Subsurface old drainage detection and paleoenvironment analysis using spaceborne radar images in Alxa Plateau

GUO Huadong (郭华东)[1], LIU Hao (刘 浩)[1], WANG Xinyuan (王心源)[2,1], SHAO Yun (邵 芸)[1] & SUN Yan (孙 岩)[2]

1. Laboratory of Remote Sensing Information Sciences, Institute of Remote Sensing Applications, Chinese Academy of Sciences, Beijing 100101, China;
2. Department of Earth Sciences, Nanjing University, Nanjing 210093, China
Correspondence should be addressed to Guo Huadong (email: guohd@irsa.irsa.ac.cn)

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Abstract For geological and environmental research in an arid area, a unique advantage of radar remote sensing is that radar wave can penetrate a certain layer of dry sand (a few centimeters to meters thick) to reach the buried bedrock. The penetration capability is able to reveal the subsurface geological structure and old drainage paths. Based on the analysis of SIR-A, SIR-B, SIR-C, Radarsat ScanSAR, Landsat MSS and Landsat TM images acquired on different dates and the investigations made in several field trips in Alxa Plateau of Inner Mongolia, a number of old river valley and lake basins buried by wind-blown sand were recognized. Two parallel old drainage systems in the north and middle of the study area are delineated. The study suggests that the moving sand belts mainly follow the old drainage courses. This study also establishes a preliminary drainage evolution model for an area of about 300 000 km^2 since the Tertiary, and finds that the Alxa Plateau was once an area with many rivers and lakes with a warm and humid climate. The relief reversion caused by neotectonic movement since "Qinghai-Tibet movement" is also analyzed.

Keywords: **radar remote sensing, subsurface, old drainage, paleoenvironmental analysis, Alxa Plateau.**

Differing from optical remote sensing, synthetic aperture radar (SAR), with the ability of all-time, all-weather imaging and the capability to penetrate dry sand and soil, has become one of the most important techniques for earth observation[1, 2]. In addition to SAR penetration capability, radar remote sensing can also detect micro-relief variations, map vegetation distribution, and is sensitive to surface roughness and water content. Thus, it is superior to other remote sensing means for geological and environmental studies in arid areas. In 1982, McCauley's group reported that SIR-A penetrated the extremely dry Selima Sand Sheet, revealing previously unknown buried valleys, geologic structures, and possible Stone Age occupation sites[3]. Guo et al. found that SIR-A penetrated the some one meter thick sand sheet, and detected underneath bedrock in Altan Aobao area of Alxa Plateau[4, 5] in Inner Mongolia. Based on the analysis of various remote sensing data and investigations made in several field trips during a period of more than ten years, such a point of view was reached——the "sand rivers", which are the courses of shifting sand showing up as wide valleys in the Alxa Plateau, are old river valleys uplifted and transformed by neotectonic movement. Based on this understanding and other geographical materials, the preliminary drainage evolution model of this 300 000 km^2 area since the Tertiary is established.

1 Spaceborne SAR data and physical geographic condition of the test area

1.1 Spaceborne radar data of the test area

Four kinds of spaceborne radar data were used in this study, including three shuttle imaging radar (SIR-A, SIR-B, SIR-C) data and a scene of Radarsat ScanSAR wide mode data. SIR-A mission was carried out in 1981, an optically recording SAR system operated at L-band and HH polarization. SIR-B mission was conducted in 1984, which was a digital imaging SAR system with variable incidence angles, improved SNR and dynamic range[5]. SIR-C/X-SAR mission was performed in April and October 1994. This sensor, composed of L-, C-band SAR developed by the USA and X band SAR jointly developed by Germany and Italy, is the most advanced spaceborne SAR system in the world. It works on L, C and X bands simultaneously with polarimetric capability for L and C band[6, 7]. Canadian Radarsat was launched in November 1995, and is the first commercially operated SAR system in the world. It has seven beam modes and twenty-five imaging modes. ScanSAR mode has swath of 300 km (narrow) and 500 km (wide), and resolution of 50 m and 100 m respectively. The parameters of four sensors are listed in table 1, and SAR data coverage is shown in figs. 1 and 3.

