

Distant effects of India–Eurasia convergence and Mesozoic intracontinental deformation in Central Asia: Constraints from apatite fission-track thermochronology

Johan De Grave ^{a,b,*}, Michael M. Buslov ^c, Peter Van den haute ^b

^a Department of Geological and Environmental Sciences, Stanford University, Stanford, USA

^b Department of Mineralogy and Petrology, Geological Institute, University of Gent, 281/S8 Krijgslaan, B-9000 Gent, Belgium

^c United Institute of Geology, Geophysics and Mineralogy, Siberian Branch of the Russian Academy of Science, Novosibirsk, Russia

Received 17 January 2005; accepted 2 March 2006

Abstract

During the Mesozoic, the active southern margin of Eurasia was the site of several accretion and collision events that fit into a framework of convergence between Eurasia and advancing (peri-) Gondwanan units. Far-field effects of the Mesozoic Mongol–Okhotsk and Cimmerian orogenies have been recorded deep within the interior of Eurasia. Convergence finally culminated in the massive India–Eurasia continent–continent collision in the Early Cenozoic. This collision, continued convergence between both continents, and resulting ongoing indentation of India into Eurasia have dominated the geological, tectonic and geodynamic evolution of Eurasia. Amongst others, distant effects of these events have reactivated an array of mobile belts in Central Asia. Apatite fission-track dating and thermal history modeling performed on samples from the Kyrgyz Tien Shan and Siberian Altai Mountains record both Mesozoic deformation and Cenozoic reactivation of intracontinental Eurasia. The onset of the building and growth of the modern Tien Shan and Altai orogens is constrained to the Late Miocene and Pliocene, with a likely trend of activity younger towards the north. This would underscore the general model that deformation related to India–Eurasia convergence was progressively propagated northwards through Central Asia via the inherited structural fabric of the Eurasian crust.

© 2007 Published by Elsevier Ltd.

Keywords: India–Eurasia convergence; Central Asia; Tectonic reactivation; Apatite fission-track thermogeochronology; Mesozoic–Cenozoic

1. Introduction and location

In Central Asia, north of the India–Eurasia collision zone (north of the Tibetan Plateau), a vast array of active intracontinental mountain belts extends deep into the interior of the Eurasian continent (Fig. 1A): this is the Central Asian Deformation Zone (CADZ) or the Central Asian orogenic belt. In Russian literature the CADZ is often labeled as the Ural–Mongolian Fold Belt, while Sengör et al. (1993) refer to it as the Altaids. The CADZ stretches for over 5000 km, comprising the Tien Shan Mountains in

the south, across the Altai–Sayan Mountains, all the way northeast to the Baikal rift zone at the rim of the stable Siberian craton, making it the world's largest intracontinental orogenic system. A continuously growing data set of active tectonic and seismic information also designates it as one of the world's most active intracontinental orogenic systems.

The CADZ crust was largely formed in the Paleozoic and Mesozoic during several accretion events, while the modern CADZ reactivation is attributed to the Cenozoic India–Eurasia collision, and to ongoing indentation of India into Eurasia (Molnar and Tapponnier, 1975, 1977; Tapponnier and Molnar, 1979; Peltzer and Tapponnier, 1988). India–Eurasia collision and continued convergence dominated much of Asia's Cenozoic geological, tectonic,

* Corresponding author. Tel.: +32 9 264 4564; fax: +32 9 264 4984.
E-mail addresses: Johan.Degrave@UGent.be, jdegrave@pangea.stanford.edu (J. De Grave).

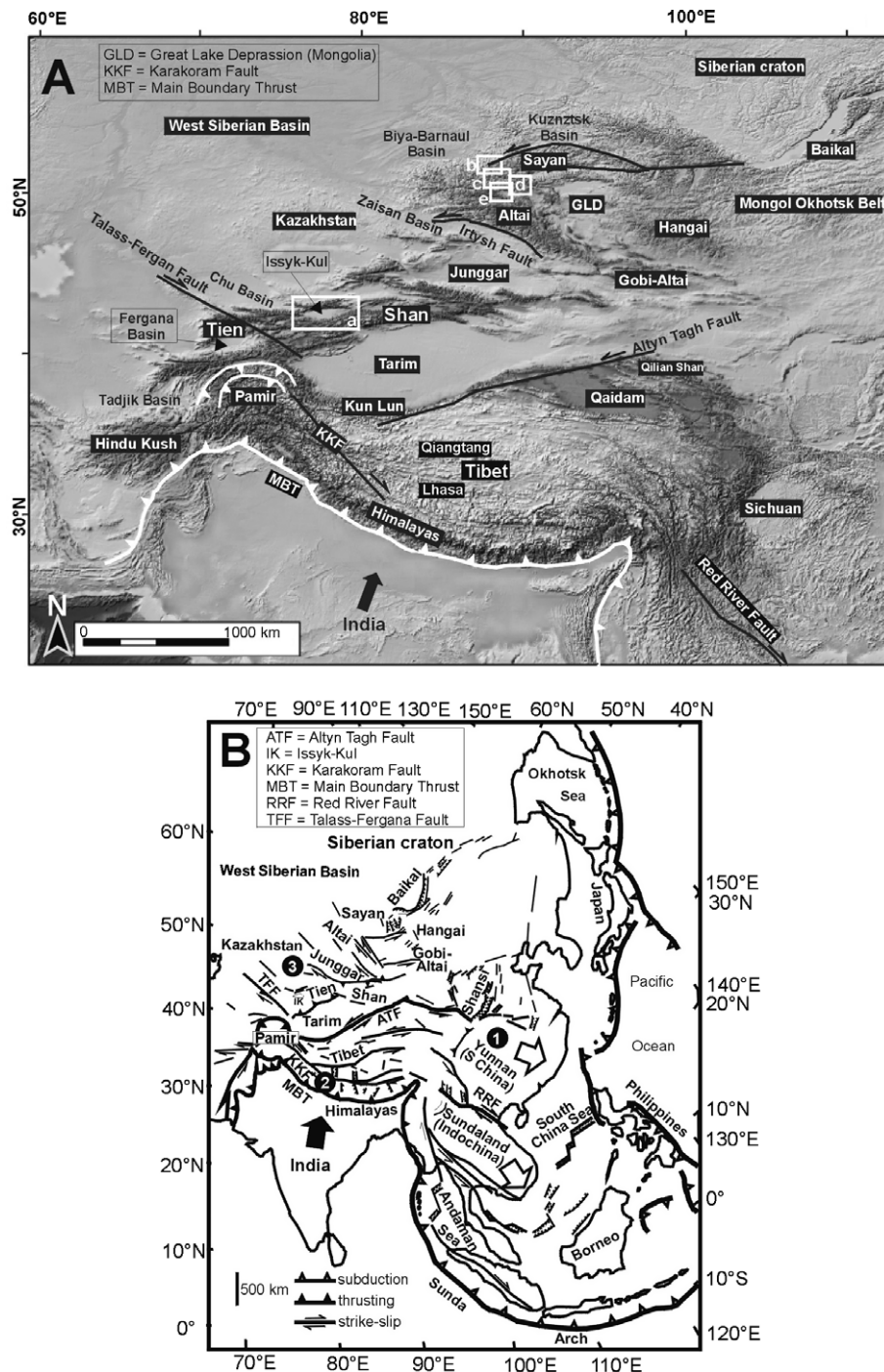


Fig. 1. (A) Map of Central Asia with location of the intracontinental Central Asian Deformation Zone (CADZ) north of the Himalayas and the Tibetan Plateau. Sample localities: (a) Issyk Kul Lake area, (b) Teletskoye Graben area, (c) Chulyshman Plateau, (d) Dzhulukul Basin area, and (e) Chuya–Kurai Basin area. (B) Simplified map of large-scale Cenozoic structures in Asia as a result of India–Eurasia convergence (after Peltzer and Tapponnier, 1988): (1) Lateral extrusion or escape tectonics, (2) Crustal thickening (uplift and fold-and-thrust tectonics), and (3) Intracontinental reactivation of the CADZ.

