How was the Carboniferous Balkhash–West Junggar remnant ocean filled and closed? Insights from the Well Tacan-1 strata in the Tacheng Basin, NW China

Di Li, Dengfa He * , Xuefeng Qi, Ningning Zhang

The Key Laboratory of Marine Reservoir Evolution and Hydrocarbon Accumulation Mechanism, The Ministry of Education, China University of Geosciences, Beijing 100083, China

Abstract

The Balkhash–West Junggar remnant ocean is a conspicuous tectonic feature that had an important effect on the Paleozoic tectonic evolution of the Central Asian Orogenic Belt. How the Carboniferous Balkhash–West Junggar remnant ocean was filled and closed is poorly understood. In this study, we focus on the integrated tectonic-sedimentary evolution of the Tacheng Basin, which is located in the eastern part of the Balkhash–West Junggar remnant ocean, using high-resolution seismic reflection, well-line, geochronological and geochemical data to establish the filling of the basin by sediments and its evolution. The Carboniferous Balkhash–West Junggar remnant ocean basin was filled by Early Carboniferous deep marine mudstone and interbedded sandstone with minor andesite, basalt and tuff, and late Carboniferous basalt, andesite, breccia and tuff and shallow marine mudstone and sandstone. The Carboniferous igneous assemblage mainly consists of basalt with high Nb content and (Nb/La)PM values and concomitant magnesian andesites with adakite geochemical characteristics of high Sr and low Y and Yb, suggesting a subduction-related tectonic setting. Zircons in the tuff that underlies the basalts and magnesian andesites were dated to ca. 315 Ma by LA-ICP-MS U–Pb. The identified unconformity between the Carboniferous and Lower Permian from seismic reflection profile in Well Tacan-1 subdivided the Carboniferous–Early Permian strata into two tectonostratigraphic units. The Lower Permian sequences overlap the Carboniferous strata and the facies transition from the submarine Carboniferous to the terrigenous Lower Permian indicates that the Balkhash–West Junggar remnant ocean closed during the Early Permian. These new data suggest that the sedimentary filling of the basin was in response to subduction and accretionary processes and that oceanic subduction was an important mechanism that led to the shrinking, filling and closure of the Balkhash–West Junggar remnant ocean because of compression. Therefore, lateral crust growth through subduction–accretionary processes still played an important role in the Carboniferous construction of western Junggar.

© 2013 International Association for Gondwana Research. Published by Elsevier B.V. All rights reserved.

1. Introduction

The Central Asian Orogenic Belt (CAOB) corresponds to the Altai tectonic collage by Şengör and coworkers (Şengör et al., 1993; Şengör and Natal'in, 1996) and is the world’s largest Phanerozoic accretionary orogen. It is the product of the successive accretion and amalgamation of Precambrian continental blocks, ancient island arcs, accretionary complexes, ophiolites and passive continental margins since the Late Precambrian continental blocks, ancient island arcs, accretionary complexes, ophiolites and passive continental margins since the Late Precambrian continental blocks, ancient island arcs, accretionary complexes, ophiolites and passive continental margins since the Neoproterozoic (Şengör and Natal'in, 1996; Buslov et al., 2001; Badarch et al., 2002; Khain et al., 2002, 2003; Xiao et al., 2003; Dobretsov et al., 2004; Jahn et al., 2004; Safonova et al., 2004; Yakubchuk, 2004; Helo et al., 2006; Kröner et al., 2007; Windley et al., 2007; Xiao et al., 2009, 2010) (Fig. 1a). The western Junggar region, located at the eastern margin of the Kazakhstan orocline (Windley et al., 2007; Xiao et al., 2010) (Fig. 1b), has long been an important region for studying the evolution of the CAOB (Khain et al., 2002; Yakubchuk, 2004; Seltmann and Porter, 2005; Windley et al., 2007; Kröner et al., 2008; Santosh et al., 2009; Shen et al., 2009, 2010). Several belts of ophiolitic mélanges and subduction-related volcanic rocks with positive εNd values contain evidence for the oceanic evolution from the Cambrian to Carboniferous (Zhang et al., 1995; Buckman and Aitchison, 2004), which constrains the long-lived accretion history without much involvement of ancient continental crust (Feng et al., 1989; Zhang et al., 1993; Jian et al., 2005; Zhu and Xu, 2006; Gu et al., 2009; Zhang and Guo, 2010; Li et al., 2012; Xu et al., 2012; He et al., 2013) and without the short amalgamation phases of multiple microcontinents (Mossakovskiy et al., 1993). Moreover, the extensive occurrence of Carboniferous adakites, high-Mg diorite dikes and charnockites in this area indicates that there may have been an oceanic island arc setting in the Carboniferous in western Junggar (Geng et al., 2009; Liu et al., 2009; Tang et al., 2009; Yin et al., 2010). Tectonic evolution models, such as a single subduction zone (Wang et al., 2003), arc–arc collisions (Feng et al., 1991; Zhang et al., 1995; Buckman and Aitchison, 2004) and oceanic-ridge subduction (Geng et al., 2009; Liu et al., 2009; Tang et al., 2009, 2010; Yin et al., 2010) have been proposed to explain the evolution of the western Junggar region in the Carboniferous. The
Balkhash area, located in the central Kazakhstan orocline and the westward extension of the western Junggar region, shares the same tectonic evolution history with the western Junggar region. The comparison of tectonic features proved the existence of a limited Carboniferous remnant oceanic basin that existed in the Balkhash–West Junggar region (He and Xu, 2003; He et al., 2004). The floor of the ocean basin was covered by marine lavas, peperite and sedimentary rocks (Li and Jin, 1989; Jin and Li, 1999; Guo et al., 2002). Recently, Chen et al. (2013) identified Late Devonian peperites at the base of the Taigulaga Formation in the western Junggar, which further confirms the existence of a Carboniferous western Junggar remnant ocean basin. Latest Carboniferous–Middle Permian stitching plutons intruded the western Junggar accretionary complexes and adjacent parts of East Kazakhstan (Vladimirov et al., 2008; Kubida et al., 2009). In addition, Early Permian bimodal volcanic rocks, A-type granites and molasses are present in western Junggar (Zhou et al., 2008; Chen et al., 2010). The data indicate that western Junggar had entered a post-collisional evolution stage during the Late Carboniferous–Middle Permian (Han et al., 2006; Su et al., 2006; Su et al., 2006; T.F. Zhou et al., 2006; Zhou et al., 2008; Chen et al., 2010) while the Balkhash–West Junggar remnant ocean basin disappeared in this period. The well-exposed Carboniferous strata in western Junggar provide an opportunity to unravel the accretionary processes spatially and temporally; however, few detailed data are reported that could explain how the Carboniferous Balkhash–West Junggar remnant ocean filled and closed.

The Tacheng Basin, a link to the Balkhash and western Junggar remnant ocean, contains well-preserved volcanic–sedimentary sequences. Naturally, the fill material and tectonic setting are keys to understand the filling and evolution of the basin. The subsequent deformation, uplift, erosion and crustal growth in Central Asia modified the original tectonic framework; nonetheless, relatively well-developed sequences are preserved in this basin. Thus, these filling sequences are valuable records of the tectonic evolution of the accretionary orogen and the volcanic rocks can further constrain the tectonic evolution. To explore the tectonic–sedimentary evolution of the Balkhash–West Junggar remnant ocean basin, we conducted a comprehensive study of the Well Tacan-1 in the Tacheng Basin (Fig. 2a). The dataset, including high-resolution seismic reflection data and the relatively complete stratigraphic sequence provides critical information for unraveling the filling of the Balkhash–West Junggar remnant ocean. In addition, we carried out whole-rock and Sr–Nd isotope geochemistry and zircon U–Pb geochronological analysis of the Upper Carboniferous volcanic rocks to constrain the Carboniferous tectonic setting. The new results were combined with previously reported data to discuss the evolution of the sedimentary filling and the closing mechanism of the Balkhash–West Junggar remnant ocean basin.