Table 1 System parameters of SIR-A, SIR-B, SIR-C/X-SAR and Radarsat scan SAR mode

System parameters	Radarsat scan SAR	SIR-A	SIR-B	SIR-C/X-SAR	
Orbit altitude/km	823	260	352	225	
Band	C	L	L	L/C	X
Wavelength/cm	5.3	23.5	23.5	23.5/5.3	3.1
Incidence angle/(°)	51—70	47	15—60	20—55	20—55
Polarization	HH	HH	HH	HH,HV,VH,VV	VV
Azimuth resolution/m	104.7	40	25	30×30	
Range resolution/m	110.1	40	48—17	13×26	10×20
Swath/km	500	50	20—40	15—90	15—60
Data recording	digital	optical	digital	digital	

1.2 Physical geography of the test area

The Alxa Plateau is bounded on the east by Helan Mountains, on the west by Mazongshan Mountains, on the north by Mongolia and on the south by Hexi Corridor (fig. 1). It has an area of 300 000 km^2, an average altitude of 1 000 m a.s.l., and a relief that depresses gradually from east to west and from south to north. Gobi, desert and relict mountain are the major landforms. In addition to the Badain Jaran, Tengger and Ulan Buh deserts, there are also several small deserts scattered in the plateau, such as Yamalik and Benbatai deserts[8]. Located in the inland of northwestern China and adjacent to Mongolia high-pressure center, this plateau presents a typical arid continental climate characterized by very little rainfall and prevailing west and northwest wind[9]. From east to west precipitation and humidity decreases, but evaporation and wind-speed increases gradually. Under such a climate condition and due to high permeability of sand and gravel surface, the drainage system is poorly developed in this plateau. Except the east of the plateau which the

Yellow River passes through, the rest parts are all composed of seasonal rivers and inland lakes. The Ejin River is the biggest seasonal inland river in this plateau, with running water only from July to October every year. Jartai, Gaxun Nur and Sogo Nur are three major lakes, but they almost dry up.

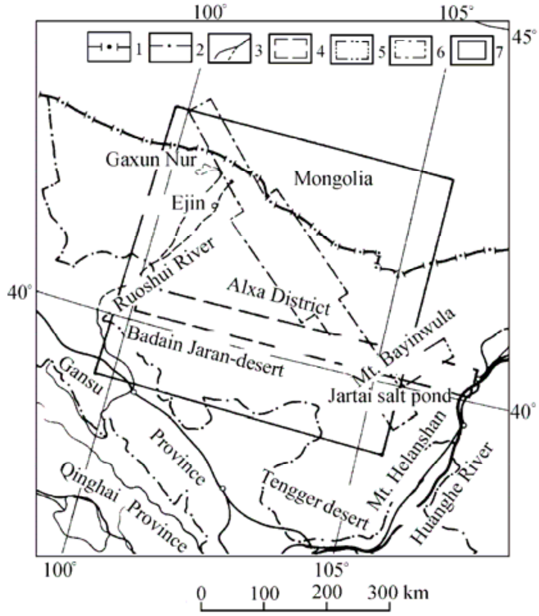

Fig. 1. Radar data coverage map in Alxa area of China. 1, Country border; 2, boundary of province and autonomous region; 3, river, seasonal and dry river; 4, SIR-A; 5, SIR-B; 6, SIR-C; 7, Radarsat.

Geologically, the Alxa Plateau was a denudation area with stable upwelling. The tectonic movement became active since early- and mid-Jurassic, and the Yanshan movement, and the fault-block mountains and fault basins gradually took their shapes. The Helan, Changlingshan and Langshan Mountains with steep relief are typical fault-block uplifting mountains. The Yabrai and Zongnai Mountains with gentle relief are relict mountains which have suffered denudation for a long time. Most of these mountains are oriented in NWW-SEE or NEE-SWW direction. Controlled by geologic structures, the Badain Jaran, Tengger and Ulan Buh deserts occurred in fault basins. The Jurassic, Cretaceous and Tertiary inland lacustrine strata outcrop on the edge of these basins. Quaternary fluviolacustrine loose deposit and eolian sand cover the bedrock. Lithologically, the rocks mainly consist of pre-Paleozoic metamorphic rock and quartzite, Mesozoic mudstone, sandstone and conglomerate, Cenozoic sandstone, conglomerate and clay[10]. Based on these facts, it can be inferred that these deserts were once inland lakes during Tertiary or Quaternary period. Other scientists' study suggested that about 33—23 thousand years ago there was a fresh water lake with an area of more than 16 200 km^2 and water depth of 25 m in the northwest of the present Tengger Desert [11]. The current Jartai salt lake was formed by the shrinkage of a very large lake.