geodynamic and even climatic evolution in various ways. The tectonic effects of the collision and convergence are grouped in three categories: (1) lateral extrusion, (2) crustal thickening and (3) intracontinental reactivation (Fig. 1B):

(1) Indentation of India into Eurasia has squeezed out large lithospheric segments along long-lived, vast strike-slip fault zones (e.g., Red River–Ailao Shan, Altyn Tagh) (e.g., Yue and Liou, 1999; Yin and Harrison, 2000; Yin et al.,

2002; Ritts et al., 2004). This lateral extrusion or escape tectonics is directed mainly eastwards, to the less constraining Pacific plate boundary as opposed to the more rigid interior of the Eurasian continent to the west. These strike-slip faults show active movements, however peak activity occurred largely in the Late Eocene – Early Miocene (e.g., Yue and Liou, 1999; Yin and Harrison, 2000; Morley, 2001; Yin et al., 2002; Ritts et al., 2004).

(2) Another accommodation aspect of India–Eurasia convergence is crustal thickening in the collision zone. This includes thrust-and-fold tectonics in the Himalaya and mountain belts north of Tibet (Kun Lun, for example). This also includes uplift of the Tibetan Plateau itself, notwithstanding that the exact mechanisms driving the latter are still an area of debate (e.g., Harrison et al., 1992; Molnar et al., 1993; Fielding, 1996; Chung et al., 1998; Yin and Harrison, 2000; Tapponnier et al., 2001; Zhisheng et al., 2001). Crustal thickening has been a major effect of India–Eurasia convergence since the Late Oligocene – Early Miocene (e.g., Yin and Harrison, 2000, and references therein).

(3) Since the Late Miocene and Pliocene, continued strain and stress build-up has been partly partitioned by propagation northward to Eurasia's interior along pre-existing zones of weakness in the lithosphere. These correspond to older sutures and structures inherited from earlier collision and accretion events. In this manner deformation along these zones has been responsible for the reactivation and building of the modern intracontinental mountain belts in the CADZ (Molnar and Tapponnier, 1975, 1977; Tapponnier and Molnar, 1979; Peltzer and Tapponnier, 1988; Dobretsov et al., 1996).

In order to reconstruct the thermotectonic evolution of the CADZ, in particular, with respect to Mesozoic–Cenozoic reactivation, we performed an apatite fission-track (AFT) study, including thermal history modeling, on samples from various key areas of the CADZ: the Kyrgyz Tien Shan (25 samples) and the Siberian Altai Mountains (50 samples). While the specific numerical results and technical details per sampled region are discussed in detail elsewhere (De Grave and Van den

haute, 2002; De Grave, 2003), this paper uses the thermal history models to reconstruct a general trend in the thermotectonic history of the CADZ and reports on the Mesozoic deformation and Cenozoic reactivation of the CADZ from a broader perspective.

2. Geodynamical evolution and tectonic setting

2.1. Paleozoic

The CADZ basement was formed during the Paleozoic evolution of the Paleo-Asian Ocean (PAO) that extended amid Mesoproterozoic and older continental blocks (Baltica, Siberia, Tarim, Kazakhstan and North China) in the Early Neoproterozoic–Middle Paleozoic (Dobretsov et al., 1995; Khain et al., 2003). The PAO evolution marks an important phase in the formation, accretion and growth of Eurasia, leading to the present-day, complex blocky-mosaic architecture of the CADZ (Sengör et al., 1993).

2.1.1. Tien Shan region

Branches of the PAO (North and South Tien Shan Ocean or Turkestan Ocean) stretched between southern Kazakhstan and the Tarim Plate. Two distinct Late Paleozoic (Late Devonian–Early Permian) ophiolite-bearing sutures are recognized in the Tien Shan Paleozoic basement (microcontinental and oceanic type domains), dividing it into three units that strike roughly longitudinally (Fig. 2a): the South, Central and North Tien Shan (STS, CTS, NTS) (Allen et al., 1992; Carroll et al., 1995; Chen et al., 1999).

In the western, or Kyrgyz Tien Shan, the CTS is directly truncated to the north by the relatively undeformed

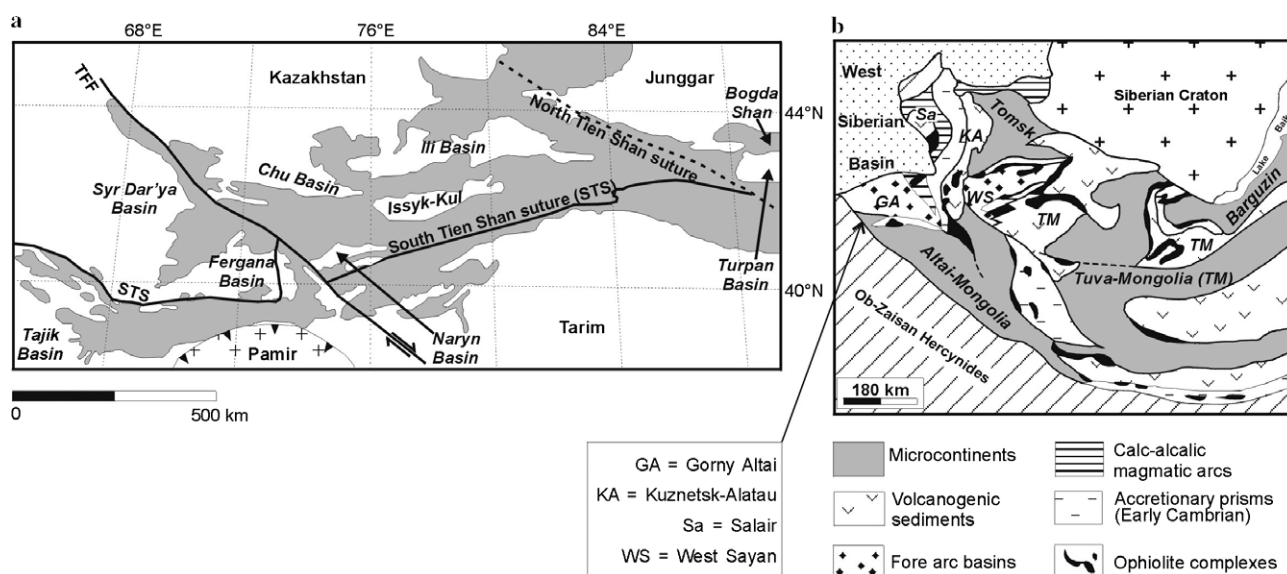


Fig. 2. (a) Paleozoic sutures in the Tien Shan Mountains. The sutures, displaced by the Talas-Fergana fault (TFF), delineate the North, Central and South Tien Shan domains (see text). (b) Schematic outline of the Paleozoic Altai region wedged between the Siberian craton and the amalgamated Kazakhstan plate ('Ob-Zaisan Hercynides'). Altai terrains are composed of microcontinents and accretionary prisms with volcanogenic sediments, magmatic arcs and fore- and back arc basins (after Dobretsov et al., 1996).

