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Facies analysis and depositional systems of Cenozoic sediments in the Hoh Xil basin, northern Tibet

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Abstract

A sedimentary succession more than 5800 m thick, including the Lower Eocene to Lower Oligocene Fenghuoshan Group, the Lower Oligocene Yaxicuo Group, and the Lower Miocene Wudaoliang Group, is widely distributed in the Hoh Xil piggyback basin, the largest Cenozoic sedimentary basin in the hinterland of the Tibetan plateau. The strata of the Fenghuoshan and Yaxicuo groups have undergone strong deformation, whereas only minor tilting has occurred in the Wudaoliang Group. We analyze their sedimentary facies and depositional systems to help characterize continental collision and early uplift of the Tibetan plateau. The results indicate fluvial, lacustrine, and fan-delta facies for the Fenghuoshan Group, fluvial and lacustrine facies for the Yaxicuo Group, and lacustrine facies for the Wudaoliang Group. Development of the Hoh Xil basin underwent three stages: (1) the Fenghuoshan Group was deposited mainly in the Fenghuoshan-Hantaishan sub-basin between 56.0 and 31.8 Ma ago; (2) the Yaxicuo Group was deposited mainly in the Wudaoliang and Zhuolai Lake sub-basins between 31.8 and 30.0 Ma ago; and (3) the Wudaoliang Group was deposited throughout the entire Hoh Xil basin during the Early Miocene. The Fenghuoshan and Yaxicuo groups were deposited in piggyback basins during the Early Eocene to Early Oligocene, whereas the Wudaoliang Group was deposited in a relatively stable large lake. The Hoh Xil basin underwent two periods of strong north–south shortening, which could have been produced by the collision between India and Asia and the early uplift of the Tibetan plateau. The study suggests the Hoh Xil region could reach a high elevation during the Late Oligocene and the diachronous uplift history for the Tibetan plateau from east to west.

Keywords: Facies analysis; Fluvial; Uplift; Cenozoic; Hoh Xil; Tibet

1. Introduction

The Tibetan plateau and Himalayas are composed of six blocks and five suture zones separating them, resulting largely from the progressive accretion of blocks to the active southern margin of Asia (Allègre et al., 1984; Burg and Chen, 1984; Dewey et al., 1990) (Fig. 1). The uplift of this Tibetan–Himalayan assemblage has not only altered the environment of the Tibetan plateau and the Himalayas themselves, but has also significantly influenced the Asian and even the global natural environment (e.g. Ruddiman and Kutzbach, 1991; Ruddiman et al., 1997). Studies of geology in the region have concentrated primarily on the Himalayas (e.g. Burchfiel et al., 1992; Murphy and Harrison, 1999), the part of Tibet near Lhasa (e.g. Yin et al., 1994), the Tarim area (e.g. Sobel, 1999), and on Cenozoic deformation (e.g. Tapponnier et al., 1982; Yin et al., 1999). The geology of Cenozoic

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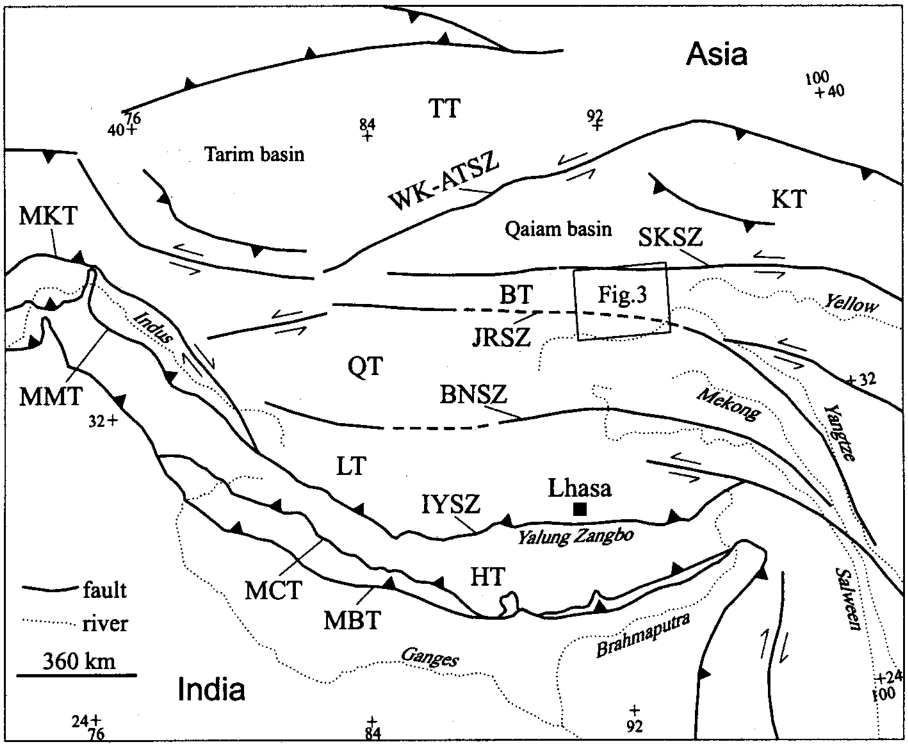


Fig. 1. Schematic map of the Tibetan plateau and adjacent Himalayas showing the locations of major tectonic boundaries and blocks. HT, Himalayan terrane; LT, Lhasa terrane; QT, Qiangtang terrane; BT, Baya Har terrane; KT, Kunlun terrane; TT, Tarim terrane; IYSZ, Indus–Yarlung Zangbo suture zone; BNSZ, Bangong–Nujiang suture zone; JRSZ, Jinsha River suture zone; SKSZ, South Kunlun suture zone; WK–ATSZ, West Kunlun–Altyn Tagh suture zone; MBT, Main Boundary thrust; MCT, Main Central thrust; MMT, Main Mantle thrust; MKT, Main Karakoram thrust. Modified from Harrison et al. (1992) and Chung et al. (1998). Box in the map indicates the area of Fig. 3.

sedimentary basins in the hinterland of Tibet, however, has remained poorly understood.

We have studied the sedimentary record in the Hoh Xil basin of northern Tibet to obtain clues that characterize continental collision and uplift of the Tibetan plateau. From the Early Eocene to the Early Miocene, a sediment pile of more than 5400 m thick of fluvial mudstone, sandstone, and conglomerate and nearly 400 m thick of limestone was formed in the Hoh Xil basin. The strata were originally designated the Fenghuoshan Group (Lower Cretaceous), the Yaxicuo Group (Oligocene), and the Wudaoliang Group (Miocene) (Bureau of Geology and Mineral Resources of Qinghai, 1987). Subsequently, the age of the Fenghuoshan Group was changed to Paleogene according to fossils of Chareae: *Rhabdochara*? sp., Cyrogoneae gen, indet., Ostracoda: *Cypris* sp., Gasteropod: *Sinoplanorbis* sp., *Amnicola* sp. (Yin et al., 1990), and to Cretaceous on the basis of a small number of fossils of Ostracoda and Gasteropod (Zhang and Zheng, 1994), respectively. More recently, we established the lithostratigraphy and magnetostratigraphy of the Fenghuoshan and Yaxicuo groups (Liu et al., 2000a, submitted for publication). A total of 1253 individual oriented paleomagnetic samples spaced at stratigraphic intervals were collected from five measured sections with their thickness of more than 5400 m in the Hoh Xil basin. The progressive thermal and alternating field demagnetization experiments were conducted by a 2G cryogenic magnetometer at the paleomagnetic laboratory of the University of California, Sata Cruz (UCSC). On the basis of distinct magnetic reversal zones and biostratigraphic data, 14 magnetozones can be recognized at the Hoh Xil basin that range from Chrons C24 to C11 for the Fenghuoshan Group and C11 to C10 for the

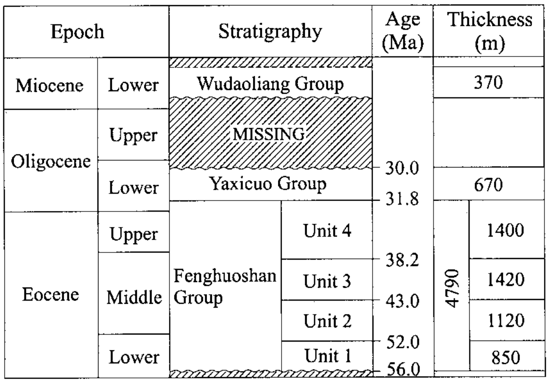


Fig. 2. Chronostratigraphy of Cenozoic strata in the Hoh Xil basin. The ages of the Fenghuoshan and Yaxicuo Groups are after Liu et al. (submitted for publication).

Yaxicuo Group (Liu et al., submitted for publication). The normal and reversal time intervals of magnetic sub-zones are according to the geomagnetic polarity time scale of Harland et al. (1990). Correlating to the sedimentary column, therefore, the relatively precise age could be obtained for some geologic events. The Fenghuoshan Group was deposited from 56.0 to 31.8 Ma ago, and the Yaxicuo Group from 31.8 to 30.0 Ma (Fig. 2). This sedimentary record was reported to contain significant information on crustal shortening and early uplift of the Tibetan plateau (Wang et al., 1999; Wang and Liu, 2000). Moreover, the sedimentary record sheds light on the events that occurred during the global cooling at the end of the Middle Eocene (around 37 Ma) and the cooling and drying event in the earliest Oligocene (around 33 Ma) (Liu and Wang, 2000).

In this paper, we clarify the facies analysis of the Fenghuoshan and Yaxicuo groups, and then we discuss the development of the Cenozoic Hoh Xil basin for the first time.

2. Geologic setting

The Hoh Xil basin, with an area of 101,000 km^2 and an average elevation of over 5000 m, is the largest Cenozoic sedimentary basin in the hinterland of the Tibetan plateau. It is situated in the middle part of the Baya Har terrane (BT) and the northern part of the Qiangtang terrane (QT), and it covers the Jinsha River suture zone (JRSZ) (Fig. 1). The basin is bounded on the northern margin by the Kunlun Mountains and the South Kunlun suture zone, and on the southern margin by the Tanggula Mountains and the Tanggula fault. The Tibet–Qinghai highway from Lhasa to Golmud crosses the eastern part of the basin (Fig. 3).