Up to now, only a few conventional geologic explorations have been made in this area. The extremely poor working conditions prevent the detailed studies of field surveys. Guo Huadong and his colleagues divided the continent of China into several units based on backscattering coefficient maps derived from ERS-1 Wind Scatterometer data[12, 13]. Badain Jaran desert belongs to one of the most arid units in China. For this type of geomorphology, radar penetration has unique advantage for geologic and environmental research.

2 Analysis of radar penetration to sand

Radar penetration has attracted extensive attention[3—5, 14—19] since SIR-A revealed subsurface relict old valley in Selima Sand Sheet of eastern Sahara in 1982. The penetration depth of microwave is defined as the depth (δ_p) when the electric field intensity attenuates to $1/e$ of its incident value in a dielectric media[3].

$$\delta_P = 1/2\alpha,$$

and

$$\alpha = \frac{2\pi}{\lambda}\left(\frac{\mu\varepsilon_r}{2}\left\{\left[1+\left(\frac{\varepsilon_i}{\varepsilon_r}\right)^2\right]^{1/2}-1\right\}\right)^{1/2},$$

where α is electric field attenuation coefficient, λ is free space wavelength, ε_i is the imagery part of complex dielectric constant of a target, ε_r is the real part of complex dielectric constant of the target, μ is magnetic permeability. We can see that the penetration depth is in direct proportion to wavelength, and in inverse proportion to complex dielectric constant. For natural loose media, complex dielectric constant is mainly related to water content.

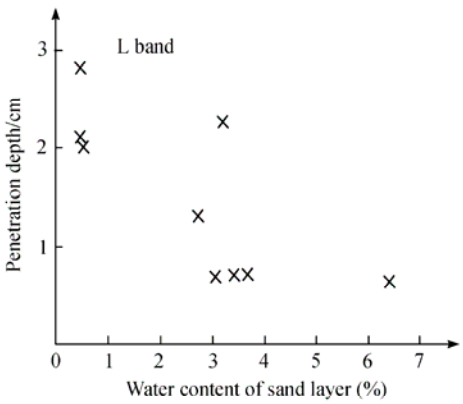

Fig. 2. Relationship of penetration depth and moisture. (by Shao Yun, Guo Huadong, Liu Hao, 1995)

As a principal investigator on the SIR-C/X-SAR Science Team for China's project, Guo Huadong led his team to carry out radar penetration experiment in Alxa Plateau in 1994. Corner reflectors were buried under sand at two test sites. One test site is in natural sand sheet, and the other is in gobi. This experiment proves that the maximum penetration depth of L band wave to dry sand can reach 2.82 m, and the penetration depth is in inverse proportion to water content of sand[17]. In the field survey, we found that there were some wet sands with 4—6% of water in tens of centimeters under the ground surface. Fig. 2 suggests that, even for this kind of sand, the L band penetration depth can also reach one meter. It should be pointed out that the theoretical penetration depth is a conventional expression, but it does not indicate the real depth at which the subsurface target can be revealed by radar image. When the electric field intensity attenuates to $1/e$, the loss of incident energy is less than 1 dB. Normally the detected dynamic range of SAR is more than 40 dB. Therefore, the maximum depth at which the subsurface target is detectable is determined by SNR of SAR system and the contrast between the last response of the subsurface target and the response of the background. In addition, the radar wave will be refracted when it passes through the interface between air and sand layer, causing the incidence angle to become smaller. This effect will enhance the backscattering response from the subsurface interface. Elachi's study proved that for HH polarization, with an increased incidence angle, the backscattering response from subsurface interface was enhanced[14].