Kazakh Platform. The CTS block (or Ili Microcontinent) is intruded by a vast Late to Middle Paleozoic batholith that forms the basement of the Issyk–Kul intramontane basin in northern Kyrgyzstan (e.g., the Kungey and Terzkey ranges). The Tarim and Junggar basins served as foreland basins to the ancestral Tien Shan orogen, with their basin margins flexurally loaded by Tien Shan thrust sheets. By the Late Permian the entire PAO, including its Turkestan branch, had closed completely.

2.1.2. Altai region

The Paleozoic basement of the present-day Altai Mountains formed between the rigid Siberian craton (north) and the amalgamated Kazakhstan continent (south). Trapped in between are many smaller blocks of various tectonic signature (Fig. 2b). These include microcontinents (e.g., Tuva–Mongolia and Altai–Mongolia), with Precambrian basement and, ‘oceanic’ units such as fore- and back-arc basins (e.g., West Sayan block), turbidite sequences, island arcs (e.g., Gorny Altai block) and seamount arrays (Buslov et al., 2001). Main accretion stages are Ediacaran–Early Silurian and Devonian–Carboniferous (Bachtadse et al., 2000; Kravchinsky et al., 2001; Buslov et al., 2001).

Final closure of the western PAO occurred in the Early Permian when Kazakhstan collided with Siberia as part of Pangea amalgamation, and the entire mobile belt between Siberia, Baltica and Kazakhstan was subjected to large-scale strike-slip deformation (Sengör et al., 1993; Buslov et al., 2003b) shaping the CADZ basement more or less to its current form. The basement was intruded by large magma volumes, building extensive igneous complexes in the Middle and Late Paleozoic that added to the crustal growth of Eurasia (Sengör et al., 1993; Dobretsov and Vladimirov, 2001).

2.2. Mesozoic

2.2.1. Tien Shan region

The Mesozoic evolution of the Tien Shan region was dominated by the closure of various tracts of the Tethys Ocean that separated Eurasia and Gondwana. Between the Late Triassic and Early Cretaceous the southern rim of the Tarim Plate (with the ancestral Tien Shan Belt to its north) became part of the vast active southern Eurasian margin, underneath which Tethyan lithosphere was subducted (e.g., Garzanti et al., 1999; Yin and Harrison, 2000). Various smaller peri-Gondwanan blocks rifted off Gondwana, drifted northwards and converged towards Eurasia in the Early Mesozoic. These Mesozoic, Tethyan peri-Gondwanan fragments are often referred to as the Cimmerian blocks. To the west of our study area they include the tectonic blocks of Turkey, Iran and the Afghan or Farah Block, to the east the Burmese and Indochinese blocks. Directly south of Tarim, along the Jinsha, Kun Lun and Altyn Tagh sutures, there are the Tibetan blocks, Qiangtang and Lhasa, and the Pamir

and Karakoram blocks. Other tectonic units, principally oceanic domains (e.g., the Kohistan–Ladakh island arc) are wedged between these assorted blocks. Collision of the different Cimmeria blocks was diachronous and occurred between the Late Triassic and Early Cretaceous. These events are mutually called the Cimmerian or Cimmeride orogeny. Of special importance to the discussion here are the collisions of the Tibetan blocks. In the Early to Middle Jurassic the Qiangtang Block docked with Eurasia and the Tethyan subduction zone and associated volcanic arc jumped southward and finally pulled the Lhasa Block into the active margin by Late Jurassic–Early Cretaceous times along the Bangong–Nujiang suture. Continued Tethyan subduction underneath Lhasa was responsible for the formation of the Cretaceous Transhimalayan or Gangdese Batholith and eventually culminated in the India–Eurasia collision (e.g., Yin and Harrison, 2000).

The Cimmerian orogeny also affected the Eurasian hinterland, and reactivation of Paleozoic structures is recorded throughout the Tien Shan region and the Junggar–Tarim basins (Hendrix et al., 1992; Allen and Vincent, 1997; Otto, 1997; Allen et al., 2001). The ancestral Tien Shan was reactivated and formed a distinct physiographic boundary between the Junggar and Tarim basins at this time (Hendrix, 2000). The Tien Shan basement was thrust over the Junggar and Tarim basin margins and both basins accumulated thick foreland-type sediments from the eroding Tien Shan orogen.

2.2.2. Altai region

In the Mesozoic the Altai area was bordered by two active zones (Fig. 3). Firstly, to the north and northwest this is the West Siberian Basin (WSB). This enormous Meso-Cenozoic basin is located between the Ural Mountains and the Siberian craton (Fig. 1) and is characterized by active rifting during the Mesozoic (e.g., Aplonov, 1988; Surkov et al., 1997). The WSB collects continental sediments supplied by the Siberian (including the Altai) and Uralian orogens (Surkov et al., 1997). Its basement is composed of typical units that also make up the Paleozoic basement of the CADZ, and in that sense it is an integral part of these Paleozoic fold belts. Rifting in the WSB occurred during most of the Early Mesozoic and in the early phases (~250 Ma ago) it was associated with a vast province of rift basalts that have been correlated with the Siberian flood basalts (Siberian Traps) (Reichow et al., 2002). Most of the WSB rifts evolved and became extinct, entirely in a continental setting. However, parts might have developed into a small oceanic basin with active sea-floor spreading (Aplonov, 1988). Sediments in the WSB show several transgressive marine incursions. After active rifting, the WSB subsided in a passive tectonic regime, and in the Late Cretaceous–Early Tertiary the basin was nearly completely filled with sediments. In the Middle Cenozoic basins of the Arctic Ocean opened, shifting depocenters further northwards (Surkov et al.,

