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PALAEO
Palaeogeography, Palaeoclimatology, Palaeoecology 241 (2006) 61 – 78
www.elsevier.com/locate/palaeo

Lithostratigraphy, petrography and facies analysis of the Late Cenozoic sediments in the foreland basin of the West Kunlun

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Received 1 December 2004; accepted 26 June 2006

Abstract

The Yecheng profile, lying in the southwest Tarim Basin at the northern foot of the West Kunlun Mountains, comprises 4.5 km of conformable Miocene to Pliocene strata. The lower part of the section, the Wuqia Group, is composed of interbedded red mudstone and pale-coloured fine sandstone with a thickness of 1700 m. The Artux Formation is 800 m thick and composed of mudstone, sandstone with thin gravel and conglomerate beds. The upper part of the section, known as the Xiyu Formation, consists of 2000 m of cobble and boulder conglomerate intercalated with massive siltstone lenses.

Compositional study of the sandstones in the Wuqia Group and Artux Formation indicates that they were sourced from low relief areas of the Kunlun region and probably further south from Tibet. The provenance of the conglomerate in the Xiyu Formation is the West Kunlun Mountains. Compositional trends within the conglomerate indicate that Upper Palaeozoic marine, and Mesozoic to Tertiary terrestrial silicic rocks were eroded first, along with the Proterozoic to Lower Palaeozoic Proto-Tethys metasedimentary rocks. Erosion into deeper levels of the Kunlun Mountains provided igneous and high-grade metamorphic sediment, which first appears 640 m above the base of the Xiyu Formation.

Lithofacies change from fine-grained mudstone and sandstone to coarse clasts coincides with the onset of aeolian sedimentation, indicating major shift of regional palaeoclimatic regime. Although climatic changes may have played an important role in controlling the sedimentary regime worldwide, our study of the lithostratigraphy and petrography of the Yecheng section suggests that the lithofacies change recorded the progressive unroofing history of the source rocks in the West Kunlun Mountains.

Keywords: Lithostratigraphy; Petrography; Facies analysis; Risk perception; West Kunlun Mountains

1. Introduction

The Tibetan Plateau is one of the largest and most distinctive geographic features on Earth. The high topography of Tibet affects atmospheric circulation and strongly influences both regional and global climate (Ruddiman and Kutzbach, 1989). The plateau could have contributed to the inception of the Indian monsoon and Late Cenozoic Northern Hemisphere glaciation (Raymo and Ruddiman, 1992). However, the mechanisms and the timing of the uplift of the Tibetan Plateau have generated much debate in the past with a wide variety of models proposed to account for the origin of the Tibetan Plateau (e.g. Murphy et al., 1997; Hildebrand et al., 2001; Ducea et al., 2003; Wallis et al., 2003; Kapp

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doi:10.1016/j.palaeo.2006.06.015

et al., 2005). Interpretations of the timing when uplift of the plateau occurred range from Miocene to as recently as the Pleistocene (Dewey et al., 1986; Copeland et al., 1987; Quade et al., 1989; Harrison et al., 1992; Raymo and Ruddiman, 1992; Molnar et al., 1993; Fielding, 1996; Zheng et al., 2000).

Until recently, the northwestern part of the Tibetan Plateau has remained one of the least studied areas in central Asia. As accessibility to northern Tibet has increased, more studies are being undertaken to examine the uplift history of this part of the plateau to compare with the more extensively studied regions in southern Tibet and the Himalayas (e.g. Ducea et al., 2003; Kapp et al., 2005).

As mountain ranges rise, enormous amounts of terrigenous sediments are accumulated in foreland basins adjacent to the uplifted areas. By studying clastic successions that are shed off mountain belts, it is possible to characterise the timing and nature of the deformation and uplift. Detailed facies and palaeoenvironmental studies show how depositional environments reflect the changing relief of the source area. Provenance and palaeocurrent studies of a sedimentary wedge reveal source areas, unroofing histories and drainage patterns. If accurate magnetostratigraphy is available, it is possible to constrain the timing of deformation events and to measure sedimentation rates.

The aim of this study is to conduct a detailed sedimentological and provenance study on a sedimentary wedge at the foot of the West Kunlun Mountains. A magnetostratigraphic study of the section has previously been completed (Zheng et al., 2000), and integration of

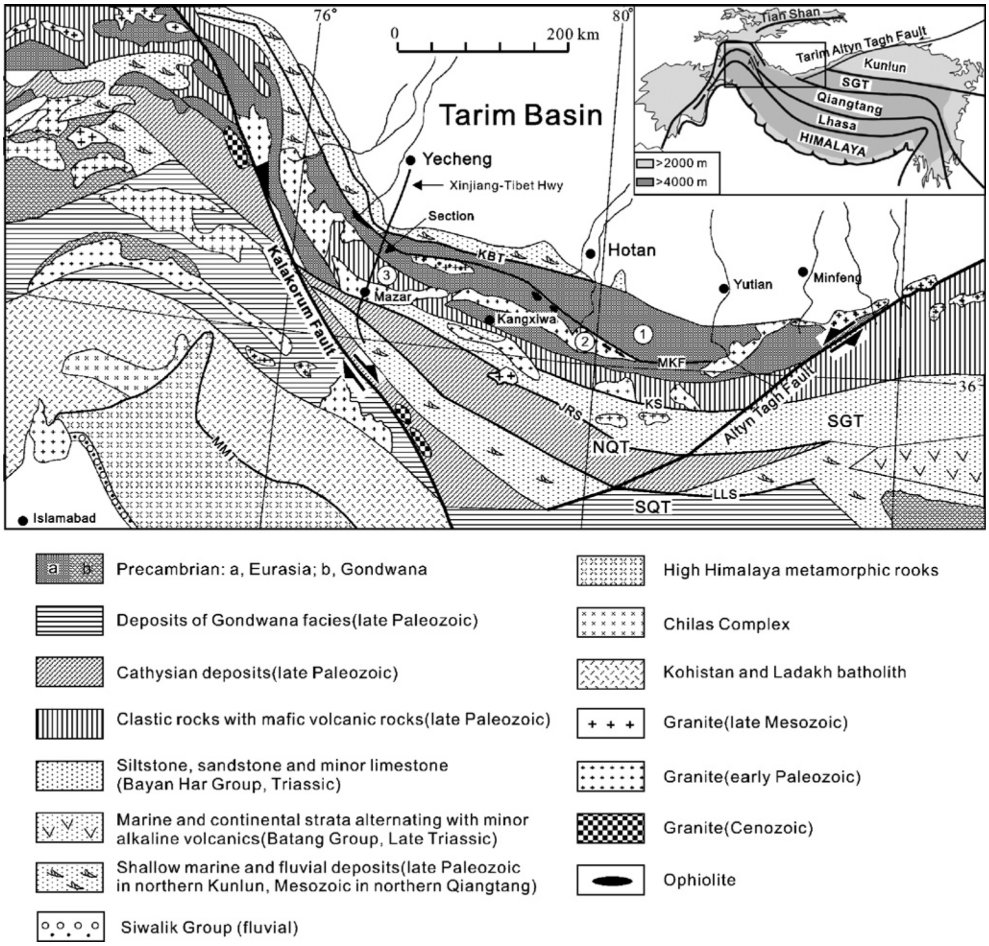

Fig. 1. Geological map of Western Kunlun and adjacent areas (after Chang, 1994). KBT = Kunlun Boundary Fault; KS = Kunlun Suture; JRS = Jinsha River Suture; MKF = Mazar-Kangxiwa Fault; LLS = Longmucuo-Lancang River Suture; SGT = Songpan-Ganzi Terrene; NQT = Northern Qiangtang Terrene; SQT = Southern Qiangtang Terrene; ① = Southern uplifted belt of Tarim Basin; ② = Middle Kunlun oceanic belt; ③ = Central Kunlun Belt.

this study with sedimentology and provenance aims to constrain an unroofing history of the West Kunlun Mountains in this area.

2. Regional geology

The field region is situated in the southwest Tarim Basin and on the northern margin of the West Kunlun Mountains. The Kunlun Mountains mark the northern margin of the Tibetan Plateau (Fig. 1).

Tibet was formed by the successive accretion of continental terranes onto the southern margin of Eurasia. Five terranes are generally recognized within the Tibetan Plateau (Pan, 1992; Matte et al., 1996), representing collisions spanning the Palaeozoic to Tertiary. From north to south, the geological terranes are: the Kunlun, Songpan-Ganze (SQT), Qiangtang, Lhasa and Himalayan Terranes (Fig. 1).

The basement of the Tarim Basin is Archaean and Proterozoic crystalline metamorphic rocks of mostly amphibolite to granulite facies. Rock types include gneisses, schists and marbles, with minor granite and pegmatite dykes (Lee, 1985). Mesozoic strata act as the cover of the basement and are deformed. Palaeocene to Miocene deposits unconformably overlie Jurassic strata and mainly comprise thick deposits of terrestrial red-bed clastics. Shallow-marine limestones and calcareous shales were deposited periodically until during the Oligocene. In the Miocene, the whole Tarim Basin subsided and a series of terrestrial red sandstones, shales and mudstones were deposited.