3 Detection of old drainage using spaceborne radar

Old drainage refers to the river channels or lakes in a historical period[20]. At present, they have either dried up, and are buried by loose deposit or outcrop as some kinds of negative landform. There are usually a large amount of loose silt, sand and gravel deposits in the old drainage, which are the sources of shifting sand. Because the old drainage was in negative landform, these places serve as pass ways for drift sand movement or as a storage place for eolian sand. The three large deserts, i.e. Badain Jaran, Tengger and Ulan Buh, are typical cases of this kind of sand migration.

On the Radarsat ScanSAR wide mode image (fig. 3(a)), two main sand strips and four branch strips can be recognized according to their dark tone. The one in the north is named Yamalik sand strip, and the one in the south is named Badain Jaran sand strip. This study focuses on the Yamalik sand strip. The dash line in fig. 3(a) represents Yamalik river. The solid line is main faults in the figure.

On SIR-A image (fig. 3(b)), the Honggueryulin segment of Yamalik sand strip shows a dark tone mottled with bright points. For sand dune, the intensity of radar response is mainly determined by the relationship between radar illumination and aspect of sandfall slope. Guo's research indicates that when the incidence angle is near 50°, most sandfall slopes will give a strong response and produce a bright point in radar image; when the incidence angle is near 10°, only the edge of sandfall slope will be illuminated, and only an intermediate response will be yielded; when the incidence angle is near –20°, only windward slope is illuminated, and almost no response will be produced[4, 5]. This "sand river" with 5 km width is interpreted as an old valley incised into bedrock, similar to the relict trunk valley revealed by McCauley in eastern Sahara[3], but it is a more comprehensive one with main channel and branches. The dislocation of the valley caused by fault movement is revealed though buried by drift sand (fig. 3(a), (b)), and an outlet of the north branch of this old drainage to Jartai basin can be delineated on SIR-B image[21] (fig. 3(c)). A vertical section of 1.6 m depth was dug on the northern edge of the main valley. It was noted that on top of N_2 red clay (implying hot-warm climate) there is a fluviolacustrine loose sand layer at 10 cm thick, and the upper deposit layer is at 1.5 m thick alluvium and fluvium. According to geologic exploration records, a large extent of lacustrine deposit existed and was distributed on the northern side of the Honggor Olong segment of Yamalik Sand Sheet, and some lacustrine deposit was scattered in this sand sheet. All these facts provide proofs for the existence of this old drainage.

In SIR-C image (Plate I-1), a triangle-shaped bedrock shows clearly, which is invisible on Landsat MSS and TM image due to the cover of sand layer. Radar can penetrate this sand layer