The pre-Cenozoic sedimentary basement of the Hoh Xil basin consists of slate, phyllite, and meta-sandstone deposited during the Carboniferous, Permian, and Triassic (Zhang and Zheng, 1994, shown as pre-Cenozoic sedimentary basement in Fig. 3). The Fenghuoshan Group (Lower Eocene–Lower Oligocene) is nearly 4790 m thick and consists of gray–violet sandstone, mudstone, and conglomerate, intercalated gray–green Cu mineral-bearing sandstone, dark-gray bioclastic limestone, and gray layered and tubercular gypsum. The Fenghuoshan Group is divided into four lithological units (Fig. 2). In ascending order, these are: sandstone, mudstone, and intercalated gypsum with a thickness of nearly 850 m (Unit 1); alternating mudstone and sandstone with intercalated limestone, with a thickness of nearly 1120 m (Unit 2); sandstone and conglomerate, with a thickness exceeding 1420 m (Unit 3); and sandstone and mudstone, with a thickness of nearly 1400 m (Unit 4). The Yaxicuo Group (Early Oligocene) is 670 m thick and consists mainly of alternating sandstone and mudstone with intercalated gray layered and tubercular gypsum. The Wudaoliang Group ranges in thickness from nearly 60 m in the south to nearly 370 m in the north, and consists mainly of lacustrine carbonate rock with minor amounts of black oil shale (Liu and Wang, 1999). The age of the Wudaoliang Group is widely accepted as Early Miocene, based on abundant fossils (Bureau of Geology and Mineral Resources of Qinghai, 1991; Zhang and Zheng, 1994).

A series of WNW-striking thrust faults offset both the pre-Cenozoic sedimentary basement and the Cenozoic sedimentary deposits (Fig. 3). The strata of the Fenghuoshan and Yaxicuo groups have undergone strong deformation (Dewey et al., 1990), whereas only minor tilting has occurred in the Wudaoliang Group. Thus, deformation of the Paleogene sediments mainly occurred during the Late

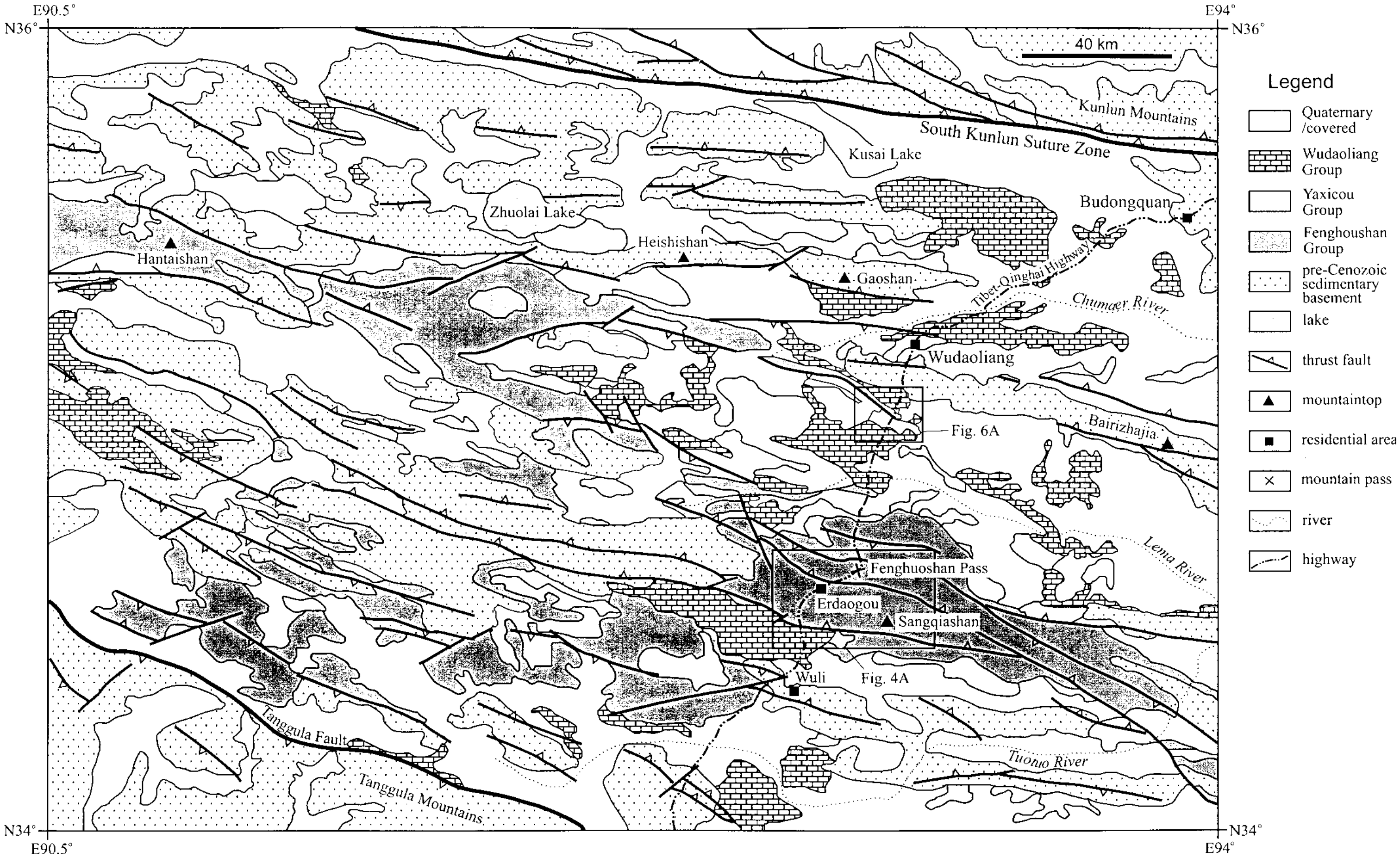


Fig. 3. Simplified geologic map of the Hoh Xil basin, showing north and south boundaries of the basin, tectonic framework, and distribution of Cenozoic sediments. Map area is shown in Fig. 1. Boxes in the map indicate the areas of Figs. 4a and 6a. Modified form Zhang and Zheng (1994).

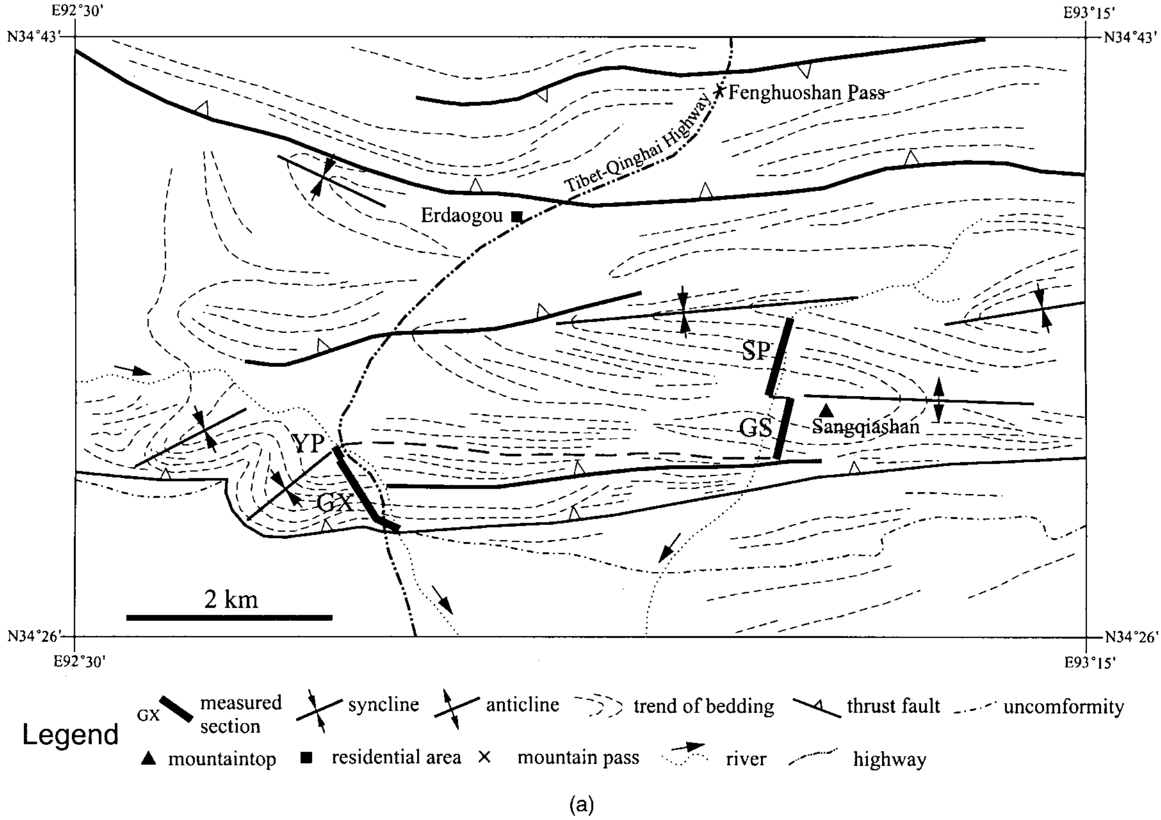


Fig. 4. (a) Geologic sketch map of the Fenghuoshan area in the southern Hoh Xil basin, showing tectonic and stratigraphic framework and locations of measured sections of the Fenghuoshan Group. Map area is shown in Fig. 3. (b–d), Measured stratigraphic sections of the Fenghuoshan Group, showing characteristics of lithology, lithofacies, structures, and paleocurrents, and distributions of lithologic units, elements, and facies. Unidirectional paleocurrents were measured from asymmetry ripple, flute, planar cross-bedding, climbing-ripple cross-lamination, pebble imbrication, and channel, and bidirectional paleocurrents were measured from symmetry ripple and parting lineation. See Table 1 for explanation of lithofacies and Table 2 for explanation of elements. The section sites are shown in Fig. 4a.

