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Upper Jurassic−Lower Cretaceous stratigraphy in south-eastern Tibet: a comparison with the western Himalayas

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Abstract

Lithostratigraphic studies of the Upper Jurassic−Lower Cretaceous sedimentary successions exposed in the Tingri−Gyangze area, south-eastern Tibet resulted in the establishment of a revised stratigraphic framework. A major crustal fault separates the southern Tibetan sedimentary successions into a Southern Zone and a Northern Zone. The Upper Jurassic−Lower Cretaceous strata of the Southern Zone are subdivided into the Menkadun Formation (Oxfordian, Kimmeridgian, up to lower Upper Tithonian), the Gucuo Formation (Upper Tithonian to Lower Albian) and the overlying Dongshan Formation (Upper Albian). The Gucuo Formation is further subdivided into a quartz arenite unit, which is overlain by a shale unit, in turn overlain by a volcaniclastic sandstone unit. The youngest cluster of detrital zircon absolute age data (127.7 ± 1.8 Ma) from the lower part of the volcaniclastic unit of the Gucuo Formation place the volcanic event before the Late Barremian.

In the Northern Zone, the Upper Jurassic−Lower Cretaceous strata have been subdivided into four formations: the Zhera Formation (Upper Jurassic), the Weimei Formation (Tithonian), the Rilang Formation (?Berriasian) and the Gyabula Formation (? post-Valanginian).

The appearance of silica cemented quartz arenites in both the quartz arenite unit of the Gucuo Formation and the Weimei Formation in the uppermost Jurassic is considered to provide strong evidence for an eustatic sea level drop affecting the northern margin of Greater India. In contrast the appearance of volcaniclastic sandstones in the Gucuo and Rilang formations are interpreted to represent a rift related volcanic event.

The Menkadun−Zhera formations, the quartz arenite unit of the Gucuo Formation−Weimei Formation, the volcaniclastic sandstone unit−Rilang Formation in south-eastern Tibet are lithologically similar and broadly correlative with the Spiti Shale, Takh and Pingdon La formations in Zanskar (India), and Spiti Shale, Dangardzong, Kagbeni and Dzong formations in the Thakkhola area (Nepal). The onset of quartzose and subsequently volcaniclastic deposition becomes progressively younger westward, from the Gucuo region toward Zanskar.

Keywords: Stratigraphy; South-eastern Tibet; Tethys Himalaya; Lower Cretaceous; Upper Jurassic

1. Introduction

Mesozoic sedimentary strata deposited on the northern Greater India continental margin crop out in the Tethys Himalayas, along the whole length of the Himalayan mountain chain, from Ladakh in the west to south-eastern Tibet (Fig. 1). Detailed studies of the Mesozoic sedimentary strata were mostly carried out in the western Himalayas (Gansser, 1964; Fuchs, 1982; Gaetani et al., 1986; Gaetani and Garzanti, 1991; Bhargava and Bassi, 1998; and references cited therein). Later, the interest has increasingly focused on the Mesozoic sedimentary strata in the Thakkhola region of the central Himalayas (Bordet et al., 1967, 1971, 1975; Garzanti and Pagni Frette, 1991; Gradstein et al., 1989, 1991; Gibling et al., 1994. Nagy et al., 1995), in an attempt to investigate the tectonic evolution of the conjugated margins of northern Greater India (Powell et al., 1988; Gradstein and von Rad, 1991). It was found that Jurassic and Lower Cretaceous sedimentary successions in central Nepal have many similarities with the strata drilled by the Ocean Drilling Project (ODP)

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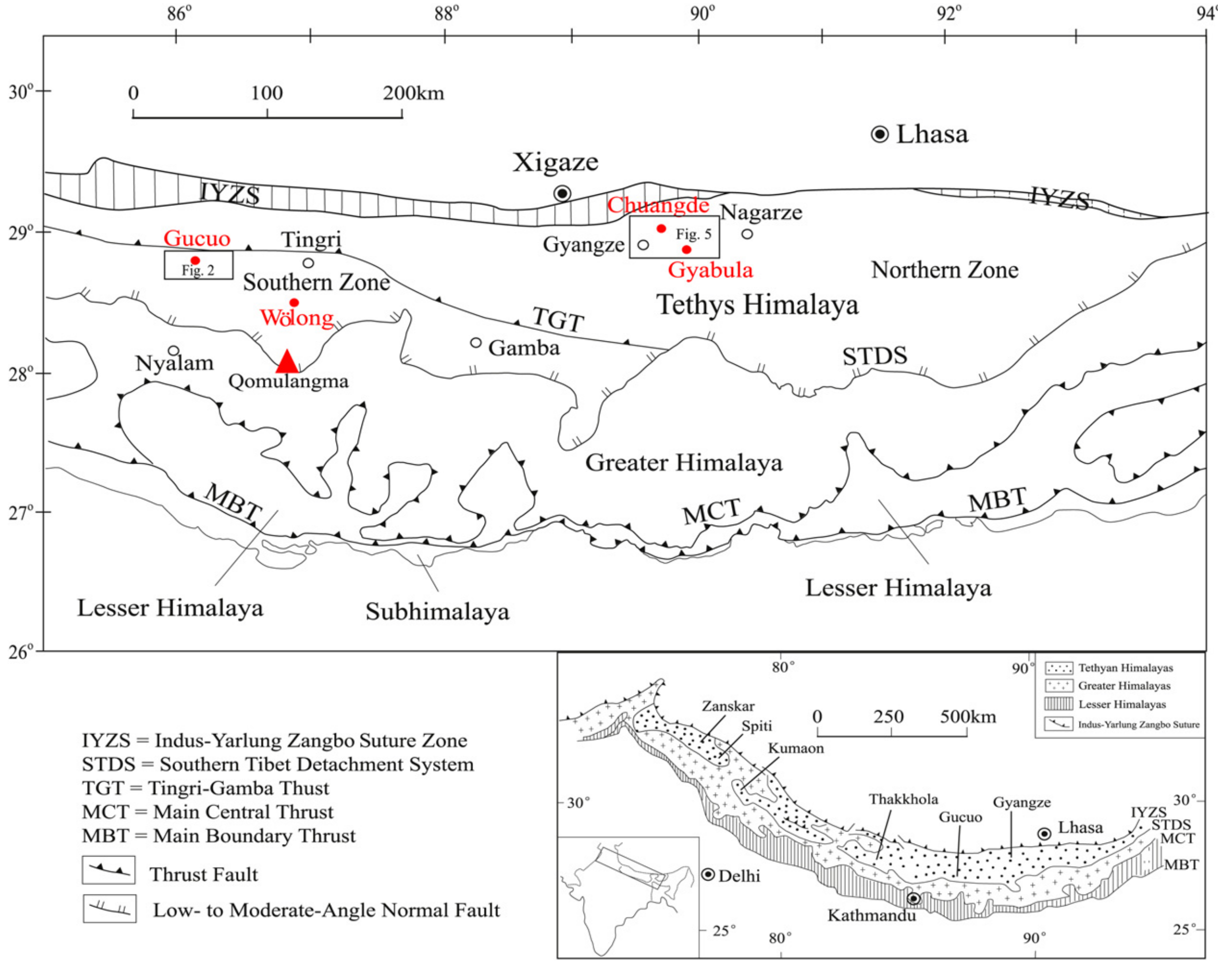

Fig. 1. Sketch geological map of the central Himalayas showing the tectonic setting and location of studied sections – the Gucuo, Chuangde and Gyabula sections; and the Wölong section investigated by Jadoul et al. (1998).

off north-western Australia (Gradstein and von Rad, 1991; Gibling et al., 1994). Later, several studies were published comparing the Mesozoic sedimentary strata of southern Tibet with the coeval strata cropping out in northern central Nepal (Garzanti et al., 1998; Jadoul et al., 1998).

In southern Tibet (Fig. 1) Upper Jurassic–Lower Cretaceous strata were studied predominantly in the Gucuo area, located west of Old Tingri and in the Gyabula area east of Gyangze. These studies were mainly biostratigraphic. The ammonite fauna was studied by Liu (1983, 1988), Liu and Wang (1987), Yin and Enay (2004), the bivalves by Yao et al. (1991), Li and Grant-Mackie (1994), Gou (1985, 1997), and the belemnites by Yin (1975). No detailed lithostratigraphic and sedimentological studies of the Upper Jurassic–Lower Cretaceous strata were published from the above areas. During the last ten years, we have made six field expeditions into the Tingri–Gyangze area to study the Mesozoic sedimentary strata, their compositions and depositional evolutions.

