Early Cretaceous stratigraphy and SHRIMP U-Pb age constrain the Valanginian–Hauterivian boundary in southern Tibet

XIAOQIAO WAN, ROBERT SCOTT, WEN CHEN, LIANFENG GAO AND YIYI ZHANG

The Late Jurassic to the Early Cretaceous marine strata are extensively distributed in southern Tibet. In Gyangze, the strata are divided into the Weimei and Jiabula formations. In Nagarze, they are divided into the Weimei and Sangxiu formations. Previous work has reported diverse ammonite species of *Haplophylloceras* and *Himalayites* in the Weimei Formation, and a few species of *Spiticeras* in the lower Jiabula and Sangxiu formations. The present study has found the bivalve *Inoceramus* and nannofossil assemblages in the lower Jiabula and Sangxiu formations. The nannofossil assemblage of *Nannoconus steinmannii steinmannii*, *N. steinmannii minor* and *Watznaueria barnesae* indicates Berriasian age, and the *Calcicalathina oblonga–Speetonia colligata* assemblage is Valanginian in age. Numerical ages for the Jiabula and Jiabula-goukou sections in Gyangze have been interpolated by comparing the fossil ranges with ages calibrated in other sections. The correlation experiment plots fossil ranges in the two sections to the CRET1 Database. The estimated rate of sediment accumulation of the lower Sangxiu Formation is 22.6 m/myr. The Jurassic–Cretaceous (*J*–*K*) boundary is at the bottom of the Jiabula Formation in Gyangze, and the base of the Sangxiu Formation in Nagarze. The boundary is marked by the appearance of the ammonite *Spiticeras* and the nannofossil assemblage of *Nannoconus st. steinmannii–N. st. minor–Watznaueria barnesae*. The radiometric age in Tibet is the first to be integrated with upper Valanginian fossils. The volcanic rocks of the upper Sangxiu Formation are dated at 136 ± 3.0 Ma deduced from zircon SHRIMP age of rhyolite. By consideration of the rate of sediment accumulation of the underlying sedimentary deposits, the *J*–*K* boundary in the Gyangze–Nagarze area is approximately 145 Ma as suggested by the newly issued International Stratigraphic Chart, and the Valanginian/Hauterivian boundary lies between 134 Ma and 136 Ma. Biostratigraphy, graphic plot, Jurassic/Cretaceous boundary, nannofossil, SHRIMP U-Pb age, Southern Tibet, Valanginian/Hauterivian boundary.

Lower Cretaceous strata are well exposed in southern Tibet. The definition and identification of the Jurassic and Cretaceous boundary are two of the most challenging issues in the time-scale of the Phanerozoic Eon. The stratigraphic properties of this boundary have long been argued but not yet agreed upon by the global geosciences community. Fortunately, marine strata spanning the boundary crop out widely in southern Tibet, and may provide data useful in defining such a controversial boundary. There is no doubt that further research on this hot topic will contribute to the improvement of detailed stratigraphic classification of the Mesozoic and, as a result, is expected to have a great impact on regional geological mapping and generate a more accurate theory of plate tectonics as well.

One concern in the debate about the marine Jurassic–Cretaceous (*J*–*K*) boundary has been the definition and relevance of the Berriasian Stage. Currently, most geologists are convinced that the Berriasian Stage is useful as the basal stage of the Lower Cretaceous Series. Unfortunately, it is well known that the marine biosphere evolved little during the Jurassic/Cretaceous transition spanning the Tithonian/Berriasian stage boundary. Particularly the ammonites, which are the basis for dividing the Mesozoic strata into zones and stages, did not evolve greatly across this boundary. Because...
ammonite species are restricted to biogeographic provinces, the zonal succession in the Jurassic type region of France differs from that in other regions. It is necessary to correlate zones in intervening regions in order to extend the Jurassic/Cretaceous boundary. The Jurassic/Cretaceous section in the Tibetan Tethys reported here is such a link between the Western Tethys and the Pacific region.