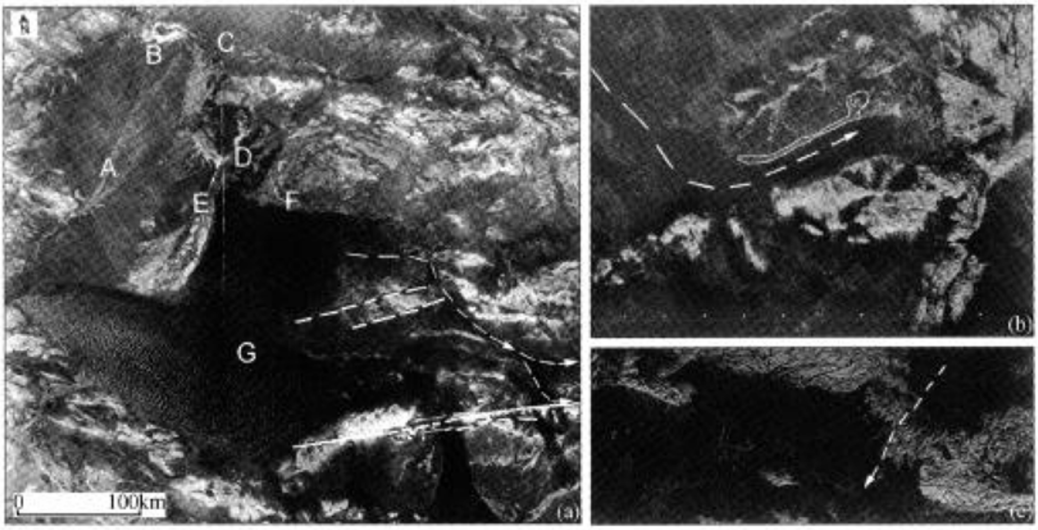

Fig. 3. (a) Radarsat wide Scan SAR mode image shows the main part of research area. Bold white line indicates some major faults in this area. Arrow-headed white fine line indicates the flowing direction of the main stem, north branch and south branch of Yamalik old drainage. A, Ejin River; B, Gaxun Nur Lake; C, Sogo Nur Lake; D, Juyan Paleo-lake; E, one alluvial linked with Juyan Paleo-lake; F, Guaizihu strip-shaped belt of fluviolacustrine deposit; G, Badain Jaran desert. (b) SIR-A image shows the south branch of Yamalik old drainage. It is a sand-covered wide valley incised on bedrock. The strip-shaped belt of lacustrine deposit on the north side of the valley indicates that there ever existed a lake formed when the river was blocked by fault block upwelling of Bayan Ulshan Mountain shrinked to lake. (c) SIR-B shows the outlet of the north branch of Yamalik old drainage.

about one meter thick to detect the underneath bedrock. Depressions covered by sand layer thicker than 2—3 meters usually deliver weak response for all bands and polarizations, and yield a dark brown or black shade on SIR-C false color composite, due to the smoothness of the surface and the weakness of the possible response from underneath interface. The newly formed old channel or lake can deliver stronger L-HH and L-HV response and yield a bright yellow shade on SIR-C image, due to higher subsurface water content and densely distributed dunes formed by straw and shrub obstructing drift sand. Based on these features, an old drainage, flowing from southwest to northeast and injecting to main course of Yamalik old drainage, can be delineated (Plate I-1, 2). The finding of this northeastward-flowing drainage can verify the generation of tilting of this plateau caused by the uplifting of Qianghai-Tibet Plateau.

Tracing back along the main course of Yamalik valley to northwest, a broken point appears at Mt. Zongnaishan (fig. 3(a), Plate I-3). The Mt. Zongnaishan is a flat-topped fault block mountain framed with granite. It can be inferred that late-upwelling of this mountain caused the breakup of Yamalik drainage, and the upper stream of this old drainage should join Badain Jaran old lake or Ejina drainage through Guaizihu old channel. Widespread mid- and late-Pleistocene alluvial and lacustrine formation made up of fine sand, silt and clay on the west side of Alxa plateau (Ejin Banner)[9], indicates that there ever existed a very large lake. The shrinking termination of a large inland drainage should be a salt lake, but this is not the case with Ejin old drainage, so it should be an external drainage and it is possible that Yamalik drainage is its outlet.

4 Significance of the finding of Yamalik old drainage to paleoenvironmental reconstruction

According to the classification of Quaternary basin system in arid northwestern China given in ref. [22], the area of Yamalik sand strip is a piedmont fault-sag basin, which is an ideal place for generation of drainage. In the flow direction of Yamalik old drainage is mainly from northwest to southeast, not tallying with the current relief that the southern part is higher than the northern part and the eastern part higher than the western part. This phenomenon can only be explained with the relief reversion caused by neotectonic movement1).

The Alxa Plateau is surrounded by major faults, Ruoshui fault on the western side, Shaerja fault on the northern side, Hetao fault on the eastern side, and Tengger left-lateral strike-slip fault on the southern side, and there are Bayan Nuru fault, Bayan Ulshan fault and Zongnaishan fault inside. This area had ever been a tectonically stable region for a fairly long time, but since late-Paleozoic era, this stable period came to its end. Affected by early- and mid-Jurassic Yanshan movement, on the southern edge of this area, left-lateral strike-slip brought up the generation of several pull-apart basins, filled with Jurassic and Cretaceous continental fragment deposit. Since Cenozoic era, intensive Qinghai-Tibet movement[23, 24] (3.6—1.7 Ma) caused further left-lateral strike-slip movement[25] and made the depression expand northward. The widespread N_2 red fragmental rock was formed during this period. The red clay layer on this formation indicates the hot and wet environment at that time. In the early-Pleistocene epoch, matching with C episode in Qinghai-Tibet movement, intensive upwelling of Qinghai-Tibet Plateau induced the tilting upheaval of the whole Mongolia Plateau (including Alxa area), and the south-higher-than-north relief was formed from that time on[26]. This process can be inferred from changing of flow direction in Plate I-2.