2. Geological setting

The Balkhash–West Junggar remnant ocean occupies the central segment of the CAOB and extends E-W for more than 1000 km from Balkhash to western Junggar (Fig. 1b). It is surrounded by northern (Chingiz) and southern (North Tian shan) Paleozoic volcanic belts that contain Paleozoic ophiolites in the Balkhash and western Junggar regions (Zhao and He, 2013), indicating that they may have originated from the same paleo-oceanic tectonic setting. Therefore, the Balkhash and western Junggar remnant ocean had a similar evolution and filling history.

The western Junggar terrane is divided into northern and southern by the Xiensitai fault. In the north, western Junggar terrane mainly consists of the Zhangsu–Saur and Boshchekul–Chingiz volcanic arcs and is characterized by E–W-trending faults and fault-bounded blocks (BGMRX, Bureau of Geology Mineral Resources of Xinjiang Uyghur Autonomous Region, 1993; Fig. 2a). These arcs consist of Late Paleozoic tuffaceous limestone and sandstone and Early Paleozoic tuffaceous siltstone, tuffaceous sandstone and muddy siltstone, which are intruded by 304–263 Ma intermediate to felsic plutons (Han et al., 2006; Zhou et al., 2008; Chen et al., 2010; Shen et al., 2012). The plutons reflect the result of the southward subduction of the Irtys–Zaysan Ocean beneath the Kazakhsthan block (Windley et al., 2007; Vladimirov et al., 2008). The southern western Junggar terrane, in contrast, consists of successive accretionary complexes separated by NE–SW oriented faults, such as the Darbut fault (Fig. 2a). These complexes consist of Devonian to Carboniferous sandstone and volcanic rocks, including basalt, andesitic basalt and andesite (BGMRX, Bureau of Geology Mineral Resources of Xinjiang Uyghur Autonomous Region, 1993; Shen and Jin, 1993). They are intruded by alkali–feldspar granite batholiths and mafic dikes. The age of the granodioritic stocks is between 315 and 298 Ma (Chen et al., 2006; Han et al., 2006; Su et al., 2006; Geng et al., 2009; Tang et al., 2009; Yin et al., 2010; Tang et al., 2012a). The Carboniferous volcanic rocks in these accretionary complexes have SHRIMP and LA–ICP–MS U–Pb ages of 358–328 Ma (An and Zhu, 2009; Guo et al., 2010), which implies that the Late Carboniferous strata were denuded or had not formed. This may lead to misunderstanding of the Carboniferous tectonic environment of West Junggar (Coleman, 1989; Chen and Jahn, 2004; Han et al., 2006; Xiao et al., 2008; Geng et al., 2009, 2011). Therefore, much more geochemical work on the Late Carboniferous volcanic rocks is needed to clarify the source regions and tectonic setting.
Western Junggar is in the south of the Tacheng Basin and the Zharma–Saur Mountains are in the north. The sedimentary rocks of the basin range from Late Paleozoic to Cenozoic and experienced an extensional stage in Early Paleozoic and a convergence stage in Late Paleozoic (He et al., 1994). Tectonically, the northern part of the Tacheng Basin mainly involves the Zharma–Saur and Boshchekul–Chingiz volcanic arcs from north to south. Parts of the Boshchekul–Chingiz volcanic arc are covered by Meso-Cenozoic strata of the Tacheng Basin (Fig. 1b). The Zharma–Saur volcanic arc is separated by the Irtysh–Zaysan suture zone from the Altai orogen in the north and from the Boshchekul–Chingiz volcanic arc and Tacheng Basin by the Kujibai ophiolitic belts. The latter occur along large-scale E–W or NE–SW oriented faults and may extend eastward to the Hebuksaiar and Honggulelen ophiolitic belts. The latter occur along large-scale E–W or NE–SW oriented faults and may extend eastward to the Hebuksaiar and Honggulelen ophiolitic belts. Devonian–Early Carboniferous plutons outcrop along both sides of the Irtysh–Zaysan suture zone and the intruding plutons have zircon U–Pb ages of 307–299 Ma (Kuibida et al., 2009), suggesting that suturing may have occurred in the Late Carboniferous (Buslov et al., 2001; Windley et al., 2007; Han et al., 2010). The altered gabbros from the Kujibai ophiolite yielded a SHRIMP zircon U–Pb age of 478 Ma (Zhu and Xu, 2006), which is similar to the age of the Honggulelen ophiolite (475 Ma, Jian et al., 2005) and together they may represent remnants of the Early Devonian interarc oceanic basin (Filippova et al., 2001). The age of the Barleik ophiolite in the southern part of the Tacheng Basin is considered Middle Devonian based on radiolarians in chert (Feng, 1987) and may be slices of another ophiolite separated and displaced by faulting (Buckman and Aitchison, 2004). The age of the Darbut ophiolite ranges from 303 to 426 Ma (Zhang and Huang, 1992; Gu et al., 2009; Liu et al., 2009; Chen and Zhu, 2011; Yang et al., 2012), demonstrating a complex accretionary history that even continued into the Late Carboniferous.

3. Stratigraphic successions and sample descriptions

The Tacheng Basin is located in the western part of the West Junggar region where the connected Chingiz arc and Junggar composite basin contain a 4 km thick Carboniferous–Cenozoic sedimentary
sequence. The basin is divided into four first-order tectonic units (Fig. 2a): the Central Uplift, the Southern Depression, the Eastern Depression and the Northern Depression. The Well Tacan-1 is located at the transitional zone of a strong–weak magnetic anomaly in the Southern Depression and mainly goes through Neogene (0–154 m), Paleogene (154–346 m), Jurassic (346–572 m), Lower Permian (Kalagang Formation, 572–940 m), Upper Carboniferous (Jimunai Formation, 940–2778 m) and part of Lower Carboniferous (Nanmingshui Formation, 2778–3300 m) (Fig. 2b). In general, a period of volcanioclastic activity shows the cycle of a volcano from eruption to lava gushes. According to the eruption-and-gushing-out model, thirty-two periods of volcanic activity were identified in the Well Tacan-1. The mudstones at 790–810 m contain monosaccate pollen of Protaphloxyllum and Striatooideites. Some Hamiapollenites, monosaccate pollen, Costa pollen and Pteridophyta spores were also discovered. This assemblage of gymnosperm pollen and little fern spore did not contain Early Carboniferous pollen or spore assemblages. In contrast, the Early Carboniferous samples from North Xinjiang and the low content of Cordaitina and Hamiapollenites differ from that of the Middle–Late Permian, suggesting a Carboniferous age for the Jimunai Formation. The nearly 2360 m thick Carboniferous formation in the Well Tacan-1 is at a depth of 940–3300 m, and includes the Upper Carboniferous Jimunai Formation (C4) and the Lower Carboniferous Nanmingshui Formation (C1) (Fig. 3). The Jimunai Formation mainly consists of basalt, volcanic breccia, tuff, andesite, rhyolite, conglomerate and mudstone. The Nanmingshui Formation mainly consists of dark gray andesite, tuff, mudstone and basalt. The contact between the Early and Late Carboniferous formations is conformable, whereas the Lower Permian sequence is unconformably overlain by the Upper Carboniferous. The Lower Permian Kalagang Formation (P1k) consists of gray basalt interbedded with tuffite, thin sandstone and mudstone (Fig. 3). The Carboniferous strata contain more volcanic–sedimentary rocks than those outcropping in the field and show significant southward thinning. This Paleozoic stratigraphic succession suggests that the Tacheng region might have been a remnant ocean basin in Devonian–Carboniferous. In the Late Carboniferous, its rising amplitude was enlarged owing to external compression and, thus, its top denudation and weathering residues were formed. The Kalagang Formation (P1k) was undergoing sedimentation in the Early Permian period, whereas the uplifted areas were apparently denuding because the overlying deposits are visible in the central segment of the Tacheng Basin (profile AA, Fig. 2b). The Tacheng Basin was then covered by the Mesozoic and Cenozoic formations. The seismic data used in this study comprise two industry seismic surveys of high-resolution 2D seismic profiles acquired in 2008. The strata in the Cenozoic and Mesozoic, Permian and the upper part of Carboniferous formations have produced continuous reflection events and clear faults and unconformities, which reflect almost horizontal beds deposited in a relatively stable sedimentary environment. The middle–lower Carboniferous formations, in contrast, are poorly reflective with poor continuity and medium–weak reflection intensities. However, the faults are clearly distinguished and unconformitybounded and better reflect the severe deformation of this period.