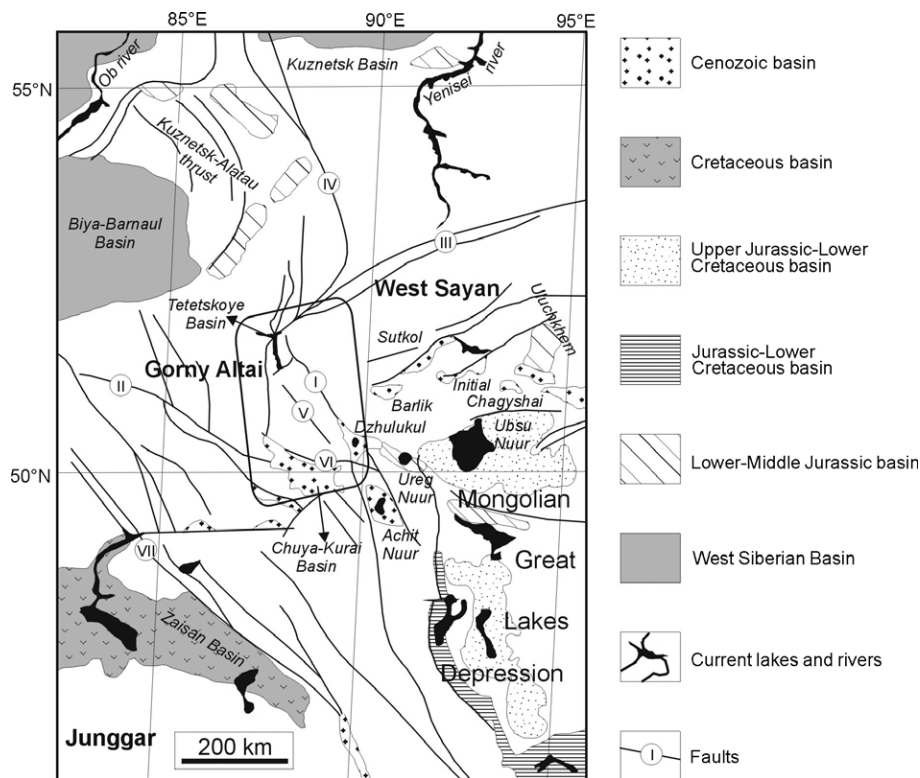


Fig. 3. Meso-Cenozoic basins within and adjacent to the Altai–Sayan region (after Dobretsov et al., 1996). Faults: I, Shapshal; II, Charysh–Terekta; III, West Sayan; IV, Kuznetsk–Alatau; V, Chulyshman; VI, Kurai; VII, Irtysh. Box indicates sample area in the Siberian Altai Mountains.

1997). These depocenters persist until the present while the WSB became a tectonically stable platform residing near sea level, with small oscillations possibly linked to Arctic Ocean spreading. WSB sub-basins border the Altai to the north: the Biya-Barnaul and Kuznetsk basins (Fig. 3), separated by a poorly understood Mesozoic thrust (Buslov et al., 2003b).

Secondly, directly east of the Altai, the Mongol–Okhotsk (MO) belt developed in the Middle to Late Jurassic–Early Cretaceous (Xu et al., 1997; Zorin, 1999; Wang et al., 2004; Liu et al., 2005). This still poorly studied orogenic belt was constructed as a result of the collision of the Siberian continent with the composite North Chinese–Mongolian continent (Sino-Korean craton). Northward subduction of the MO Ocean lithosphere that existed between both continents resulted in its oblique, west to east closure (Zorin, 1999). Because of this geometry, it is thought that initial deformation started in the western MO belt, and as convergence continued, deformation propagated eastward until final closure of the basin in the Early Cretaceous. This major continent–continent collision is thought to have constructed a Himalayan-type orogen with deformation affecting the Siberian and Mongolian hinterland (Ermikov, 1994; Zorin, 1999). Immediately after exclusively compressive tectonics, Mongolia and the Baikal region in Siberia experienced an important stage of extension and several large basins were created (e.g., Ermikov, 1994; Delvaux et al., 1995; Graham et al., 2001; Johnson, 2004).

To a lesser extent the Altai area shows signs of Mesozoic activity as well, although it is not clear how or if it is related to WSB and/or MO tectonics. Several smaller Triassic–Jurassic plutons are emplaced in the Paleozoic basement (Dobretsov and Vladimirov, 2001), while remnants of small intramontane Jurassic basins are found in several areas within the Altai orogen. These basins are filled mainly with coarse, continental, often coal-bearing, Jurassic sediments atop relict Triassic red beds. This might imply regional Jurassic denudation–sedimentation, which is also seen in the sedimentary profiles of large adjacent basins: Junggar–Zaisan Basin, southeastern tracts of the WSB (Biya-Barnaul and Kuznetsk basins, Fig. 3), and the Mongolian basins (e.g., Johnson, 2004).

2.3. Cenozoic

Continued Tethyan subduction eventually gave rise to major India–Eurasia continent–continent collision at the Meso-Cenozoic transition. This collision and ongoing convergence between both continents have dominated Asian tectonic evolution ever since, as outlined in Introduction (Fig. 1). Extrusion tectonics in SE Asia, fold-and-thrust tectonics in the Himalayan Arc and uplift of the Tibetan Plateau are a few of the principal effects of this collision. As convergence is persisting to this day, the build-up and accumulation of stress and strain has in addition been partitioned by propagating deformation northwards into the intracontinental interior of Central Asia via the regional

reactivation of the pre-existing structural fabric (Fig. 4). Our study focuses further on this aspect.

2.3.1. Tien Shan region

Continued indentation of the Indian Plate into Eurasia is partly accommodated by thrusting North Tibetan mountain ranges, such as the Kun Lun Shan and Altyn Shan, over the southern Tarim margin (e.g., Avouac et al., 1993; Abdrakhmatov et al., 1996; Yin and Harrison, 2000; Tapponnier et al., 2001). Also, as the Indian indenter penetrated further in the Eurasian lithosphere, it pushed the Tarim Plate northwards (Fig. 4). As a consequence, the southern ranges of the Tien Shan Mountains are thrust over the northern Tarim margin (Dobretsov et al., 1996; Allen et al., 1999). As thrust sheets override both the northern and southern edges of the Tarim Plate, deformation is limited mainly to distinct marginal zones, while the rigid Precambrian basement underlying the Tarim Basin, as well as its Meso-Cenozoic cover, remains relatively undeformed. In the same fashion, the Pamir Block (west of Tarim, Fig. 1) has also pushed north and Pamir thrusts have directly overridden the southwestern Tien Shan and Tajik Basin area (Coutand et al., 2002). These compressive tectonic forces and flexural loading have reactivated the entire Tien Shan mountain belt. Reactivation varies from pure compression, over transpression to pure strike-slip, e.g., Talas–Fergana strike-slip fault (Cobbold et al.,

1994; Cunningham et al., 1996; Allen et al., 2001; Buslov et al., 2003a). Subtle signs of incipient Late Cenozoic reactivation in the Tien Shan are traced to the Late Oligocene, while clear indications are dated as Miocene (Allen et al., 1994). Since the Late Miocene–Pliocene, intense tectonic activity, mountain building and climatic processes have shaped the Tien Shan landscape as it appears today (Yin et al., 1998). Late Cenozoic and ongoing activity is shown by various indicators: seismology (Lukk et al., 1995; Abdrakhmatov et al., 2002), stratigraphy (Cobbold et al., 1994; Sun et al., 2004) structure-geomorphology (Molnar et al., 1994; Burbank et al., 1999; Buslov et al., 2003a; Fu et al., 2003), geochronology (Bullen et al., 2001, 2003; Thompson et al., 2002), paleomagnetism (Dupont-Nivet et al., 2002) and geodesy (Abdrakhmatov et al., 1996).

To the north the more or less E–W trending Tien Shan mountain ranges with sub-parallel intermittent intramontane basins are bordered by the comparatively undeformed Junggar Basin (east) and the Kazakh Plate (west) (both with rigid Precambrian microcontinental basement). Pinched in between these rigid blocks and the Tarim Basin to the south, the Tien Shan forms an E–W striking pop-up or flower structure with southward dipping thrusts at the northern edge and vice versa (Fig. 4). In this way, the Junggar and Tarim Basins can be considered as Neogene flexural foreland basins of the reactivated Tien Shan orogen (Metivier and Gaudemer, 1997).