3. Stratigraphy

The Yecheng section is located at the northern foot of the West Kunlun Mountains and comprises over 4.5 km of Late Neogene sediments (Fig. 2). The lower part of the section consists of alternating beds of mudstone, siltstone and fine- to medium-grained sandstone. Based on regional stratigraphic correlation, the strata are equivalent to the upper part of the Miocene Wuqia Group (Sobel and Dumitru, 1997). The middle part of the section contains fine-grained sandstone, mudstone and thin layers of fine gravel, which comprise the Artux Formation. The uppermost part of the section is dominated by pebble to boulder conglomerate intercalated with lenses of pale-yellow siltstone. This is known as the Xiyu Formation and is widely distributed along the margins of the Tarim Basin (Li, 1996). All three units are conformable at this location. The Pleistocene Wusu Formation sits unconformably above the Xiyu Formation to the north of the section. Quaternary loess drapes the whole region (Fig. 2).

3.1. Wuqia Group

Outcrop of the Wuqia Group measured 1695 m thick and detailed magnetostratigraphy suggests the age of this section to be approximately 10 Ma (Zheng et al., 2000). The lower part of the unit is covered by Quaternary loess, and the contact with the overlying Artux Formation is conformable. The strata dip consistently between 70° and 75° to the north. The exposed section contains

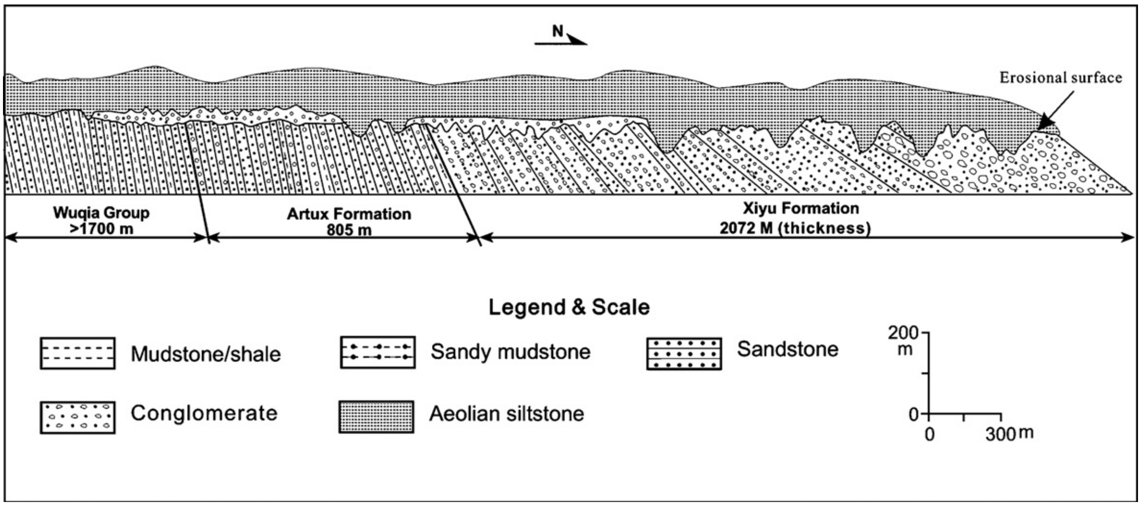

Fig. 2. Yecheng sedimentary section exposed by the Keliyang River depicting stratigraphy and shallowing dip towards the north (modified after Zheng et al., 2000).

interbedded mudstone, shale, thin sandstone and large, massive sandstone beds. The proportions of the rock types vary significantly within the Wuqia Group.

3.2. Artux Formation

The Artux Formation conformably overlies the Wuqia Group and conformably underlies the Xiyu Formation. The Artux Formation lies within the Gilbert Reversed Chron, with an age ranging from 4.6 to 3.5 Ma (Zheng et al., 2000), and has an approximate minimum sedimentation rate of 0.8 mm/year. The unit is 805 m thick and dips ~ 70° to the north, shallowing slightly in the upper part of the formation. The base of the Artux Formation is defined as the first appearance of pebble conglomerate. Siltstone and fine sandstone are the dominant rock types with a minor amount of granule to pebble conglomerate. The most distinctive trend in the Artux Formation is the increase in thickness, concentration and maximum clast-size of conglomerate up-section. The top of the formation is defined as the first appearance of thick (>5 m) conglomerate beds and the disappearance of shale and fine sandstone (Zhu, 1994).

The conglomerate beds are interbedded with: (i) thick beds of massive siltstone (up to 50 m) with millimetre-scale shale layers occasionally defining bedding; (ii) massive fine sandstone with minor laminated shale and granule conglomerate; and (iii) decimeter planar interbeds of shale, fine sandstone, siltstone and granule conglomerate. Granule conglomerate bands are matrix supported with maximum clast sizes of 2–4 mm in a siltstone–fine-sandstone matrix. The conglomerate units vary from 6 cm thick at the base of the Artux Formation, to a 15 m succession of conglomerate beds (up to 3 m thick) intercalated with siltstone lenses, at the top of the unit. Clast sizes reach 40 cm, however average 5 mm. The conglomerate is polymictic, with sub-rounded to sub-angular, poorly sorted clasts. Beds commonly truncate underlying strata and are massive, normal or reverse graded.

3.3. Xiyu Formation

The Xiyu Formation is the uppermost exposed part of the Yecheng section and comprises 2000 m of polymictic pebble to boulder conglomerate intercalated with siltstone lenses. The Xiyu Formation has an age between 3.5 and 1.8 Ma (Zheng et al., 2000). Sorting decreases up-section, whereas maximum clast-size increases (up to 2.5 m) in the upper part. Most beds are massive although many of the thinner beds show normal or reverse grading. Some reversely graded beds have large clasts protruding at the top, where they are blanketed by overlying siltstone.

Lenses of pale-yellow siltstone occur between the conglomerate beds. These siltstone beds are massive and vary in thickness from 30 cm to 10 m. Gravel is interspersed within the siltstone lenses, but commonly is concentrated at the base. The lenses are commonly completely truncated by the overlying conglomerate. The abundance of the intercalated siltstone beds varies within the Xiyu Formation. Some parts contain thick and numerous siltstone lenses (up to 40% siltstone), whereas typically the unit has only 5–10% siltstone.

4. Petrography

Thirty-one sandstone thin sections were examined in detail for the petrographic study. The samples were impregnated with casting resin, thinner and a catalyst, and then heated to enable setting of the friable material. Further impregnation with petropoxy was required to make the thin sections. Samples were stained with potassium ferricyanide for potassium feldspar recognition. Mineral percentages are quoted as per rock volume unless stated as recalculated QFR proportions.

Standard petrological techniques using a polarising microscope were employed to describe the thin sections. Qualitative microprobe analysis was used to identity some accessory minerals and cement compositions. Thin sections were also point-counted using a Swill automatic point counter. A total of 750 points were counted per thin section. These quantitative data were used to establish

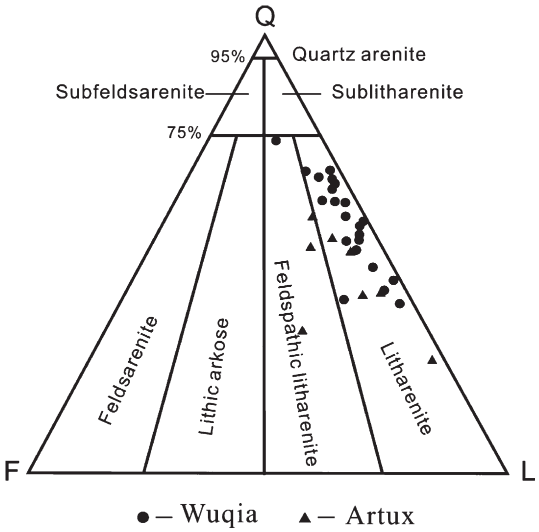

Fig. 3. Classification of sandstones in the Wuqia Group and Artux Formation based on the Q-F-L diagram after Folk et al. (1970). Q = quartz, F = feldspar, L = lithic fragments.

the composition and also classify the rocks according to Folk et al. (1970).

4.1. Wuqia Group sandstones

Detailed descriptions were made of 23 sandstones from the Wuqia Group (Fig. 3). The sandstones were sampled from thick lenses, massive sandstone bodies and thin, planar beds. They are typically very fine- to fine-grained sandstones with a few medium-grained samples. A ternary plot of the quartzose, feldspar and lithic fractions classifies all the sandstones as litharenites, except one from the base of the exposed Wuqia Group.

The stratigraphic trends show volcanic clasts increasing at the expense of the other lithic clasts, while quartzose clasts remain a minor and unchanged component. This corresponds to a move from a collision-orogen source towards an arc-orogen source (Folk et al., 1970). This progression from different orogenic provenance types represents an unroofing sequence culminating in the exhumation and erosion of older arc terranes.

4.1.1. Quartz

The quartz component of these samples is dominated by monocrystalline quartz showing straight extinction (average 25% of whole rock volume). There is also a significant amount of strained monocrystalline quartz (average 9%) and polycrystalline quartz (average 9%), which is rarely sheared. The grains are sub-rounded to sub-angular with angularity generally increasing up-section. Volcanic quartz, recognized from the presence of embayments, is present in minor amounts in most samples.