The fault movement inside this area is a key factor for the formation of east-higher-than-west relief. Some of these faults were still active lately. For example, it was found by field survey that along Bayan Nuru fault and its branch faults, there existed dissected talus fans, direction-changed gullies, displaced outcrop and horizontal scratch produced by strike-slip. It is possible that "Kunlun-Huanghe movement"[27] (1.1—0.6 Ma) that happened between early-Pleistocene and mid-Pleistocene epoch brought up the formation of east-higher-than-west relief. The reciprocal compression between Eurasian plate, Indian plate and Pacific plate induced the compression between Alxa terrain and Ordos terrain, and made Alxa terrain rotate anti-clockwise, causing the left-lateral strike-slip of these faults. The later release of stress inside plate led to the formation of thrust fault[28], fault block upwelling and neighbor depression. The extremely thick Pleistocene series deposit inside Jartai basin is a proof of this tectonic movement. The later "Gonghe movement"[23, 24] (0.15 Ma) caused the intensive upwelling of fault block mountains such as Mt. Lang-

1) Wang Xinyuan, Analysis of tectonic geology using radar remote sensing in Alxa Plateau.

shan, Mt. Bayan Ulshan, and Mt. Helan. Till this time the original west-higher-than-east relief was completely reversed to east-higher-than-west relief. One stratigraphic proof is that along the south branch of Yamalik old drainage, Q2 fluvial and alluvial deposit outcrops on the east side of Mt. Hawula. The Holocene stripe-shaped lacustrine deposit outcrops along Honggor Olong segment. Along the north branch of Yamalik old drainage, Holocene series fluvial sand and gravel outcrops at Ulan Enger area. Such a distribution of Quaternary deposit can verify that the south branch of Yamalik old drainage was blocked by the upwelling mountains in the east part of Alxa Plateau, the south branch was abandoned and evolved into strip-shaped lake, and the flow took its way along the north branch. It can be inferred that in mid- and late-Holocene epoch, further upwelling of fault block mountains and climate's becoming more arid caused the separation of western and eastern drainage in Alxa Plateau. The Ruoshui drainage appeared in the west, and Jartai lake gradually shrank to a salt lake.

The southeast-flowing Yamalik old drainage composed of connected rivers and lakes ever spanned the whole Alxa Plateau, and was the main drainage from mid-tertiary period (?) to Pleistocene epoch. This finding verifies the point of view that Alxa Plateau was ever a place with many rivers and lakes[9—11, 29—31]. Due to the later intensive upwelling of Qinghai-Tibet Plateau, alteration of atmospheric circulation led to the arid climate[32], shrinkage of rivers and lakes, and the appearance of Gobi and desert.

Yamalik old drainage was the main feeding source of water and salt for Jartai basin. Besides scientific significance, the finding of this old drainage is also meaningful for the harness of Jartai salt lake. One main difficulty for mining to this salt lake is the depressing of intercrystalline brine level due to lack of groundwater recharge[33]. The local people are making efforts to find groundwater sources that can compensate for this lack, and a groundwater source inside tertiary strata to the north of the salt lake has been explored. It is possible that this groundwater source has keen relationship with Yamalik old drainage.

5 Conclusion

1) With its capability to penetrate dry sand and its sensitivity to water content and micro-relief, radar remote sensing is effective for geologic and environmental study in an arid area, especially for revealing sand-covered subsurface old drainage and geologic structure on the background of bedrock.

2) Yamalik sand sheet, which is the storage place and the way for drift sand movement, used to be an old drainage composed of connected rivers and lakes. Studying the formation and migration of this sand sheet is meaningful for sand control.

3) The finding of Yamalik old drainage verifies that Alxa Plateau was once a place with many rivers and lakes in a warm and wet climate, and can give other evidence for paleoenvironmental research.