During Late Jurassic and Early Cretaceous, southern Tibet was located on the northern margin of Indian plate, which included the continental shelf and slope sedimentary environments. To the north was the Tethyan pelagic ocean. During the Late Cretaceous the Indian and Asian plates joined along the Yarlung Zangbo suture (Fig. 1). Deep water facies favourable to coccolith were deposited on the Indian continental slope and are now exposed in the Gyange–Nagarze and Nyalam areas (Fig. 1). Because of the dynamics of Yarlung-Zangbo suture, biostatigraphically meaningful macrofossils were poorly preserved in the Gyange–Nagarze area, although some ammonite fossils were reported (Liu 1988; Yin & Enay 2004). Nevertheless, for the first time, we have found Early Cretaceous calcareous nannofossils have been found in these strata, that constrain the position of the J/K boundary. What is most interesting is that a thick group of volcanic rocks overlies the Jurassic and Cretaceous boundary strata in the Nagarze section.

The objectives of this paper are to identify the position of the Jurassic/Cretaceous boundary in these sections using nannofossil assemblages and to constrain the numerical age of the Valanginian nannofossils. The authors selected the rhyolite from the Sangxiu Formation in the Kadong section for zircon SHRIMP dating. The previous ammonite data are also discussed as reference material.

Stratigraphy

Two sections were measured near Gyange. The Jiabula section (Fig. 2) is located in the Jiabula valley 20 km east of Gyange town at 28°51’85.5” N, 89°49’36.1” E to 28°51’94.4” N, 89°49’38.1” E. The Jiabula-goukou section (Fig. 3) is situated at the entrance to the Jiabula valley, about 1.4 km south of the Jiabula section. The Uppermost Jurassic–Lower Cretaceous sequence in the two sections (Figs 2, 3) consists of the Weimei Formation and the Jiabula Formation. The Weimei Formation is composed of coarse sandstones, conglomerate, siltstone and black shale and is not fully exposed. The Jiabula Formation is 1382-m thick and spans most of the Lower Cretaceous in the studied area. This work only discusses the lower part of the formation in the Jiabula and Jiabula-goukou sections (Figs 2, 3). The lower units of the studied sequence consist of dark grey, silty shale and siliceous rocks containing a number of sandy nodules, intercalated with thin-bedded siltstone and a 2 m-thick basalt bed in its lower part. The upper units are mostly grey to dark grey fine-grained lithic sandstone and black silty siliceous rock, with intercalations of calcareous siltstone and nodules. A large group of fossils from the strata includes calcareous nannofossils, bivalves, belemnites, ammonites and gastropods.

In Nagarze, the marine J-K sequence is exposed along the south side of Yamzho Yumco Lake. The Kadong section (Figs 4, 6–1) is located on the north side of Kadong village, from 28°46’01.9” N, 90°42’30.4” E to 28°46’13.8” N, 90°42’31.6” E. The Weimei Formation is composed of the same lithological characters as at Gyange. The overlying Sangxiu
Formation is a thick group of sedimentary–volcanic strata divided into two parts. The lower part (units 2–7 on Fig. 4) are 118.4-m thick and mostly composed of black shale, muddy siltstone and silty shale with lenses of siliceous siltstone. Abundant fossils have been found in the lower part, including calcareous nannofossils, bivalves, belemnites, ammonites and gastropods. The upper part of the formation (units 8–14 on Fig. 4) is a 204-m thick sequence of volcanic and volcaniclastic sedimentary rocks. The succession of the volcanic rocks from bottom to top is: light grey dacite, greyish yellow massive-bedded, coarse-grained feldspathic sandstone, with fine-grained sandstone bands and some intercalated tuffaceous sandstone; greyish green olive basalt, gabro and dolerite; greyish green dacite and rhyolite; greyish green to light green metamorphosed basalt with coarse phenocrysts, and coarse phenocryst dacite with greyish green tuffaceous sandstone at the top.

**Material and methods**

Nannofossils were processed in the Micropaleontological Laboratory of the China University of Geosciences (Beijing). A total of 53 samples at Gyangze and 26 at Nagarze were processed, but nannofossils were only obtained from 12 shale samples at the Jiabula, Jiabuagoukou and Kadong sections (Table 1). Smear slides were prepared for shales and siltstones after powdering a small quantity of rock. Permanent slides were mounted. Thin sections were prepared only for hard
To make a smear slide, an amount of sample powder for nannofossil analysis was placed on a microscope slide and dispersed sufficiently by dropping distilled water firstly, then neutral resin and a glass cover slip were applied after being dried. The smear slides were examined and identified at high magnification ($\times1000$) with a polarizing light microscope. Some marker species for important chronological ages and a few common species were identified under SEM and taken photos under the polarizing light microscope (Fig. 5).