4.1.2. Feldspar

Potassium feldspar comprises the majority of the feldspar component, with only minor plagioclase in most samples. Potassium feldspar averages 2.7% and is mostly orthoclase with a small amount of microcline. Most grains show partial dissolution and alteration along the cleavage planes. The grains are rounded to sub-rounded and commonly tend to a tabular shape.

4.1.3. Lithic fragments

Lithic fragments are a major component, ranging from 11% to 45% and averaging 27% of the rock volume. The lithic fragments are highly variable and are dominantly sedimentary and low-grade metasedimentary in origin, with minor volcanic and plutonic clasts. The main sedimentary clasts include chert, greywacke, sandstone and mudstone. Distinctive, purple, fine-grained sedimentary clasts increase in abundance up-section in the Wuqia Group. Clasts derived from metamorphic rocks are dominantly schist, phyllite and gneiss fragments. Silicified marble is present in the samples near the top of the Wuqia Group. Volcanic clasts are present in most of the samples in minor amounts up to 1.4%, and appear to have a dominantly felsic composition. Hematite staining of fine-grained sedimentary and volcanic clasts made exact identification difficult. Plutonic grains were identified in a fifth of the samples examined, mostly hypabyssal dolerite clasts.

4.1.4. Accessory minerals

Accessory minerals, including mica, carbonate grains and heavy minerals, are present in all samples in minor or trace amounts. Micas (e.g. muscovite, biotite and chlorite) occur as tabular crystals. Muscovite is the most abundant, while biotite increases in abundance in the upper part of the Wuqia Group. Chlorite occurs only in trace amounts and is formed by the alteration of biotite. Heavy minerals include (in order of decreasing abundance) opaque iron oxides, zircon, tourmaline, rutile, barite and strontianite. The latter two minerals occur only in one sample.

4.1.5. Matrix

Tile sandstones contain an average of 4.6% and a maximum of 9.7% matrix. It consists of silt-sized quartz and clay minerals. The difficulty in distinguishing between matrix, iron-oxide cement and pseudomatrix (sedimentary lithic fragments compressed between quartz grains) could have slightly increased the recorded matrix proportion.

4.1.6. Cement

Authigenic mineral cements include calcite, hematite, serieite, quartz and pyrolusite. Sandstones contain an average of 24% and a maximum of 48% cement by volume. Calcite cement is the most abundant and tends to form large poikilotopic crystals that envelop several grains or calcite mosaics of equant crystals that partially or fully occlude pores. Hematite is the other major cement type and imparts a red/brown colouring to the sandstone. Hematite typically occurs as a very thin coating around grains, but it also stains the matrix and occludes pores. Three samples bare significant silica cement. It occurs as overgrowths around grains, completely infilling pores and as a finely crystalline mosaic of microquartz. Sericite occurs as a minor cement, and pyrolusite forms a layered cement along bedding planes at the base of 7 m thick sandstone lens.

4.2. Artux Formation sandstones

Seven samples were examined from the Artux Formation. Four samples are from fine-grained massive sandstones, whereas three are from fine sandstones containing minor gravel. Large clasts are classified according to the composition of sand-sized minerals they contain. All samples classify as litharenites, except one, which plots as a feldspathic litharenite (Fig. 3).

4.2.1. Quartz

The quartz component is dominated by monocrystalline quartz, with polycrystalline and monocrystalline quartz (showing undulose extinction) comprising a significant, but lesser constituent. Volcanic quartz, typically hexagonal in shape and containing embayments, is present in most samples, as is sheared polycrystalline quartz derived from a metamorphic source. The grains are sub-rounded to sub-angular; however, there is a higher proportion of sub-angular grains.

4.2.2. Feldspar

Potassium feldspar is far more abundant than plagioclase, averaging 6.8% by rock volume compared to 0.5% for plagioclase. Feldspar grains are rounded to sub-rounded and some grains are partially altered to carbonate along the cleavages.

4.2.3. Lithic fragments

Lithic fragments comprise on average 29.5% and range from 31% to 44% by rock volume. In the fine-grained sandstones, sedimentary lithics (chert, siltstone, greywacke and sandstone) dominate, whereas in the samples with a component of gravel, metamorphic clasts (schist, gneiss and siliceous marble) are more abundant than sedimentary lithics. Volcanic and plutonic clasts are a minor component and include basalt, rhyolite, granite and dolerite.

4.2.4. Accessory minerals

All samples contain accessory minerals, including micas and heavy minerals, in minor or trace amounts. Both muscovite and biotite occur in all samples, with muscovite more abundant, although the percentage of biotite increases up-section in the Artux Formation. Heavy minerals present, in order of decreasing abundance, are opaque iron oxides, zircon, tourmaline, rutile, barite and trace amounts of staurolite.

Matrix comprises 5.4% on average of the samples. It consists of silt-sized quartz and minor hematite-stained clays.

4.2.5. Cement

Calcite, hematite, quartz and sericite occur as cements in Artux sandstones. Calcite is the most common cement, hematite is present in all samples, and silica and sericite cement are rare. Calcite occurs as poikilotopic grains, but mostly as partial cements of finely crystalline aggregates. Hematite forms thin coatings around most grains and also infills pores and stains the clay matrix. Muscovite and quartz form poikilotopic cements along discrete laminae in three samples.

4.3. Xiyu Formation

4.3.1. Sandstone petrology

The only sandstone in the Xiyu Formation is a 15 m thick feldspathic litharenite, 1260 m above the contact with the Artux Formation. The unit is a moderately sorted, fine- to medium-grained, trough cross-bedded, light-green sandstone. It has a distinctive mineralogy that is dominated by clinopyroxene (25%) and potassium feldspar (18%). Clinopyroxene is sub-rounded with both lath- and equant-shaped grains, and has an average grain size of 0.3 mm and maximum of 1 mm. Feldspar grains are sub-rounded to sub-angular with plagioclase (3.2%) forming characteristic elongate laths. Quartz (14%) is mostly unstrained, monocrystalline, sub-rounded to sub-angular grains averaging 0.2 mm. Hornblende and biotite are significant accessory minerals in this rock, as is apatite, titanite and zircon. A mosaic of calcite partially cements the sample. Lithic fragments consisting of clinopyroxene laths within an aphanitic, potassium-rich groundmass suggest the clinopyroxene may have been derived from a volcanic protolith.

4.3.2. Conglomerate petrology

Conglomerate beds are composed of cobble- and boulder-sized clasts of sedimentary, metamorphic and volcanic origin, with minor plutonic-sourced clasts. The conglomerates are marginally clast supported and contain a matrix of silt/fine-sand and fine gravel. The sedimentary clasts include green, white, red and black conglomerate clasts, purple siltstone, limestones, sandstones and greywackes. They tend to be fairly angular and are generally smaller than igneous and metamorphic clasts. Low-grade metamorphic clasts are very common and include greenschist, slate, marble and phyllite. Volcanic clasts are mainly pink porphyritic rhyolite, but minor basalt is also present. Plutonic clasts included granite, diorite, dolerite and gabbro, and medium- to high-grade metamorphic clasts observed were felsic and mafic gneiss, granulite and amphibolite. Plutonic clasts do not appear until approximately 1000 m above the base of the Xiyu Formation.

4.3.3. Silt/fine-sand matrix

The silt/fine-sand matrix fraction in the conglomerate beds is dominated by monocrystalline quartz (55%) with minor polycrystalline quartz. The quartz is angular to sub-rounded (averages sub-angular) and has an average grain size of 0.5 mm. The matrix contains biotite, iron oxides, feldspar and zircon in minor and trace amounts. Carbonate (16.4%) and hematite (13%) cement the matrix.

4.3.4. Fine-gravel matrix

The fine-gravel matrix fraction is largely composed of sedimentary lithics with minor low-grade metasediments such as phyllite and slate. Sedimentary lithics include siltstone, mudstone (including purple fine-grained sediments), chert, limestone, sandstone and greywacke. Grain size ranges from 2 to 7 mm, averaging 3.5 mm.

4.4. Sandstone diagenesis

The sandstones examined from the Yecheng section exhibit evidence of diagenesis resulting from near-surface processes such as cementation and compaction. However, there is no evidence of pressure dissolution or grain replacement due to deeper burial. Cementation is generally patchy, as indicated by the highly friable nature of the sandstones. The diagenetic events are listed below in chronological order although some events overlap and other timing relationships are poorly constrained.

4.4.1. Calcite

Calcite is the major cement type and occurs as calcite spar (finely crystalline mosaics) and as poikilotopic crystals enveloping several grains. Calcite is often trapped between detrital grains indicating an early diagenetic origin.

4.4.2. Hematite

Hematite cement rims detrital grains and partially occludes pores. It also overgrows calcite cement and infills along cleavages indicating that hematite cement was precipitated after calcite. Hematite generally encloses grains, including along grain contacts, indicating that it was formed prior to compaction.