A major difficulty encountered during this study is the general scarcity of fossils, including microfossils, in the Lower Cretaceous sedimentary strata, hindering precise biostratigraphic dating. The other difficulty emanates from the intensive tectonic deformation and faulting of the region, so providing rarely tectonically undisturbed sedimentary successions. Lithostratigraphy has been used to establish a stratigraphic framework for the studied areas and for inter-regional correlation. This approach revealed several disagreements between biostratigraphic ages and ages derived from regional lithostratigraphic correlations and isotopic absolute age determination.

The results of our stratigraphic studies of the Upper Jurassic–Lower Cretaceous strata cropping out in south-eastern Tibet are presented. The correlation of Upper Jurassic–Lower Cretaceous strata between the western and eastern Himalayas is also discussed.

2. Geologic setting

Mesozoic sedimentary rocks are exposed in the Tibetan Tethyan Himalayas between the Greater Himalayas and the Indus–Yarlung Zangbo Suture (Gansser, 1964; Wang et al., 1996; Yin and Harrison, 2000) (Fig. 1). They were deposited along the Greater India continental margin, which was part of the Pangaea supercontinent (Powell et al., 1988; Patzelt et al., 1996).

Deposition on the margin began during the Late Palaeozoic (Gaetani and Garzanti, 1991; Garzanti, 1999) and continued through the Mesozoic, when a broad, passive, continental margin was built along the northern edge of the Indian supercontinent. During the mid-Cretaceous northward-directed subduction of the Neo-Tethyan oceanic crust beneath the southern margin of Asia resulted in the development of a magmatic arc and of an associated fore-arc basin along the southern margin of the Lhasa continental block (Einsele et al., 1994; Dürr, 1996). With continued subduction, the India Plate–Asia Plate collided at about 65 Ma (Yin and Harrison, 2000; Wan et al., 2002), even though some researchers place the collision as young as the Eocene (Fuchs, 1982; DeCelles et al., 2004; Najman et al., 2005).

Continental collision resulted in the onset of the Himalayan orogenesis when the strata experienced variable tectonic deformation. Mesozoic strata are variably exposed in thrust sheets in southern Tibet. The Tingri–Gamba thrust separates the Mesozoic strata in southern Tibet into a Southern and a Northern Tectonic Zone (Fig. 1). The Southern Zone is characterized by the presence of shallow-water calcareous and terrigenous rocks of Early Palaeozoic to Eocene age (Liu and Einsele, 1994; Willems et al., 1996), whereas the Northern Zone of Mesozoic to Palaeogene age is dominated by deep-water outer shelf, continental slope and rise deposits (Yu and Wang, 1990; Liu and Einsele, 1994; Wang et al., 1996; Li et al., 2005).

The Upper Jurassic–Cretaceous sedimentary sequences have been studied in both tectonic zones – in the Southern Zone at Gucuo locality (GPS: N28°46'56''; E86°19'13''), situated northwest of Old Tingri town (Figs. 1, 2); and in the Northern Zone at Gyabula (GPS: N28°52'02''; E89°49'30'') and Chuangde localities (GPS: N28°58'00''; E89°44'05'') near the town of Gyangze (Figs. 1, 6).

3. Methods

In the field we measured the sedimentary strata, described their compositions, sedimentary textures and collected samples for detailed petrographic, geochemical and isotopic analyses. Two samples (GC9 and GC10) were taken from Subunit 10 (Figs. 3, 4), at the lower part of the volcaniclastic sandstone unit of the Gucuo Formation for detrital zircon analysis.

Zircon separates were prepared using standard techniques. Zircon grains were picked under the binocular microscope, mounted in epoxy blocks, and polished for further analysis. The selection of grains was designed to include all visually recognised populations in approximate proportion to their abundance in the sample, without attempting a statistically representative selection. 63 zircon grains were analysed in sample GC10 along with 47 zircon grains in sample GC9. Internal structure was revealed by back-scattered electron (BSE) imaging on the electron microprobe (EMPA). U–Pb analysis was carried out using a New Wave Research 213 nm laser-ablation microprobe (LAM) attached to a Hewlett Packard 4500 inductively coupled plasma mass spectrometer (LAM-ICP-MS), which was described by Jackson et al. (2004) at the GEMOC, Department of Earth and Planetary Sciences, Macquarie University, Australia. We have used the more precise $^{206}Pb/^{238}U$ ages for grains with $^{207}Pb/^{206}Pb$ ages < 1000 Ma, and $^{207}Pb/^{206}Pb$ ages for older grains. Because most grains were concordant as analyzed, no common-lead corrections have been applied (e.g., Andersen, 2002). We have discarded grains that are discordant by more than 20% (i.e., where the $^{206}Pb/^{238}U$ age is less than 80% of the $^{207}Pb/^{206}Pb$ age).

4. Upper Jurassic–Lower Cretaceous stratigraphy of the Southern Zone

The stratigraphic framework of the Upper Jurassic–Lower Cretaceous in southern Tibet was not well-established (Wang et al., 1980; Wan, 1985; Liu and Wang, 1987; Jadoul et al., 1998), with numerous problems (Table 1). In this study, the Upper Jurassic–Lower Cretaceous sedimentary strata of the Southern Zone were studied in detail at Gucuo area (Figs. 2, 3). Mainly based on lithostratigraphic changes, the stratigraphic classification is revised herein. The strata are subdivided into the Menkadun Formation (Upper Jurassic), which is overlain by the Gucuo Formation (Upper Tithonian to Lower Albian), in turn overlain by the Dongshan Formation of the Gamba Group (Upper Albian) (Table 1). In the Gucuo area, only the basal part of the Gamba Group (Dongshan Formation) is present, as the upper part of the strata is cut out by a thrust fault.

4.1. Menkadun Formation

The Upper Jurassic strata in southern Tibet are dominated by dark grey shales similar to the Spiti Shale facies of the western Himalayas and of north-central Nepal. The strata named the Menkadun Formation in southern Tibet were correlated with the Spiti Shale by Wang and Zhang (1974), Yu et al. (1983), Wang et al. (1996), and Jadoul et al. (1998). The Menkadun Formation crops out in the Gucuo–Lalungla region (Fig. 1) where it was studied in detail by Westermann and Wang (1988) and Wan et al. (2000) in the Lalungla area, and by Jadoul et al. (1998) in the Wölong area. The thickness of the Menkadun Formation is about 250 m in the Lalungla–Gucuo area, but only 18–20 m of it is exposed in the Wölong area (Jadoul et al., 1998). It consists of dark grey, black shales and silty shales enclosing carbonate and phosphate nodules, which locally yield a rich belemnite, ammonite and inoceramid fauna of Oxfordian to Tithonian age (Westermann and Wang, 1988; Jadoul et al., 1998). From the uppermost part of the Menkadun Formation in the Gucuo area (subunits 1–2, Fig. 4) Westermann and Wang (1988) and Yin and Enay (2004) reported the ammonites *Haplophylloceras pingue*, *Pterolytoceras exoticum*, *Ptychophylloceras* sp., *Aulacosphinctoides* cf. *hundesianus*, *Virgatosphinctes* cf. *pompeckji*, *V.* aff. *subquadratus*, *V. kutianus*, *V. frequens*, *V. giganteus*, *Ptychophylloceras sp*. and the bivalves *Buchia spitiensis*, *B. blanfordians*, *B. extensa*, *B. nyalamensis*, which indicate an early Late Tithonian age for the strata. The boundary between the Menkadun Formation and the overlying Gucuo Formation is placed at the occurrence of the first quartzose sandstone bed beneath the regionally traceable white quartz-cemented quartz arenites.