To better constrain on the process and time of the remnant ocean, we selected ten Carboniferous volcanic samples from the Well Tacan-1 to study their petrogenetic and tectonic setting characteristics and a tuff for zircon U–Pb dating. Ten basalt and andesite samples were obtained from four different depths (respectively, 952–960 m, 1095–1097 m, 1428–1433 m and 1548–1550 m) (Fig. 3). These samples have high resistivities, medium natural potentials and medium-low natural gamma rays in the logging curve. The rocks are gray or dark gray and massive (Fig. 3). The samples are divided into basaltic andesites and basalt depending on their characteristics under the microscope (Fig. 3). The basaltic andesites consist of phenocrysts of plagioclase, augite, magnetite, hornblende, minor biotite and microcrystals of plagioclase and augite in a fine-grained groundmass containing several zircon grains. The basalts, which have undergone weak chloritization, contain altered phenocrysts of plagioclase, augite and hornblende in a cryptocrystalline–glassy groundmass that contains magnetite grains (Fig. 3). The groundmass and phenocrysts in the basalts and basaltic andesites have similar characteristics, suggesting that they may be the products of coeval magmatic activity. The main components of the tuff underlying the basalts and andesites are ashes and phenocrysts (Fig. 3). The phenocrysts show irregular edges and are mainly composed of worse crystalized leucocratic mineral and minor calcite debris, but this tuff exhibits homogeneous petrography characteristics under the microscope and were mostly the products of single eruption in a certain magmatic event.

4. Methods and analytical procedures

4.1. LA–ICP–MS U–Pb dating

LA–ICP–MS U–Pb and major and trace element analyses were performed at the State Key Laboratory of Continental Dynamics, Northwest University, Xi'an, China. Handpicked zircon grains were embedded in epoxy and polished down to half size and cleaned in an acid bath before analysis. CL imaging was carried out at the School of Earth and Space Sciences, Peking University. Zircon U–Th–Pb measurements were made on 30 lm diameter regions of single grains using an ICP–MS (Agilent 7500a) and an excimer laser-ablation system (193 nm, Geolas 200M, Lambda Physic). Trace element and U–Th–Pb isotopic data were simultaneously acquired on the same spot. The analytical procedures are similar to those reported by Yuan et al. (2007). The isotopic ratios and element concentration of zircons were calculated using GLITTER (ver. 4.0, Macquarie University). Concordia ages and diagrams were obtained using Isoplot/Ex (ver. 2.94) (Ludwig, 2003). Common lead was corrected using the LA–ICP–MS common lead correction (ver. 3.15) after Andersen (2002).

4.2. Major and trace element analyses

Major element abundances, except FeO and LOI that were analyzed by wet chemical methods, were analyzed by XRF on fused glass disks using the BCR-2 and GBW07105 reference materials. The relative standard deviations of the XRF analyses are less than 2%. Trace elements and REE contents were determined by ICP–MS (Elan 6100DRC), following the method of Gao et al. (1999). The USCG standards (AVG-1, BCR-1 and BHVO-1) were used for calibration. The lowest analytical limit for trace elements is about 0.1 ppm and the analytical accuracies are better than 5% for Co, Ni, Zn, Ga, Rb, Y, Zr, Nb, Hf, Ta and REE (expect Hf and Lu) and 5–10% for the rest.

4.3. Whole-rock Sr–Nd isotope analysis

Sr–Nd isotopic compositions were analyzed at the Institute of Geology and Geophysics, Chinese Academy of Sciences, using a multi-collector VG 354 mass spectrometer in static mode. Approximately 100–150 mg of whole-rock powder was decomposed in a mixture of HF–HClO4 in screw-top Teflon beakers, and Rb, Sr, Sm and Nd were separated by using cation-exchange columns. Rb, Sr, Sm and Nd concentrations were determined by isotope dilution, using a mixed 86Rb, 84Sr–146Sm, 142Nd spike solution. Procedural blanks were <200 pg for Sr and 50 pg for Nd. 143Nd/144Nd was normalized to 146Nd/144Nd = 0.7219 and 87Sr/86Sr was normalized to 86Sr/88Sr = 0.1194. The detailed analytical procedures are described in F.K Chen et al. (2001). During the course of this study, standards NBS 607 and BCR-1 gave 87Sr/86Sr of 0.7102 ± 0.0002 and 143Nd/144Nd of 0.51266 ± 0.0002, respectively. The analytical precision is –1% for 87Sr/86Sr and 0.5% for 143Nd/144Nd. The depleted mantle Nd model ages (TDM) were calculated using the present-day depleted mantle 143Nd/144Nd and 147Sm/144Nd values of 0.513151 and 0.21357, respectively, and the age of the rock formation.

Please cite this article as: Li, D., et al., How was the Carboniferous Balkhash–West Junggar remnant ocean filled and closed? Insights from the Well Tacan-1 strata in the Tacheng Basin, NW China, Gondwana Research (2013), http://dx.doi.org/10.1016/j.gr.2013.10.003
5. Analytical results

5.1. LA–ICP–MS zircon U–Pb dating results

The zircon U–Pb data are summarized in Table 1 and presented in concordia diagrams in Fig. 5a. Thirty-five zircons, analyzed by LA–ICP–MS, were from the tuff (TCA-1) underlying the basalts and andesites. The CL images (Fig. 4) show that most zircon grains are colorless, transparent to semi-transparent, euhedral to slightly elongate with length between 80 and 100 μm and unclear oscillatory zoning, typical of extrusive rock zircons with length/width ratios of 1.5–2.5. A few zircons contain dark enclaves, others are rounded with sector zoning and several of them contain tiny, relict cores.

Thirty-five zircons from the tuff sample (TCA-1) were analyzed using the LA–ICP–MS U–Pb dating method (Table 1). The results show that all of the analyzed spots fitted along a curve in the U–Pb diagram.

Please cite this article as: Li, D., et al., How was the Carboniferous Balkhash–West Junggar remnant ocean filled and closed? Insights from the Well Tacan-1 strata in the Tacheng Basin, NW China, Gondwana Research (2013), http://dx.doi.org/10.1016/j.gr.2013.10.003
(Fig. 5a). The $^{206}$Pb/$^{238}$U ages ranged from 306 ± 4 Ma to 1763 ± 11 Ma (Fig. 5a) and could be clearly divided into two groups. The younger age group contains 34 analysis spots and $^{206}$Pb/$^{238}$U ages between 306 ± 4 Ma and 324 ± 11 Ma. These zircons are spread around a $^{206}$Pb/$^{238}$U age of 315.3 ± 1.6 Ma (Fig. 5b), indicating a Late Carboniferous age. More importantly, all the obtained trace element compositions and age results from these zircons having different appearances and structure characteristics are both consistent in their error range. In addition, the zircon grains have high and variable U (35.2–290.6 ppm), Th (20.2–313.4 ppm) and Th/U ratios (0.4–1.5 with an average of 0.8) (Table 1), indicating that all the analyzed zircons are of magmatic origin. Based on the results described above, we believe that the age of this suite of tuffs reveals the age of the main magmatic stage in the Tacheng area and provides a lower limit age for the basalts and andesites of Well Tacan-1. In summary, the tuff formed in the Early Carboniferous (315.3 ± 1.6 Ma), indicating that these basalts and andesites formed no earlier than 315 Ma. One zircon has a $^{207}$Pb/$^{206}$Pb age of 1844 ± 26 Ma or a $^{208}$Pb/$^{238}$U age of 1763 ± 11 Ma, which may be captured from wall rocks (e.g. sedimentary rocks) during the magmatic ascent.