4.4.3. Compaction and dissolution

Compaction appears to have been a fairly minor process judging from the preservation of most point contacts between grains and only a few long contacts between quartz grains. However, sedimentary and metasedimentary lithics are commonly compacted and deformed between quartz grains. Mica grains are also sporadically deformed by compaction. Feldspar grains are only partially altered along cleavages indicating dissolution was not a major process.

4.4.4. Silica

Precipitation of silica was observed in a number of samples, occurring as poikilotopic cements generally encloses grains, suggesting it was precipitated subsequent to compaction.

4.4.5. Sericite

Sericite is similar to silica cement in that it is a minor cement, optically continuous and developed after compaction. Distinguishing between the timing of sericitic and silica cement was not possible.

5. Point-count and stratigraphic trends

The provenance of a sediment includes all aspects of the source area, including source rocks, climate and relief. In areas of intense tectonic/magmatic activity, source-rock type is the major control on provenance, while in tectonically inactive areas, climate and relief are more important factors (Dickinson, 1970). Modal compositions of sandstones and conglomerates can be used to infer the tectonic setting of the basin and source rocks (Dickinson and Suczek, 1979). A point-count study of Yecheng sandstones was carried out and the stratigraphic trends were revealed, the results of which enable the sandstones to be classified into a general plate-tectonic setting. The conglomerate was deposited in a foreland basin, indicated by the similarity of the deposits currently forming in the basin, so the point-count results are only used to classify the type of orogenic belt that the rocks were sourced from.

5.1. Sandstone provenance

Sandstones were sampled from the three units at the Yecheng section: 23 from the Wuqia Group, 7 from the Artux Formation and one from the Xiyu Conglomerate. Where possible, the spacing between the sample sites was kept constant. The rocks were impregnated, thin-sectioned and stained with potassium ferricyanide to detect potassium feldspar. The 31 samples were then point-counted, with 750 counts per section, and plotted using the categories and triangular plots outlined in Dickinson and Suczek (1979).

All samples are quartzolithic and have average composition of $Q_{64}F_5R_{31}$. Point-count data reveal changing composition of detritus within the sedimentary wedge. These trends can result from changes in the source composition, transportation distance and regime, and also climate. The various components and up-section trends are discussed below. Percentages are presented as whole-rock volume. Changes in the proportions of clasts are presented on graphs below. The graphs are presented in similar orientation to the field section where left- to-right progresses stratigraphically up-section.

5.1.1. Quartz

Monocrystalline quartz is by far the most abundant quartz type through the sequence. Of this, unstrained quartz with straight extinction is more common (20.6%) than strained quartz with undulose extinction (10.1%). Polycrystalline quartz averaging 6.3% and commonly shows a metamorphic fabric. Polycrystalline and monocrystalline quartz, both strained and unstrained, can be derived from plutonic and low- to high-grade metamorphic sources. However, undulose and polycrystalline quartz is more likely to be sourced from metamorphic rocks, especially low-grade metamorphics (Basu et al., 1975). Monocrystalline, unstrained quartz is most commonly derived from recycled sedimentary rocks, as the other quartz types are less stable and are selectively removed.

5.1.2. Feldspar

Feldspars are a minor component of the sandstones, averaging 3.6% of the rock volume. Potassium feldspar (3.3%) is far more common than plagioclase (0.3%) and is mostly orthoclase with minor microcline. The

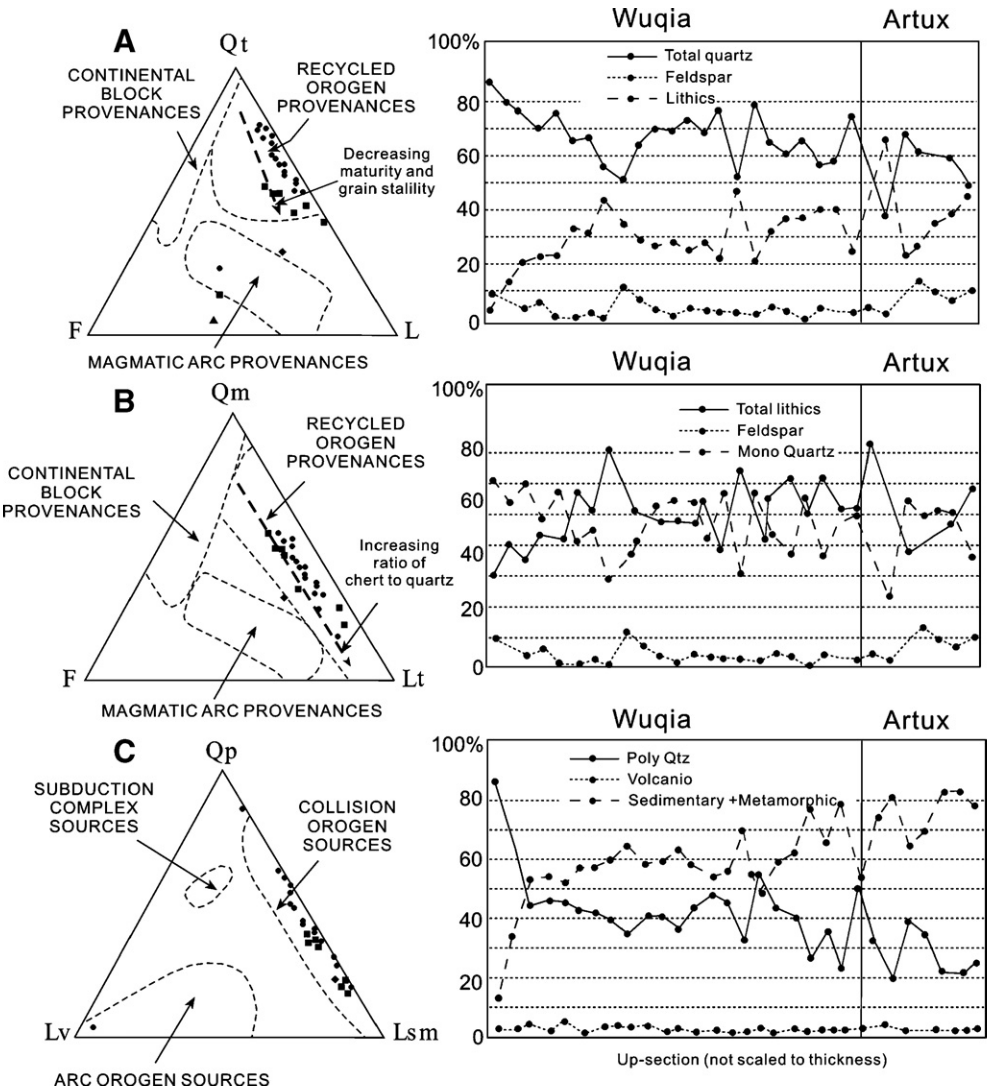

Fig. 4. The total quartzose fraction of sandstones from the Wuqia Group and Artux Formation. (A) Qt = total quartz, F = feldspar, L = lithic fragments. (B) Qm = monocrystalline quartz, F = feldspar, Lt = total lithic fragments. (C) Qp = polycrystalline quartz, Lv = volcanic lithic, Lsm = sedimentary and metamorphic lithics (circle = Wuqia Group, square = Artux Fm., triangle = Xiyu Fm.).

dominance of potassium feldspar indicates derivation from granites and gneisses (Tucker, 1981). Potassium feldspar tends to occur as pulses and then fall back to an average of around 5% of the framework grains. Potassium feldspar increases in the Artux Formation indicating a slight decrease in compositional maturity. Plagioclase content remains a minor component throughout the section.

5.1.3. Lithic fragments

Lithic fragments are an important component of the sandstones and comprise on average 21.3% of the rock volume. The composition of rock fragments is highly variable: mainly sedimentary and metamorphic clasts, with minor volcanic and plutonic-sourced clasts. Metamorphic clasts are dominantly low-grade slate, quartzite and phyllite. Lithic clasts show high variability and lack any definite trends up the section. Sedimentary lithics are most abundant and remain fairly constant throughout the section after an initial increase at the base of the exposed Wuqia Group. Weak trends up-section include decreasing chert content and increasing metamorphic clasts.

The tectonic setting of the source area exerts primary control on sandstone compositions (Ingersoll et al., 1984). Triangular diagrams, where parameters are plotted to classify the plate-tectonic regime of the provenance, have been produced from studies of modern sands from known tectonic settings. Three triangular plots are presented in Fig. 4. Orogenic recycling occurs where sedimentary rocks are deformed, uplifted and eroded. Compositionally, they tend to vary and are dependent on the type of orogenic belt, from which they were derived. Sources may be cratonic, arkosic or volcaniclastic, and may be modified by metamorphic processes (Dickinson, 1985). Sediments of orogenic provenance are generally rich in indurated sedimentary and low-grade metamorphic clasts and have consistently low contents of feldspar and volcanic rock fragments (Dickinson and Suczek, 1979).

In Fig. 4A, the total quartzose fraction (including chert and polycrystalline quartz) was plotted together and is presented as Qt, and is therefore an indication of grain stability, and maturity of the sediment. The corresponding graph shows the proportion of quartz decreasing as the lithic component increases. This is equivalent to a trend moving towards the L corner on the QtFL triangle and indicates decreasing maturity or stability.