Table 1
Previous proposals for the lithostratigraphic subdivision and dating of the Upper Jurassic–Lower Cretaceous strata in the Southern Tethyan Zone

<table>
<tr><th colspan="2">Age</th><th colspan="2">Wang et al., 1980</th><th>Wan, 1985</th><th>Liu and Wang 1987</th><th>Jadoul et al., 1998</th><th colspan="2">This study</th></tr>
<tr><td rowspan="3">K_2</td><td rowspan="2">San. – Tur.</td><td rowspan="7">Gamba Gp</td><td rowspan="2">Gambacunkou Fm</td><td>Jiubao Fm</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="4">Gamba Gp</td><td rowspan="3"></td></tr>
<tr><td>Xiawuchubo Fm</td></tr>
<tr><td>Cen.</td><td rowspan="3">Chaqiela Fm</td><td>Lengqingre Fm</td></tr>
<tr><td rowspan="4">K_1</td><td rowspan="2">Alb.</td><td rowspan="2">Chaqiela Fm</td><td>Gucuo 5 Fm</td><td rowspan="2">Grey to multicoloured marly mudrocks</td><td>Dongshan Fm</td></tr>
<tr><td>Gucuo 4 Fm</td><td rowspan="5">Gucuo Fm</td><td rowspan="3">Volcaniclastic sandstone unit</td></tr>
<tr><td rowspan="2">Apt. – Ber.</td><td rowspan="2">Dongshan Fm</td><td rowspan="2">Dongshan Fm</td><td>Gucuo 3 Fm</td><td rowspan="2">Wölong Volcaniclastics</td></tr>
<tr><td>Gucuo 2 Fm</td></tr>
<tr><td rowspan="3">J_3</td><td rowspan="3">Tith. – Oxf.</td><td rowspan="3" colspan="2">Menkadun Fm</td><td rowspan="3"></td><td rowspan="2">Gucuo 1 Fm</td><td rowspan="3">Spiti Shale</td><td>Shale unit</td></tr>
<tr><td>Quartz arenite unit</td></tr>
<tr><td></td><td colspan="2">Menkadun Fm</td></tr>
</table>

4.2. Gucuo Formation

The Gucuo Formation is stratigraphically subdivided into a lower quartz arenite unit, a shale unit and the upper volcaniclastic sandstone unit.

4.2.1. Quartz arenite unit

This unit is about 45 m thick at the Gucuo locality (Subunit 3, Fig. 4). It forms a distinct regional mappable unit, whitish in colour, appearing as a white belt overlying dark shales on distant horizons. At Gucuo the beds in the quartz arenite unit are steeply inclined and comprised by white, thick-bedded, medium to coarse-grained quartz arenites composed of >95% quartz grains, tightly cemented by quartz. Dust seams around the quartz grains indicate an initially subrounded to well-rounded shape of the grains. Feldspar and heavy minerals occur in trace amounts.

Irregular surfaces at the base of some of the sandstone beds resemble load and flute casts. Near the top of the quartz arenite unit there are at least three levels (0.3–1 m thick) of fine pebbly conglomerates and pebbly sandstones, with pebbles up to 15 mm in size. The age of the quartz arenite unit is

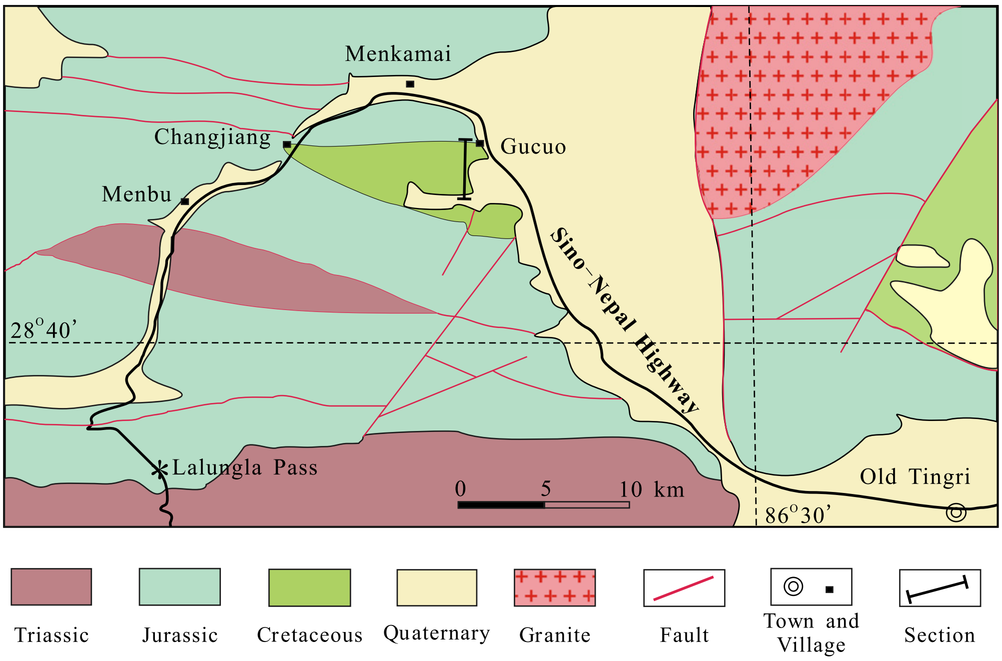

Fig. 2. Geological map of the Gucuo area (simplified from Zhu et al., 2002).

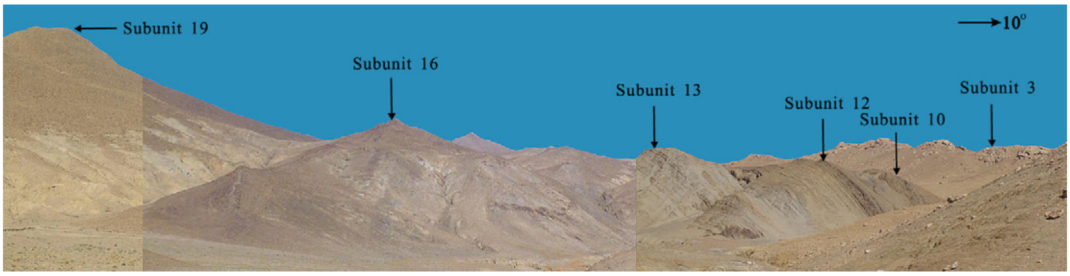

Fig. 3. Panoramic photograph of the Gucuo section, showing the subunit numbers marked in the Fig. 4.

not established, but it is bracketed by the underlying Menkadun Formation and the overlying uppermost Tithonian shale unit. The boundary with the overlying shale unit is sharp.

4.2.2. Shale unit

The shale unit is ~200 m thick at Gucuo (subunits 4–7, Fig. 4) and consists of dark grey, paper-thin shales, intercalated with minor thin-bedded sandstones and siltstones. Calcareous concretions are common and yielded abundant belemnites, the coral *Microsmilia* cf. *oppeli* and the ammonites *Blanfordiceras wallichi*, *B. acuticosta*, *Virgatosphinctes* cf. *kraffti* reported by Liu and Wang (1987) and Yin and Enay (2004), which indicate a latest Tithonian age. Approximately 100 m above the top of the quartz arenite unit is a prominent, weathering resistant 1 m thick bed, with 20 cm of speckled limonitic clay at the top, probably representing a highly altered volcanic ash. The overlying beds show rhythmic alternation on a meter-scale of medium grey shale with 10–20 cm thick siltstone beds, becoming more frequent to the top of the shale unit. A fault hidden in the valley separates the shale unit from the overlying volcaniclastic sandstone unit (Fig. 4).

4.2.3. Volcaniclastic sandstone unit

The occurrence of Lower Cretaceous volcaniclastic sandstones at Gucuo was first noted by L. Jansa in 1995 and similar strata were later described from the Mt. Everest region, near the Wölong village (Fig. 1) by Jadoul et al. (1998), who named them the Wölong Volcaniclastics. At Gucuo, the volcaniclastic sandstone unit is about 800 m thick, with the thickness highly attenuated as a result of local tectonics. However, as about one-third of the strata are covered, the position of faults, or even folds remain conjectural. Lithological differences allow us to subdivide this unit informally into three intervals (subunits 8–20, Fig. 4). Except for the lower interval which is in a fault contact with the underlying shale unit, the middle and upper intervals of the strata begin with black shales at the base, passing stratigraphically upward into shales and silty shales interbedded with greenish-grey, fine to medium-grain size litharenites. The thickness of the sandstone beds varies from 20 to 100 cm. The sandstones are characterized by volcanic grains, which in some beds comprise more than 50% of the rock. Volcanic grains are predominantly of a mafic origin, displaying pilotaxitic and trachytic texture in the lower part of the strata, with grains of felsic composition appearing in the middle and upper intervals of the unit, probably indicating progressive change from basaltic to bimodal volcanic activity.

The lower interval, ~130 m thick (subunits 8–12, Fig. 4), differs from the underlying shale unit by the presence of sandstone beds, which are 10~50 cm thick and intercalated with shale and silty shale. Several levels of pebbly conglomerates are present, showing normal grading. Imbrications indicate palaeocurrent direction to the north-northwest. Bioturbation traces and wood debris are common in the sandstones.