5.2. Major and trace elements

Ten samples were analyzed for major and trace elements and the dataset is presented in Table 2. Data sources for the northern Xinjiang adakitic rock (Zhang et al., 2004; Xiong et al., 2005; Zhang et al., 2006; Wang et al., 2007; Mao et al., 2012) and Nb-enriched basalts and basaltic andesites (Zhang et al., 2003, 2004; Wang et al., 2007; Niu et al., 2009; Mao et al., 2012) are also plotted in geochemical diagrams (Fig. 6). For convenience and detailed discussions, we divide the dataset into four groups, based on the depth in the Well Tacan-1 from where the samples were retrieved. The loss on ignition for the samples in this study ranges from 2.69% (K24-8) to 4.26% (K24-11) except for a sample with a high value of 6.08% (K24-13), suggesting that these samples may be affected by low-temperature alteration, which affected the mobile elements (e.g. K, Na, Rb) (Pearce and Cann, 1973; Winchester and Floyd, 1977).

5.2.1. Magnesian andesites

The andesites have a relatively low, but restricted, range of SiO$_2$ (54.56–57.29%) and TiO$_2$ (0.82–0.90%). In the SiO$_2$–(Na$_2$O + K$_2$O) diagram shown in Fig. 6a, the andesites appear in the basaltic trachyandesite, basaltic andesite and trachyandesite fields. Commonly, they have relatively high MgO (3.61–4.73%, Mg# = 50.3–50.9) and low Al$_2$O$_3$ (15.38–17.15%) and CaO (3.15–8.02%). Interestingly, the samples have similar Na$_2$O (3.30–4.77%), K$_2$O (1.81–2.65%) and CaO (3.15–8.02%) with the magnesian andesites in the western Aeolites Komandorsky region (Yogodzinski et al., 1994, 1995) (Fig. 6c). The content of these major elements compositionally resembles that of typical calc-alkaline high-K rocks (Fig. 6b). Moreover, the samples have adakite-like (La/Yb)$_N$ and Sr/Y ratios, low Y and Yb concentrations (18.02–18.40 and 1.58–1.65 ppm, respectively) (Fig. 7), and negative Nb and Ta anomalies on a primitive mantle-normalized trace element diagram (Fig. 6b and Table 2). Negative Ti and positive Sr anomalies and concave midle and heavy REE patterns are also evident in Fig. 8. These andesites have low Ni (64.4–69.5 ppm) and Cr (87.9–89.1 ppm) concentrations, which makes them comparable to the Alatay adakites in northern Tianshan (Wang et al., 2007). However, the andesites from...
Well Tacan-1 have higher MgO and Mg# (Table 2), which differentiates them from typical adakitic rocks (Defant and Drummond, 1990) and are more similar to magnesian andesites with some adakitic rock geochemical characteristics.

5.2.2. Basalts
The basalts in Well Tacan-1 are strongly spatially associated with the magnesian andesites. They have low SiO$_2$ (48.22–51.18%) and fall within the basalt and trachybasalt fields (Fig. 6a). They are sodium-rich (Na$_2$O/K$_2$O = 0.31–63; the majority >4) (Fig. 6c) and characterized by relatively higher TiO$_2$ (1.14–1.50%), P$_2$O$_5$ (0.40–0.81%) and Zr (141–181 ppm) contents, and higher (Nb/Th)$_{PM}$ (0.63–1.17), (Nb/La)$_{PM}$ (0.35–0.51) and Nb/U (11.34–29.36) ratios than typical arc basalts (Table 2 and Fig. 9). The total rare-earth-element (Σ REE) content of the basalts from Well Tacan-1 varies between 105 and 153 ppm (Table 2). The chondrite-normalized REE patterns (Fig. 8c) show LREE enrichment ((La/Sm)$_N$ = 2.55–3.24; (La/Yb)$_N$ = 6.83–8.06) and slightly negative or no Eu anomalies (Eu/Eu*$ = 0.91–1.03$), which resembles typical OIB (Sun and McDonough, 1989). The HREE are less fractionated as revealed by the low ratios of (Gd/Yb)$_N$ (1.80–2.19) similar to N-MORB. Furthermore, these basalts have also similar primitive mantle-normalized trace element content to OIB but tend to have lower Nb/U (11.34–29.36) and Ce/Pb (5.45–18.34) than OIB and MORB (Sun and McDonough, 1989). In addition, all the rocks exhibit some enrichment in LILE (Rb, Ba and K), depletion in Nb and Ta and slightly positive or negative Ba, Sr and Ti (Fig. 8b), indicating that their formation may be related to subduction. Compositionally, two rocks (K24-7 and K24-8) have higher Nb concentrations ranging from 13.80 to 13.95 ppm than most basalts of intra-oceanic arcs (Martin et al., 2005) and are almost identical to those of Nb-enriched basalts in China and elsewhere (Defant et al., 1991; Sajona et al., 1996; Aguillón-Robles et al., 2001; Manya et al., 2007; Wang et al., 2007; Mao et al., 2012).

5.3. Sr–Nd isotope compositions
The Sr–Nd isotopic analysis data for the Carboniferous andesites and basalts from Well Tacan-1 are given in Table 3. Initial $^{87}$Sr/$^{86}$Sr and
**Table 2**

| Major elements (%) and trace elements (ppm) in the basalts and andesites from Well Tacan-1.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Andesite</th>
<th>Basalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2O</td>
<td>2.65</td>
<td>1.81</td>
</tr>
<tr>
<td>Cr</td>
<td>87.86</td>
<td>105.0</td>
</tr>
<tr>
<td>Co</td>
<td>24.04</td>
<td>105.0</td>
</tr>
<tr>
<td>Ni</td>
<td>66.33</td>
<td>105.0</td>
</tr>
<tr>
<td>Cu</td>
<td>101.0</td>
<td>105.0</td>
</tr>
<tr>
<td>Zn</td>
<td>71.97</td>
<td>105.0</td>
</tr>
<tr>
<td>Ga</td>
<td>13.87</td>
<td>105.0</td>
</tr>
<tr>
<td>Rb</td>
<td>43.18</td>
<td>105.0</td>
</tr>
<tr>
<td>Sr</td>
<td>663.8</td>
<td>105.0</td>
</tr>
<tr>
<td>Y</td>
<td>8.40</td>
<td>105.0</td>
</tr>
<tr>
<td>Zr</td>
<td>144.0</td>
<td>105.0</td>
</tr>
<tr>
<td>Nb</td>
<td>7.13</td>
<td>105.0</td>
</tr>
<tr>
<td>Cs</td>
<td>0.08</td>
<td>105.0</td>
</tr>
<tr>
<td>Ba</td>
<td>1306.8</td>
<td>105.0</td>
</tr>
<tr>
<td>La</td>
<td>15.90</td>
<td>105.0</td>
</tr>
<tr>
<td>Ce</td>
<td>41.48</td>
<td>105.0</td>
</tr>
<tr>
<td>Pr</td>
<td>5.03</td>
<td>105.0</td>
</tr>
<tr>
<td>Nd</td>
<td>21.27</td>
<td>105.0</td>
</tr>
<tr>
<td>Sm</td>
<td>4.31</td>
<td>105.0</td>
</tr>
<tr>
<td>Eu</td>
<td>1.30</td>
<td>105.0</td>
</tr>
<tr>
<td>Gd</td>
<td>3.90</td>
<td>105.0</td>
</tr>
<tr>
<td>Tb</td>
<td>0.56</td>
<td>105.0</td>
</tr>
<tr>
<td>Dy</td>
<td>3.21</td>
<td>105.0</td>
</tr>
<tr>
<td>Ho</td>
<td>0.64</td>
<td>105.0</td>
</tr>
<tr>
<td>Er</td>
<td>1.78</td>
<td>105.0</td>
</tr>
<tr>
<td>Tm</td>
<td>0.26</td>
<td>105.0</td>
</tr>
<tr>
<td>Yb</td>
<td>1.65</td>
<td>105.0</td>
</tr>
<tr>
<td>Lu</td>
<td>0.24</td>
<td>105.0</td>
</tr>
<tr>
<td>Hf</td>
<td>3.22</td>
<td>105.0</td>
</tr>
<tr>
<td>Ta</td>
<td>0.42</td>
<td>105.0</td>
</tr>
<tr>
<td>Pb</td>
<td>4.80</td>
<td>105.0</td>
</tr>
<tr>
<td>Th</td>
<td>2.96</td>
<td>105.0</td>
</tr>
<tr>
<td>U</td>
<td>0.83</td>
<td>105.0</td>
</tr>
<tr>
<td>REE (La/Yb)nu</td>
<td>25.78</td>
<td>105.0</td>
</tr>
<tr>
<td>Sr (Sr87/Sr86)</td>
<td>0.703770-0.703853</td>
<td>0.703765-0.703853</td>
</tr>
<tr>
<td>Nd (Nd143/Nd144)</td>
<td>0.509457-0.509533</td>
<td>0.509457-0.509533</td>
</tr>
<tr>
<td>εNd(t)</td>
<td>-9.5</td>
<td>-9.5</td>
</tr>
</tbody>
</table>