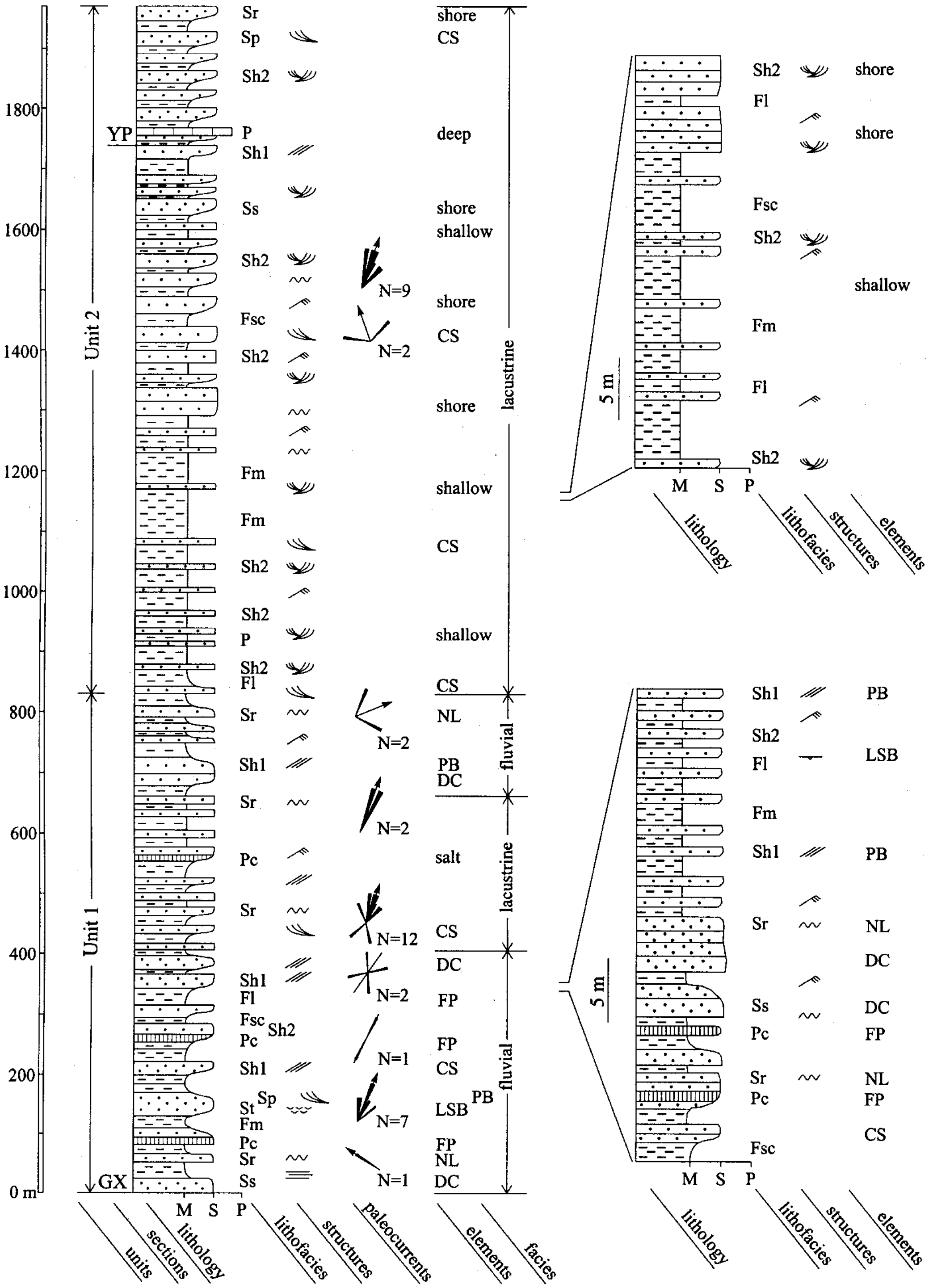
Oligocene. Satellite imagery interpretation, along with fieldwork, indicates that the contact between the Fenghuoshan Group and the overlying Yaxicuo Group is concordant, but that the Wudaoliang Group discordantly overlies the deformed Paleogene Fenghuoshan and Yaxicuo groups.

3. Facies analysis

We conducted sedimentary facies analysis at standard lithostratigraphic and magnetostratigraphic sections of the Fenghuoshan Group and the Yaxicuo Group. The depositional environment of the Wudaoliang Group is accepted as shallow to deep lake, based on analysis of widely distributed bioclastic limestone (Zhang and Zheng, 1994).

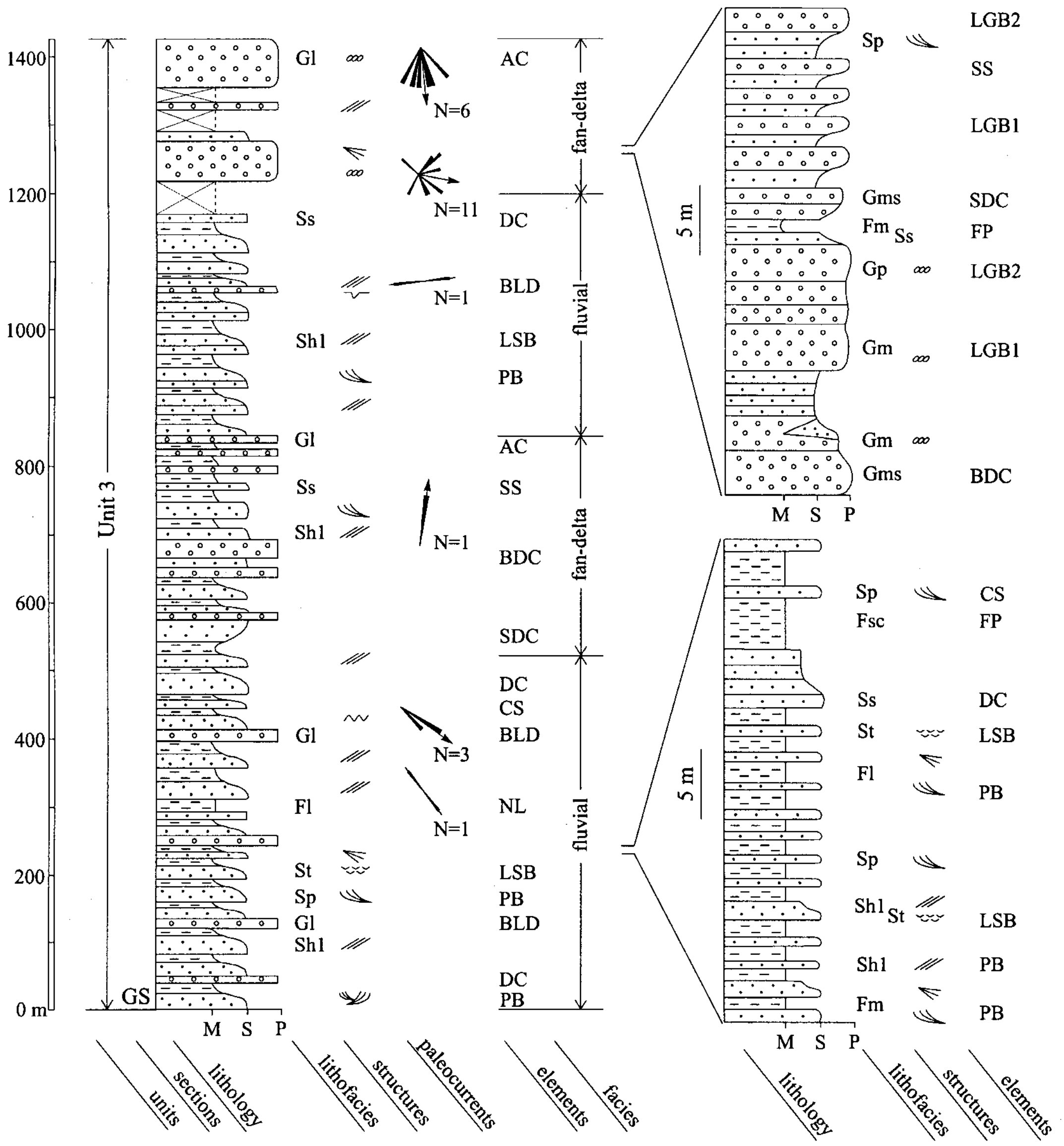
3.1. The Fenghuoshan Group

The standard sections of the Fenghuoshan Group are situated in the Fenghuoshan area, in the southern part of the Hoh Xil basin (Figs. 3 and 4a). Because thrusts and folds have developed in the Fenghuoshan sequence, continuous stratigraphic measurement was conducted at four sections, designated GX, YP, GS, and SP, which were established along the strike of strata on the basis of field investigation and interpretation of satellite imagery. The Fenghuoshan Group consists mainly of fluvial and lacustrine facies, with



(b)

Fig. 4. (*continued*)



(c)

Fig. 4. (*continued*)

subordinate fan-delta facies near the middle of the section. The facies analyses of the four sections are shown in Fig. 4b–d; interpretations of lithofacies, elements, and facies are indicated in Tables 1 and 2. Facies codes and their interpretations are modified from Miall (1978, 1984); elements are modified from Miall (1985).

3.1.1. Fluvial

The fluvial facies of the Fenghuoshan Group is characterized by normal graded bedding sandstone and conglomerate that fine and thin upward and mudstone (Fig. 5A). It contains channel and overbank subfacies and occurs in lithological Units 1, 3, and 4 (Fig. 4b–d). The channel subfacies includes

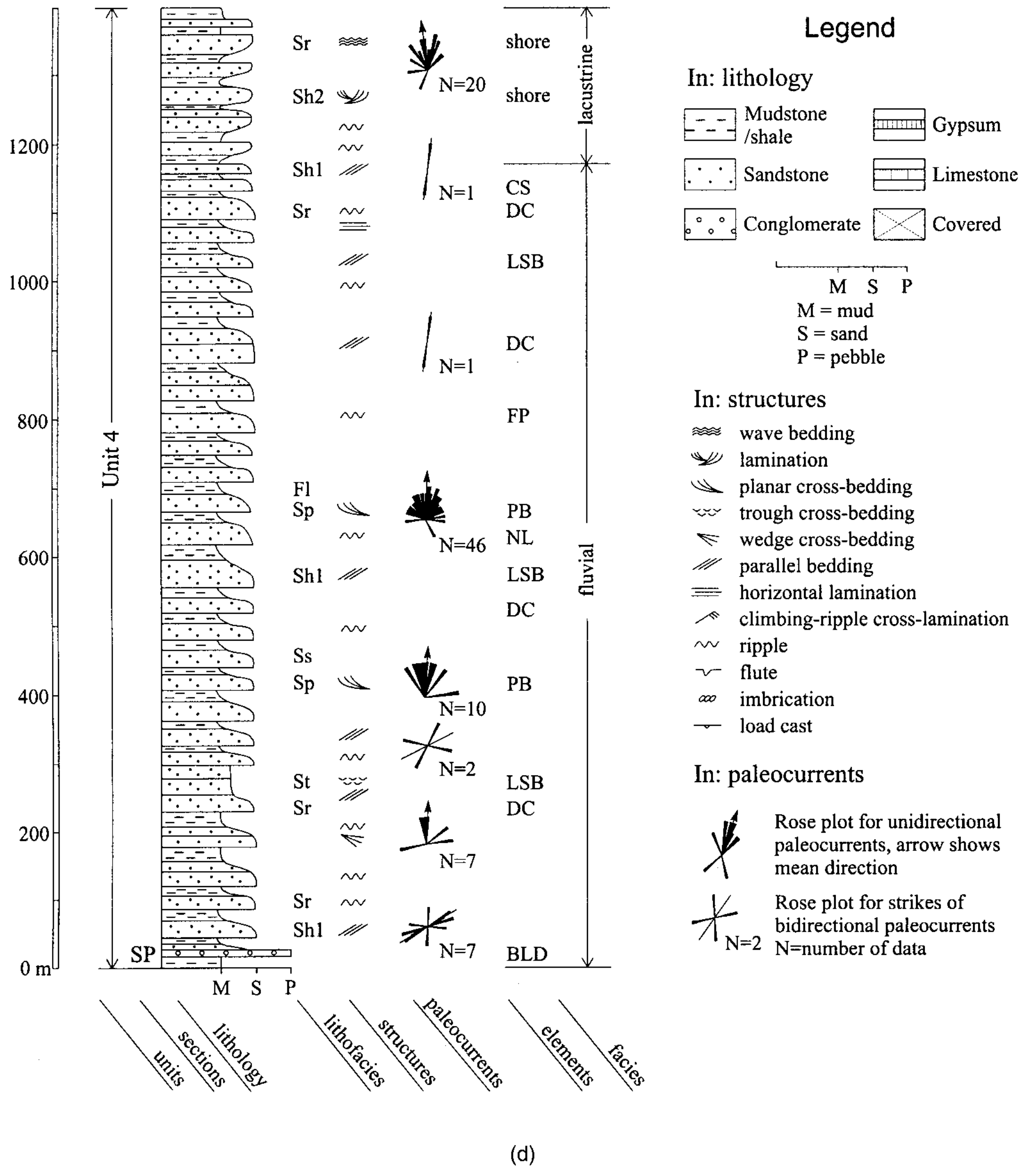


Fig. 4. (*continued*)

distributary channels, longitudinal sand bars, bedform lag deposits, and point bars and the overbank subfacies includes natural levees, crevasse splays, and flood plain deposits (Table 2).