The middle interval, which is ~470 m thick (subunits 13–18, Fig. 4) includes about 120 m of debris covered, unexposed area. It is dominated by dark grey to black shales, which weathers light grey and whitish. Intercalated are thin beds of argillaceous siltstones, and fine-grained volcanic litharenite beds (10~30 cm thick) which become more frequent toward the top of the middle interval of the unit. Some of the siltstones beds show c, d, e divisions of the Bouma sequence. Planar cross lamination and horizontal lamination are also present. Load casts and flute casts are also observed and indicate northwesterly directed palaeocurrents. The strata are cross-cut by numerous, subvertical sandstones dykes.

The upper interval, ~200 m thick (subunits 19 and 20, Fig. 4) begins with dark grey siltstone and fine-grained upward coarsening volcaniclastic sandstone beds. Planar cross-bedding was noted in some of the sandstone beds, as well as parallel and hummocky cross lamination, indicating deposition during storm events. Bivalve coquinas occur at the base of some of the sandstone beds. The top of the upper part of the unit is comprised of sandy shale, intercalated with fine-grained sandstone. The latter displays normal graded bedding, parallel lamination and hummocky cross lamination. Many, highly altered, white-weathering volcanic ash beds are intercalated within this part of the strata. The disappearance of the volcaniclastic sandstones marks the boundary between the volcaniclastic sandstone unit and the overlying Dongshan Formation.

During our study we encountered a major stratigraphic dilemma. According to the previously published biostratigraphy, the Jurassic–Cretaceous boundary is located between the lower and middle interval of the volcaniclastic sandstone unit of the Gucuo Formation (Liu and Wang, 1987; Liu, 1988; Yao et al., 1991; Yin and Enay, 2004). From Subunit 13 (Fig. 4) Liu and Wang (1987) and Yin and Enay (2004) reported abundant ammonites identified as *Blanfordiceras* cf. *berthei*, *B. rotundum*, *B. parvulum*, *Haplophylloceras strigile*, *H. pingue*, bivalves *Buchia subextensa*, *B. guchoensis*,

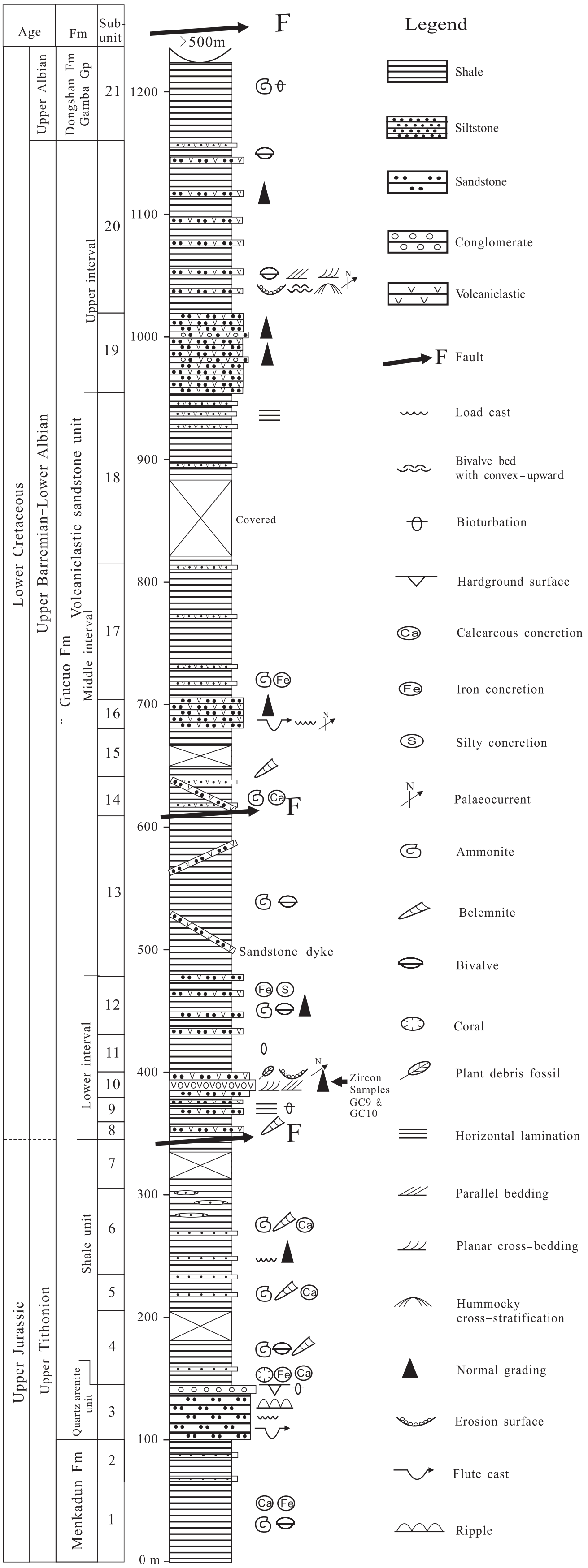

Fig. 4. Stratigraphic column of the Gucuo section.

B. nyalamensis, *B. shumoensis* which indicate a Berriasian age. The ammonites *Thurmanniceras jenkinsis*, *Th. cf. stippi* were also found in Subunit 14 by Liu and Wang (1987) who suggested a Valanginian–Hauterivian age for this part of the strata. In Subunit 17 (Fig. 4) – the uppermost of the middle part of the volcaniclastic sandstone unit, Liu and Wang (1987) found abundant ammonites including *Pulchellia compressissima*, *P.* cf. *hettneri*, *P.* cf. *rolloti*, *P. veleziensis*, *P.* cf. *veleziensis*, *P. ouachensis*, *P.* sp., *Cleoniceras lecontei*?, *C. xizangense*, *Karstenia* cf. *collinsi*, *Aconeceras flexuoum*, *Aconeceras* sp. which they interpreted as indicating a Barremian age.

However, recently, at the Gucuo locality, a few agglutinated foraminifers were discovered from subunits 15 and 18 in the middle interval of the volcaniclastic sandstone unit, including *Haplophragmoides*, *Recurvoides*, *Bulbobaculites problematicus*, *Falsogaudryinella moesiana* (Kuhnt and Holbourn, pers. comm., 2007). These foraminiferal data suggest an Albian age for those strata. Thus, we strongly doubt the previously published ammonite biostratigraphy by Liu and Wang (1987) and Liu (1988).

In this study, we analysed 110 detrital zircons using LAM-ICP-MS from two samples GC9 and GC10 from Subunit 10, within the lower interval of the volcaniclastic sandstone unit of the Gucuo Formation at Gucuo locality (Fig. 4). The isotopic analyses show there is an obviously youngest cluster age with weighted mean $^{206}Pb/^{238}U$ zircon age of 127.7 ± 1.8 Ma (2σ) (Fig. 5). This indicates that the lower part of the volcaniclastic sandstone unit can not be older than Late Barremian, according to the stratigraphic chart of Gradstein et al. (2004). The absolute age data from detrital zircons from the volcaniclastic sandstone are thus in a major disagreement with the previous ammonite biostratigraphic age interpretation of the same strata. Several causes could lead to such data disparity: (1) ammonites published before may have been collected not *in situ*; (2) ammonites may be reworked; (3) small scale tectonics may not be recognized accordingly in the field; (4) the macro-fauna

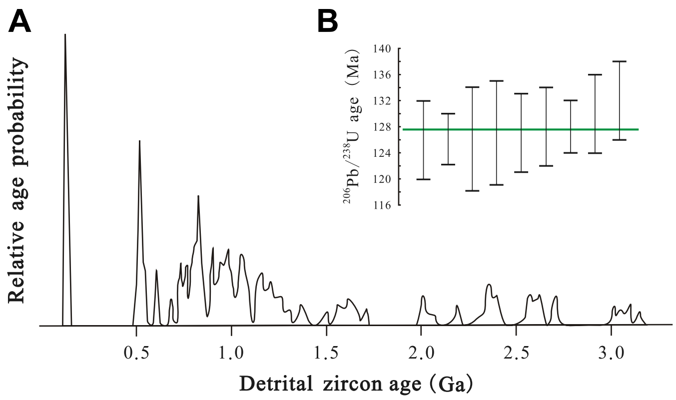

Fig. 5. A. U–Pb relative age probability diagrams for samples (GC9 and GC10) from the lower part of the volcaniclastic sandstone unit of the Gucuo Formation, Gucuo, Tibet. B. Weighted average diagram for the Early Cretaceous zircon age population from the volcaniclastic sandstone unit of the Gucuo Formation; weighted mean by data-point errors = 127.7 ± 1.8 Ma (2σ), MSWD = 0.50 (n = 9) and probability = 0.86.

is provincial and not synchronous with similar species described from Europe; (5) Some mismatches may appear in the Gradstein et al. (2004)'s time scale for Early Cretaceous time in term of the correlation between absolute and relative time scales.