LOI = Loss on ignition, Mg# = Mg2+/(Mg2+ + Fe2+) × 100, Eu/Eu* = EuN/(SmN × GdN)1/2, N = chondrite-normalized data.
6. Discussion

6.1. Alteration and crustal contamination

Basalts from different geodynamic settings have different compositions; as a result, basalts within accretionary belts hold key information for reconstructing their origin and tectonic evolution. However, after basalt erupts onto the surface or oceanic floor, post-magmatic processes affect its composition. Therefore, the effect of the alteration must be discussed before interpreting basalt geochemistry and reconstructing their geodynamic history.

The REE and primitive mantle-normalized patterns are coherent with a narrow range of absolute abundances and small or no Ce or Eu anomalies (Fig. 8). (Nb/La)PM does not correlate with the CIA (chemical index of alteration), Eu/Eu*, or loss on ignition (Fig. 11). Most samples have LOI $\leq 4.5\%$. A LOI value of 6.08% in one sample probably reflects the alteration of pyroxene by chlorite. Some Pb mobility is evident in variable troughs relative to Ce and Sr (Fig. 8). REE and HFSE provide strong evidence for low element mobility, as they are considered the least mobile elements (Winchester and Floyd, 1977; Ludden et al., 1982; Condie, 1994). Therefore, we suggest that the geochemical data provide a reliable representation of the original compositions. All the rocks have Mg# values between 0.40 and 0.59, indicating that they were not contaminated by crust. The diagenetic system of the samples is easily identified in the La–La/Sm diagram (Allegre and Minster, 1978). The La/Sm ratio of basalts is nearly constant (4.05–5.14) with, in effect, constant La content (Fig. 12a), suggesting that their petrogenesis is related to fractional crystallization. This is also consistent with the characteristics of the Zr–Zr/Sm diagram (Fig. 12b). The negative Nb anomalies in all the samples seem to reflect some crustal contamination. However, the total trace element content is rather low. The (Nb/La)PM ratios (0.3–0.5) that are greater than 0.25 do not correlate with the (Th/La)PM ratios (0.44–1.23) and La content (16.7–27.1 ppm) that is higher than 16 ppm, which differs from the typical characteristics of contaminated volcanic rocks from the Vetreny belt (Redman and Keays, 1985; Arndt and Jenner, 1986). Therefore, crustal contamination can be ruled out as a possible mechanism for
causing the observed variations in the radiogenic elements and isotopes and the correlations between elements and isotopes.

6.2. Petrogenesis of the Upper Carboniferous magnesian andesites and basalts

As mentioned above, the Well Tacan-1 magnesian andesites have high Mg# values and low initial 87Sr/86Sr (0.703770–0.703853) and positive εNd(t) values (5.2–6.3), suggesting that the samples were derived from partial melting of mantle sources. There are different opinions for the genesis of magnesian andesites. Some researchers consider them partial melts of metasomatized mantle source (Stern and Hanson, 1991; Smithies and Champion, 2000), whereas others favor interaction between mantle and melts from the subducting oceanic slab (Rapp et al., 1999; Smithies et al., 2004, 2007). Most importantly, the magnesian andesites show significant depletion in Y (18.02–18.40 ppm) and HREE (Yb = 1.58–1.65 ppm, <1.8 ppm), high Sr (663–803 ppm) and Ba (629–1305 ppm). The primitive mantle-normalized trace element patterns display positive Sr anomalies and high La/Yb (11.84–13.73) and Sr/Y (36.03–44.55) ratios. In the chondrite-normalized REE diagram (Fig. 8a), all the magnesian andesites display relatively flat patterns with negligible negative or positive Eu anomalies (Eu/Eu* = 0.97–1.01). In Sr/Y–Y diagram (Fig. 7a), all the andesites plot in the adakite field. Furthermore, the (La/Yb)N–Yb diagram (Fig. 7b) shows that they have low (La/Yb)N ratios and mainly plot in the high degree partial melting curve of 10% garnet amphibolite. These geochemical characteristics are similar to the characteristics of adakites formed by subducted young and hot ocean crust described by Defant and Drummond (1990) and of experimentally determined metasaltic and eclogitic melts (1-4.0 GPa) (Figs. 8a and 13). However, their MgO content (3.61–4.73%, >3%; Mg# = 0.53–0.59, >5), is higher than typical adakites (Defant and Drummond, 1990), indicating that the Well Tacan-1 magnesian andesites are not produced by melting of ancient lower continental crust but could have been formed by partial melting of depleted mantle metasomatized by slab melts (Shirey and Hanson, 1984; Calmus et al., 2003).

The basalt samples have low SiO2 (48.22–51.18%) and low Mg# values (40–58) (Table 2), indicating evolved compositions. This is also confirmed by the Zr/Sm–Zr fractional crystallization discrimination diagram (Fig. 12). The similar trace element patterns (Fig. 8c and d) and low initial 87Sr/86Sr and positive εNd(t) values suggest that the basalts were derived from depleted mantle source. The high Nb concentrations may result from subduction melts and fluids. The basalts have low Nb/La ratios (0.36–0.53) that are close to those found in typical island arc basalts (>0.5) but different from values found in rift settings (>0.5) (Che et al., 1996; D.L. Chen et al., 2001; Xia et al., 2004a, 2004b; Wang et al., 2006). The enrichment in LILE and LREE suggests hydrous fluid interaction with the overlying mantle wedge, as the mantle is modified by addition of materials from the subducting slab. In addition, the elevated Ba/Nb and low Ba/La ratios (Fig. 14a) suggest significant fluid enrichment at the source. Moreover, the Nb/Zr versus Th/Zr diagram (Fig. 14b) suggests a slab-melt enrichment signature. Thus, we conclude that these basalts may have formed in a subduction-related setting and that both fluids and slab melts were involved in their petrogenesis. Note that two (K24-7, K24-8) of the basalts are similar to calc-alkaline Nb-enriched basalts. Generally, two alternative mantle sources for Nb-enriched basalts have been proposed: (1) an OIB mantle or enriched mantle component in the mantle wedge (Castillo et al., 1999; Calmus et al., 2003).
TDM values calculated using present-day (147Sm/144Nd)DM = 0.2137 and (143Nd/144Nd)DM = 0.51315.

Wang et al., 2007; Niu et al., 2009; Mao et al., 2012). The symbols are the same as Xinjiang Nb-enriched basalt from Defant et al. (1992). (b) Nb/La ε87Rb/86Sr and 147Sm/144Nd ratios calculated using Rb, Sr, Sm and Nd contents, measured by ICP-MS.