The distributary channels consist mainly of medium to coarse grained and/or pebbly quartzolithic and quartzofeldspathic sandstone and are characterized by lithofacies association of Ss, St, and Sp. The channel sandstones were deposited mainly on scour surfaces and developed some grading and parallel bedding, as well as planar and trough cross-bedding (Fig. 5B). The parallel bedding directs the strikes of paleocurrents as southeast–northwest (Fig. 4b). A single sedimentary cycle of pebbly to medium sandstone to mudstone is typically about 0.5–2.5 m thick, and could form in a braided river environment (shown

Table 1
Facies codes, sedimentary structures, and interpretations of the Fenghuoshan and Yaxicuo groups, modified from Miall (1978, 1984)

Facies Code	Lithofacies	Sedimentary structures	Interpretation
Gms	Massive, matrix supported gravel	None	Debris-flow deposits
Gm	Massive or crudely bedded, grain supported gravel	Horizontal bedding, imbrication	Grain-flow deposits, longitudinal bars
Gp	Stratified, grain supported gravel	Planar crossbeds	Linguoid bars, scour fills
Gl	Thin-stratified or lens-shaped, matrix or grain supported gravel	Grading or none	Minor channel fills
St	Sand, medium to coarse, may be pebbly	Trough crossbeds	Dunes
Sp	Sand, medium to coarse, may be pebbly	Planar crossbeds	Linguoid bars
Sr	Sand, very fine to coarse	Ripple marks of all types	Ripples
Sh1	Sand, medium to coarse, may be pebbly	Parallel bedding, streaming lineation	Planar bed flow
Sh2	Sand, very fine to coarse	Horizontal lamination	Lower flow regime
Ss	Sand, very fine to coarse, may be pebbly	None	Grain flow deposits
Fl	Sand, silt, mud	Fine lamination, very small ripples	Overbank, waning flood deposits, or lake
Fsc	Silt, mud	Laminated to massive	Backswamp deposits or lake
Fm	Mud, silt	Massive, desiccation cracks	Overbank or lake
P	Carbonaceous mud, silty limestone, thin-stratified	Containing silts, or fossils	Backswamp deposits or lake
Pc	Gypsum, very thin-stratified	Layer	Backswamp deposits or lake
Pt	Gypsum, nodulated	Concretion	Backswamp deposits or lake

as facies element DC within the short detailed measured sections at the right-lower side in Fig. 4b and c).

The longitudinal sand bars consist of fine to coarse grained and/or pebbly, medium to thick stratified sandstone and are characterized by lithofacies association of St and Sh1. The sand bars usually intercalate thin mudstone and indicate the sedimentary cycle with normal graded bedding of sandstone and mudstone (Fig. 5C). A single sedimentary cycle of the sand bars and mudstone is typically up to 0.5–1 m thick. In the Wudaoliang area, foreset beds, which mainly consist of graded flat pebbles, occur in trough cross-bedding. In the Erdaogou area, parallel bedding has been scoured by overlying trough cross-bedding in a longitudinal sand bar. The sand bars, which moved downstream or beveled main stream channel, could produce this association. They indicate average northeast direction of paleocurrents (shown as facies element LSB in Fig. 4b).

The bedform lag deposits consist of graded conglomerate and sandstone with lithofacies association of Gl and Ss (Fig. 5D). They often cover scour surfaces and typically grade upward to longitudinal sand bars (shown as facies element BLD in Fig. 4c). The conglomerate is stratified or lens-shaped and grain supported, and the pebbles consists of quartzite, volcanic rock, and slate.

The point bars consist mainly of fine to coarse grained and/or pebbly, medium to thick stratified sandstone and are characterized by lithofacies association of Sp and Sh1. A single point bar system is typically up to 4 m thick, and mainly contains planar cross-bedding and parallel bedding. In the Erdaogou area, the forest beds of planar cross-bedding are composed of oriented, flat, red mudstone pebbles, which show the paleocurrents direct to north (shown as facies element PB in Fig. 4d).

The natural levees consist of violet, thin-stratified or lens-shaped siltstone and mudstone, and are characterized by lithofacies association of Sr, Sh2, and Fl. Siltstone lenses may be less than 5 cm thick and less than 50 cm in length. In the Erdaogou area, interbedding siltstone and mudstone, buildup the natural levees,

Table 2
Facies associations of the Fenghuoshan and Yaxicuo groups. Elements are modified from Miall (1985). See Table 1 for explanation of lithofacies

Facies		Subfacies	Elements (lithofacies)
Fenghuoshan Group	Lacustrine	Shore	Sr, Sh2, Ss, Fl
		Shallow	Sh2, Sr, Fl, Fsc, P
		Deep	Sh2, P
		Salt	Pc, Fm
	Fan-delta	Fan-delta front	Subaqueous distributary channel (SDC): Gms
			longitudinal gravel bar (LGB1): Gm
			Linguoid gravel bar (LGB2): Gp
			Sand sheet (SS): Ss, Sr
		Fan-delta plain	Braided distributary channel (BDC): Gms, Gm
			Longitudinal gravel bar (LGB1): Gm
			Abandoned channel (AC): Gl, Sh2
			Flood plain (FP): Ss, Fm
	Fluvial	Channel	Distributary channel (DC): Ss, St, Sp
			Longitudinal sand bar (LSB): St, Sh1
			Bedform lag deposit (BLD): Gl, Ss
			Point bar (PB): Sp, Sh1
		Overbank	Natural levee (NL): Sr, Sh2, Fl
			Crevasse splay (CS): Sp, Fsc, Fm
			Flood plain (FP): Ss, Sr, Sh2, Fl, Fsc
Yaxicuo Group	Lacustrine	Shore	Sr, Sh2, Ss, Fl
		Shallow	Sh2, Sr, Fl, Fsc, P
		Salt	Pc, Pt, Fm
	Fluvial	Channel	Linguoid sand bar (LSB): Sp, Sh1
		Overbank	Natural levee (NL): Sr, Sh2, Fl
			Flood plain (FP): Ss, Sr, Sh2, Fl, Fsc

with a sedimentary cycle of typically 0.5–0.8 m thick (Fig. 5E). Ripples, wave bedding, lamination, and climbing-ripple cross-lamination are common (Fig. 5F).

Inferred crevasse splay deposits consist mainly of thin to medium stratified or lens-shaped, violet, fine to medium grained sandstone, siltstone, and mudstone, and are characterized by lithofacies association of Sp, Fsc, and Fm. Individual sandstone beds may be more than 20 cm thick. Planar cross-bedding lamination is common. These deposits formed on the natural levee during periods of flooding.

The flood plains consist of violet mudstone with intercalated thin siltstone or muddy siltstone. They may contain lithofacies association of Ss, Sr, Sh2, Fl, and Fsc. Individual muddy siltstone beds are commonly less than 10 cm thick, but mudstone beds may be more than 30 cm thick. Ripples, wave bedding, lamination, organic traces, and desiccation cracks are common, as are small ripples on bedding planes. In the Sangqiashan area, a rock wall with curved crest ripples on the strata surfaces indicates the rocks were deposited in a flood basin within the flood plains (Fig. 5G).

3.1.2. Lacustrine

The lacustrine facies of the Fenghuoshan Group occurs mainly in lithological Unit 2 and less commonly in Units 1 and 4. This facies includes shore, shallow, deep, and salt lake depositional environments, and is characterized by coarsening and thickening upward siltstone and sandstone (shown as the short detailed measured section at the right-upper side in Fig. 4b).

The shore subfacies consists of violet mudstone with intercalated fine to medium sandstone and siltstone. It shows lithofacies association of Sr, Sh2, Ss, and Fl. A single sandstone or siltstone may be up to 20–40 cm thick. Horizontal lamination, wave bedding, climbing-ripple cross-lamination, small planar cross-bedding, and organic tracks are developed. In the Erdaogou area, two groups of linear