In addition, the fault between the volcaniclastic sandstone unit and shale unit may have resulted in a tectonic reduction of the earlier – Berriasian–Lower Barremian strata in this area.

4.3. Dongshan Formation

The strata overlying the volcaniclastic sandstone unit belong to the Dongshan Formation, the lower part of the Gamba Group. They consist of grey and dark grey, paper-thin shales, intercalated with siltstone beds (Wen, 1987; Willems et al., 1996). Frequent siderite concretions are concentrated in 5–10 cm thick zones, reoccurring in about 0.5–1 m intervals. About five hundred meters of such strata are exposed at Gucuo, the top of the strata being in fault contact with the overlying thrust sheet. Enigmatic micritic limestone olistoliths, up to 10 m in size are embedded in the middle part of this shale unit. This documents that the tectonic deformation and overprint is much more intensive than can be interpreted from partially exposed strata. The lithologic composition of the Dongshan Formation here in Gucuo is similar to correlative strata in the Gamba and Tingri areas (Willems, 1993; Willems et al., 1996), where it was dated by those authors as Early Albian using foraminifers. The presence of ammonites in the lower part of the sequence (*Procheloniceras pachistephanum*, *Parahoplites* sp., *Oxytropid*) according to Liu and Wang (1987) also suggests an Albian age.

5. Upper Jurassic–Lower Cretaceous stratigraphy of the Northern Zone

Compared to coeval strata in the Southern Zone, the Upper Jurassic–Lower Cretaceous strata of the Northern Zone were much less studied. Only several groups of Chinese geologists made field expeditions mainly along the main road in the area of Gyangze (Yang and Wu, 1964; Wang et al., 1976; Wu, 1984; Li et al., 1999, 2005). The most important established stratigraphic subdivisions are listed in Table 2. In this study, the Upper Jurassic–Lower Cretaceous strata of the Northern Zone were studied at Chuangde and Gyabula localities in the Gyangze area (Fig. 6). We subdivided the strata into four formations: the Zhera Formation (Upper Jurassic), the Weimei Formation (Tithonian), the Rilang Formation (?Berriasian) and the Gyabula Formation (? post-Valanginian) (Figs. 7, 8).

5.1. Zhera Formation

The Zhera Formation is ~37 m thick at Chuangde and consists of dark grey siliceous shales, intercalated with thin bedded, dark grey micritic limestones and marlstones. Trace fossils (predominantly *Planolites* and *Chondrites*) are common in the shales. Some of the shales in thin sections show pelleted packestone texture, indicating intensive biological activity at the sea floor and gentle reworking by waves. Poorly preserved calcite replaced radiolarians and debris of ostracoda are rare. In the Chuangde section, the Zhera Formation overlies a basaltic andesite sill (Subunit 1–4, Figs. 7, 8). The boundary with the overlying Weimei Formation is placed at the first quartz arenite bed (Subunit 9, Fig. 8). No age indicative fauna was

Table 2
Comparison of proposed lithostratigraphic subdivision of the Upper Jurassic–Lower Cretaceous strata in Gyangze area, Northern Tethyan Zone

<table>
<tr><th>Age</th><th>Yang and Wu, 1964</th><th>Wang et al., 1976</th><th>Wu, 1984</th><th>XZBGM, 1993</th><th colspan="2">Li et al., 1999, 2005</th><th>This study</th></tr>
<tr><td rowspan="5">K_1</td><td rowspan="5">Zongzhuo Fm</td><td>Zongzhuo Fm</td><td rowspan="3">Zongzhuo Fm</td><td rowspan="3">Zongzhuo Fm</td><td rowspan="5">Gyabula Fm</td><td rowspan="2">Jibuli Member</td><td rowspan="4">Gyabula Fm</td></tr>
<tr><td rowspan="4">Gyabula Fm</td></tr>
<tr><td rowspan="3">Chuangde Pu Member</td></tr>
<tr><td rowspan="2">Gyabula Fm</td><td rowspan="2">Gyabula Fm</td></tr>
<tr><td>Rilang Fm</td></tr>
<tr><td rowspan="2">J_3</td><td rowspan="2">Gyabula Fm</td><td rowspan="2">Weimei Fm</td><td>Weimei Fm</td><td>Weimei Fm</td><td colspan="2" rowspan="2"></td><td>Weimei Fm</td></tr>
<tr><td>Gyangze Fm</td><td>Zhela Fm</td><td>Zhela Fm</td></tr>
</table>

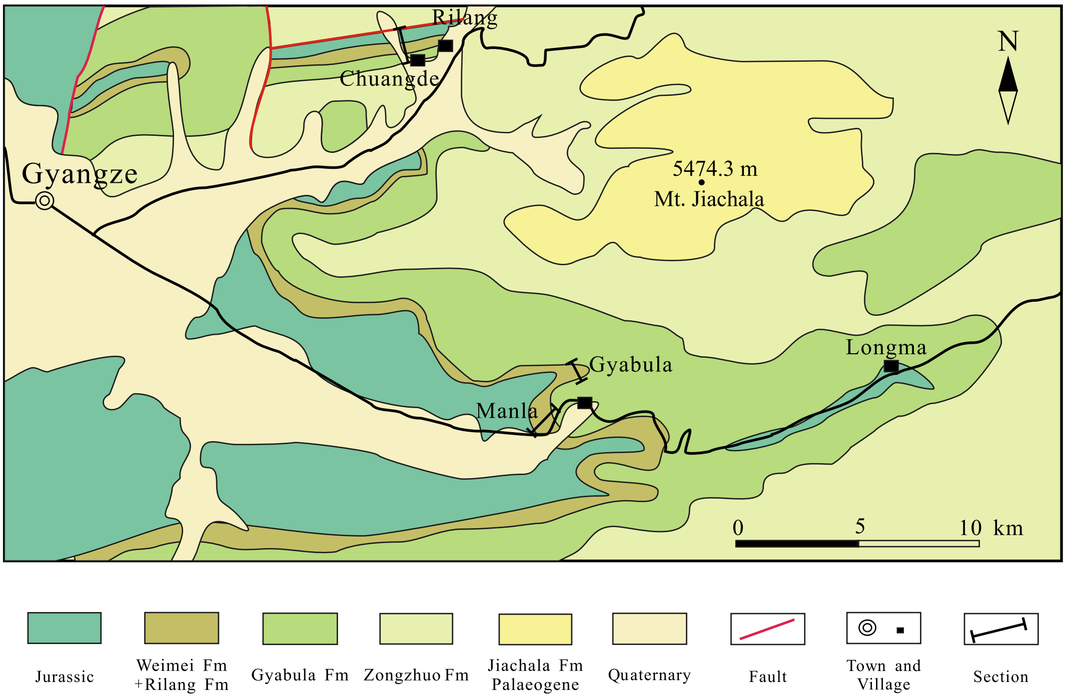

Fig. 6. Geological map near Gyangze showing the location of the Chuangde, Gyabula and Manla sections (modified after Liu et al., 2002).

found in the Zhera Formation at Gyangze. However, in the nearby Nagarze area (Fig. 1), ammonites reported by XZBGM (1993) such as *Dolikephalites*, *Reineckeia*, *Macrocephalites*, *Haplophylloceras strigile*, *Garantiana*, *Indocephalites*, the belemnite *Hibolithes*, and the bivalve *Plagiostroma* indicate a Middle to Late Jurassic age of the strata. On the basis of lithological composition and associated fauna we consider this formation to be correlative with the Menkadun Formation of the Southern Zone.