Whole rock Sr Table 3

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rock</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>87Rb/86Sr</th>
<th>87Sr/86Sr</th>
<th>2ε</th>
<th>147Sm/144Nd</th>
<th>143Nd/144Nd</th>
<th>2ε</th>
<th>εNd(t)</th>
<th>TDM (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K24-4</td>
<td>Andesite</td>
<td>43.2</td>
<td>663</td>
<td>0.188401</td>
<td>0.704615</td>
<td>11</td>
<td>0.703770</td>
<td>4.31</td>
<td>21.3</td>
<td>0.122469</td>
<td>0.512752</td>
</tr>
<tr>
<td>K24-6</td>
<td>Andesite</td>
<td>34.7</td>
<td>803</td>
<td>0.124888</td>
<td>0.704413</td>
<td>9</td>
<td>0.703853</td>
<td>4.21</td>
<td>21.0</td>
<td>0.120952</td>
<td>0.512805</td>
</tr>
<tr>
<td>K24-7</td>
<td>Basalt</td>
<td>5.04</td>
<td>1032</td>
<td>0.014121</td>
<td>0.703892</td>
<td>9</td>
<td>0.703829</td>
<td>6.28</td>
<td>30.9</td>
<td>0.122693</td>
<td>0.512843</td>
</tr>
<tr>
<td>K24-8</td>
<td>Basalt</td>
<td>17.3</td>
<td>968</td>
<td>0.051652</td>
<td>0.704044</td>
<td>8</td>
<td>0.703812</td>
<td>6.44</td>
<td>31.8</td>
<td>0.122408</td>
<td>0.512785</td>
</tr>
<tr>
<td>K24-9</td>
<td>Basalt</td>
<td>3.93</td>
<td>363</td>
<td>0.031442</td>
<td>0.703953</td>
<td>14</td>
<td>0.703812</td>
<td>5.93</td>
<td>28.6</td>
<td>0.125301</td>
<td>0.512841</td>
</tr>
<tr>
<td>K24-11</td>
<td>Basalt</td>
<td>2.40</td>
<td>301</td>
<td>0.023093</td>
<td>0.703918</td>
<td>11</td>
<td>0.703814</td>
<td>6.22</td>
<td>30.2</td>
<td>0.124267</td>
<td>0.512843</td>
</tr>
<tr>
<td>K24-12</td>
<td>Basalt</td>
<td>9.78</td>
<td>956</td>
<td>0.029586</td>
<td>0.703920</td>
<td>11</td>
<td>0.703787</td>
<td>6.70</td>
<td>32.5</td>
<td>0.124720</td>
<td>0.512840</td>
</tr>
<tr>
<td>K24-13</td>
<td>Basalt</td>
<td>55.3</td>
<td>590</td>
<td>0.271108</td>
<td>0.704880</td>
<td>13</td>
<td>0.703765</td>
<td>5.18</td>
<td>25.3</td>
<td>0.123880</td>
<td>0.512829</td>
</tr>
</tbody>
</table>

Fig. 9. (a) TiO2–P2O5 diagram. The arc volcanic rock and Nb-enriched arc basalt fields are from Defant et al. (1992). (b) Nb/La–MgO diagram (Kepezhinskas et al., 1996). The island arc basalt and Nb-enriched basalt fields are from Kepezhinskas et al. (1996). The northern Xinjiang Nb-enriched basalt field is constructed using published data (Zhang et al., 2003, 2004; Wang et al., 2007; Niu et al., 2009; Mao et al., 2012). The symbols are the same as those in Fig. 6.

Aguillón-Robles et al., 2001; Bourdon et al., 2002; Smithies et al., 2005). The low Nb/U and Ce/Pb ratios in the studied samples show that these Nb-enriched basalts differ from those in OIB (Nb/U = 48; Ce/Pb = 25), eliminating the probability of deriving from an OIB mantle. The high Th/Nb ratios (0.10–0.19) are similar to ratios found in EMII-type OIB (Stern et al., 2006) and may be related to the partial melting of sediments above the subducted oceanic crust (Turner et al., 1997). In fact, we consider that the above mentioned mantle source probably played a more important role than source (1) in the petrogenesis of these Nb-enriched basalts because the basalts have a close spatial and temporal association with adakites. Such basalts are thought to derive from the melting of mantle wedge peridotite, which was also previously metasomatized by adakite (Defant et al., 1992; Defant and Drummond, 1993; Sajona et al., 1993, 1996; Kepezhinskas et al., 1996; Aguillón-Robles et al., 2001; Prouteau et al., 2001; Defant et al., 2002; Wang et al., 2007). In addition, the basalts of Well Tacan-1 have similar 87Sr/86Sr values (0.703765–0.703829) and higher εNd(t) values (5.9–6.9) compared to magnesian adesites with some adakitic geochemical characteristics but slightly lower than those early Carboniferous basalts (Defant et al., 1991; Yogodzinski et al., 1995; Sajona et al., 1996; Yogodzinski et al., 2001; Tsutami and Hanyu, 2003). The association of magnesian adesites and basalts is attributed to (1) adakite liquids from slab melting during subduction of young oceanic crust (Defant et al., 1992; Sajona et al., 1996; Aguillón-Robles et al., 2001; Defant et al., 2002; Wang et al., 2007); (2) the reaction of such liquids with the mantle wedge peridotites, resulting in magnesian magmas; and (3) partial melting of mantle wedge peridotite that is metasomatized by adakitic material and subduction fluids generated Nb-enriched and other basaltic magma, respectively (Kepezhinskas et al., 1996).

6.3. Closure mechanism of the Balkhash–Western Junggar remnant ocean

The Kazakhstan orocline is a horseshoe-shaped belt around the Balkhash–Western Junggar remnant ocean, with northern (Chingiz) and southern (North Tianshan) Devonian and late Paleozoic volcanic arcs (Fig. 1b). This orocline played an important role in the closure history of the Balkhash-West Junggar remnant ocean. Large-scale rotations of its northern and southern limbs occurred after Late Devonian because of the compressive stresses exerted by the convergence of the Baltic, Tarim, and Siberia cratons (Zoneshina et al., 1990; Van der Voo, 2004). The rotations have been documented by increasing amounts of paleomagnetic data from both segments of the orocline (Collins et al., 2003; Abrajevitch et al., 2007, 2008; Levashova et al., 2007). To the north, the Saur and Irtysh accretionary complex were generated during the final extinction of the Irtyskh–Zaysan Ocean by its south-dipping subduction (Fig. 1b) (Buslov et al., 2001, 2004; Windley et al., 2007; Vladimirov et al., 2008; Han et al., 2010), which was confined to the Late Carboniferous (Zhou et al., 2008; Kuibida et al., 2009; Chen et al., 2010), indicating that the interaction between the Kazakhstan orocline and the Siberian craton continued into the Late Carboniferous. To the south, although arc–continent collision was mentioned by Abrajevitch et al. (2008), the northward subduction of the South Tianshan Ocean still took place during the Carboniferous, based on ultrahigh-pressure and high-pressure metamorphism (Gao et al., 1994, 1995, 1998; Gao and Klemd, 2000). Some Late Carboniferous to Permian ages of the ultrahigh-pressure metamorphic rocks in SW Tianshan (Zhang et al., 2007) and the Late Permian radiolarian fossils in the accretionary complex along the South Tianshan (Li et al., 2005) indicate that the subduction likely continued to Permian. Although controversial, the closure of the South Tianshan Ocean has been proposed to be either in the Carboniferous based on Carboniferous peak
metamorphic age of high-pressure rocks (Gao et al., 1994; Han et al., 2010) or even in the Permian based on the facts of Carboniferous to Permian ages of the ultrahigh-pressure metamorphic rocks and the Late Permian radiolarian fossils in the accretionary complex in South Tianshan (Xiao et al., 2013). These facts suggest that external compressive stress, resulting from the motion of the converging Siberia and Tarim cratons, is an important mechanism involved in the Kazakhstan oroclinal bending and the closure of the Carboniferous Balkhash–West Junggar remnant ocean.