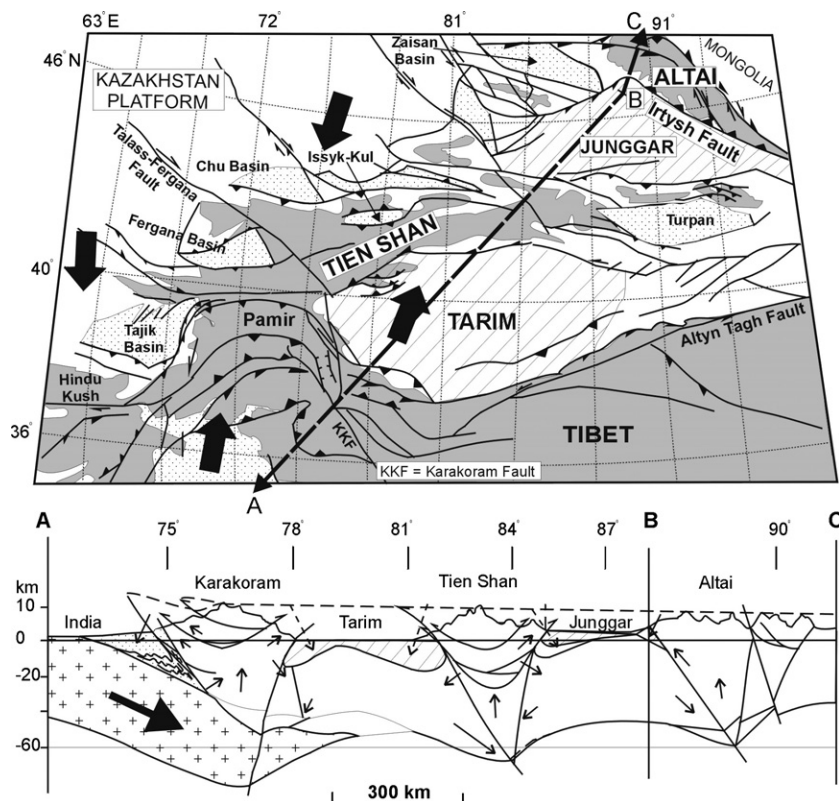


Fig. 4. Schematic map and cross section (ABC) indicating neotectonic features in Central Asia (after Buslov et al., 2003a). Thick black arrows indicate compression.

2.3.2. Altai region

Driven by analogous mechanisms, the Altai Mountains are subjected to Late Cenozoic reactivation as a response to continued indentation of India into Eurasia (Dobretsov et al., 1996), and represent an active transpressional mountain belt between the rigid Junggar and Kazakhstan basement (southwest) and Siberia and Mongolia (northeast) (Figs. 3 and 4). A current transpressional tectonic regime is demonstrated by strike-slip and thrust movements along major faults (e.g., Irtysh Fault Zone, Shapshal Fault Zone) (Cunningham et al., 1996; Buslov et al., 1999). Locally, however, recent tectonic reactivation has produced transtensional and extensional structures (e.g., the Teletskoye Graben). Late Cenozoic deformation in the Altai is evident in the Oligocene–Miocene, but the main, still active deformation is clearly constrained to the Pliocene–Quaternary. This modern deformation involves various smaller Paleozoic tectonic units and is manifested mainly along the older, inherited Paleozoic structures (Buslov et al., 1999, 2003b; Dehandschutter et al., 2002). The timing of reactivation is largely substantiated by the tectonic break-up of a ubiquitous Late Cretaceous–Paleogene peneplanation surface and by the Neogene sediments in adjacent and intramontane basins (Fig. 3). In the Late Neogene and Quaternary, neotectonic activity intensified as demonstrated by deposition of coarse molassic sediments in these basins (Buslov et al., 1999). Various geological, seismological and geomorphological indicators show that the Altai are still affected by active tectonics (e.g., Cunningham et al., 1996; Owen et al., 1999; Philip and Ritz, 1999).

3. Sampling areas

In the Tien Shan Mountains several E–W trending ranges in the vicinity of the intramontane Issyk–Kul Basin in northeastern Kyrgyzstan were sampled: (1) the central Terzkey Range; (2) the central Kungey Range; (3) the west Kungey Range (and Boom Canyon area); and (4) the Kindil Las Range (Fig. 5). All these ranges are formed by Ordovician granitoids that intruded the Precambrian basement of the CTS or Ili Microcontinent. The large (over 200 km long and up to 80 km wide) Issyk–Kul Basin is situated centrally in the CTS or Ili Microcontinent and covers it with mainly Cenozoic, lacustrine sediments that locally exceed 4 km in thickness (Cobbold et al., 1994). At present a deep (668 m) lake is located within the basin. The Terzkey (south) and Kungey (north) ranges override the Cenozoic Issyk–Kul sediments along thrust faults, giving the basin its typical ramp-structure and demonstrating the recent (Late Cenozoic) tectonic activity of the region. Our 25 samples are all granitoids from these ranges, including two samples from the nearby, smaller Kindil Las Range (Fig. 5).

Sample sites in the Siberian Altai Mountains can be grouped into four major zones: (1) the Teletskoye graben region, (2) the Chulyshman Plateau, (3) the Dhulukul Basin area and (4) the Chuya–Kuray Basin area (Fig. 6). All 50 samples were taken from the Paleozoic crystalline basement (mainly granitoids and gneisses). From these, the majority (32 samples) comes from the basement of the Teletskoye Graben in the northern Siberian Altai Mountains. This young, narrow graben

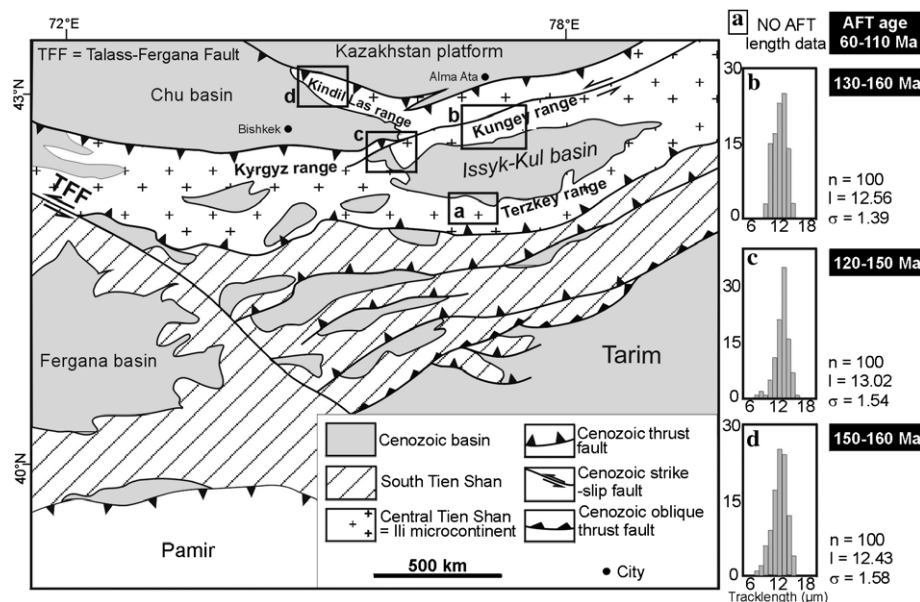


Fig. 5. Cenozoic tectonic framework of the Kyrgyz Tien Shan region with indication of AFT sample localities and data. Our sample areas are all located in the basement of the Central Tien Shan or Ili microcontinent. Sample locations: (a) Terzkey Range, (b) Kungey Range, (c) West Kungey Range (Boom Canyon area), and (d) Kindil Las Range. For each of the sample regions, except for the Terzkey Range (insufficient number of confined tracks), a representative AFT length distribution and length data are shown: n, number of measured confined tracks; l, mean track length, (= standard deviation). Also for each sample area the range of observed apparent AFT ages is given.

