N J, Densmore A L, Seward D, et al. Did incision of the Three Gorges begin in the Eocene? Geology, vol. 38, no.6, pp. 551-554, 2010.

[13] Yang D Y. The genesis and evolution of Yangtze Gorges. Journal of Nanjing University (Natural Science Edition), vol. 24, no.3, pp. 466-74(in Chinese with English abstract), 1988.

[14] Wang J, Li C A, Yang Y, et al. Detrital zircon geochronology and provenance of core sediments in Zhoulao Town, Jianghan plain, China. Journal of Earth Science, vol. 21, no.3, pp. 257-71, 2010.

[15] Xiang F, Zhu L D, Wang C S, et al. Quaternary sediment in the Yichang area: Implications for the formation of the Three Gorges of the Yangtze River. Geomorphology, vol. 85, no.3-4, pp. 249-58, 2007.

[16] Zhao C. River capture and origin of the Yangtze Gorges. Journal of Changchun University of Earth Sciences, vol. 26, no.4, pp. 428-33, 1996.

[17] Zhao C, Wang, S.M., New recognition of river captures in the Three Gorges and its upper reaches. Journal of University of Hydraulic and Electric Engineering, vol. 22, no.3, pp. 196-9, 2000.

[18] Filosofov V P. Brief guide to morphometric methods in search of tectonic structures. Saratov, pp. Saratov Univ. Publ. House, 1960.

[19] Golts S, Rosenthal, E., A morphotectonic map of northern Arava in Israel, derived from isobase lines. Geomorphology, vol. 7, pp.305-15, 1993.

[20] Grohmann C H. Morphometric analysis in geographic information systems, pp. applications of free software GRASS and R. Computers & Geosciences, vol. 30, no.9-10, pp. 1055-67, 2004.

[21] Grohmann C H, Riccomini C, Alves F M. SRTM-based morphotectonic analysis of the Poços de Caldas Alkaline Massif, southeastern Brazil. Computers & Geosciences, vol. 33, no.1, pp. 10-9, 2007.

[22] Grohmann C H, Riccomini, C., Chamani, M.A.C.,. Regional scale analysis of landform configuration with base-level maps. Hydrol Earth Syst Sci, Discuss, 8, pp.89-110, 2011.

[23] Mezosi G, Kiss R. Geomorphometrical Mapping of Relief-Dissection Using GIS [M]//Westort C Y. Digital earth moving. LNCS; Springer-Verlag Berlin Heidelberg, 2001.

[24] Jasiewicz J, Metz M. A new GRASS GIS toolkit for Hortonian analysis of drainage networks. Computers & Geosciences, vol. 37, no.8, pp. 1162-73, 2011.

[25] Horton R E. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geological Society of America Bulletin, vol. 56, no.3, pp. 275-370, 1945.

[26] Strahler A N., Hypotheses of stream development in the folded Appalachians of Pennsylvania Appalachians of Pennsylvania. Geological Society of America Bulletin, vol. 56, no.1, pp. 45-88, 1945.

[27] Douglass J, Meek, N., Dorn, R.I., Schmeeckle, M.W., A criteria-based methodology for determining the mechanism of transverse drainage development, with application to the southwestern United States. GSA Bulletin, vol. 121, no.3/4, pp. 586-98, 2009.

[28] Gregory K J. Fold //Goudie A S. Encyclopedia of Geomorpology. London, New York; Routledge. pp. 1202, 2004.

[29] Humphrey N F, Konrad S K. River incision or diversion in response to bedrock uplift. Geology, vol. 28, no.1, pp. 43-6, 2000.

[30] Stokes M, Mather, A.E.,. Tectonic origin and evolution of a transverse drainage, pp. the Rio Almanzora, Betic Cordillera, Southeast Spain. Geomorphology, vol. 50, pp.59-81, 2003.

[31] Bishop P. Drainage rearrangement by river capture, beheading and diversion. Progress in Physical Geography, vol. 19, no.4, pp. 449-73, 1995.

[32] Montgomery D R, Dietrich W E. Where do channels begin? Nature (London), vol. 336, no.6196, pp. 232-234, 1988.

[33] Twidale C R. River patterns and their meaning. Earth-Science Reviews, vol. 67, no.3-4, pp. 159-218, 2004.