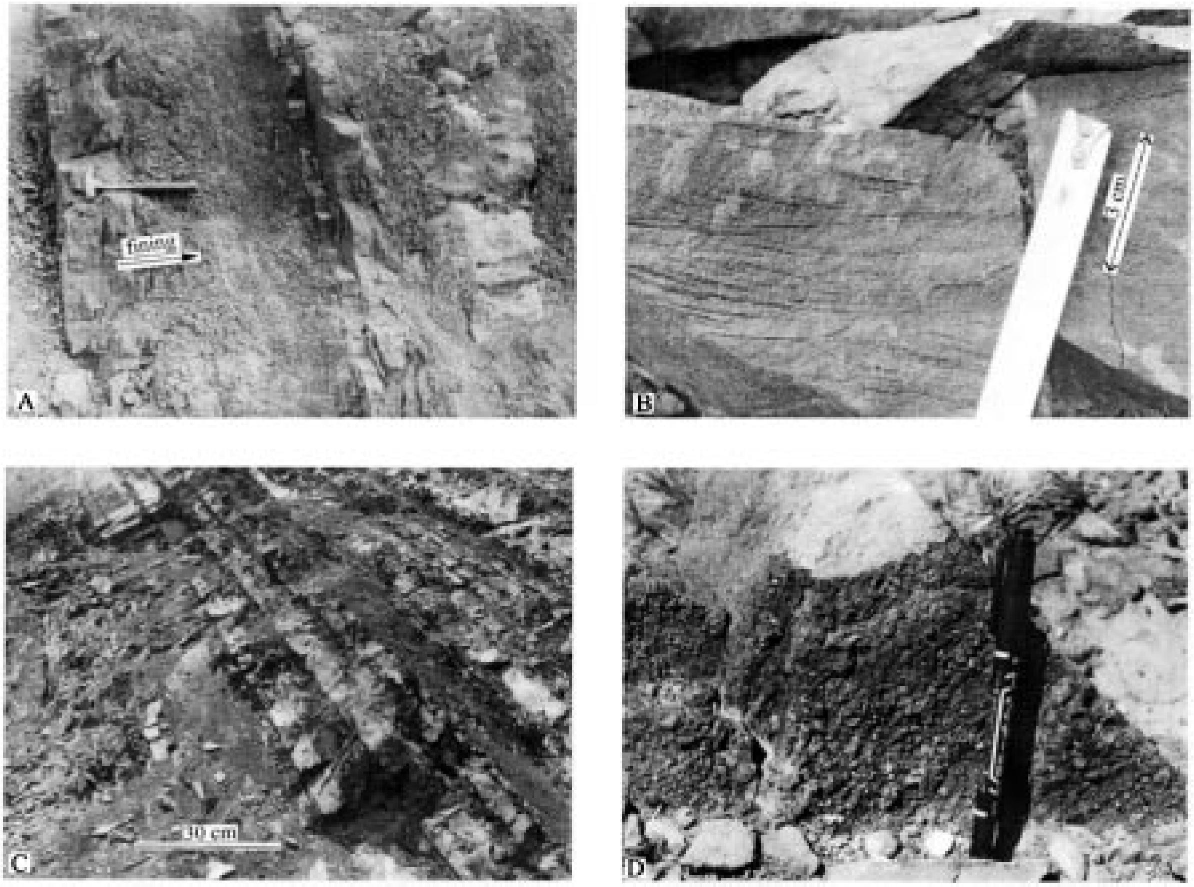


Fig. 5. Outcrop photographs of the Fenghuoshan Group. (A) Sedimentary cycles of violet sandstone that fine and thin upward and mudstone, indicating the typical fluvial depositional environment. (B) Violet coarse sandstone with trough cross-bedding, showing the distributary channel environment. (C) Sedimentary cycles of the longitudinal sand bar sandstone with normal graded bedding and mudstone. (D) Gray–green, Cu mineral-bearing, fine conglomerate of bedform lag deposit environment. The conglomerate is grain supported and thinly stratified. (E) Sedimentary cycles of interbedding siltstone and mudstone, indicating the natural levee environment. (F) Violet muddy siltstone of natural levee environment, developing linguoid ripple. (G) A large rock wall with lots of curved crest ripples on the strata surfaces, indicating the flood plain environment. (H) Violet siltstone of the shore environment, showing two groups of linear crest ripples, whose paleocurrents are almost perpendicular to each other, on one stratigraphic surface. (I) Violet thick mudstone intercalating thin sandstone and silty limestone, indicating the shallow lake environment. (J) Violet–gray conglomerate coarsening and thickening upward, showing the fan-delta plain and front depositional environments. (K) Violet–gray coarse conglomerate of distributary channel environment of fan-delta, which could be produced by debris flow or grain flow. (L) Scoured contact between gray medium conglomerate of gravel bar environment and fine conglomerate of channel environment. The pebbles are imbricated (arrow shows paleocurrent direction). Pen is 14 cm long, hammer is 45 cm long, and person is 170 cm tall, for scale.

crest ripples are developed on a single stratigraphic surface, whose paleocurrents are almost perpendicular to each other (Fig. 5H). The paleocurrent direction of the big ripple is 21°, and that of the small one is 286°. They could indicate that injection flow (main current) and longshore current (secondary current) both occurred in the shore area, though these lower flow structures could be formed due to other sorts of secondary flow currents. The paleocurrents measured from unidirectional ripples mainly direct to north (Fig. 4b and d).

The shallow lake subfacies consists of violet thick

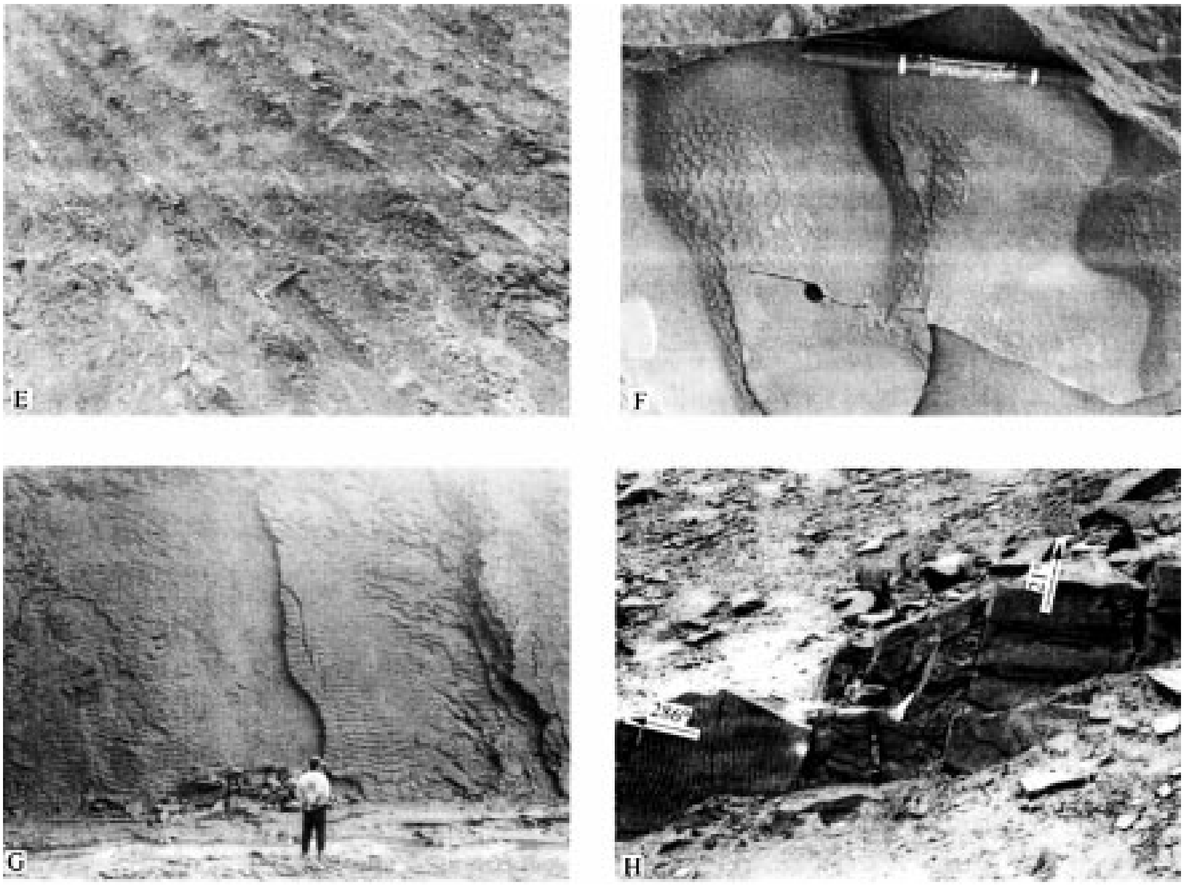


Fig. 5. (*continued*)

mudstone with intercalated thin sandstone and less commonly thin silty limestone (Fig. 5I). It shows lithofacies association of Sh2, Sr, Fl, Fsc, and P. Presence of bioturbation indicates an oxygenated environment. Climbing-ripple cross-lamination is widely distributed, suggesting that source sediments were supplied in abundance or that sediment gravity flows (i.e. turbidites) developed in the shallow lake.

The deep lake subfacies is characterized by gray–green sandstone and siltstone and intercalated black thin to medium stratified limestone, with the lithofacies association of Sh2 and P. A total of 15 intercalated beds of limestone or silty limestone were found in Unit 2 of sections GX and YP (Fig. 4B). The thickness of limestone ranges between 10 and 80 cm. Basal contacts between limestone and sandstone may be transitional or abrupt. The limestone includes fossils of Ostracoda, Gastropoda, and Chareae.

The salt lake subfacies occurred only in the middle of Unit 1 at a section of GX (Fig. 4b). It represents a special shore or shallow lake sedimentary environment. This subfacies consists of violet gypsum-bearing mudstone and muddy siltstone and has lithofacies association of Pc and Fm. The mudstone is massive, whereas the siltstone contains local lamination and ripples. The gypsum is thinly stratified and represents a limited salt lake environment.

3.1.3. Fan-delta

The fan-delta facies of the Fenghuoshan Group is characterized mainly by coarsening and thickening