The QmFLt plot (Fig. 4B) has all the lithic fragments plotted together as Lt and once more all samples plot in the recycled orogen provenance of Dickinson (1985). There is no obvious trend up section on the graph but the sandstones from the Artux Formation lend to plot toward the Lt corner of the plot.

The QpLvLsm triangle (Fig. 4C) emphasises the type of orogenic environment from which the detritus was derived (Dickinson, 1985). Orogenic provenances can include subduction complexes that contain deformed ophiolitic material, arc orogens rich in feldspars, volcanic rocks deposited within a retro-arc foreland basin and intercontinental collision orogens (Dickinson, 1985). The majority of samples plot in the continental collision orogen field, which generally has a high Ls/Lv ratio and is rich in sedimentary and metasedimentary clasts (Dickinson and Suczek, 1979). Samples collected stratigraphically higher in the Yecheng section show increasing sedimentary and metamorphic clasts while polycrystalline quartz, including chert, decreases up the section.

In summary, modal composition ternary plots indicate that the likely tectonic setting of the source rocks was a recycled orogen. The sandstones have large lithic components consisting mainly of sedimentary and metasedimentary fragments, and are low in feldspar and volcanic-derived fragments, typical of rocks derived from a continental collision orogen. Changes up the section include a slight increase in lithic and feldspar content and, conversely, a decrease in quartz content. These trends suggest detritus becomes more immature stratigraphically higher in the section.

5.2. Conglomerate provenance

Point-counting of conglomeratic units was conducted in the field at 18 locations in the Artux and Xiyu Formations (Fig. 5). One site was selected in the Wusu Formation, which unconformably overlies the Xiyu Conglomerate and crops out to the north of the section. The aim was to identity the type and proportions of clasts that comprise the conglomerates. Three locations in the thicker conglomerate beds of the Artux Foundation were examined, and 15 locations, approximately 150 m stratigraphically apart, were chosen in the Xiyu Formation. Two groups of 100 counts were made at each locality, each from a different bed.

Point-count results are presented in Fig. 5. The spacing of the point-counted samples was not even, so combining results with a stratigraphic section indicates the position of each site. The section below briefly describes the trends of the various clast types up-section.

5.2.1. Sedimentary clasts

These are the most abundant clast type and are compositionally variable. Distinctive clasts of purple, bedded, claystone and siltstone are common throughout. Pink and grey limestone is also very common, especially

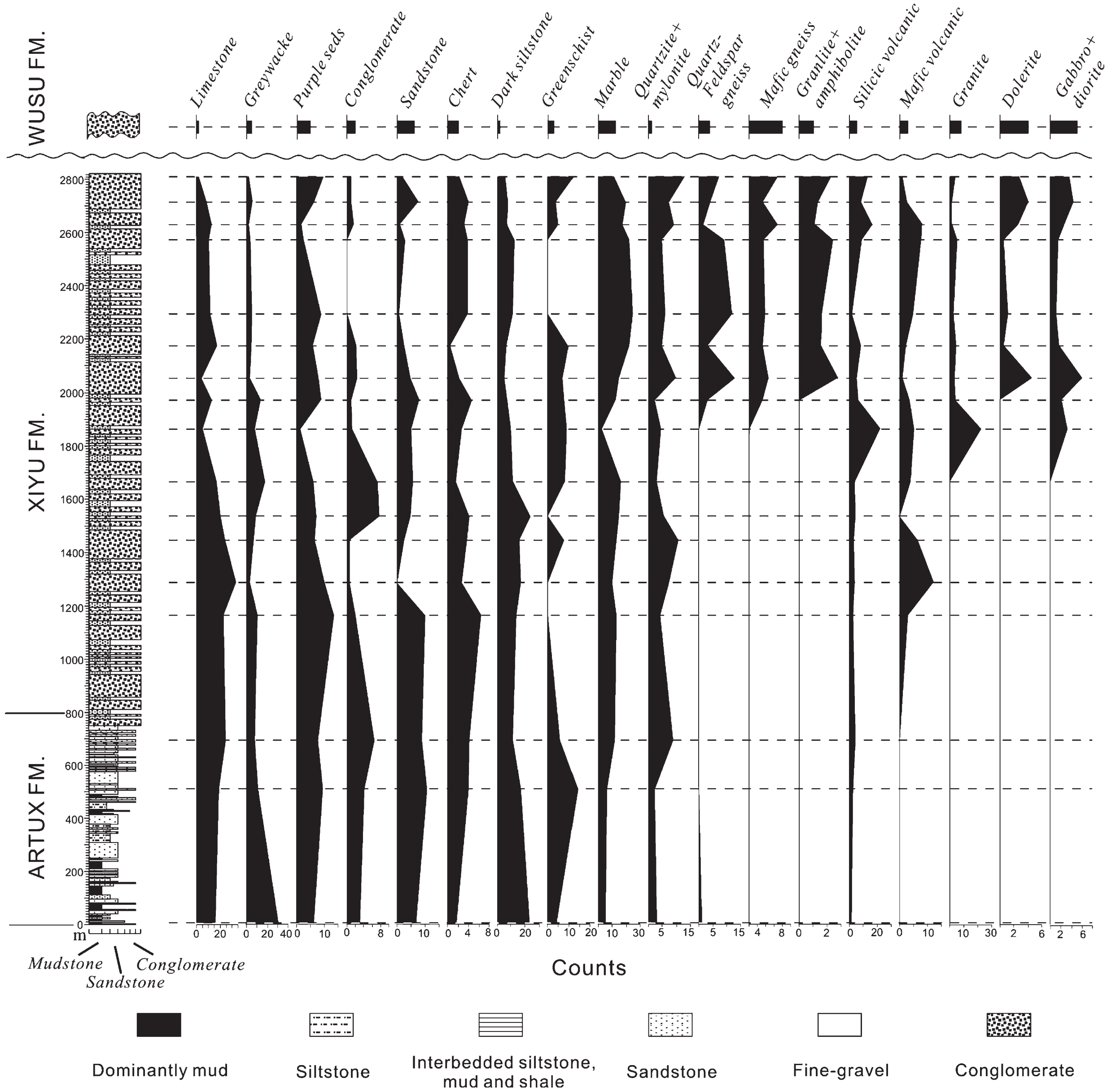

Fig. 5. Point-count results of Artux and Xiyu Formations, plotted with a stratigraphic column demonstrating up-section trends. Point-count locations are indicated by the dashed lines.

in the lower half of the conglomerate section. Other sedimentary types include greywacke, sandstone, and purple, green, black and cream varieties of conglomerate.

5.2.2. Volcanic clast

Both silicic and mafic volcanic clasts arc present in the section. Silicic volcanics are more abundant, averaging 7.9% and reaching as much as 27.6% in the overlying Wusu Formation. They are mostly rhyolitic in composition, with a distinctive pink, porphyritic, felsic volcanic the most common type. Mafic volcanics are fairly minor, averaging 3.6% and are dominantly basaltic. Up-section the abundance of volcanic clasts increases significantly from a very minor component in the Artux Formation and the base of the Xiyu Formation to the most common clast type at the top of the Xiyu and in the Wusu Formation (Fig. 5).

5.2.3. Metamorphic clasts

Low-grade metamorphic clasts are common throughout the section, totalling on average 30.3% of the clasts. The most common types are greenschist, indurated dark green metasiltstone and siliceous marble. Marble is widespread, especially in the middle of the Xiyu Formation where it comprises up to 24.5%. Slate or metasiltstone, and greenschist, are also very common, especially in the Artux Formation and the lower part of the Xiyu Formation (Fig. 5). High-grade metamorphic clasts are absent or present only in trace amounts up to the middle part of the Xiyu Formation, above which they generally increase in abundance (Fig. 5). Quartz-feldspar gneiss is the most common high-grade metamorphic rock, and includes potassium-feldspar-rich and plagioclase-hornblende-rich varieties. Other clast types include mafic gneiss and minor mafic granulite and amphibolite.

5.2.4. Plutonic clasts

Plutonic clasts are a minor part of the conglomerate units, only appearing 640 m above the contact between the Artux Formation and Xiyu Formation. Granite, rich in potassium feldspar, and dolerite are the most common clast types, with subordinate diorite and gabbro. Granite clasts occur as a pulse in the middle part of the Xiyu Formation (reaching 22.5%) and are only minor above this (Fig. 5). The stratigraphic trends show volcanic clasts increasing at the expense of the other lithic clasts, while quartzose clasts remain a minor and unchanged component. This corresponds to a move from a collision-orogen source towards an arc-orogen source. This progression from different orogenic provenance types represents an unroofing sequence culminating in the exhumation and erosion of older arc terranes.

6. Facies analysis and sedimentary environments

The great thickness of the section examined at Yecheng precluded detailed classification of the lithofacies throughout the section. Rather, lithofacies were defined following reconnaissance mapping, and the section was then classified into facies associations based on the lithofacies which were most likely to occur in succession. The objectives of facies analysis are to better define a body of rocks with specific characteristics; therefore, the sedimentary environments in which the rocks are formed can be classified. This will further give insight into how tectonics and/or climates may have controlled the formation of the sedimentary sequence.