5.2. Weimei Formation

The Weimei Formation (Wang et al., 1980) is about 60 m thick at Chuangde and about 77 m thick at Manla. It is characterized by the presence of light-grey quartz arenites. The sandstones are medium to thick bedded, fine to coarse-grained, with beds separated by dark grey shales. At Chuangde the sandstone beds are intercalated with silty and siliceous shales. Sandstone beds are 10–20 cm thick, with a thicker sandstone bed near the base of the Weimei Formation (0.7 m thick – Subunit 9, Fig. 8), and at the top of the Weimei Formation an amalgamated sandstone bed is 13 m thick (Subunit 16, Fig. 8). Sandstone beds appear structureless and homogenous in grain size. An exception are two thicker sandstone packages (subunits 13 and Subunit 16, Fig. 8), where the base of some of the sandstone beds has a low amplitude wave form on a horizontal scale of 1–2 m, with a vertical amplitude of several cm, which could be very shallow channels. This interpretation is supported by the observation that few of these beds thin out laterally.

At Gyabula, the Weimei Formation is exposed along the Gyabula river and at the top of some of the surrounding

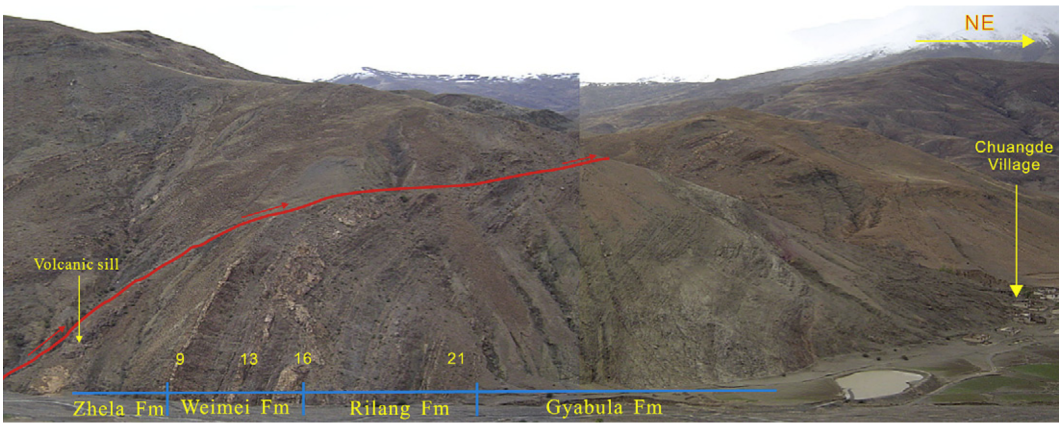

Fig. 7. Panoramic photograph of the Chuangde section, showing the subunit numbers and stratigraphic formations marked in the Fig. 8.

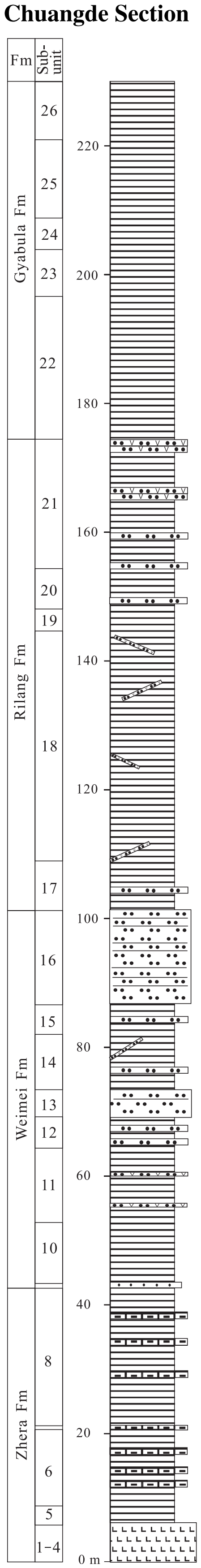

Fig. 8. Integrated stratigraphic column of the Chuangde section, Northern Zone of Tethys Himalayas. Key as in Fig. 4.

high mountains, where it appears as a whitish band comprised of four weathering resistant sandstones beds. The sandstone package is ∼28 m thick. The sandstone is whitish in colour, quartzitic, weathering rusty brown. At the base a poorly sorted pebbly sandstone bed is in sharp contact with the underlying Zhera Formation shale. The basal pebbly sandstone bed is overlain by several sandstone beds, 1–2 m thick. Some of the basal contacts have undulatory relief, which could either be due to load casts, or erosional relief.

The Weimei Formation (∼77 m) is also exposed in the valley, near the road about 1.5 km southwest of the Gyabula village – referred here as the Manla locality (GPS: N28°51'40''; E89°48'40'', Fig. 6). The sandstones at the base of the Manla sandstone package (subunits 1–5, Fig. 9) are predominantly fine grained, quartz wacke with mud supported texture. Argillaceous matrix comprises 30–35% of the sandstone. Quartz grains are bimodal, moderately well sorted. In the fine fraction quartz grains are subangular, less frequently angular in shape. In the coarser sand fraction grains are rounded. Benthic foraminifera occur in trace amounts. The overlying sandstone beds (subunits 6 and 8, Fig. 9), each up to 8 m thick, are separated by lens-shaped coarse – grained sandstone and conglomerate beds, with cobble sized clasts up to 30 cm in diameter. The pebbles are comprised of sandstones, shales and cherts. The sandstones in subunits 9–17 (Fig. 9) are mainly fine grained, silica cemented quartz arenites. Quartz grains are subrounded to rounded, and well sorted. In a few samples a trace of argillaceous matrix was noted. The texture of the sandstone is grain supported, with occasional microstylolitic contacts between some of the grains and frequent pressure-solution boundaries.

Near the Gyabula village, the Weimei Formation yields abundant ammonites (Wu, 1984), such as *Himalayites* sp., *Haplophylloceras strigile*, *Berriasella* sp., bivalves (Gou, 1985) *Buchia rugosa*, *B. blanfordiana*, *B. piochii*, *B.* cf. *quchuoensis*, *B. mankanrnensis*, *B. curtusa*, *B. xiumonensis*, *Inoceramus* (*Mytyloides*) cf. *minoformis*, *Palaeonucula* sp., and belemnites (Yang and Wu, 1964; Yin, 1975) *Belemnopsis gerardi*, *B. taliabuticus*, *B. acucklandica*, *Hibolithes flemingi*, indicating a Tithonian age for the formation according to those authors. We interpret this formation as a lithostratigraphic correlative with the quartz arenite unit of the Gucuo Formation of the Southern Zone.

At Chuangde the Weimei Formation is comformably overlain by the Rilang Formation. We place the boundary at the top of Subunit 16 (Fig. 8), where the sandstone is in sharp contact with the overlying shale and the sandstone composition is sharply changing from silica cemented quartz arenites to arkosic arenites.

5.3. Rilang Formation

The Rilang Formation at the Chuangde locality is about 73 m thick, and is comprised of medium dark grey shales intercalated with sandstones beds, which become more frequent and thicker towards the top of the formation. Sandstones are fine-grained, light greenish grey in colour and occur in beds

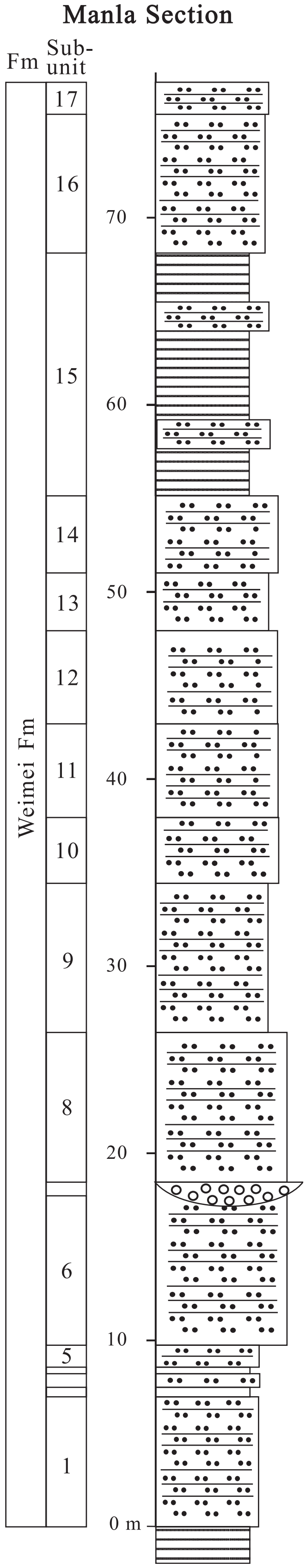

Fig. 9. Integrated stratigraphic column of the Manla section, Northern Zone of Tethys Himalayas. Key as in Fig. 4.