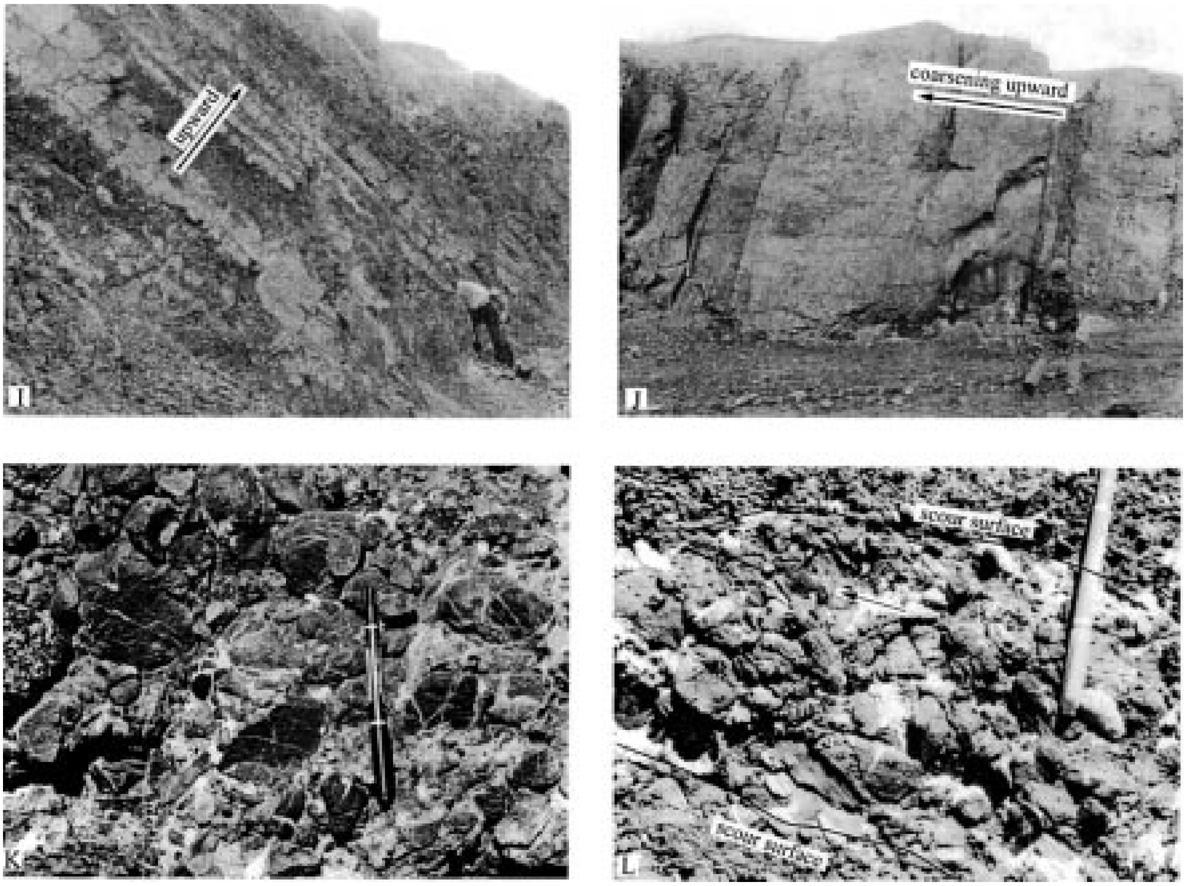


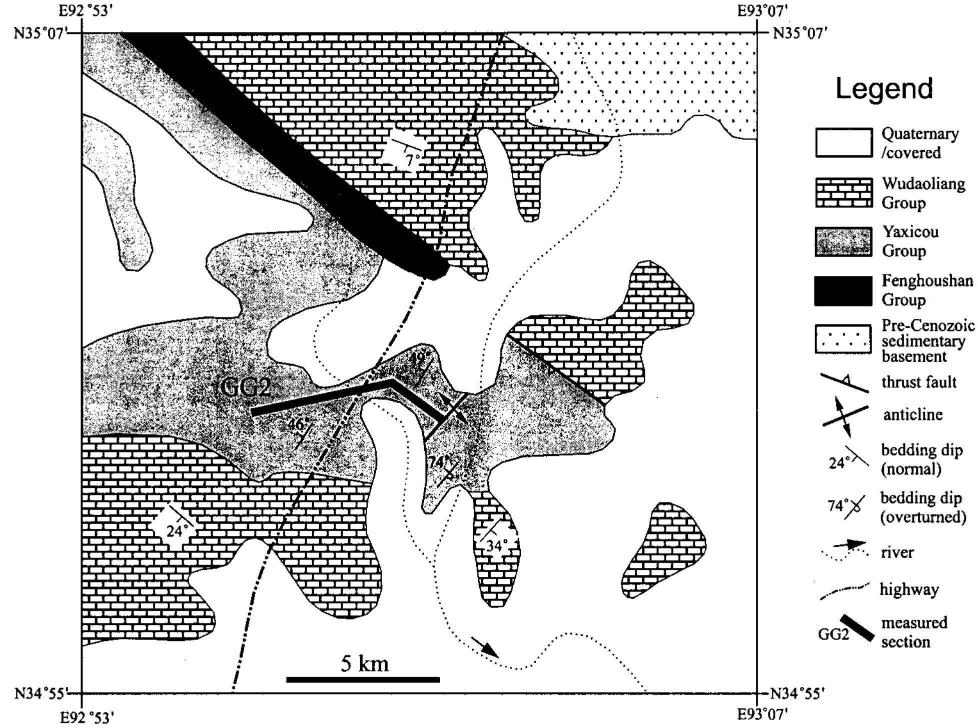
Fig. 5. (*continued*)

upward conglomerate (shown as the short detailed measured section at the right-upper side in Figs. 4c and 5J). These deposits developed in Unit 3 at section GS and contain a fan-delta plain and front (Fig. 4c, Table 2). The fan-delta plain can be subdivided into braided distributary channels, longitudinal gravel bars, abandoned channels, and flood plains. The fan-delta fronts can also be subdivided as subaqueous distributary channels, longitudinal gravel bars, linguoid gravel bars, and sand sheets.

The braided distributary channels and the subaqueous distributary channels consist of thick, massive, coarse conglomerate with the lithofacies association of Gms and/or Gm (Fig. 5K). The conglomerate is lens-shaped, as much as 0.5 km long or more, and in places, is grain supported with parallel bedding and inconspicuous imbrication. The channel could have been produced by grain flow.

The longitudinal gravel bars and the linguoid gravel bars consist of grain supported conglomerate with the lithofacies association of Gm and Gp. They show some sedimentary structures, such as parallel bedding and imbrication (Fig. 5L). The pebble imbrication in the upper part of Unit 3 indicates the paleocurrents as eastward or southward (Fig. 4c). The linguoid gravel bars, in addition, show planar cross-bedding. The upper and lower contacts of conglomerate with sandstone of strata are abrupt, with flat or convex-up upper surfaces and scouring on bottom contacts. Grain flow or tractive flow could have produced these features.

The abandoned channels contain lithofacies association of Gl and Sh2 and are characterized by matrix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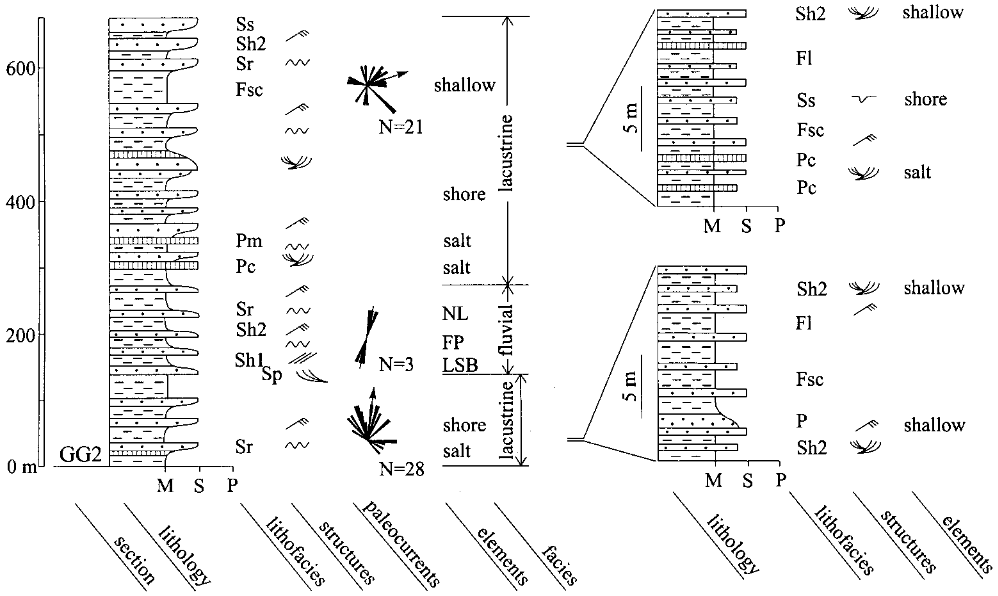
(a)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Ss
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Sr
Fsc
Pm
Pc
Sh1
Sp
N=21
N=3
N=28
shallow
shore
salt
NL
FP
LSB
lacustrine
fluvial
5 m
Fl
P
section
lithology
lithofacies
structures
paleocurrents
elements
facies

(b)

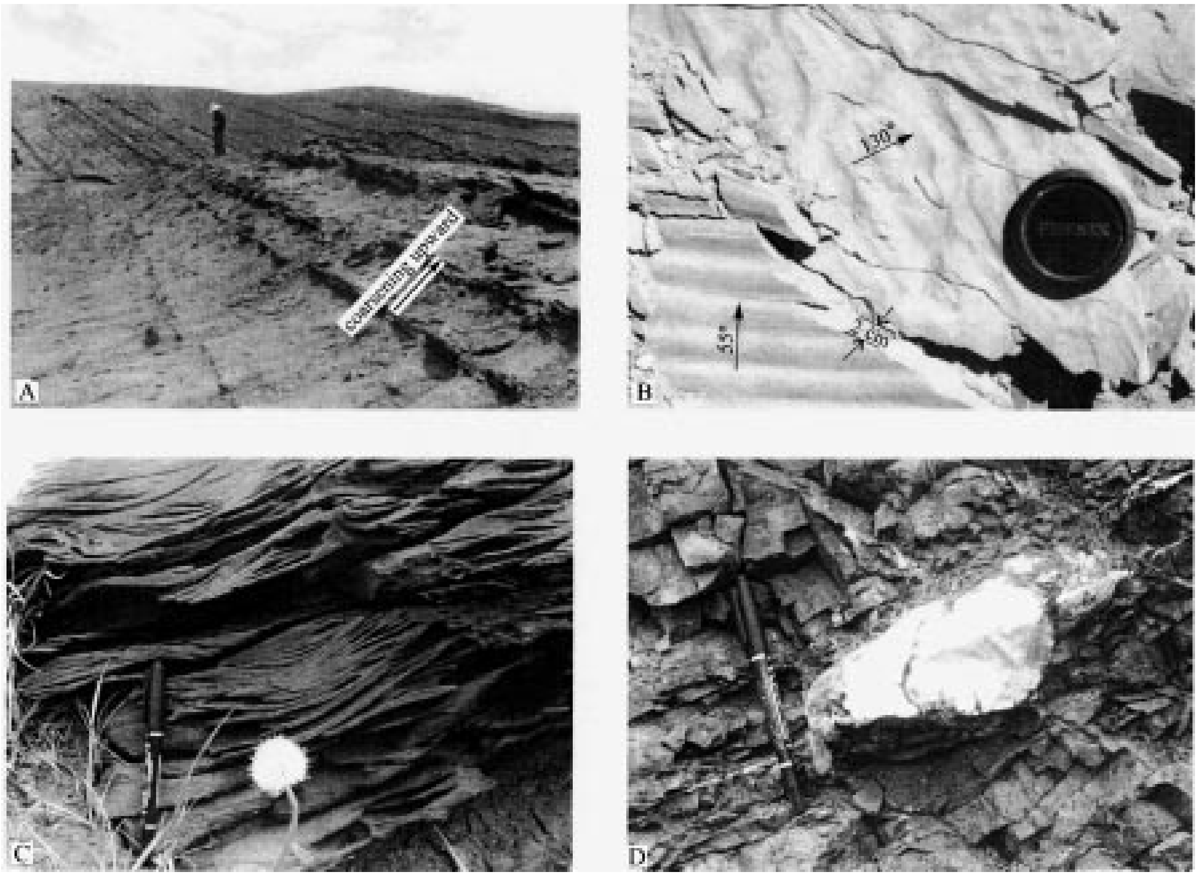

Fig. 7. Outcrop photographs of the Yaxicuo Group. (A) Sedimentary cycles of coarsening and thickening upward sandstone and mudstone, indicating the typical lacustrine depositional environment. (B) Shallow red, thin-stratified, muddy siltstone of shore environment. Two groups of ripples, indicating paleoflow almost perpendicular to each other, are developed on surfaces of two contiguous thin siltstone beds. (C) Violet siltstone of shallow lake environment, showing widely developed climbing-ripple cross-lamination. (D) White gypsum concretion of salt lake environment, which is distributed along a stratigraphic horizon. Pen is 14 cm long, lens cap is 5 cm in diameter, and person is 170 cm tall, for scale.

or grain supported, thin-stratified or lens-shaped, fine conglomerate in the lower part and lamination siltstone in the upper part. They indicate two-layer structures and could have been produced by shortening or migration of the river.