A rhyolite sample (no. XZ0506) from unit 13 of the Sangxiu Formation was dated by a SHRIMP analysis (Fig. 4). The phenocrysts in the rhyolite are mainly quartz and plagioclase. The quartz particles are clean and characterized by corroded rims. The plagioclase is idiomorphic, with inconspicuous albite macles in some particles. Zircon was extracted by conventional techniques including gravitation sorting and handpicking under a microscope. Zircons from rhyolite and pieces of the zircon standard (TEM, 417 Ma) were mounted on epoxy resin discs and polished to expose their centres. These grains were used for examination by transmitted light, cathodoluminescence (CL) imaging and SHRIMP U-Pb dating. The CL study was undertaken on an electron microprobe at the Institute of Mineral Resources, Chinese Academy of Geological Sciences. The SHRIMP U-Pb analyses were performed on the Beijing SHRIMP-II in the Chinese Academy of Geological Sciences. Errors on individual analyses and average weighted age of 206Pb/238U are all at the 1σ level. Ages for the young magmatic zircon are based
on $^{206}\text{Pb}/^{238}\text{U}$ and for the old inherited zircon are derived from $^{207}\text{Pb}/^{235}\text{U}$.

Nannofossil biostratigraphy

The J–K boundary succession is normally constrained by ammonites. As reported by previous research (Liu 1988; Yin & Enay 2004), the boundary lies biostratigraphically between *Haplophylloceras strigile* and *Spiticeras* in the Gyangze–Nagarze area. Unfortunately ammonites are mostly domestic elements and calcareous nannofossils have become a key biostratigraphic tool. This is the first report of Cretaceous nannofossils in southern Tibet, and it is obvious that the data afforded by nannofossil lineages will play a key-role elsewhere. More and more J/K studies have been based on nannofossil stratigraphy (Thierstein 1975; Roth 1983; Cooper 1984; Bralower et al. 1989; Bornemann et al. 2003). The Tethyan Upper Jurassic/Lower Cretaceous calcareous nannofossil zonations have been established by Bralower et al. (1989) and dated by Hardenbol et al. (1998) who designated subzones NJK-A, NJK-B, NJK-C and NJK-D spanning Tithonian and Berriasian (Table 1). The first occurrence of the nannofossil *Nannoconus* spp. indicates the J/K boundary, and *Nannoconus steinmannii* was used as the first zonal fossil of Early Cretaceous (Sissingh...
Table 1. Correlation of Upper Jurassic–Lower Cretaceous calcareous nannofossil zones in southern Tibet and other regions.

<table>
<thead>
<tr>
<th>Area/Age</th>
<th>Boreal (Mutterlose &amp; Kessels 2000)</th>
<th>Atlantic (Bornemann et al. 2003)</th>
<th>Tethys (Hardenbol et al. 1998)</th>
<th>Gyange–Nagarze, southern Tibet (This work)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Cretaceous Valangian</td>
<td>Crucibiscutum salebrosum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berriasian</td>
<td>Watznaueria barnesae, Biscutum constans</td>
<td>Watznaueria spp., Biscutum constans, Rhagodiscus asper</td>
<td>Cretarhabdus angustiforatus (NK-2)</td>
<td>Nannoconus steinmannii steinmannii minor–Watznaueria barnesae Assemblage</td>
</tr>
<tr>
<td>Late Jurassic Tithonian</td>
<td>Crucibiscutum salebrosum, Micrantholithus speetonensis</td>
<td>Conusphaera mexicana, Polycostella beckmannii, Nannoconus spp., Watznaueria spp., Watznaueria spp., Cyclagelosphaera margerelii, Zeurghabdotus spp.</td>
<td>Conusphaera mexicana (NJ-20)</td>
<td>Zeugrhabdotus embergeri (NJ-19)</td>
</tr>
</tbody>
</table>

1977; Cooper 1984). Some researchers also take Nannoconus colonii as the lowermost zonal index (Thierstein 1973, 1975; Roth 1983). Lithraphidites carniolensis and Polycostella beckmannii were also used to mark the base of Cretaceous (Perch-nielsen 1985).