of several tens of cm, rarely up to 1 m thick. In contrast to the Weimei quartz arenites, the Gyangze sandstones are subarkosic and sublitharenitic. They are composed of moderately sorted, subangular to subrounded quartz grains and feldspars (15–20%) dominated by K-feldspar. Minor component is plagioclase, which is fresh and chessboard-albite which is less frequent. Muscovite and heavy minerals, such as zircon, rutile, tourmaline, and titanite occur in trace amounts. Volcanic grains are present only in the sandstones at the top of the formation. They comprise minor components (3%), consisting of mafic grains with trachytic texture. These are essentially devoid of any potassium-bearing phases and modal quartz and are comprised by plagioclase lath, completely albitized, forming microlites and phenocrysts in a cryptocrystalline dark matrix. The boundary with the overlying Gyabula Formation is placed at the top of the uppermost sandstone at the contact with the overlying shale. Abundant ammonites found by Wang et al. (1976), Liu (1983), Xu et al. (1990) within the formation are *Berriasella* sp., *Blanfordiceras celebrant*, *Euthymiceras* sp., *E.* cf. *breveti*, *Himalayites stoliczkai*, *Himalayites seideli*, *H. ventricoscus*, *Haplophylloceras strigile*, *Himalayites* sp., *Neocomites* sp., *Palaeoneilo* sp., *Phylloceras* sp., *Spiticeras indicus*, *Spiticeras spitiense*, *Subthurmannia patella* which according to the above authors indicates a Berriasian age for the strata. The occurrence of volcanic grains in the sandstones however, provides evidence that this formation is at least partially correlative with the volcaniclastic sandstone unit of the Gucuo Formation which from zircon dating is not older than Barremian.

5.4. Gyabula Formation

The Gyabula Formation, firstly introduced by Wang et al. (1976), is about 150 m thick at Chuangde, and conformably overlies the Rilang Formation (Li et al., 1999, 2005; Wang et al., 2000). It consists of greenish grey, medium dark grey and light grey weathering calcareous shales and marly limestones which are frequently bioturbated. The bioturbation is similar to a typical lithofacies frequently described in the literature as the shales with fucoids and in western Tethys occurring in the Albian (e.g. Graziano, 2000). Near the Gyabula village, abundant ammonites were reported by Wang et al. (1976), Liu (1983), Xu et al. (1990) within the lower part of the formation including ?*Neohaploceras* sp., *C. pyconoptycus*, *Calliptychoceras* sp., *Calliptychoceras walkeri*, *Kilianella* cf. *leptosoma*, *N. jiabulaensis*, *Neocomites* cf. *neocomiensis*, *Pseudocomites jiangziensis*, *Pterolytoceras exoticum*, *Sarasinella* sp.. Belemnites are also abundant. Yin (1975) reported from the lower part of the Gyabula Formation *Belemnopsis uhligi*, *B. regularis*, *Hibolithes mirificus*, *H. jiabulensis*, *H. jiabulensis tenuihastatus*, *Hibolithes xizangensis*, *H. verbeeki*, which suggest a Valanginian age for the lower part of this formation (Li et al., 2005). The lithology of the formation is similar to the Dongshan Formation in the Southern Zone. Therefore, from lithologic evidence and broad regional correlation, the Gyabula Formation should not be older than Albian.

6. Discussion

6.1. Depositional setting

The sediment composition, texture, and sedimentary features together with the enclosed fauna allow the depositional regimes for the Upper Jurassic–Lower Cretaceous strata cropping out in the Southern Zone to be interpreted. The Jurassic strata, which are excellently exposed at the Lalungla pass in southern Tibet, have been extensively studied (e.g. Yu et al., 1983; Li and Grant-Mackie, 1994; Liu and Einsele, 1994; Wan et al., 2000). The dominance of dark shales with frequent ammonite fauna in the Upper Jurassic Menkadun Formation suggests deposition in a deeper, poorly oxygenated outer shelf environment.

The appearance of quartz arenites in the uppermost Jurassic is evidence for either major sea level fall, or major land uplift, when the sand was transported from the coast to the ocean. The well-sorted and rounded grains indicate high energy coastal environment, similar to present nearshore zones off the eastern USA or Australia. Therefore, we interpret the appearance of quartz arenites at the uppermost Jurassic as predominantly nearshore sand bars and barriers. Since the sandstones are clean quartz arenites, it is highly improbable that they can be the result of active inland tectonics as proposed by Dürr and Gibling (1994), as this would result in supply of sandstone with a more variable mineralogical composition, such as arkosic sandstone, graywacke and or litharenites. Therefore the quartz arenites are evidence of a major eustatic sea level drop, as similar changes near the Jurassic-Cretaceous boundaries are well known from other areas of western Tethys (e.g. Hallam, 2001).

The younger Lower Cretaceous sandstones of the volcaniclastic sandstone unit of the Gucuo Formation are sublitharenites and subarkosic sandstones. The grains are mostly subangular, poorly to moderately sorted and contain argillaceous matrix. These were not exposed to high energy conditions as compared to the quartz grains in the underlying quartz arenites. The presence of hummocky cross-lamination and frequent ripple marks in the upper part of this formation supports their deposition on a shallow shelf with the sea floor above the storm wave base. The occurrence of fresh, unweathered volcaniclastic grains in the sandstones indicate their origin from a contemporary volcanic event. This is supported by the occurrence of basalt grains within the volcaniclastic sandstones at Gucuo which are plastically deformed, providing strong evidence that they represent volcanic tuff. As the volcanic grains show minimal to no abrasion, the source could not be too distant from the place of deposition. The volcanic components at the base of the volcaniclastic sandstone unit is dominated by alkalic basalt, with trachytic and acid volcanic grains becoming more common toward the top of the unit. This indicates progressive change from basalt to bimodal volcanic activity. This volcanic event is considered to represent rift related volcanism (Garzanti, 1993, 1999; Gibling et al., 1994; Dürr and Gibling, 1994; Jadoul et al., 1998).

The depositional setting of the Upper Jurassic–Lower Cretaceous strata of the Northern Zone is more difficult to interpret, mainly due to intensive tectonics, as the strata are highly tectonically deformed and broken with many faults, folds and thrusts. At Gyangze, where an almost complete succession is exposed in one of the thrust sheets, the shales of the Upper Jurassic Zhera Formation were most probably deposited on a deeper outer shelf, as indicated by the fauna and extensive bioturbation in the shales. The overlying sandstone depositional environment of the Weimei and Rilang Formation is more difficult to interpret as the sandstones are homogeneous, sheet-like, lack any sedimentary structures and have both sharp contacts with the surrounding shales. Lateral thinning of some of the sandstone beds in the Weimei Formation and undulatory basal contacts of some of the thicker sandstone beds suggest that they represent wide channel fills, with the palaeocurrent north-northwest directed. Such features suggest that they represent sheet sand beds, probably deposited from plumes on the outer shelf, or even on the upper slope of the passive continental margin. This margin was very rapidly subsiding, as the Upper Cretaceous strata are represented by pelagic grey and red shale facies, deposited at the toe of the continental slope, below the carbonate compensation depth (CCD) (Wang et al., 2005; Hu et al., 2006).

6.2. Regional correlations

The Upper Jurassic–Lower Cretaceous sandstones crop out widely along the length of the Himalayas, from the Zanskar Range of northern India, the Spiti Himalayas, the Kumaon Himalayas, the Thakkhola region of central Nepal, and to southeastern Tibet.

In a transect from the west to the east at the Zanskar Himalayas, the Upper Jurassic to Lower Cretaceous Spiti Shale is conformably overlain by the Giumal Group. The latter was subdivided into two formations by Garzanti (1991). The Barremian to Aptian Takh Formation is characterized by the occurrence of subarkoses and quartz arenites interbedded with burrowed siltstones and black shales. The overlying Pingdon La Formation, largely ascribed to the Albian (Garzanti, 1991), consists of volcanic arenites. The Giumal Group is overlain by pelagic limestones of the Chikkim Formation, or Fatu La Formation of Late Albian or Early Turonian age (Garzanti, 1991; Premoli Silva et al., 1991; Bertle and Suttner, 2005).

In the Malla Johar area, Kumaon Himalayas, the Oxfordian–Berriasian Spiti Shale (Gansser, 1964; Sinha, 1989; Kumar et al., 1977; Vijaya and Kumar, 2002) is overlain conformably by the Lower Cretaceous Giumal Sandstone, 400 m thick, composed by greenish-grey glauconitic sandstones and silty shale (Sinha, 1989). The overlying Upper Cretaceous Sangcha Malla Formation consists of deep-water turbiditic sandstones and reddish shales (Kumar et al., 1977; Sinha, 1989; Juyal et al., 2002).