Facies associations are groups of facies that occur together and are considered to be environmentally or genetically related. The concept of facies associations is fundamental to environmental interpretation and is an application of Walther's Law, which states that facies occurring in a conformable vertical sequence were formed in laterally adjacent environments. Grouping of several associated facies allows a facies of ambiguous origin to be classified and interpreted, because the combined facies association forms a unique and diagnostic sedimentary environment.

6.1. Meandering-stream association (FA 1)

Thick successions of interbedded mudstone, siltstone, shale and fine-sandstone lenses are interpreted as deposition from a meandering fluvial system (Reading, 1996). This association occurs over a thickness of 400 m, directly above the base of the exposed Wuqia Group (Fig. 6). Similar lithofacies were observed at the Aertashi (60 km to the west) and Keliyang (80 km to the east) sections at the base of the Miocene Wuqia Group, suggesting that this depositional system was laterally extensive, and active over a long period of time.

6.2. Braided-stream association (FA 2)

This facies association forms thick, nested sand beds in cosets up to 60 m thick in the middle part of the Wuqia Group, between 650 and 1150 m above the exposed base. Sedimentary structures include water-escape, ripples and flute casts, and animal tracks. Three sub-facies (FA 2A, B and C) are recognized as part of the braided-stream association (Reading, 1996), which exhibits variations in bed thickness and sedimentary structures. FA 2A is dominated by fine-sandstone beds, which coarsen to medium-grained at the base of graded sandstone lenses. The lenses are commonly erosional at the base and surround thin shale crescents formed as water-escape structures. Shale and siltstone is a very minor component of this sub-facies. FA 2B is a very thick unit of fine to medium sandstone with three thin mud intraclast layers. The base of the unit is a layer of sandstone containing brecciated mudstone. FA 2C consists of thick beds of fine (with minor medium-grained) sandstone with very thin layers of shale. Sandstones are finely laminated or massive and have planar contacts. Indistinct cross-beds in coarser layers were occasionally observed.

This facies association represents deposition in a braided fluvial system (Reading, 1996). This depositional environment tends to be sandstone dominant with little fine-grained sediment. The sandstone lenses in FA 2A containing coarse cross-beds representing in-channel lag deposits, the fine-sandstone and shale layers probably formed on the "bar top", from alternate deposition of sand out of the channel during flooding, and thin vertical-accretion deposits. The large thickness of the

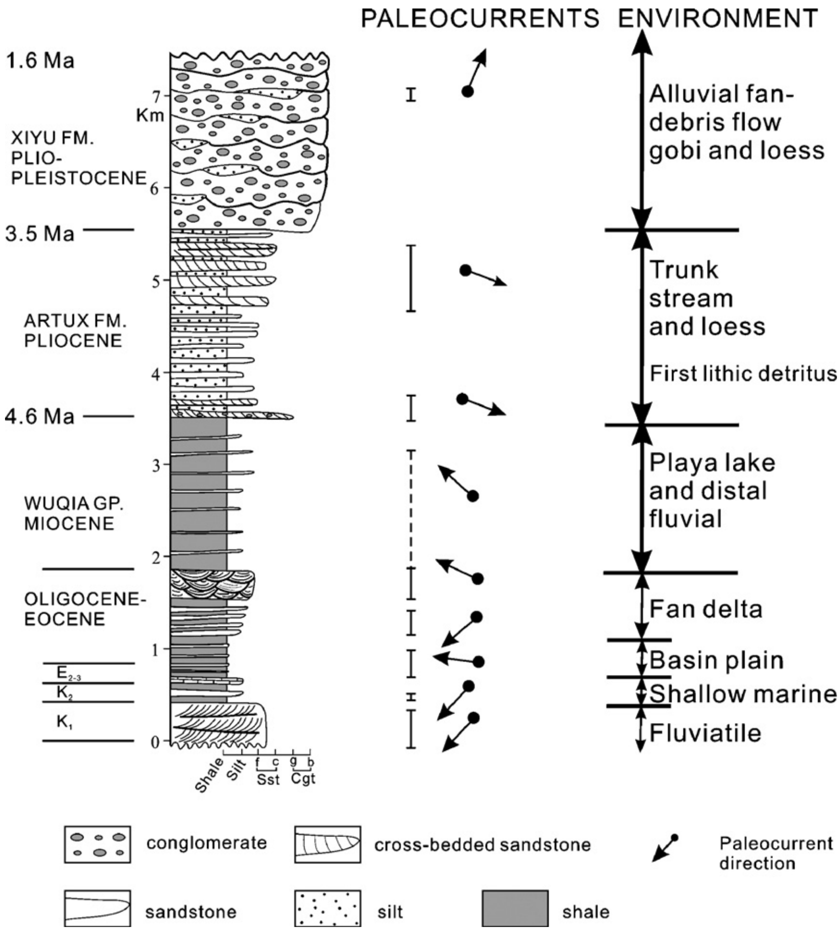

Fig. 6. A schematic diagram showing the composite stratigraphy, paleocurrents and sedimentary environments of the Cenozoic sediments in the foreland basins of the West Kunlun. Ages and lithology of the Late Neogene strata are based on magnetostratigraphy and field mapping of Yecheng section. Paleocurrents of Early Cenozoic strata are obtained from other sections in adjacent area.

unit suggests that avulsion was rare, the channel remaining stable and aggrading vertically for significant periods of time.

FA 2B is interpreted as resulting from a highly concentrated mass flow during a catastrophic flood event (Reading, 1996). The basal mud breccia layer is probably due to hydraulic fracture as sand was injected at a high velocity into an underlying shale bed. The three thick sandstones separated by intraclastic mud lenses suggest that there were three pulses within the one large event. FA 2C could represent deposition in a braided system where transportation was by laminar, rather than turbulent, flow (Reading, 1996). The interbedding with shale suggests a lower flow regime at the channel margins with regular flooding and deposition of fine suspension particles (Reading, 1996). Current and linguoid ripples, as well as animal tracks, all suggest shallow, lower flow-regime deposition producing thinly bedded sandstone and shale amongst the thick, aggradational sandstones.

6.3. Floodplain association (FA 3)

This association is fairly uniform and thick, extending from 1150 m above the exposed base of the Wuqia Group to the lower 50 m of the Artux Formation, or a thickness of around 650 m. It is dominantly mudstone, with minor shale, siltstone and thin sandstone beds. Sandstones are fine- to very fine-grained, between 20 cm and 1.5 m thick, and commonly form scouring lenses. Sporadic mudcracks are observed in silty mudstone beds.

This unit was deposited on a floodplain with episodic injections of coarse material into a muddy environment (Reading, 1996). There is little evidence of large channels, as most of the facies association was vertically accreted during periods of flooding. The change from thick channel sandstones in the lower part of the Wuqia Group to dominantly overbank accumulation with minor, thin, channel-sandstone lenses could be due to a change in climate or a change in the palaeodrainage of the area. Most likely, the river system that produced the large thickness of braided fluvial deposits underlying FA 3 had avulsed into another area of the basin. More regional studies would need to be completed to ascertain any climatic influence on a drier depositional area.

6.4. Distal- to mid-fan association (FA 4)

This association is represented throughout the Artux Formation and includes the oldest exposed granule and cobble conglomerate at the Yecheng section, near the base of the Artux Formation (Fig. 6). Interpreted as deposits of a distal to mid-alluvial fan (Reading, 1996), the distinction between this and more distal areas of the fan has not been made as the boundary is transitional and difficult to pin-point. The distal fan sub-facies contain medium to coarse, cross-bedded sandstone interbedded with gravel beds, siltstone and only very minor shale (FA 4A).

Stratigraphically higher in the Artux Formation, the section is dominated by massive, pink, fine-sandstone beds interbedded with granule conglomerate, massive siltstone and very minor shale. This part is separated into FA 4B and 4C on the basis of bed thickness; FA 4B has thick beds of fine sandstone; and FA 4C is more thinly bedded and contains more siltstone and shale. FA 4D is massive siltstone which forms very thick (up to 50 m) deposits in the Artux Formation. Finally, FA 4E comprises pebble- to cobble-conglomerate beds that are usually massive but may possess normal- or reverse-grading.

These deposits are interpreted as having formed in a more proximal part of a braided fluvial system and on the distal part of an alluvial fan (Reading, 1996). FA 4A is typical of normally graded, braided stream deposition with fairly coarse bed-load. The siltstone represents levee deposition and the shales are mud-drapes which formed over sand bodies after flooding. FA 4B and 4C are both interpreted as mid- to lower-fan deposits. The abundance of tabular, planar-laminated and massive sandstone beds that lack any indication of water movement (no channels, ripples, etc.) suggests a fairly dry environment with transportation into the basin by sheet-flow with some aeolian action (Reading, 1996). Sporadic intercalation by gravel represent ephemeral floods and the thin shales represent the waning of the flood events.

The massive siltstone beds (FA 4D) are classified as aeolian as they are well-sorted, cemented by carbonate and internally structureless, similar to loess currently being deposited on the tops of low hills of the Kunlun Mountain front (Reading, 1996). Grain size and geochemical analyses were carried out on siltstones sampled from the Artux and Xiyu Formations to compare with typical loess (Zheng et al., 2003). FA 4E was deposited in a mid- to lower-alluvial fan environment indicated by an influx of coarser sediment, poor-sorting, matrix-rich and weakly reverse-graded beds. Conglomerate is only a minor component of the depositional environment in the Artux Formation.