4) Yamalik old drainage is NW-SE flowing, not in accordance with the current

south-higher-than-north and east-higher-than-west relief. This fact indicates a relief reversion process caused by neotectonic movement from Pleistocene epoch to Holocene epoch. This inference gives a reasonable explanation for the outlet of large Ejin old lake and the feeding source of water and salt of Jartai basin.

5) Yamalik old drainage is an abundant source of groundwater. Detailed study on the relationship of this old drainage and groundwater recharge of Jartai salt lake will contribute to the exploitation of this salt lake.

6) The finding of Yamalik old drainage opens the door for studying the paleoenvironmental and paleogeographic evolution, and provides an important clue for exploiting exogenous ore deposit such as halite, gypsum and mirabilite.

7) Alxa Plateau had been an old and stable region, but became active since Mesozoic era. The environmental evolution of this area was affected by each tectonic phase caused by reciprocal compression between Eurasian plate, Indian plate and Pacific plate, so paleoenvironmental research in this area can also provide evidence for studying environmental impact of the upwelling of the Qinghai-Tibet Plateau and formation of east Asian monsoon.

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References

1. Guo Huadong, Zhu Liangpu, Shao Yun et al., Detection of structural and lithological features underneath vegetation canopy using SIR-C/X-SAR data in Zhao Qing test site of southern China, Journal of Geophysical Research, 1996, 101(E10): 23101.
2. Chen Shupeng, Tong Qingxi, Guo Huadong, The Research on Remote Sensing Information Mechanism (in Chinese), Beijing: Science Press, 1998, 234—315.
3. McCauley, J. F., Schaber, G. G., Breed, C. S. et al., Subsurface valleys and geoarcheology of the Eastern Sahara revealed by shuttle radar, Science, 1982, 218: 1004.
4. Guo Huadong, Schaber, G. G., Breed, C. S. et al., Shuttle imaging radar response from sand dunes and subsurface rocks of Alxa Plateau in North-central China, in Remote Sensing for Resources Development and Environmental Management (ed. Dame, M. C. J.), Rotterdam: A. A. Balkema, 1986.
5. Guo Huadong, Space shuttle radar response from sand dunes and subsurface rocks of Alxa plateau, Remote Sensing of Environment (in Chinese), 1986, (1): 34.
6. Elachi, C., Spaceborne Radar Remote Sensing: Applications and Techniques, IEEE Press, 1988.
7. Ulaby, F. T., Elachi, C. eds., Radar Polarimetry for Geoscience Applications, Norwood, MA: Artech House, 1990.
8. Zhu Zhenda, Wu zheng, Liu Xu, Generality of Chinese Deserts (in Chinese), Beijing: Science Press, 1980.
9. Sun Peishan, Sun Deqing, The preliminary research on hydro-geology of the western Inner Mongolia plateau, in Sand Control Team of Chinese Academy of Sciences (ed. Sand Control Research) (in Chinese), Beijing: Science Press, 1985, 186—196.
10. Han Qing, Gao Qianzao, Shen Yongling, The formation and distribution of salt water in desert area of Alxa plateau, in Physical Geography of Chinese Arid Regions (ed. Zhao Songqiao) (in Chinese), Beijing: Science Press, 1985, 186—196.
11. Zhang Hucai, Wünnemann, B., Preliminary study on the chronolgy of lacusrine deposits and determination of high pa-