Calcareous nannofossils were recovered from the dark grey shale of the Jiabula Formation at Gyangze (Fig. 5). Watznaueria dominates the fossil group, and makes up 60–90% of its abundance. Watznaueria is common in Early Cretaceous. W. barnesae and W. fossicincta largely occur in the Gyangze sections. W. barnesae occurs above the base of the Jiabula Formation. Other rich species are Cyclagelosphaera margerelii, Biscutum constans and Manivitella pemmatoidae. Manivitella pemmatoidae ranges from Berriasian to Coniacian–Santonian. Biscutum constans occurs in Cretaceous (Bown & Young 1998). Nannoconus steinmannii minor and N. steinmannii steinmannii are the Berriasian key fossils (Bralower et al. 1989; Hardenbol et al. 1998). Polycostella senaria is also a Berriasian species and Speetonia colligata ranges from Berriasian to Hauterivian (Gartner 1967). These species are common to abundant in the Gyangze sections and indicate that the lower part of the Jiabula Formation is earliest Early Cretaceous age.

The shale beds of the lower part of the Sangxiu Formation in Nagarze yield the nannofossils Tubidiscus verenae, Diazomatolithus lehmani, Calcicalathina oblongata, Zeugrhabdotus spp., Polycostella senaria, Manivitella pemmatoidae and Watznaueria barnesae. The fossil group of the Sangxiu Formation is similar to that from the lower part of the Jiabula Formation, although the abundance of the species is relatively lower. By fossil correlation, the age of this fossil assemblage is assigned to the early Early Cretaceous as well.
The calcareous nannofossils in the Gyangze–Nagarze area comprise the *Nannoconus steinmannii steinmannii–N. steinmannii minor–Watznaueria barnesae* assemblage and the *Calcicalathina oblongata–Speetonia colligata* assemblage. The former assemblage can be correlated to NJK-D and NK-1 of the Tethys zonation, and the latter assemblage to NK-3 (Table 1). Compared with the corresponding fossil zones in other areas in the world, the calcareous nannofossils found in the lower part of the Jiabula and Sangxiu formations are characteristic of Berriasian and Valanginian (Table 1).
In addition to the nannofossils at Nagarze, the bivalve *Inoceramus everesti* occurs from a 1.2-m thick packstone bed (Fig. 6–2) in the lower part of the Sangxiu Formation. The strata in this place share the same horizon with those in the Jiabula Formation in Gyangze where *Inoceramus everesti* is less abundant. *Inoceramus everesti* is present in other areas in southern Tibet like Tianba and Yamzho Yumco. This species was also reported in northwestern Australia and in western Himalayas (Guo et al. 1991). Its age is restricted to the Berriasian to Valanginian in Early Cretaceous.

**Chronostratigraphic age interpolation**

Numerical ages for the Jiabula and Jiabula-goukou sections in Gyangze can be interpolated by comparing the fossil ranges with ages calibrated in other sections. The objective is to identify which species ranges in the Gyangze sections approximate the maximum known global ranges so that their ages can be interpolated into the Gyangze sections. Two different datasets are available to test this hypothesis. First, ages of some nannofossil species have been integrated with Lower Cretaceous magnetochrons (Bralower et al. 1995; Hardenbol et al. 1998; Ogg et al. 2004). Second, the ranges of Lower Cretaceous nannofossils have been integrated by graphic correlation with magnetochrons, ammonites, and calpionellids from 23 published reference sections (Tables 2 and 3, section files LOK.1–23). This dataset was composited with the MIDK45CS range data, which spans from Aptian to Maastrichtian and includes more than 3200 taxa and stratigraphic event horizons from more than 150 sections (Scott 2009). The result is a database of numerical ages of fossil ranges and event beds that spans the entire Cretaceous System, CRET1. The fossil ranges in the Gyangze section were compared to this mainly
Sections & Points (GSSP’s) or well known reference are defined either at candidate Global Stratotype Sections & Points (GSSP’s) or well known reference sections. The criteria defining the stage bases in this database are those bioevents recommended by numerous specialists and reviewed by Ogg et al. (2004) and Rebulot et al. (2008).

The base of the Berriasian Stage at the Jurassic/Cretaceous boundary is commonly defined by the FO of Berriasella jacobi. This boundary is bracketed by numerous nanofossil bioevents (Bralower et al. 1989; de Kaenel et al. 1996; Bown & Young 1998). The uppermost Tithonian records the FOs of Manivitella pemnatoidea, Nannoconus winterveri, Crucilipopsis cuvillieri, Speetonia colligata, and Polycostella senaria. The basal Berriasian records the first occurrences of Nannoconus kampteri, Nannoconus steinmannii minor, Cretarhabdus octofenestrata, and Markalius circumradiatus among others.