In the Thakkhola area, central Nepal, the uppermost beds of the Spiti Shale were dated by ammonites and foraminifera as of Late Tithonian age (Gradstein et al., 1991). They are conformably overlain by quartzarenitic sandstone (Dangardzong Formation of Garzanti and Pagni Frette, 1991, Chuk Formation of Gradstein et al., 1989). While the basal few meters of the Dangardzong Formation are Tithonian in age, the bulk of the formation is Berriasian as dated by ammonites and palynomorph assemblages (Gibling et al., 1994). Approximately 500 m of the overlying strata – named the Kagbeni Formation and the Dzong Formation by Bassoullet and Mouterde (1977), Garzanti (1999) and the Tangbe Formation by Gradstein et al. (1989) and Gibling et al. (1994) – consists of intercalated sandstones, siltstones and black shales, with prominent volcaniclastic sandstone dominated by basalt detritus in the lower part of the strata. The Tangbe Formation was dated by ammonites, foraminifera and palynomorphs as of Valanginian–Late Albian age (Bassoullet and Mouterde, 1977; Gibling et al., 1994; Nagy et al., 1995; Garzanti, 1999). The overlying Muding Formation consists of greenish grey marlstones, sandy marlstones and calcareous sandstones and siltstones, dated by foraminifera and dinocyst as of latest Albian age (Premoli Silva et al., 1991; Gibling et al., 1994).

The distinct lithological differences of strata deposited along the India continental shelf allow us to inter-correlate marine Upper Jurassic–Lower Cretaceous sedimentary strata. The Menkadun–Zhera Formations, the quartz arenite unit of the Gucuo Formation–Weimei Formation, and the volcaniclastic sandstone unit of the Gucuo Formation–Rilang Formation in south-eastern Tibet are of similar composition to the Spiti Shale, Takh Formation, and Pingdon La Formation in Zanskar area; and to the Spiti Shale, Dangardzong Formation, Kagbeni and Dzong formations in north central Nepal (Fig. 10). Despite that our study revealed several unresolved differences in stratigraphic age of the Lower Cretaceous strata in southern Tibet, the overall data indicate some diachronism along the Himalayan Belt. The onsets of both the quartz arenites and of the volcaniclastic sandstones deposition become progressively older in an eastward direction, from the Zanskar–Spiti Himalayas (Garzanti, 1993), to Central Nepal (Bordet et al., 1971), and southern Tibet (Jadoul et al., 1998) (Fig. 10).

7. Conclusions

Recent field studies in south-eastern Tibet have contributed new lithostratigraphic data for the Upper Jurassic–Lower Cretaceous sedimentary successions and point to several areas where lithostratigraphy supported by the isotope age determination does not agree with previous biostratigraphic age interpretations.

The Upper Jurassic–Lower Cretaceous sedimentary sequences of the Southern Zone in south-eastern Tibet are separated into the Upper Jurassic (Oxfordian–lower Upper

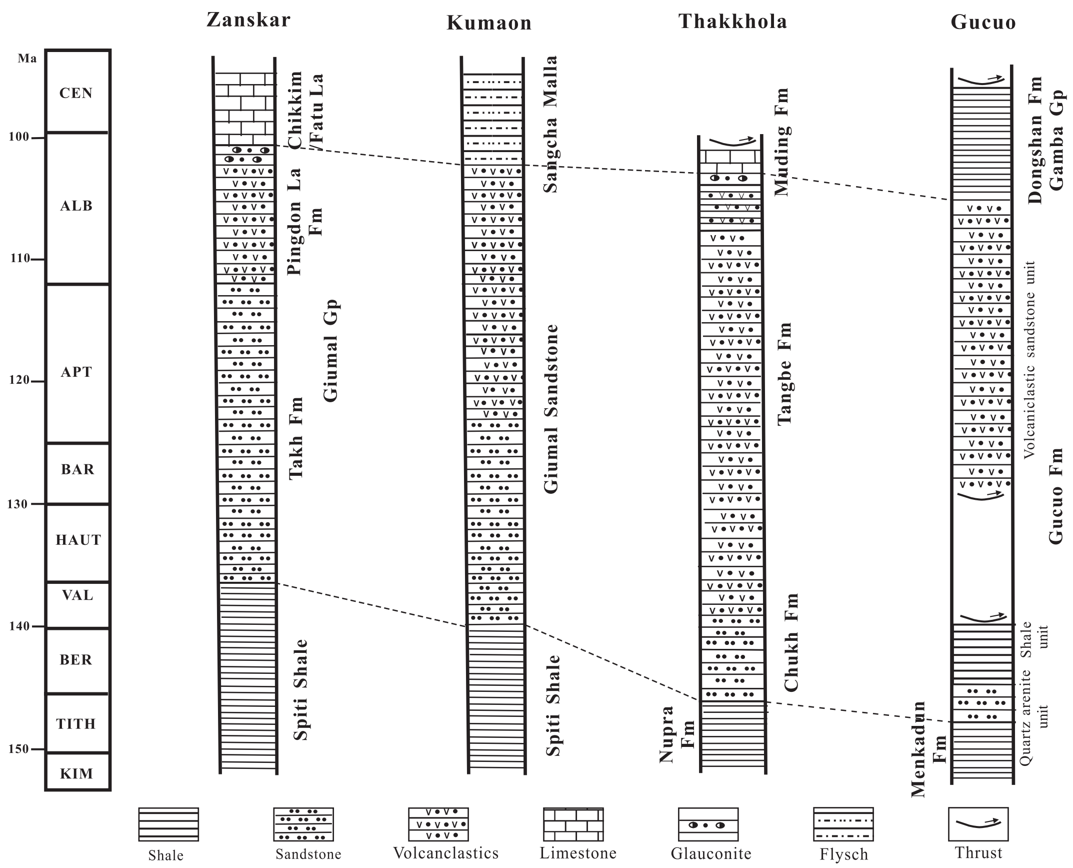

Fig. 10. Stratigraphic correlation of the Uppermost Jurassic to Lower Cretaceous strata in Tethys Himalayan from Zanskar at west, Kumaon, to Thakkhola and Gucuo at the east (age after Gradstein et al., 2004).

Tithonian) Menkadun Formation, the Uppermost Tithonian to Lower Albian Gucuo Formation, which includes the Upper Barremian–Lower Albian volcaniclastic sandstone unit, and the post-Albian Dongshan Formation. The Upper Jurassic–Lower Cretaceous strata of the Northern Zone are subdivided into: the Zhera Formation (Upper Jurassic), the Weimei Formation (Tithonian), the Rilang Formation (?Berriasian), and the Gyabula Formation (?post-Valanginian).

The appearance of silica cemented quartz arenites in the uppermost Jurassic provides strong evidence for an eustatic sea level drop affecting the northern margin of Greater India. In contrast the appearance of volcaniclastic sandstones in the Gucuo and Rilang formations are evidence for a rift related volcanic event. The absolute age data from detrital zircons from the volcaniclastic sandstone from the Gucuo area disagree with previous biostratigraphic interpretation of the same strata. The detrital zircon absolute age (127.7 ± 1.8 Ma), indicates that the lower interval of the volcaniclastic sandstone unit in the Gucuo area can not be older than Late Barremian age while the biostratigraphic data placed the Jurassic–Cretaceous boundary stratigraphically above the dated bed.

The Menkadun–Zhera formations, the quartz arenite unit of the Gucuo Formation–Weimei Formation, the volcaniclastic sandstone unit–Rilang Formation in south-eastern Tibet are lithologically similar and broadly correlative with – the Spiti Shale, Takh and Pingdon La formations in Zanskar (India), and the Spiti Shale, Dangardzong, Kagbeni and Dzong formations in the Thakkhola area (Nepal). The onset of the quartzose and of the volcaniclastic deposition becomes progressively younger westward, from the Gucuo region toward Zanskar. If such change reflects tectonic changes along the northern margin of Great India, than it is an evidence for westward progressing rifting along the northern edge of the India continental plate.

Despite progress in studies of the Mesozoic sedimentary sequences in southern Tibet, much more detailed biostratigraphic, microtectonic and absolute age isotopic studies are needed to clarify the stratigraphic differences we have discussed above. A more close collaboration between Chinese and international geologists, especially in the fields of biostratigraphy, is needed to increase our understanding of the stratigraphic evolution of the Tibetan Tethys Himalayas.

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