As the basin is filled with clastic components generated by the uplift and denudation of the surrounding orogenic belt, a number of volcanic rocks and volcaniclastic rocks also entered the Balkhash–West Junggar remnant ocean basin. This feature requires its own geodynamic mechanism. Carboniferous strata outcropping in western Junggar is mainly dominated by volcanic–sedimentary rocks, such as tuff, tuffaceous sandstone, siltstone and chert, intercalated with mafic and intermediate lavas. Recently, the U–Pb age of tuff from the Carboniferous Tailegula and Baogutu Formations in the southern western Junggar terrane was estimated between 328 and 342 Ma (Wang and Zhu, 2007; An and Zhu, 2009). Furthermore, calc-alkaline rocks with adakitic affinities were described and their formation was attributed to slab melting and

![Fig. 10. Plots of εNd(t) values versus initial 87Sr/86Sr ratio (a) and the age of the volcanic rocks (b) from Well Tacan-1 compared with the western Junggar ophiolites and Carboniferous volcanic rocks in the western Junggar region. Subducted oceanic crust derived adakites and thickened and delaminated mafic lower crust derived adakitic rocks are after Wang et al. (2006), Huang et al. (2008) and references therein. Subducted continental crust derived adakites are after Wang et al. (2008). The Hata basalt are from Tang et al. (2012b), the Baogutu adakites are from Tang et al. (2010), the Early Carboniferous normal arc-type volcanic rocks are from Geng et al. (2011); and the western Junggar granitoids are from Chen and Arakawa (2005) and Geng et al. (2009). Data for the Cambrian–Ordovician ophiolites are from Zhang and Huang (1992) and the enriched mantle EMI and EMII members (Hart, 1988) are shown for comparison.](Fig_10.png)

![Fig. 11. (Nb/La)PM versus loss on ignition (LOI), chemical index of alteration (CIA) and Eu/Eu* (Nesbitt and Young, 1982) for the volcanic rocks, indicating that the Nb–La inter-element ratios do not correlate with alteration and metamorphism. The dashed lines are primitive mantle ratios from Sun and McDoungohg (1989) (CIA = Al2O3/(CaO + Na2O + K2O + Al2O3)).](Fig_11.png)

![Fig. 12. (a) La–La/Sm diagram and (b) Zr–Zr/Sm diagram for the andesite and basalt samples from Well Tacan-1. Data in panels (a) and (b) are after Allegre and Minster, 1978.](Fig_12.png)
ridge subduction (Geng et al., 2009; Zhang et al., 2011a). The Late Carboniferous magmatic suites consisting of A-type and I-type plutons may have resulted either from the post-collisional environment (Chen and Arakawa, 2005; Han et al., 2006; Su et al., 2006) or from the subduction-dominated regime (Zhang et al., 2006; Xiao et al., 2009). It is difficult to constrain their formation in the Late Carboniferous tectonic setting because of the lack of complete and accurate successions in the Late Carboniferous stratigraphic data.

Our petrogenesis analysis shows that the Well Tacan-1 basalts and andesites were generated by partial melting of mantle wedge peridotites, which were previously metasomatized by adakites, showing that hot oceanic crustal subduction and slab melting were important crustal growth mechanisms in the CAOB (Geng et al., 2009; Tang et al., 2009; Yin et al., 2010). The basalts and andesites were confirmed as being Late Carboniferous, indicating that oceanic slab subduction and melting still occurred in the Tacheng area in the Late Carboniferous. On the Y/15-La/10-Nb/8 (Cabani and Lecolle, 1989) and Ti/100-Zr/Y*3 (Pearce and Mei, 1990) diagrams, all the samples fall into the calc-alkaline basalt field (Fig. 15a, d) and this is supported by the Hf/3-Th-Ta discrimination diagrams (Fig. 15c) (Wood, 1980; Wood et al., 1981). These characteristics, in combination with the compressive structural deformation from the seismic profile mentioned above and regional geology (Xiao et al., 2008; Zhang et al., 2011b), support the conclusion for a subduction-related tectonic setting for the Tacheng area in the Late Carboniferous.

Therefore, the andesites and basalts from Well Tacan-1 in the Tacheng Basin suggest that the subduction-related tectonic environment in the Late Carboniferous was an important closure mechanism of the Balkhash–West Junggar remnant ocean. Based on the accumulation of Permian coarse red sandstones and conglomerates in the field (Feng et al., 1989; Allen et al., 1995; Jin and Li, 1999; Buckman and Aitchison, 2004) and the unconformity between Carboniferous and Permian in the basin, the continuous subduction in western Junggar probably ended before the Early Permian (Choulet et al., 2012).

6.4. The sedimentary filling and closure process for the Balkhash–Western Junggar remnant ocean

The study of western Junggar accretionary processes requires understanding the relation between the convergent setting and the tectonic–sedimentary evolution of the Balkhash–West Junggar remnant ocean basin. The sedimentary filling and closure history of the Balkhash–West Junggar remnant ocean basin involved contributions from subduction and accretion, recorded in the strata of Well Tacan-1. The Carboniferous strata of Well Tacan-1 at the Southern Depression of the Tacheng Basin record moderate–high magnetic anomalies, similar to the magnetic anomaly characteristics of volcanic rocks on both sides of the Darbut suture zone and the intermediate–basaltic volcanic rocks in the Luliang area in the north of Junggar Basin (L. Zhou et al., 2006). The distribution and lithologic features of these volcanic rocks also match the Carboniferous volcanic rocks that outcrop in southern West Junggar. In the 2D seismic profiles of the Tacheng area, the faults can be clearly distinguished by the seismic reflector wave cut-offs (Fig. 16). The seismic interpretation reveals two groups of faults. The first cuts the Upper Carboniferous and has westward-verging thrust imbricates with growth strata in the eastern area of the Tacheng Basin, whereas the second cuts the Mesozoic to Cenozoic and shows eastward-verging thrust imbricates in the western area of the Tacheng
Data in panel (a) is after Cabanis and Lecolle, 1989, panel (b) after Pearce and Mei, 1990, and panel (c) after Wood, 1980; Wood et al., 1981.

MORB; 3C partitioning during oblique subduction (Choulet et al., 2012).

The geometry characteristics and growth strata suggest that these westward-thrust faults caused Late Carboniferous deformation in the hanging wall layers. In addition, several faults in the central segment of the Tacheng Basin have steep dip angles (80°–90°), similar to the Darbut strike-slip fault, which developed in response to the strain partitioning during oblique subduction (Choulet et al., 2012).