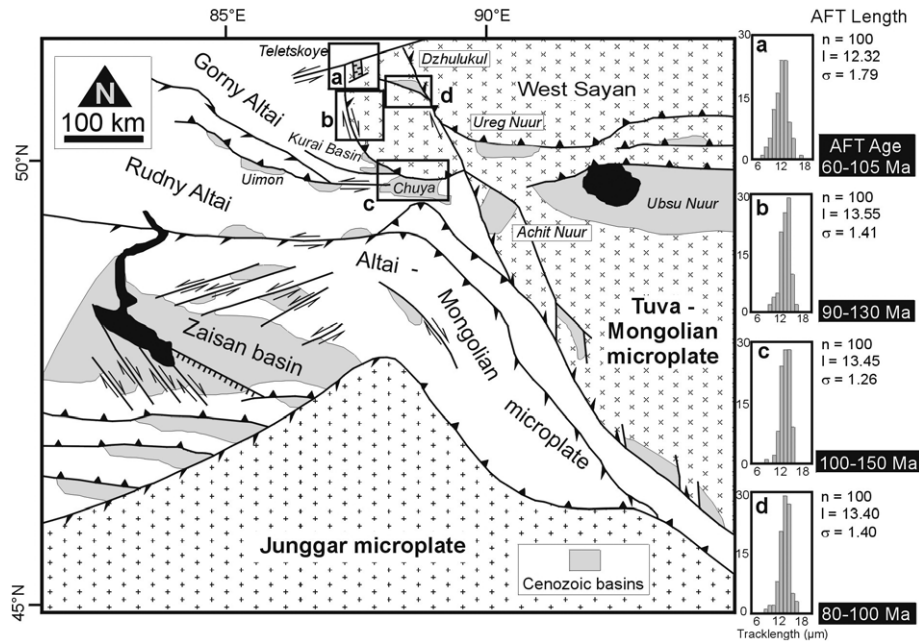


Fig. 6. Cenozoic tectonic framework of the Altai region with AFT sample localities and data. The Siberian Altai Mountains are a reactivated mobile belt wedged between rigid units (Junggar and Siberia with West Sayan and Tuva-Mongolia). Sample locations: (a) Teletskoye Graben, (b) Chulyshman Plateau, (c) Chuya-Kurai Basin and (d) Dzhulukul Basin. For each of the sample regions, a representative AFT length distribution and length data are shown: n, number of measured confined tracks, l, mean track length, (= standard deviation). Also for each sample area the range of observed apparent AFT ages is given.

accommodates a deep lake, and is thought to have formed about 2 Ma ago, clearly bearing witness to the neotectonic evolution of the Altai orogen (Dehandschutter et al., 2002). The graben is situated between two Paleozoic tectonic units (Gorny Altai and West Sayan) that were accreted to Siberia during the Paleozoic evolution of the PAO. All three other sampled regions show similar characteristics: Paleozoic basement accreted to Siberia during PAO evolution with superimposed Late Cenozoic tectonic features and basins.

4. Methodology and analytical procedures

For this study 75 crystalline basement rock samples yielded sufficient high-quality apatite crystals for apatite fission-track (AFT) analysis. Apatite was separated using conventional heavy liquid and magnetic techniques, embedded in epoxy resin, polished and dated with the external detector (ED) method (muscovite ED). Spontaneous tracks in the apatite were etched with a 2.5% HNO_3 solution (70 s at 22 °C). Induced tracks in the muscovite ED were etched with a 40% HF solution (40 min at 22 °C). Apatite-ED mounts were irradiated in several batches in the Thetis research reactor at the University of Gent. The thermal neutron fluence was determined with absolute techniques, using metal activation monitors. Track counting and length measurements were done using an Olympus BH-2 microscope (100× dry objective). At least 1000 spontaneous tracks were counted per sample, spread over minimum 20 separate

grains; where possible 100 confined tracks were measured to construct an AFT length-frequency distribution and a mean length was calculated. AFT age and length data were modeled using the Laslett et al. (1987) annealing model and the Ketcham et al. (2000) modeling software AFTSolve.

The apatites were dated using both an absolute approach (De Grave and Van den haute, 2002; Grimmer et al., 2002) and the conventional zeta (ζ) method (Hurford and Green, 1983; Hurford, 1990). An overall weighted mean zeta (OWMZ) was calculated on the basis of 32 apatite age standard mounts of Durango and Fish Canyon Tuff apatite and the IRMM-540 dosimeter glass (De Corte et al., 1998). We obtained an OWMZ calibration factor is 253.1 ± 2.4 . Only conventional ζ -ages were used for modeling.

5. Results and models

In this paper we focus on the general trends observed in the modeled cooling paths from the apatite samples of the Kyrgyz Tien Shan and Siberian Altai Mountains in the context of the geodynamic and tectonic evolution of Central Asia as a whole. In particular, we focus on the effects of Mesozoic Tethyan subduction and accretion events, and the subsequent Cenozoic India-Eurasia collision and ongoing convergence. Detailed description and analysis of the AFT results are reported elsewhere (De Grave and Van den haute, 2002; De Grave, 2003). Here we present 6 representative thermal history models from various sam-