6.5. Proximal alluvial fan (FA 5)

This facies association occurs throughout the entire Xiyu Formation and is composed of thick cobble- to boulder-conglomerate beds intercalated with siltstone lenses. The conglomerate clasts average 15 cm and reach a maximum size of 2.5 m. The beds are highly varied, occurring as reverse-graded beds, massive, thick units with weak internal stratification and channels with erosional bases. Massive siltstone occurs as lenses within the conglomerate. It commonly contains interspersed gravel and drapes over large boulders that protrude into the overlying fine sediment. Siltstone lenses vary in thickness from 30 cm to more than 10 m, with the thicker beds usually occurring closely spaced.

The Xiyu Formation (FA 5) is interpreted as sediment deposited in a proximal alluvial fan setting in an arid to semi-arid climate (Reading, 1996). There is little evidence of water movement, the clasts are fairly angular, there is abundant matrix, and stream-channel conglomerate beds are minor part of the unit. Deposition occurred by debris flow, which formed poorly sorted, often reverse-graded beds and by sheet-flood deposition resulting in thick beds with weak internal stratification of average clast size. The siltstone lenses in the conglomerate beds appear to be loess, deposited on the uneven fan-floor before being buried by the next debris or sheet flow. This indicates an arid to semi-arid climate, similar to the modern environment with widespread loess deposition in the Tarim Basin.

6.6. Interpretation of sedimentary environments

The Yecheng section represents a transition from a floodplain to an alluvial fan environment (Fig. 6). This implies an increase in the energy of the system and the proximity of the source, as well as a decrease in the maturity of the sediment. In addition, the change in gradient has implications for uplift of the source area. The type of fluvial system and also the activity of the system influence deposition. The section shows overall increase in grain size from deposition in meandering rivers to a braided system, and finally sheet-flood and debris-flow deposition on an alluvial fan. Facies analysis indicates that lithofacies changes through the Yecheng section has mainly controlled by changes in sedimentary environments, which are in turn caused by topographic relief. Climate may have also played a role in modifying the lithology though time, as suggested by petrologic and geochemical studies (Zhang et al., 2001; Zheng et al., 2003).

Where possible palaeocurrent indicators such as cross-bedding, foresets of climbing ripple laminae, through axes and clast imbrication were measured using a Brunton magnetic compass and a dip frisbee (Fig. 6). A minimum of 15 imbricate orientations was measured within suitable conglomerate. Imbrication was plotted as π poles and the mean direction determined. Bedding orientations were used to rotate the strata back to horizontal (assuming the original depositional slope was near horizontal) using standard equal-angle, stereonet procedures. The resulting mean direction records the upstream direction of the palaeoflow. Palaeocurrent directions are plotted in Fig. 6 relative to the stratigraphic log. Palaeocurrent measurements indicate a change of flow directions from west–east to north. More palaeocurrent data are needed to characterise the pattern of the palaeodrainage.

7. Discussion: unroofing history of West Kunlun

Provenance studies were used to define the plate tectonic setting of the source rocks for the Yecheng section. This is especially possible in young orogenic belts, where likely source areas are not completely eroded, so detritus can be compared with possible source terranes. In these settings, tectonics, rather than climate, relief and transportation, tend to be the major influence on detrital composition (Dickinson, 1970). The unroofing history, or the sequential erosion of the source area, should be reflected in the changing proportions of detrital components.

The sandstone-dominant part of the section is treated separately from the conglomeratic part, as the nature of the source area must have changed to produce such contrasting detrital grain size, most likely by source relief or source proximity, or a combination of the two. An unroofing history is proposed, which is integrated with magnetostratigraphy to characterise the uplift history of the source region.

7.1. Sandstone source area

In order to deduce the location of a source area of the sedimentary rocks, two questions need to be considered: (i) what direction the sediment came from and (ii) how far it travelled before deposition. Sandstones from the Wuqia Group and the Artux Formation formed in fluvial environments; thus, palaeocurrents are used to determine the direction of transport. Transportation distance can be inferred by examining textural and compositional aspects of sandstones. Palaeocurrent directions measured in the Wuqia Group and Artux Formation generally indicate flow was toward the north and northwest (Fig. 6). A thick channel-sandstone lens in the Wuqia Group records flow toward the west. The overall drainage pattern is interpreted as a gentle slope to the north, with an axial stream draining west parallel to the slope. Therefore, the source of the detritus was probably to the south or southeast of the depositional area.

Sandstones in the Yecheng section are fairly immature, as they are rich in lithic fragments, sub-angular to sub-rounded, contain 5–10% matrix and partially altered feldspars. The climate of the region has become increasingly arid since the Late Miocene, with the onset of the Northern Hemisphere monsoon and rain-shadow north of the Himalayas (Ruddiman and Kutzbach, 1989). This will tend to minimize the mechanical and chemical weathering of sediments, and thus transportation distance could be longer than implied by the maturity of the sediment. The majority of the sediment in the Wuqia Group is silt, mud and fine-sand sized suggesting transportation was fairly long and low-energy, without significant relief near the depositional site.

Quartz content decreases up-section in the Wuqia Group and Artux Formation, while the proportions of lithic fragments and feldspar increase. This corresponds to a decrease in the compositional maturity of the sediment. The appearance of granule and cobble conglomerate in the Artux Formation marks a change in the source area. The compositional trends and grain size transition in the Artux Formation is attributed to a more proximal source and therefore a shorter transportation distance, an increase in relief of the source, or climate becoming more arid (Zheng et al., 2003).

Compositionally, the sandstones were derived from a continental-collision orogeny (Fig. 4). The modern collisional orogen settings are therefore the likely source areas to the depositional site. The palaeoslope graded to the west based on palaeocurrent measurement; therefore, the sediment was sourced from the Kunlun Mountains, or further south from the Tibetan Plateau. If the Kunlun area was the source area, relief must have been far less than at present to have produced the fine-sand and mud-sized detritus of the Wuqia Group.

The pebble- to cobble-sized detritus seen in the overlying Artux Formation indicates a change in the source environment. The clasts are poorly sorted, subangular, deposited in sheet and debris flows, and mostly sedimentary and low-grade metamorphic rocks. The facies, angularity, size and composition of the clasts indicate a short transportation distance out of an uplifted source. The conglomerate beds are a very minor component of the Artux Formation; therefore, fine-sediment input continued into the basin from areas south of the Kunlun Mountains.

In summary, detritus of the Wuqia Group and Artux Formation sandstones were sourced from areas to the south and southeast of the depositional site. The Kunlun region was at low relief during the Miocene and is therefore a possible source of the fine sandstones, mudstone and siltstone of the Wuqia Group. Uplifted areas of southern Tibet may also have been drained along a gentle, northward-sloping regional gradient by meandering rivers, transporting metamorphic and sedimentary clasts. Minor uplift of the Kunlun Mountains generated the coarser material in the Artux Formation, but comprised only a small component of the overall sediment input.

7.2. Conglomerate source area

The Xiyu Formation was deposited in a foreland basin along the northern edge of the West Kunlun Mountains. Deposition was by debris flows, sheet flows and stream channels. This requires movement from high relief areas onto the floor of an alluvial fan. Therefore the detritus was most probably sourced from the West Kunlun Mountains which lie at 5 km elevation and directly south of the section. Drainage out of the Kunlun Mountains is northward onto the alluvial fan; but further south, within the Kunlun Mountains, streams generally flow east–west at present.

Sedimentary clasts tend to breakdown during transport; therefore their presence suggests the source was fairly proximal to the alluvial fan. Plutonic and high-grade metamorphic clasts tend to be the largest and roundest clasts, as they are most resistant to abrasion, possibly indicating extended transport compared to the sedimentary lithics. The appearance and then increase of large, well-rounded, metamorphic and plutonic clasts in the Xiyu Formation could indicate internal mountain drainage commenced erosion of plutonic and metamorphic terranes. Clasts were transported within the mountains and then onto the alluvial fan during flood events in debris and sheet flows.

In summary, much of the Xiyu Formation is interpreted as detritus sourced from the West Kunlun Mountains eroded and transported as debris and sheet flows during flood events. The source area includes the drainage catchment within the mountains and possibly further south onto the northern Tibetan Plateau. The appearance of metamorphic and plutonic clasts suggests erosion to deeper crustal levels, below the cover sedimentary and low-grade metamorphic rocks.

7.3. Unroofing history

The Xiyu Formation was sourced mainly from the West Kunlun Mountains. During field-work, clast samples were collected from the bedrock of the West Kunlun Mountains along the Xinjiang–Tibet Highway. The purpose was to compare the rocks sourced from the West Kunlun Mountains with clasts in the Artux and Xiyu Formations. Rocks that outcropped along the road were collected to 150 km along the highway from Yecheng, near Akuzi, whereupon clasts were collected from the stream-bed, presumably sourced from areas upstream, further south and east of Akuzi.