Considering the strata drilled in Well Tacan-1 (Fig. 3), we divide the Carboniferous–Early Permian strata that filled the Tacheng Basin into two tectonostratigraphic units (Fig. 16), because of the lithological combinations and unconformity between the Carboniferous and Lower Permian. The first one (Carboniferous tectonostratigraphic–T1) includes 29 periods of volcanic activity with tuff and tuffite intercalated with minor mudstone, sandstone and conglomerates. However, the Early and Late Carboniferous exhibit significant differences in the rock associations. The Early Carboniferous strata consist of tuff, sandstone and mudstone with minor andesite and basalt. The regionally distributing sandstone and interbedded mudstone were deposited as turbidites during the early ‘starved’ stages in the basin and the thinness of the marine sedimentary fill attests to the tectonic instability of the basin and the occurrence of re-sedimentation processes (Jin and Li, 1999). There were multiple periods of sedimentary intermission, during which thin gray–black mudstone formed. The abundance of tuff and arc-related lavas in the basin fill indicates that there was volcanism nearby. Furthermore, the early Carboniferous strata preserved within the basin are similar to those on both sides of Darbut, indicating a deep-sea environment (Li and Jin, 1989; Jin and Li, 1999; Guo et al., 2002). Moreover, at the eastern side of the Tacheng Basin, the geochemical characteristics of the 328 Ma Baobei volcanic rocks and some 321 Ma magnesian diorite dikes with high Sr/Y ratio indicate that they formed in an oceanic island arc setting in the Late Carboniferous (Zhu and Feng, 1994; Wang and Sun, 2005; Yin et al., 2010). Nearly all the Late Carboniferous strata consist of basalt, andesite and tuff, except for minor mixed marine and non-marine deposits in the upper parts. The identification of Late Carboniferous magnesian andesites and basalt supports an island arc tectonic setting in the Late Carboniferous. This is consistent with the recent conclusions regarding the NW-directed subduction in western Junggar (Geng et al., 2009; Tang et al., 2009; Yang et al., 2012). The occurrences of the Late Carboniferous adakite, Nb-enriched basalt and charnockites suggest that the western Junggar accretionary complex is formed by north-westward subduction in the Late Carboniferous. Although the north-westward subduction for the western Junggar arc was established in the modern Darbut area (Geng et al., 2009; Liu et al., 2009; Tang et al., 2009), this was a relatively mature island arc with adakitic magmatism during the Late Carboniferous, whereas intra-oceanic normal subduction still occurred in the Tacheng area. Thus, we suggest that the abundant tuff and interbedded lavas in the Tacheng area were generated from another subduction system and the minor mudstone deposits indicate a shallow sea sedimentary sequence in the Late Carboniferous. The decreasing volcanic activity and the transition from marine to non-marine facies indicate that the remnant ocean basin was shrinking during the Late Carboniferous. The obvious unconformity between Carboniferous and Early Permian was tided from Well Tacan-1 to seismic data. The Early Permian molasses locally overly the western Junggar accretionary complex (Jin and Li, 1999) and are preserved in the northern Paleozoic Saur volcanic arc (Chen et al., 2010). In addition, the Late Carboniferous–Middle Permian stitching plutons crosscut all of the western Junggar and the adjacent Kazakhstan tectonic units with several mélangé belts (e.g. Karamay mélangé, Darbut ophiolitic mélangé, Barlek mélangé and Irtys–Zaysan ophiolitic mélangé). All these data indicate that the closure of the Balkhash–West Junggar remnant ocean most likely occurred in Early Permian and got into intracontinental evolution. The Early Permian strata of Well Tacan-1 only contain three periods of volcanic activity with mainly basalt, andesite, tuffite and terrigenous buff sand conglomerates, sandstone and mudstone, which represent the sedimentary response to the closure of remnant ocean. Moreover, the Early Permian strata become progressively thicker toward the west, suggesting that the Early Permian source was from the N/NW of the basin. This was also controlled by the uplift of the western part of the Tacheng Basin, resulting from an Early Permian NW-oriented thrust fault (Fig. 16). Depth conversion of the seismic profile AA’ was performed using the averaged interval velocity for the stratigraphic restoration calculation shown in Fig. 17. A balanced cross-section is a structural cross-section that is consistent with and can be restored to its pre-deformation state (Dahlstrom, 1969; Woodward et al., 1989). During the Carboniferous, the Tacheng region was undergoing EW shortening and the amount of shortening is approximately 3.9 km on the profile AA’ (Fig. 17). The Carboniferous strata were shortened by approximately 0.8 km between the Jurassic and the present (Fig. 17). In contrast, the closure of the Balkhash remnant ocean most likely occurred in the Early Carboniferous and earlier than that of the western Junggar remnant ocean, because the Early Carboniferous siliceous rocks that contain Ordovician conodonts in western Junggar are found in the Silurian strata of the Balkhash region (Fig. 18). In addition, the Devonian strata in northern Balkhash and Bakanas–Alakol of East Kazakhstan represent a very thick flysch consisting of interbedded sandstone and siltstone with some limestone. The depositional characteristics are similar to those of the Carboniferous western Junggar remnant ocean. Moreover, non-marine unconformities
occurred from Devonian to Carboniferous in the Kazakhstan area, whereas they took place in Late Carboniferous to Early Permian in the western Junggar region. This is further confirmed by the similar rock associations between the Upper Carboniferous in the Tacheng area and the Lower Carboniferous in the Balkhash area (Fig. 18). These features indicate that the Balkhash–West Junggar remnant ocean experienced a scissors-type closure from Balkhash to western Junggar since the Early Carboniferous. However, the existence of dolomite in the boreholes suggests that the western margin of the Junggar Basin was a shallow sea sedimentary environment in the Late Carboniferous.

Based on the above discussion regarding the tectonic setting and tectonic–sedimentary evolution, a fill model for the Balkhash–West Junggar remnant ocean basin was proposed since Carboniferous in western Junggar (Fig. 19). During the Early Carboniferous (Fig. 19a), the western Junggar region was in a subduction-related tectonic setting and some deep-sea facies volcano-originated sediments filled in the remnant ocean basin. With the shrinking of the ocean basin, strong thrusting at the southeast of the ocean basin resulted in uplifts at the basin boundary and the shallow-sea facies volcaniclastic rocks with minor non-marine sediments from the southeast of the ocean filled the basin (Fig. 19b). By the Early Permian, the sedimentary environment had changed to terrigenous facies with detritus from the north of the basin (Fig. 19c). At the eastern margin of the remnant ocean basin, the Early Permian strata overlap the Carboniferous strata, indicating the end of the filling of the remnant ocean basin. At the western end of profile AA', the Carboniferous strata are thinner toward the west, unlike the Early Permian and Meso–Cenozoic. This may reflect multi-stage thrusting or re-activation of previous thrust faults. The amalgamation of island
Fig. 17. Balanced cross section and structural–stratigraphic restoration of seismic profile AA' since the Early Carboniferous (the position of seismic profile AA' is shown in Fig. 1c).
arcs and accretionary complexes, combined with sedimentary filling, led to the closure of the Balkhash–West Junggar remnant ocean and finally formed the basement of the Meso-Cenozoic Tacheng Basin.

7. Conclusions

Using geochronological and whole-rock geochemical data, tectonostratigraphic unit analysis and a range of technologies and methods on volcanic rocks from Well Tacan-1 in the Tacheng Basin, we concluded the following:

(1) Zircon U-Pb analysis of the underlying tuff suggests that the andesite and basalt from Well Tacan-1 formed in the Late Carboniferous and at ca. 315 Ma in the Tacheng area.

(2) The petrological data indicate that the andesites are similar to magnesian andesites with some adakitic geochemical characteristics and several of the basalt samples belong to Nb-enriched basalts. These volcanic rocks were derived from a metasomatized depleted mantle source in an island arc setting.

(3) The Carboniferous sedimentary fill of the Balkhash–West Junggar remnant ocean basin can be divided into two stages. Early Carboniferous deep marine sediments covered the western Junggar region, whereas the late Carboniferous sediments that filled the basin were dominated by shallow marine sediments. This sedimentary fill model resulted from accretionary processes and was a response to Carboniferous arc-related tectonic evolution.

(4) The unconformity between the Carboniferous and Lower Permian divides the Carboniferous–Early Permian strata into two tectonostratigraphic units. The Early Permian overlap on the Carboniferous strata and the transition from the Carboniferous marine to Early Permian terrigenous facies show that the Balkhash–Western Junggar remnant ocean basin closed during the Early Permian.

Acknowledgments

We are very grateful to the Editor-in-Chief Prof. M. Santosh for his constructive comments that significantly improved the original manuscript. We acknowledge Dr. Richard Glen, two anonymous referees and the Associate Editor Prof. Wenjiao Xiao for their critical and constructive comments. Xinjiang Oilfield Company kindly supplied drill core samples and part of the PSA data for the Carboniferous strata of the Tacheng Basin. We wish to thank Dr. Yuting Cao and Kaiyun Chen at Northwest University who helped us with the LA-ICP-MS zircon U-Pb analyses and Dr. Chaofeng Li and Qiannan Li for their help in carrying out the Sr–Nd isotopic analysis at the Institute of Geology and Geophysics, Chinese Academy of Sciences. This research was financially supported by the National Science and Technology Major Project (2011ZX05008-001, 2011ZX05002-...
002), the National Natural Science Foundation of China (41272237, 40739906) and the Chinese State 973 Project (2011CB201100).

References


Please cite this article as: Li, D., et al., How was the Carboniferous Balkhash–West Junggar remnant ocean filled and closed? Insights from the Well Tacan-1 strata in the Tacheng Basin, NW China, Gondwana Research (2013), http://dx.doi.org/10.1016/j.gr.2013.10.003


Xiao, W.J., Han, C.M., Yuan, C., Sun, M., Lin, S.F., Chen, H.L., Li, Z.L., Li, J.L., Sun, S., 2008. Mid-
Xiao, W.J., Han, C.M., Sun, S., Li, J.L., 2010. A review of the western part of the
Xiao, W.J., Windley, B.F., Yuan, C., Sun, M., Han, C.M., Lin, S.F., Chen, H.L., Yan, Q.R., Liu, D.Y.,
Please cite this article as: Li, D., et al., How was the Carboniferous Balkhash–West Junggar remnant ocean filled and closed? Insights from the West Tacent–1 strata in the Tacheng Basin, NW China, Gondwana Research (2013), http://dx.doi.org/10.1016/j.gr.2013.10.003