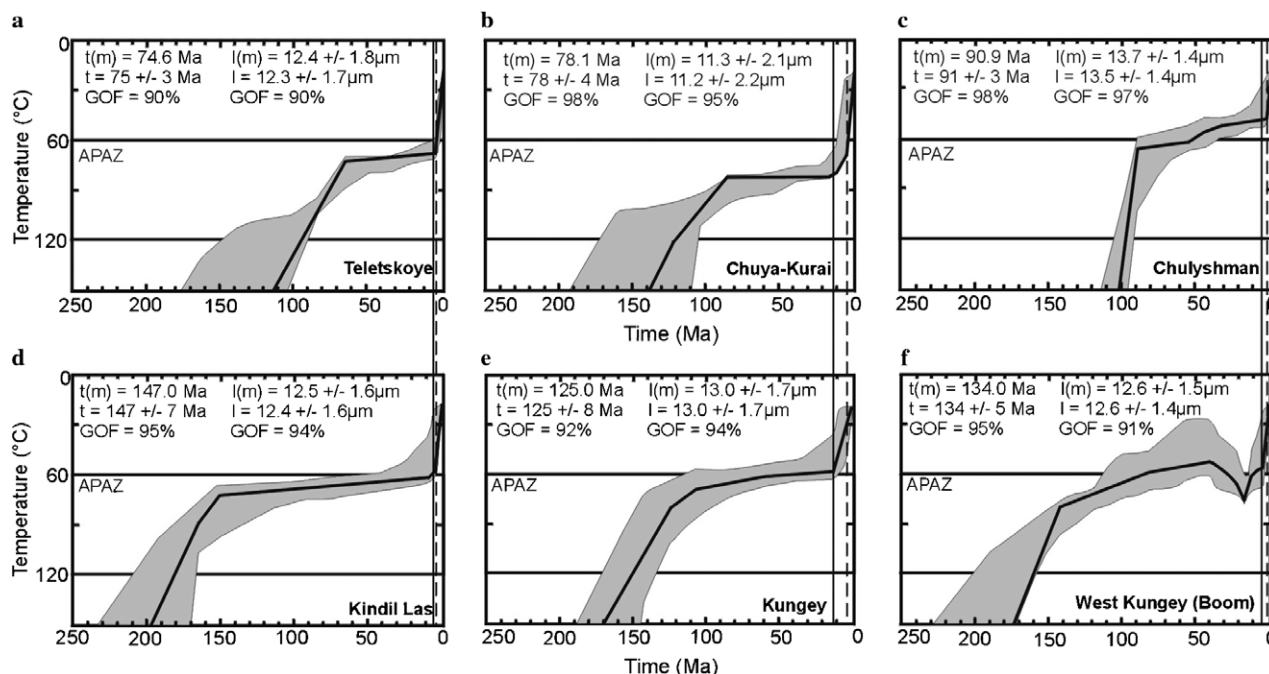


Fig. 7. Representative thermal history models obtained from AFT data from samples from the Siberian Altai (a–c) and Kyrgyz Tien Shan Mountains (d–f). Modeling performed with Laslett et al. (1987) annealing equations and the AFTSolve software by Ketcham et al. (2000). APAZ, Apatite Partial Annealing Zone; $t(m)$, modeled AFT age; t , observed AFT age; $l(m)$, modeled mean track length; l , observed mean track length; GOF, Goodness of fit. The best statistical t , T -path is represented by a line in a statistical good fits envelope (gray shading; probability greater than 50%). A full line indicates Late Cenozoic cooling for the Tien Shan samples, compared to a dashed line for the Altai samples. In general, Late Cenozoic cooling in the Altai starts later. For further description and interpretation: see text.

ple sites in the Siberian Altai and Kyrgyz Tien Shan Mountains (Fig. 7) as guidance for this discussion here. A general description of the analytical and modeling results is presented below.

5.1. Tien Shan region

For the Kyrgyz Tien Shan Mountains no reset AFT ages were found; apparent Late Jurassic–Cretaceous AFT ages show a north–south trend with older ages in the north. From north to south ages are: (1) Kindil Las Range: 150–160 Ma; (2) Central Kungey Range: 130–160 Ma; (3) West Kungey Range: 120–150 Ma; and (4) Terzkey Range: 60–110 Ma (Fig. 5).

AFT mean lengths and length distributions show manifest signs of thermal track shortening, suggesting a relatively long stay at Apatite Partial Annealing Zone (APAZ) temperatures (60–120 °C). Mean track lengths range from 12.4 to 13.2 μm ; distributions are broad ($1.2 < \sigma < 1.8 \mu\text{m}$), asymmetric and negatively skewed (Fig. 5). Here also, a regional trend is detected: shorter mean track lengths are observed for samples from northern localities. No reliable track length data were obtained from Terzkey samples because of too low confined track densities, and therefore no thermal history models are available for the Terzkey Range.

These AFT age and length data were modeled using the Laslett et al. (1987) annealing model and the AFTSolve program by Ketcham et al. (2000). Three representative

models are shown in Fig. 7: (d) Kindil Las Range; (e) Central Kungey Range; and (f) West Kungey Range. These and all other models (25) from the Kyrgyz Tien Shan samples reconstruct a three- to locally a four-stage thermal history: (1) Jurassic–Early Cretaceous cooling; (2) Late Cretaceous–Paleogene stability; (3) local Oligocene reheating; and (4) Mid Miocene to Recent cooling.

Mesozoic cooling (1) is recorded in our thermal history models between the Middle Jurassic and Early Cretaceous (180–110 Ma ago). This corresponds to somewhat older apparent AFT ages with respect to the Siberian Altai Mountains (see next section). Mesozoic cooling positioned the sampled rocks in the upper APAZ, at temperatures of ~60–80 °C (i.e., around a depth of 2.5 km, when considering a normal geothermal gradient of 25–30 °C/km). Subsequently, a period of stability or slow cooling (2) left the rocks more or less at these conditions until Late Cenozoic cooling (4) set in during the Late Miocene (15–10 Ma). Recent cooling to ambient surface temperatures exhumed the apatite-bearing rocks to their present outcrop position. A fourth feature is observed locally only. An Oligocene (40–20 Ma) reheating event (3) affected samples in the western part of the Issyk–Kul Basin, in particular samples from the West Kungey Range and Boom Canyon area. This characteristic is not shown by any of the other thermal history models of the Tien Shan sample area. Reheating brought the samples from upper AFT retention temperatures (50–60 °C) back to APAZ temperatures (70–90 °C).

5.2. Altai region

Apparent AFT ages for samples from the Siberian Altai Mountains are all Cretaceous (mostly Late Cretaceous) and range between 60 and 150 Ma. No reset ages were found for this area either. Apparent AFT ages were generally found to be younger than those obtained from our Tien Shan samples. In particular, for each of the sampled areas, we obtained ages within following intervals: (1) Teletskoye region: 60–105 Ma; (2) Chulyshman Plateau: 90–130 Ma; (3) Dzhulukul Basin area: 100–150 Ma; and (4) Chuya–Kurai Basin area: 80–100 Ma (Fig. 6). No clear regional trend can be perceived, except that samples from the most northern localities (especially near the Teletskoye graben and the WSB), and from localities directly bordering larger intramontane basins, seem to exhibit values from the younger age range. The older ages are mostly obtained on samples from higher locations in the central plateau area (Chulyshman Plateau and Dzhulukul Basin). In general, higher elevation samples yield older ages, as is to be expected considering the FT age-elevation relationship (Gleadow and Fitzgerald, 1987). AFT mean lengths and length distributions clearly show signs of thermal track shortening, suggesting a relatively long residence at APAZ temperatures (120–60 °C). All mean track lengths are 11.5–13.5 μm ; distributions are broad ($1.3 < \sigma < 2.3 \mu\text{m}$), asymmetric and negatively skewed.

Three representative models are depicted in Fig. 7: (a) Teletskoye region; (b) Chuya–Kurai region; and (c) Chulyshman Plateau. These and all other models (50) from the Siberian Altai samples reconstruct a three-stage thermal history: (1) Late Jurassic–Cretaceous cooling; (2) Late Cretaceous–Paleogene stability; and (3) Late Neogene–Quaternary cooling.