The criterion recommended as defining the base of the Valanginian in the section at Barranco de Cañada Luenga, Spain, is the FO of Calpionellites darderi, which defines the base of the Calpionellid Zone E. This bioevent is dated at 140.2 ± 3.0 Ma (Ogg et al. 2004) and at 142.01 Ma in the CRET1 Database at the Luenga section. Associated taxa close to this horizon in the CRET1 Database are the FO Calcitalathina oblongata dated at 141.15 Ma and the FO of Tirmovel la pertransiens at 140.71 Ma. The recommended criterion for defining the base of the Hauterivian Stage is the FO of Acanthodiscus radiatus, which is projected at 136.4 ± 2.0 Ma (Ogg et al. 2004) and at 134.28 Ma in the CRET1 Database at the La Charce, France section.

The correlation experiment plots fossil ranges in the Jiabula and Jiabula-goukou sections in Gyangze to the CRET1 Database (Fig. 7). The line of correlation (LOC) is based on the identification of maximum known bioevent ranges. The LOC projects bioevents in the two Gyangze sections into the CRET1 Database and projects ages from the global database into the Tibetan section. The LOC has two segments constrained by the LO of Nannoconus steinmannii minor, and the FOs of Calcitalathina oblongata, and Nannoconus steinmannii ss. This correlation solution honours the FO of C. oblongata near the base of the Valanginian Stage and the FO of N. steinmannii in the basal Berriasian Stage but not at its base. This solution also projects the age of the uppermost Tithonian ammonites at 144.68 Ma slightly older than the FO of Berriasella jacobi, which defines the base of the Berriasian at 144.50 Ma.

These two LOC segments project the base of the Berriasian Stage into the Jiabula section at 44 m above the base of the exposure, the base Valanginian at 100 m, and the base of the Hauterivian Stage as defined by the FO of Acanthodiscus radiatus (Rebulot et al. 2008) at 134.28 Ma into the section at 314 m. The tuff bed in the Kadong section yielding the

Tethyan data set and plotted on an X/Y graph (Fig. 7). References to the graphic correlation process are given by Scott (2009).

The first (FO) and last occurrence datums (LO) of

The first (FO) and last occurrence datums (LO) of...
radiometric is projected into the Jiabula section at 220 m by measuring section thickness from the contact between the Weimei and Sangxiu formations to the dated bed. The age of this level is projected by the upper LOC at 137.61 Ma, well within the 136 ± 3 Ma bar r a g e m e a s u r d o n z ir c o n sf r o mt h eS a n g x i uF o r -
m a t i o n. On the graph the error box spans the 6 myr error range of the radiometric date and is extended up section to the intersection of 136 Ma on the LOC. This box outlines the thickness range in which the tuff bed in the Kadong section might project into the Gyangze section. Also the FO of *Inoceramus everesti* Oppel is projected from the Kadong section to a position between the FO of Cretaceous nannofossils and Jurassic ammonites. The estimated rates of sediment accumulation are 22.6 m/myr in the lower interval and 28.2 m/myr in the upper part.

**SHRIMP U-Pb age in the Sangxiu Formation**

The Sangxiu Formation in Nagarze is composed of sedimentary rocks in its lower part and volcanic rocks in the upper part. This formation is the key to analyse the Valanginian-Hauterivian boundary in this area. The Sangxiu volcanic unit consists mostly of massive, amygdaloidal basalts, tuffite, gabbro and dolerite in its lower part, and the upper part is dominated by dacite and rhyolite. The analytical data of the rhyolite sample (no. XZ0506) are shown in Table 4 and plotted on a concordia diagram (Fig. 8).

The rhyolite sample was collected from the upper unit of the Sangxiu Formation (Fig. 6–3), and 15 zircon grains of the rhyolite sample were tested (Fig. 4, unit 13). The test results in an age for magmatic zircons of 136 ± 3.0 Ma, which constrains the age of rhyolitic volcanism in the Sangxiu Formation. The basalt samples in the Sangxiu Formation (Fig. 4, unit 12) were also tested, but no reliable data were obtained. Both the rhyolite and the basalt in the Sangxiu Formation were formed in an extensional tectonic setting. The zircon SHRIMP age of rhyolite, therefore, indicates that the volcanism of the upper Sangxiu Formation occurred during the Valanginian Stage following deposition of the *Calcicalathina oblongata–Specticeras colligata* assemblage zone.