leo-lake level in Tengger desert since late Pleistocene, Journal of Lanzhou University (Natural Sciences) (in Chinese), 1997, 33(2): 87.
12. Guo Huadong, Wang Chao, Wang Xiangyun et al., ERS-1 WSC data for global land surface monitoring, Journal of Remote Sensing (in Chinese), 1997, 1(4): 277.
13. Wang Xiangxun, Wang Chao, Guo Huadong et al., Application of ERS-1 scatterometer data to studing land surfaces—Distributive characteristic of backscattering coefficient over China land surfaces, Chinese Science Bulletin, 1998, 43(18): 2013.
14. Elachi, C., Roth, L. E., Schaber, G. G., Spaceborne radar surface imaging in hyper-arid regions, IEEE Trans. Geosci. Remote Sensing, 1984, GE-22, (4): 383.
15. Blom, R., Crippen, R. E., Elachi, C., Detection of subsurface feature in Seasat radar images of Means Valley, Mojave Desert, California, Geology, 1984, 12: 346.
16. McCauley, J. F., Breed, C. S., Schaber, G. G. et al., Paleodrainages of the Eastern Sahara—the radar rivers revisited (SIR-A/B implications for a Mid- tertiary Trans—African Drainage systerm), IEEE Trans. Geosci. Remote Sensing, 1986, GE-24, (4): 624.
17. Shao Yun, Guo Huadong, Liu Hao, Experiment of SIR-C/X-SAR penetration, in The New development of Remote Sensing Science. (ed. Institute of Remote Sensing Applications, Chinese Academy of Sciences) (in Chinese), Beijing: Science Press, 1995, 161—168.
18. Pachur, H. J., Rottiger, F., Evidence for a large extended paleo-lake in the Eastern Sahara as revealed by Spaceborne radar lab images, Remote Sens. Environ., 1997, 61: 437.
19. Dabbagh, A. E., Al-Hinai, K. G., Asif Khan, M., Detection of sand-covered geologic features in the Arabian Peninsula using SIR-C/X-SAR data, Remote Sens. Environ., 1997, 59: 375.
20. Wu Chen, Zhu Xuanqing, He Naihe et al., The study on the formation of abandoned channels in Huabei plain, Science in China (in Chinese), Ser. B, 1991, (2): 188.
21. Guo Huadong, ed., Analysis of Radar Remote Sensing Imagery in China (in Chinese), Beijing: Science Press, 1999, 92—135.
22. Chen Mengxiong, Water resources and Quaternary basin system in northwestern China arid area, Quaternary Geology (in Chinese), 1997, (2): 97.
23. Li Jijun, Fang Xiaomin, Ma Haizhou et al., Landform evolution of upper reach of Huanghe river in late-Cenozoic era and the upwelling of Qinghai-Tibet plateau, Science in China (in Chinese), Ser. D, 1996, 26 (4): 316.
24. Li Jijun, Fang Xiaomin, The upwelling of Qinghai-Tibet plateau and environmental change study, Chinese Science Bulletin (in Chinese), 1998, 43 (15): 1569.
25. Wang Chao, Guo Huadong, Zhang Yunhe, Radar imagery for structural analysis in Bayinnuorgong region, north China, in Radar Image Analysis and Geologic Application (ed. Guo Huadong) (in Chinese), Beijing: Science Press, 1991, 103—107.
26. Zhang Zhaogan, Neotectonic movement in middle and southern part of Inner Mongolia plateau, Journal of Nanjing University (Geography) (in Chinese), 1992, (13): 33.
27. Cui Zhijiu, Wu Yongqiu, Liu Gengnian et al., About "Kunlun-Huanghe movement", Science in China (in Chinese), Ser. D, 1998, 28(11): 53.
28. Molar, P., Tapponnier, P., Cenozoic tectonic of Asia, Effects of a Continental Collision, 1975, 189(4201): 419.
29. Team for Inner Mongolia and Ningxia integrated survey, The Landform in Inner Mongolia and West part of Northeastern China (ed Chinese Academy of Sciences) (in Chinese), Beijing: Science Press, 1980, 1—270.
30. Li Rongquan, Zheng Liangmei, Zhu Guorong, Lacustrine and Environmental Migration of Inner Mongolia (in Chinese), Beijing: Beijing Normal University Press, 1990.
31. Du Hengjian, Chen Huahui, Chao boxun, Geomorphology and Quaternary Geology (in Chinese), Beijing: Geology Press, 1981, 284—329.
32. Shi Yafeng, Tang Maochang, Study of second-term upwelling of Qinghai-Tibet plateau and its relationship with the formation of Asian monsoon, Science in China (in Chinese), Ser. D, 1998, 28(3): 263.
33. Bai Yifu, ed., Techniques for Salt Lake Exploitation, Hohhot: Salt Exploitation Association Press of Salt Resource Administration of Inner Mongolia Autonomous Region (in Chinese), 1998.