The sand sheets consist of fine sandstone and siltstone with the lithofacies association of Ss and Sr. They developed ripples and lamination that commonly are distributed widely, sometimes to shore. The sand sheets could have been produced by wave action or by transport of lake water.

3.2. The Yaxicuo group

The type section of the Yaxicuo Group is situated in the southern part of the Wudaoliang area of the Hoh

Fig. 6. (a) Geologic map of the southern Wudaoliang area in the middle Hoh Xil basin, showing locations of measured sections of the Yaxicuo Group. Map area is shown in Fig. 3. (b) Measured stratigraphic section of the Yaxicuo Group, showing characteristics of lithology, lithofacies, structures, and paleocurrents, and distributions of lithologic units, elements, and facies. Legend same as Fig. 4b–d. See Table 1 for explanation of lithofacies and Table 2 for explanation of elements. The section sites are shown in Fig. 6a.

Xil basin (Figs. 3 and 6a). Section GG2 was measured in the northwest limb of an overturned anticline. The Yaxicuo Group consists mainly of lacustrine facies, but contains less fluvial facies in the lower-middle part (Fig. 6b). The facies analysis of the section is shown in Fig. 6b. Interpretations of lithofacies, elements, and facies are indicated in Tables 1 and 2. As before, facies codes and their interpretations are modified from Miall (1978, 1984); elements are modified from Miall (1985).

3.2.1. Lacustrine

The lacustrine facies of the Yaxicuo Group consists of shore, shallow lake, and salt lake subfacies. It is characterized by coarsening and thickening upward packages of sandstone and siltstone (Fig. 7A).

The shore subfacies consists mainly of violet mudstone with intercalated thin to medium beds of fine to medium sandstone with lithofacies association of Sr, Sh2, Ss, and Fl. A single sandstone bed is typically up to 20–40 cm thick. Horizontal lamination, ripples, lamination, and organic tracks are developed. The mean paleocurrent direction measured from sedimentary structures points to north (shown as the lower part of section GG2 in Fig. 6b). Two sets of ripples, whose paleocurrent directions are almost perpendicular to each other, were found on the surfaces of two contiguous thin siltstone beds (Fig. 7B). The overlying bed is only 2 cm thick. The upper set of ripple consists of linear crest ripples with a paleocurrent direction of 55°. The lower set consists of superposed ripple with a paleocurrent direction of 130°. These features could indicate that injection flow (main current) and longshore current (secondary current) occurred in the shore area or that the directions of currents were fan-dispersed.

The shallow lake subfacies consists mainly of violet mudstone, intercalated thin, fine sandstone and siltstone, thin marl, and silty limestone. The lithofacies association includes Sh2, Sr, Fl, Fsc, and P. The contacts of mudstone with marl or silty limestone are abrupt. Many sedimentary structures are developed, such as ripples, wave bedding, and climbing-ripple cross-lamination. They indicate the paleocurrents as northeast (shown as the upper part of section GG2 in Fig. 6b). The climbing-ripple cross-lamination is especially well developed and widely distributed (Fig. 7C). This could indicate that source sediments were supplied in abundance or that sediment gravity flow developed in the shallow lake.

The salt lake subfacies is characterized by violet, gypsum-bearing mudstone and intercalated muddy fine sandstone and siltstone, with lithofacies association of Pc, Pt, and Fm. The mudstone is massive, whereas the siltstone shows a few small laminations and ripples. The gypsum occurs as thin strata and as concretions along a stratigraphic horizon (Fig. 7D). The presence of gypsum indicates a limited salt lake environment.

3.2.2. Fluvial

The Yaxicuo Group includes less fluvial facies in the lower-middle part of section GG2 (Fig. 6b). The deposits are characterized by fining and thinning upward packages of red sandstone and siltstone and consist of channel and overbank subfacies. Longitudinal sand bars make up the channel subfacies, with lithofacies association of Sp and Sh1 (Table 2). The parallel bedding measured from medium sandstone indicates the strikes of paleocurrents as nearly north-southward (Fig. 6b). The overbank subfacies includes natural levees and flood plain deposits (Table 2). The natural levees consist of red, lens-shaped siltstone and mudstone. Siltstone lenses may be less than 5 cm thick and less than 100 cm in length. Ripples, wave bedding, lamination, and climbing-ripple cross-lamination are common. The flood plains consist of red mudstone with intercalated thin siltstone or muddy siltstone and gradually transits into lacustrine deposits. They may contain lithofacies association of Ss, Sr, Sh2, Fl, and Fsc.

4. Basin development and discussion

The facies analysis indicates that the sedimentary environment of the Hoh Xil basin underwent five periods of significant change from the Early Eocene to the Early Oligocene. Moreover, the paleocurrents changed at the same time. In Unit 1 of the Fenghuoshan Group, the fluvial environment was dominant, with a short period of salt lake development. Paleocurrents were mainly towards the north-northeast (Fig. 4b). In Unit 2, the lacustrine environment became dominant, with paleocurrent directions mainly northward (Fig. 4b). In Unit 3, the environment changed from fluvial in the lower part to fan-delta in the upper part, with changes of paleocurrent directions. The directions with average eastward, altered from southeastward in the lower part, to mainly northward in the middle part, to eastward in the upper part, and to southward in the top part (Fig. 4c). In Unit 4 of the Fenghuoshan Group, the environment changed to fluvial with a short period of lacustrine in the upper part. Paleocurrents were mainly northward with several temporary alternations (Fig. 4d). In the Yaxicuo Group, the lacustrine environment became dominant with paleocurrents changing from northward in the lower part to eastward in the upper part.

The facies and their distribution are a direct result of the depositional processes that produced them. On this basis, along with the basin tectonic analysis, we infer the following depositional processes of the Hoh Xil basin during the Cenozoic. The sediments of the Fenghuoshan and Yaxicuo groups are gradually younger and thinner from southwest to northeast (Fig. 3), indicating tectonic movement northeastward. The fan-delta conglomerates in the Fenghuoshan Group are mainly distributed in front of the thrusts. Moreover, the changes of paleocurrent directions during the Paleogene indicate that the depocenters of the Hoh Xil basin migrated northward and eastward. Therefore, during the Eocene and Early Oligocene when the Fenghuoshan and Yaxicuo groups were developed, the Hoh Xil basin was formed, and filled on moving northeastward thrust sheets (Liu et al., 2000b). The type of basin was described as piggyback basin (Ori and Friend, 1984).

Three stages of depositional processes of the Hoh Xil basin are clear. (1) Between 56.0 and 31.8 Ma ago, the Fenghuoshan Group was deposited mainly in the Fenghuoshan-Hantaishan sub-basin (Fig. 8A). Initial deposition of the Fenghuoshan Group during the Early Eocene was the conglomerate, which could present the initial collision between India and Asia (Wang and Liu, 2000). Therefore, the initial movement of the Tanggula fault could be driven by the Eocene continental collision. The sedimentary environments were fluvial, lacustrine, and fan-delta, and the depocenters migrated eastward and northward. (2) From 31.8 to 30.0 Ma ago, the Yaxicuo Group was deposited, mainly in the Wudaoliang and Zhuolai Lake sub-basins (Fig. 8B). During this period, the Tanggula fault became less active and a new active ramp was formed at Bairizhajia, and a short later at Heishishan-Gaoshan areas. The sedimentary environment was mainly lacustrine, with a short period of fluvial. The depocenters continued migrating eastward and northward. During the Late Oligocene (from 30.0 to ~20.0 Ma ago), the pile of sediments of the Fenghuoshan and Yaxicuo groups were deformed by folding and thrusting and the Hoh Xil piggyback basins were finished. (3) During the Early Miocene, the Wudaoliang Group was deposited throughout the entire Hoh Xil basin, which became a large lake. The thrusts within the basin became less active. The bioclastic limestone of the Wudaoliang Group was deposited discordantly on the Paleogene Fenghuoshan and Yaxicuo groups, and has undergone little deformation since.

The north–south shortening that occurred within the deformed Fenghuoshan and Yaxicuo groups was assessed at about 40% in the Fenghuoshan area (Coward et al., 1990) and 42.8% (53.1 km) in the Fenghuoshan-Wudaoliang area (Wang et al., 1999). Because only minor tilting generally less than 30° has occurred in the Wudaoliang Group, which nonconformably overlies the former. Thus suggests that the strong deformation observed in the Paleogene sediments was mainly formed after the Early Oligocene of the Yaxicuo Group occurred but before the Early Miocene of the Wudaoliang Group occurred, probably by the Late Oligocene. Moreover, the Hoh Xil piggyback basins driven by thrusts suggest that north–south shortening still happened in the basin during the Early Eocene to Early Oligocene. Therefore, the Hoh Xil basin underwent two periods of strong north–south shortening, including the shortening period when the piggyback basins occurred from 56.0 to 30.0 Ma, which could have been produced by the collision between India and Asia in the Eocene (e.g. Rowley, 1998), and the strong deformation shortening during the Late Oligocene. The development of the Hoh Xil basin could be correlated with widespread potassic lavas on the Tibetan plateau. The potassic magmatic activities were formed from convective thinning of the underlying lithospheric mantle when the relief reaches a high elevation (England and Houseman, 1989), with the ages of 40–30 Ma in eastern Tibet (Chung et al., 1998) and 30–13 Ma in western Tibet (Turner et al., 1993). Therefore, the Hoh Xil region could reach a high elevation during