Sedimentary rock clasts dominate the conglomerate beds in the Artux Formation and the lower part of the Xiyu Formation. It is likely that they represent the early uplift stage of the source areas. Assigning the clasts to particular source rocks is difficult owing to the lack of detailed lithological descriptions of the stratigraphy of the Kunlun Mountains. A combination of general descriptions from Li (1996) and Matte et al. (1996), the regional geology map (Fig. 1) and our observations of the rocks collected from the mountains during this project, was used.

Marble, low-grade metasiltstone (or slate), greenschist and phyllite were observed on the Tibet–Qinghai Highway to the south of the thick Permian–Carboniferous limestone outcrops. They are dated as Lower Palaeozoic and Proterozoic rocks that formed part of the Proto-Tethys Ocean (Pan, 1992), which closed with the accretion of the Kunlun terranes and the Tarim Block in the Silurian. These rocks were deformed during the Triassic orogeny, providing a proximal source during the most recent uplift of the Kunlun Mountains. Approximately 150 km to the south of these outcrops, a similar aged succession of slate, greenschist, marble and phyllite is recorded in the Songpan-Ganze Terrane (Li, 1996). These rock types were collected from a stream-bed at Akuzi, indicating the Tianshuihai Group (Li, 1996) is being eroded and transported towards the Yecheng area.

Medium and high-grade metamorphic rocks include schists, which are recorded in the Upper Ordovician

Mustang Group and also in the Proterozoic Tianshuihai Group. Gneiss is part of the Archaean and Proterozoic basement; however, Proterozoic basement rocks are far more common than Archaean rocks.

The main felsic volcanic, a distinctive porphyry with large purple phenocrysts of potassium feldspar, is assigned to the Yarkand Group, dated as Lower Jurassic (Matte et al., 1996). Other volcanic rocks are felsic in composition and are possibly Upper Palaeozoic to Triassic in age. Volcanic rocks are common from this time period in the Kunlun Mountains (Yang et al., 1996).

Plutonic clasts include porphyritic granodiorite, observed intruding into greenschist or meta-basalt, is dated as Ordovician (Matte et al., 1996). The other plutonic rocks were collected in the river-bed along the Xinjiang–Tibet Highway, implying up-stream sources. Plutonic rocks could be derived from Cambrian, Silurian Ordovician or Triassic sources (Fig. 1).

The magnetostratigraphy of the Yecheng section provides a precise temporal control on the stratigraphic trends of the conglomerate clasts (Zheng et al., 2000). This enables a sequential unroofing history to be proposed. Separating the conglomerate clasts into general suites of rocks that comprise the Kunlun Mountains reveals unroofing trends. Sedimentary rocks represent the Upper Palaeozoic to Neogene cover strata, and low-grade metamorphic rocks are interpreted as a suite of Proterozoic and Lower Palaeozoic Proto-Tethys Basin deposits (Pan, 1992). The medium- to high-grade metamorphic and igneous rocks represent the basement of the Kunlun Mountains. The proportions of the rock types up-section can be separated into three rock suites. The general trend shows increasing medium to high-grade metamorphic and igneous clasts, while sedimentary clasts decrease and low-grade metamorphic clasts decrease, but to a lesser extent. The conglomerate from the Wusu Formation (latest Pleistocene) is dominated by igneous clasts, particularly felsic volcanics (60%), with 25% low-grade metamorphic and 15% sedimentary clasts.

The trends outlined in the section above are interpreted as indicating a general sequence of exposure of the source areas of the Kunlun Mountains. Early sediment input into the basin consisted of Proterozoic and Lower Palaeozoic low-grade metamorphic rocks, concurrent with Upper Palaeozoic marine rocks and Mesozoic to Neogene terrestrial clastics. Similar rock types are located in the Northern Kunlun Terrane and are most proximal to the depositional site. Exhumation of these rocks continued throughout the deposition of the Xiyu Formation, but with input of additional sources of sediment.

A major pulse of plutonic and volcanic clasts is recorded 640 m above the base of the Xiyu Formation. The main clasts type are porphyritic granodiorite which is assigned to the Early Palaeozoic granites that currently crop out north of the Mazar-Kangxiwa suture belt and felsic volcanic rocks. The volcanic rocks appear to have at least two sources: a dark-red porphyry is probably derived from Mesozoic arc-volcanism (Matte et al., 1996), and the other felsic volcanic, which is highly silicified, is possibly Palaeozoic and associated with granite batholiths (Chang, 1994). Following this pulse of uplift, igneous rocks fall back down to 20% and then progressively increase to 60% in the Wusu Formation. The medium- to high-grade metamorphic and igneous clasts tend to be large and well-rounded due to their high resistance to abrasion. This could be due to longer transportation compared with the smaller, more angular sedimentary and low-grade metamorphic clasts. Therefore, erosion of basement was probably occurring in a number of places extending into southern Kunlun Mountains and possibly further south onto the Tibetan Plateau.

Proterozoic low-grade metamorphic rocks continued to supply sediment to the basin, while the sedimentary rock supply decreased, and the proportion of basement and magmatic rocks increases. The overall unroofing sequence is therefore erosion of the cover sedimentary strata and progressive exposure and erosion into the deeper levels of the Kunlun basement magmatic rocks, associated with its long history as continental and island arcs. The fairly constant proportion of sediment sourced from Proterozoic low-grade metamorphic rocks suggests that these rocks were close to the surface along the northern margin of the Kunlun Mountains.

8. Conclusions

The Yecheng section situated at the northern foot of the West Kunlun Mountains, comprises 4.5 km of conformable Upper Miocene to Pleistocene strata. The lower part of the section is the Wuqia Group, consisting of 1700 m of interbedded red shale, siltstone and fine sandstone. This is overlain by the Artux Formation, which is 800 m thick, and comprises planar tine-sandstone, massive siltstone and thin-beds of gravel and cobble conglomerate. The upper part of the section is the Xiyu Formation, and consists of over 2000 m of cobble and boulder conglomerate intercalated with lenses of massive siltstone.

The study involved division of the section into lithofacies, which were combined into facies associations that defined a particular depositional environment.

Facies analysis suggests that the Yecheng section represents deposition in a fluvial system, beginning in a meandering system, and ending with a proximal alluvial fan. This indicates increased energy in the depositional system caused by an increase in the gradient and proximity of source area. Facies transitions up-section also suggest aridity of the region has increased since the Miocene, with a paucity of fluvial channels up-section, and aeolian deposits in the Xiyu Formation, and possibly in the underlying Artux Formation.

Sandstones in the Yecheng section are fairly immature, as they are rich in lithic fragments, sub-angular to sub-rounded, contain 5–10% matrix and partially altered feldspars. The majority of the sediment in the Wuqia Group is silt, mud and fine-sand sized, suggesting transportation was fairly long and low-energy, without significant relief near the depositional site. Quartz content decreases up-section in the Wuqia Group and Artux Formation, while the proportion of lithic fragments and feldspar increase. This corresponds to a decrease in the compositional maturity of the sediment.

Conglomerates in the Artux and Xiyu Formations are dominated by sedimentary clasts, and also have a significant content of low-grade metamorphic clasts. Trends up section include decreasing proportions of sedimentary clasts, a slight decrease in the percentage of low-grade metamorphic clasts, and a large increase in igneous, and medium- to high-grade metamorphic clasts. Plutonic and medium- to high-grade metamorphic clasts are absent in the Artux Formation and the lower part of the Xiyu Formation but increase up-section and are the largest component at the top of the formation.

Sedimentation and drainage patterns changed with the uplift of the Kunlun Mountains causing thick accumulations of conglomerate in the foreland basin at the northern foot of the mountains. The source of the detritus for the conglomerate is interpreted as the West Kunlun Mountains. The general clast types that comprise the conglomerate have been assigned into possible formations from the West Kunlun Mountains in order to infer an unroofing history of the source area. The sedimentary clasts represent the Upper Palaeozoic marine and the Mesozoic to Tertiary terrestrial clastics comprising the cover sequences in the West Kunlun Mountains. Low-grade metamorphic clasts are probably derived from the Proterozoic to Lower Palaeozoic deposits formed in the Proto-Tethys Basin. The medium- to high-grade metamorphic and plutonic clasts originate from the basement of the Kunlun Mountains.

Magnetostratigraphy, previously completed at the Yecheng section, is integrated with facies analysis and provenance to infer the uplift history of the West Kunlun Mountains. The first appearance of cobble conglomerate at the base of the Artux Formation, interpreted as the change from deposition on distal alluvial plains to more proximal alluvial fans, is dated at approximately 4.5 Ma. Gradients increased from this time until 3.6 Ma whereafter thick deposits of cobble and boulder conglomerates indicate deposition on a proximal alluvial fan in a similar setting to today. Deposition was mainly by debris flow and sheet floods, and the presence of aeolian loess intercalated within the conglomerate suggests an arid climate since at least 4.5 Ma.

Acknowledgments

This work was financially supported by grants NSFC 90211019 and 40025207, and the Ministry of Education of China through the "Cheung Kong Program". The authors are extremely grateful to Dr. Paul Kapp, Dr. Marin Clark and Dr. Ryuji Tada for reviewing the manuscript, which has improved the paper greatly.

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