**The Jurassic/Cretaceous and Valanginian/Hauterivian boundaries**

For many years, criteria for defining the Jurassic/Cretaceous boundary have been studied and debated.
One reason for the debate has been the biogeographic variation of ammonites between the Tethyan and Boreal provinces (Jeletzky 1984; Hoedemaeker 1991; Podobina & Tatyanin 2000, among many others).

According to general agreement the Berriasian Stage is the basal stage of the Cretaceous System and the first appearance of *Berriasella jacobi* defines the base of the Berriasian (Hoedemaeker 1987; Wimbledon 2008). The currently accepted numerical age of the base of the Berriasian is 145.5 Ma (Gradstein *et al.* 2004; Ogg *et al.* 2004). In the Himalayan region, ammonite biostratigraphy spanning the Jurassic/Cretaceous boundary was studied by Enay & Cariou (1997, 1999).

The Upper Jurassic and Lower Cretaceous stratigraphy of southern Tibet has been reported by many geologists (Zhang & Huang 1983; Liu 1988; Westermann & Wang 1988) since the first scientific exploration was carried out in 1966. In the Gyangze–Nagarze area, the J/K boundary was regarded as a lithologic boundary between the Weimei and Jiabula formations (Liu 1988). The ammonites found recently by the present authors in their geological survey in Gyangze provides some crucial links for the correlation with other regions of the SW Pacific domain where these ammonite genera are widely distributed. In the Gyangze area the *Haplophylloceras strigile–Corongoceras–Himalayites* assemblage is of latest Jurassic age, and the *Spiticeras* assemblage, including *S. spitiense*, *S. stanleyi*, *Sarasinella* sp., and *Cuyaniceras* sp. represents the earliest Cretaceous (Fig. 9; Howarth 1998; Yin & Enay 2004).

Table 4. Zircon SHRIMP analysis data of rhyolite in the Sangxiu Formation (XZ0506).

<table>
<thead>
<tr>
<th>Spot</th>
<th>ppm U</th>
<th>ppm Th</th>
<th>232Th/238U</th>
<th>Corr 206/238</th>
<th>% err</th>
<th>ppm Rad 206Pb</th>
<th>204corr 206Pb/238U</th>
<th>Age</th>
<th>1 err</th>
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<td>XZ0506-1.1</td>
<td>160</td>
<td>125</td>
<td>0.81</td>
<td>0.023</td>
<td>6.4</td>
<td>3.2</td>
<td>145.5</td>
<td>9.2</td>
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<td>XZ0506-9.1</td>
<td>89</td>
<td>82</td>
<td>0.95</td>
<td>0.021</td>
<td>4.3</td>
<td>1.6</td>
<td>132.1</td>
<td>5.6</td>
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</tr>
<tr>
<td>XZ0506-10.1</td>
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<td>213</td>
<td>1.69</td>
<td>0.021</td>
<td>3.3</td>
<td>2.4</td>
<td>133.5</td>
<td>4.6</td>
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<td>49</td>
<td>0.83</td>
<td>0.023</td>
<td>3.1</td>
<td>1.2</td>
<td>135.4</td>
<td>5.7</td>
<td></td>
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<tr>
<td>XZ0506-12.1</td>
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<td>1.65</td>
<td>0.022</td>
<td>4.2</td>
<td>2.6</td>
<td>141.5</td>
<td>5.9</td>
<td></td>
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<tr>
<td>XZ0506-13.1</td>
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<td>215</td>
<td>1.15</td>
<td>0.022</td>
<td>2.2</td>
<td>3.7</td>
<td>141.0</td>
<td>3.1</td>
<td></td>
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<tr>
<td>XZ0506-15.1</td>
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<td>0.43</td>
<td>0.022</td>
<td>2.2</td>
<td>4.0</td>
<td>140.5</td>
<td>3.1</td>
<td></td>
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<tr>
<td>XZ0506-16.1</td>
<td>143</td>
<td>72</td>
<td>0.52</td>
<td>0.021</td>
<td>4.6</td>
<td>2.6</td>
<td>133.5</td>
<td>6.0</td>
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</tr>
<tr>
<td>XZ0506-17.1</td>
<td>126</td>
<td>120</td>
<td>0.98</td>
<td>0.020</td>
<td>3.9</td>
<td>2.2</td>
<td>127.0</td>
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<td>XZ0506-19.1</td>
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<td>0.022</td>
<td>2.3</td>
<td>4.4</td>
<td>139.6</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>XZ0506-24.1</td>
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<td>175</td>
<td>0.99</td>
<td>0.021</td>
<td>3.1</td>
<td>3.3</td>
<td>133.0</td>
<td>4.1</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 8.** Concordia diagram of zircon SHRIMP dating for the rhyolite of the Sangxiu Formation.
nannofossils reported herein. The globally distributed *Nannoconus steinmannii–N. st. minor–Watznaueria barnesae* Assemblage indicates Berriasian age, and the *Calcicalathina oblongata–Speetonia colligata* Assemblage correlates with the Valanginian (Figs 2–4). The first appearance of the Berriasian nannofossil assemblage in the Gyangze–Nagarze area is about 3–5 m above the base of the Sangxiu and Jiabula formations (Fig. 9). Therefore, the J/K boundary is placed near the bottom of the Jiabula Formation at Gyangze, and at the basal part of the Sangxiu Formation at Nagarze. The boundary is marked by the first appearance of the ammonite *Spiticeras* and the nannofossil *Nannoconus steinmannii–N. st. minor–Watznaueria barnesae* Assemblage.