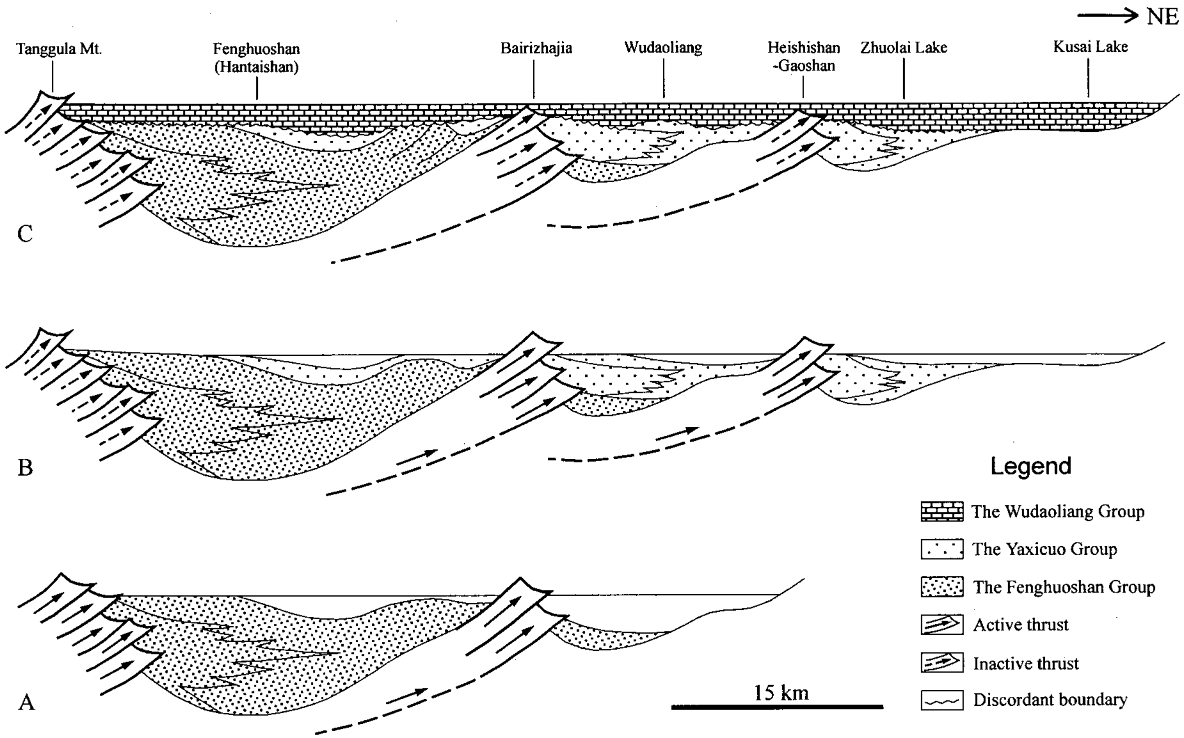

Fig. 8. Model for development of the Cenozoic Hoh Xil basin. (A) Between 56.0 and 31.8 Ma ago, the Fenghuoshan Group was deposited mainly in the Fenghuoshan-Hantaishan sub-basin. (B) Between 31.8 and 30.0 Ma ago, the Yaxicuo Group was deposited mainly in the Wudaoliang and Zhuolai Lake sub-basins. (C) During the Early Miocene, the Wudaoliang Group was deposited in the entire Hoh Xil basin and discordantly covered the Paleogene Fenghuoshan and Yaxicuo groups, which underwent strong deformation during the Late Oligocene.

the Late Oligocene when the stronger north–south shortening occurred. The study suggests the diachronous uplift history for the Tibetan plateau from east to west (Chung et al., 1998).

5. Conclusions

Lower Eocene to Lower Oligocene fluvial sediments of the Fenghuoshan and Yaxicuo groups and Lower Miocene carbonate of the Wudaoliang Group are widely distributed in the Hoh Xil piggyback basin, the largest Cenozoic sedimentary basin in the hinterland of the Tibetan plateau. We infer sedimentary facies of the 4790 m–thick Fenghuoshan Group as representing deposition on a fluvial–lacustrine–fan-delta, and of the 670 m thick Yaxicuo Group as representing fluvial–lacustrine deposition. The facies of the Wudaoliang Group has been interpreted as lacustrine. From this sedimentary record, we infer three stages of depositional processes of the Hoh Xil basin. In stage 1, the Fenghuoshan Group was deposited mainly in the Fenghuoshan-Hantaishan sub-basin between 56.0 and 31.8 Ma ago. In stage 2, the Yaxicuo Group was deposited mainly in the Wudaoliang and Zhuolai Lake sub-basins between 31.8 and 30.0 Ma ago. The depocenters of the Hoh Xil basin migrated eastward and northward during these two stages. During the Late Oligocene, the pile of sediments of the Fenghuoshan and Yaxicuo groups were deformed by folding and thrusting and the Hoh Xil piggyback basins were finished. In stage 3, the Wudaoliang Group was deposited in the entire Hoh Xil basin during the Early Miocene.

The Hoh Xil basin underwent two periods of strong north–south shortening. The first shortening, which occurred between 56.0 and 30.0 Ma ago, is believed to have been produced by the collision between India and Asia and the early uplift of the Tibetan plateau. The second shortening, which occurred during the Late Oligocene, reflects the early uplift of the Tibetan plateau. The study suggests that the Hoh Xil region could reach a high elevation during the Late Oligocene when the stronger north–south shortening occurred as well as the diachronous uplift history for the Tibetan plateau from east to west.

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References

Allègre, C.J., Courtillot, V., Tapponnier, P., and 32 others, 1984. Structure and evolution of the Himalaya-Tibet orogenic belt. Nature 307, 17–22.

Burchfiel, B.C., Chen, Z., Hodges, K.V., Liu, Y., Royden, L.H., Deng, C., Xu, J., 1992. The South Tibet detachment system, Himalayan orogen: extension contemporaneous with and parallel to shortening in a collisional mountain belt. Geol. Soc. Am. Spec. Paper, 269, 41 pp.

Bureau of Geology and Mineral Resources of Qinghai, 1987. Regional geologic survey report on Wenquan, scale 1:200,000. Bureau of Geology and Mineral Resources of Qinghai, Xining.

Bureau of Geology and Mineral Resources of Qinghai, 1991. Regional Geology of Qinghai. Geology Press, Beijing, 662 pp.

Burg, J.P., Chen, G.M., 1984. Tectonics and structural zonation of southern Tibet, China. Nature 311, 219–223.

Chung, S., Lo, C., Lee, T., Zhang, Y., Xie, Y., Li, X., Wang, K., Wang, P., 1998. Diachronous uplift of the Tibetan plateau starting 40 Myr ago. Nature 394, 769–773.

Coward, W.P., Kidd, W.S.F., Pang, Y., Shackleton, R.M., Zhang, H., 1990. The structure of 1985 Tibet Geotraverse, Lhasa to Golmud. In: Sino-British Comprehensive Geological Expedition Team of the Qinghai-Tibet Plateau (Ed.), The Geological Evolution of the Qinghai-Tibet. Science Press, Beijing, pp. 321–347.

Dewey, J.F., Shackleton, R.M., Chang, C., Sun, Y., 1990. The tectonic evolution of the Tibetan plateau. In: Sino-British Comprehensive Geological Expedition Team of the Qinghai-Tibet Plateau (Ed.), The Geological Evolution of the Qinghai-Tibet. Science Press, Beijing, pp. 384–415.

England, P., Houseman, G., 1989. Extension during continental convergence, with application to the Tibetan plateau. J. Geophys. Res. 94, 17 561–17 579.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., Smith, D.G., 1990. A Geologic Time Scale 1989. Cambridge University Press, Cambridge, 263 pp.

Harrison, T.M., Copeland, P., Kidd, W.S.F., Yin, A., 1992. Raising Tibet. Science 255, 1663–1670.

Liu, Z., Wang, C., 1999. Oil shale in the Tertiary Hoh Xil basin, northern Qinghai-Tibet plateau. Am. Assoc. Pet. Geol. Bull. 83, 1890.

Liu, Z., Wang, C., 2001. Depositional environment and paleoclimatic significance of the early Oligocene Yaxicuo Group in the Hoh Xil basin. Acta Sedimentol. Sin. 73 (3) (in press).

Liu, Z., Wang, C., Zhao, X., Liu, S., Yi, H., 2000a. Magnetostratigraphic dating: implications for Tertiary evolution of the Hoh Xil basin, northern Tibet (15th Himalaya-Karakoram-Tibet Workshop Abstracts). Earth Sci. Front. 7 (Suppl.), 157–159.

Liu, Z., Zhao, X., Wang, C., Liu, S., Yi, H., submitted for publication.

Liu, Z., Wang, C., Yi, H., Liu, S., 2000b. Hoh Xil piggyback basins: implications for Paleogene shortening of the Tibetan plateau (15th Himalaya-Karakoram-Tibet Workshop Abstracts). Earth Sci. Front. 7 (Suppl.), 152–153.

Miall, A.D., 1978. Lithofacies types and vertical profile models in braided river deposits: a summary. In: Miall, A.D. (Ed.), Fluvial Sedimentology. Can. Soc. Pet. Geol. Mem. 5, 597–604.

Miall, A.D., 1984. Principles of Sedimentary Basin Analysis. Springer, New York, 668 pp.

Miall, A.D., 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. Earth Sci. Rev. 22, 261–308.

Murphy, M.A., Harrison, T.M., 1999. Relationship between leucogranites and the Qomolangma detachment in the Rongbuk Valley, south Tibet. Geology 27, 831–834.

Ori, G.G., Friend, P.F., 1984. Sedimentary basins formed and carried piggyback on active thrust sheets. Geology 12, 475–478.

Rowley, D.B., 1998. Minimum age of initiation of collision between India and Asia North of Everest based on the subsidence history of the Zhepure Mountain section. J. Geol. 106, 229–235.

Ruddiman, W.F., Kutzbach, J.E., 1991. Plateau uplift and climatic change. Sci. Am. 264, 66–75.

Ruddiman, W.F., Raymo, M.E., Prell, W.L., Kutzbach, J.E., 1997. The uplift-climate connection: a synthesis. In: Ruddiman, W.F. (Ed.), Tectonic Uplift and Climate Change. Plenum Press, New York, pp. 471–515.

Sobel, E.R., 1999. Basin analysis of the Jurassic–Lower Cretaceous southwest Tarim basin, northwest China. Geol. Soc. Am. Bull. 111, 709–724.

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., Cobbold, P., 1982. Propagating extrusion tectonics in Asia: new insight from simple experiments with plasticine. Geology 10, 611–616.

Turner, S., Hawkesworth, C., Liu, J., Rogers, N., Kelly, S., Calsteren, P., 1993. Timing of Tibetan uplift constrained by analysis of volcanic rocks. Nature 364, 50–54.

Wang, C., Liu, Z., 2000. Early Tertiary uplift of the Tibetan plateau: evidences from Paleogene sedimentation of the Hoh Xil basin (15th Himalaya-Karakoram-Tibet Workshop Abstracts). Earth Sci. Front. 7 (Suppl.), 147–148.

Wang, C., Liu, Z., Zhao, X., Liu, S., 1999. Sedimentology of the Fenghuoshan Group in the Hoh Xil basin, northern Qinghai-Tibet plateau: implication for the plateau uplift history (14th Himalaya-Karakoram-Tibet Workshop Abstracts). Terra Nostra 99, 166–167.

Yin, A., Harrison, T.M., Kyerson, F.J., Ryerson, F.J., Chen, W., Kidd, W.S.F., Copeland, P., 1994. Tertiary structural evolution of the Gangdese thrust system, southeastern Tibet. J. Geophys. Res. 99 (B9), 18 175–18 201.

Yin, A., Kapp, P.A., Murphy, M.A., Manning, C.E., Harrison, T.M., Grove, M., Ding, L., Deng, X., Wu, C., 1999. Significant late Neogene east–west extension in northern Tibet. Geology 27, 787–790.

Yin, J., Xu, J., Liu, C., Li, H., 1990. The Tibetan plateau: regional stratigraphic contex and previous work. In: Sino-British Comprehensive Geological Expedition Team of the Qinghai-Tibet Plateau (Ed.), The Geological Evolution of the Qinghai-Tibet. Science Press, Beijing, pp. 1–48.

Zhang, Y., Zheng, J., 1994. Geological Survey of the Hoh Xil and Adjacent Regions in Qinghai Province. Seismology Press, Beijing, 177 pp.