The present SHRIMP U-Pb analysis on the rhyolite sample dates the volcanic rocks in the upper unit of the Sangxiu Formation at 136 ± 3.0 Ma. Therefore, the Berriasian–Valanginian fossil assemblages in the lower unit of the Sangxiu Formation are older, which is consistent with ages in Gradstein *et al.* (2004) and Ogg *et al.* (2004). The rhyolite sample is 190 m above the J/K biostratigraphic boundary. As estimated above, the sedimentary accumulation rate of the lower Sangxiu Formation is 22.6 m/myr. By consideration of underlying sedimentary deposits, the J/K boundary in the Gyangze–Nagarze area is approximately 145 Ma as suggested by the new International Stratigraphic Chart (Ogg *et al.* 2004).

This radiometric date in Tibet is the first to be integrated with upper Valanginian fossils and is important in constraining the age calibration of the Valanginian/Hauterivian boundary, which has been dated from 130 Ma to 136.4 Ma. The age of this boundary was calibrated at 132.0 ± 1.9 Ma based on the polarity time-scale derived from seafloor spreading rates (Channell *et al.* 1995; Gradstein *et al.* 1995). The age was recalibrated to 136.4 ± 2.0 Ma because the Pacific spreading rate model for the Hawaiian lineations was modified (Ogg *et al.* 2004). The implication of the new Tibetan radiometric age is that this boundary is younger than 136 Ma. The numerical age of 134.3 Ma measured by graphic interpolation is within the error bar of the Tibetan age. It would seem that the

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**Fig. 9.** Lower Cretaceous stratigraphic correlation of the Jiabula section in Gyangze (Fig. 2) and the Kadong section in Nagarze (Fig. 4), southern Tibet. Numbers at right of each column refer to stratigraphic units (For key see Figs 2, 4).
Conclusions

The following conclusions may be drawn:

1. In the Gyangze–Nagarze area two calcareous nannofossil assemblages are recognized. The *Nannocornus st. steinmannii*–*N. st. minor*–*Watznaueria barnesae* assemblage indicates Berriasian age, and the *Calcalathina oblongata–Speetonia colligata* assemblage is early Valanginian in age.

2. Numerical ages for the Gyangze section are interpolated by comparing the fossil ranges with ages calibrated in other sections. The correlation experiment plots fossil ranges in the Gyangze section to the CRET1 database.

3. Zircon SHRIMP U-Pb analyses on the rhyolite sample from the Sangxiu Formation at Nagarze yields a date of 136 ± 3.0 Ma. By considering the sedimentary accumulation rate of underlying strata, the J/K boundary in the Gyangze–Nagarze area is estimated to be 145 Ma, and the numerical age of the Valanginian/Hauterivian boundary is no older than 136 ± 3.0 Ma.

4. The J/K boundary is at the bottom of the Jiabula Formation in Gyangze and the base of the Sangxiu Formation in Nagarze. The boundary is marked by the lowest appearance of the ammonite *Spiticeras* and the nannofossil assemblage of *Nannocornus st. steinmannii–N. st. minor*–*Watznaueria barnesae*.

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