The Mesozoic event (1) cooled the apatites below the 120 °C threshold in the Late Jurassic, around 150 Ma ago. Considering a normal geothermal gradient of 25–30 °C/km, this implies that the apatite-bearing rocks were brought to a depth shallower than ~4 km in the crust at this time (possible lower gradients would imply greater crustal depths). According to our models, the Mesozoic cooling lasted until the Late Cretaceous ~80–90 Ma ago. These results correspond to the Late Jurassic–Cretaceous apparent AFT ages as described earlier. At the cessation of this cooling, the sampled rocks in the Siberian Altai region were still in the APAZ temperature window. They reached upper APAZ temperatures (~80–60 °C) and hence resided near a depth of 3–2 km considering a normal geothermal gradient of 25–30 °C/km. Variations of these numerical values amongst the various samples is due mostly to their present outcrop altitude, and hence their associated paleo-depth. In the Altai area, outcrop altitudes varied roughly between 500 and 2000 m. Additional scatter might be due to chemical compositional differences between individual apatites (Green et al., 1986).

After Mesozoic cooling, near-horizontal time-temperature (t, T) paths persisted from the Late Cretaceous,

throughout the Paleogene (2), until the Late Miocene. This stage in the modeled thermal history marks a period of enduring stability. Throughout this period, the sampled rocks stayed at upper APAZ temperatures, while slow cooling brought some samples down to lower AFT retention temperatures (50–60 °C). The near-horizontal t, T -paths are abruptly disturbed by rapid Pliocene to Recent cooling (3), starting ~5 Ma ago (individual samples show scatter from 7 to 2 Ma). This recent rapid cooling eventually brought the samples to ambient surface temperatures and exhumed the apatite-bearing rocks to their present outcrop position. This long APAZ residence time and associated track annealing and shortening (from Late Mesozoic to Late Cenozoic) explains the low mean track lengths and broad, negatively skewed track length distributions observed in our data.

A note of caution concerning the Late Cenozoic cooling events observed in the Kyrgyz Tien Shan and Siberian Altai Mountains should be conveyed here. It has been shown that there exists a certain tendency in AFT thermal history models using specific model parameter values (the so-called initial track length or l_0 parameter) to produce a Late Cenozoic cooling merely as an artifact. This can be further enhanced by track annealing at ambient temperatures (e.g., as observed by Vrolijk et al., 1992). The artifact was soon dubbed the ‘worldwide recent cooling’ (Ketcham et al., 1999). So it is hazardous to interpret rapid Late Cenozoic cooling simply on the basis of AFT thermal history models. It should be meticulously tested against independent geological evidence. This is what we attempted to do here. Given the fact that ample geological/tectonic evidence for Late Cenozoic activity exists in the study areas under discussion, we are convinced the Late Cenozoic cooling phases recorded in our thermal history models are real.

6. Interpretation and discussion

We interpret the various stages in the thermal histories of the Kyrgyz Tien Shan and Siberian Altai samples in the context of the Meso-Cenozoic accretionary tectonics and geodynamics affecting intracontinental Central Asia as outlined earlier. Our AFT data and models reconstruct a consistent thermotectonic evolution for Central Asia.

6.1. Tien Shan region

6.1.1. Mesozoic cooling

In the Tien Shan the Mesozoic AFT ages and cooling revealed by our thermal history models are older (~180–110 Ma) than the Siberian Altai (150–80 Ma). Cooling of the Kyrgyz Tien Shan basement occurred in the Jurassic–Early Cretaceous and is contemporaneous with the deposition of thick sedimentary sequences in the Junggar and Tarim foreland basins (Hendrix, 2000), as well as with the incipient formation of intramontane basins within the ancestral Tien Shan Mountains. We therefore interpret the cooling as a denudational response to an important

phase of tectonic reactivation (Hendrix et al., 1992; Cobbold et al., 1994; Dobretsov et al., 1996; Allen and Vincent, 1997; Otto, 1997; Allen et al., 2001). This reactivation is linked to the Cimmerian orogeny, i.e., subduction of Tethyan lithosphere underneath the southern Eurasian active margin and the ensuing collision of the Cimmerian blocks of Tibet: Qiangtang in the Late Triassic–Middle Jurassic; and Lhasa in the Late Jurassic–Early Cretaceous (e.g., Garzanti et al., 1999; Yin and Harrison, 2000). Distant effects of these collisions induced tectonic reactivation further north in Eurasia, also affecting the ancestral Tien Shan mountain belt. Renewed tectonic movements displaced blocks and created a topographic high with thrust sheets overriding both the adjoining Junggar and Tarim basins. Denudation of this Mesozoic orogen resulted in sedimentation in the Tarim and Junggar basins and in the intramontane basins. It also exhumed and subsequently cooled the Paleozoic basement as indicated by our models from the Issyk–Kul Basin area. Hence, we link the Mesozoic t , T -cooling paths to denudation accompanying Cimmerian reactivation of the Tien Shan orogen. Assuming a normal geothermal gradient (25–30 °C/km), this event would account for at least 2 km of denudation.

Mesozoic AFT ages for samples from the Tien Shan and adjacent areas (Junggar, Tarim, West Kun Lun) were reported earlier by Hendrix et al. (1994), Sobel and Dumitru (1997), and Bullen et al. (2001, 2003). In parts of their data, these authors report ages ranging between about 180 and 80 Ma (samples both bedrock as well as detrital apatites). These are in good agreement with those in our study. In particular, Sobel and Dumitru (1997) inferred a 150–200 Ma cooling event in the southern Tien Shan–West Kun Lun area, which again agrees with our data. They interpreted their findings also in terms of the docking of the Tibetan blocks during the Cimmerian orogeny. Together with these data, we can state that the Cimmerian orogeny affected a large area in the Eurasian hinterland, including at least West Kun Lun, the Tarim margins, Junggar, and the entire Tien Shan area.

6.1.2. Late Cretaceous–Paleogene stability

Near horizontal t , T -paths at lower APAZ - upper AFT retention temperatures (50–80 °C) in the Cretaceous–Paleogene reflect a period of prolonged stability in the Tien Shan. During this period the intracontinental tracts of Central Asia and Siberia experienced tectonic quiescence and the Mesozoic orogens were subjected to peneplanation. Rocks in the crust consequently remained at the position and depth they had reached after the Mesozoic orogenic and denudation phase. This implies that relaxation of the isotherms occurred and that these rocks stayed at more or less constant temperatures, reflected by the near-horizontal t , T -paths in our models. Throughout Siberia and Central Asia a vast lateritic peneplain of typical red beds developed (Ermikov, 1994; Delvaux et al., 1995; Dobretsov et al., 1996). Remnants of this peneplanation surface can be found in many parts of the region. At present this surface is

extensively deformed as a result of Late Cenozoic tectonic activity. Remnants are mainly found atop of plateau-like uplifts, or as basal sequences in Cenozoic intramontane basins. The interpretation put forward here, agrees well with observations by Van der Beek et al. (1996).

6.1.3. Oligocene reheating

Locally, only for samples in the western Kuney Range (especially in the vicinity of the Boom Canyon), the models exhibit an Oligocene (40–20 Ma) reheating event, taking the samples back to APAZ temperatures. This reheating is a local feature only. Moreover, samples from the same tectonic unit further to the east (Kuney Range) are not affected at all. Interpretation of the reheating should therefore not consider larger tectonic causes, but should only focus on local effects. Two possible scenarios are considered. A first involves burial and subsequent exhumation of this part of the basement during the Oligocene. A complete Paleogene–Neogene sedimentary section is preserved in both the Issyk–Kul Basin (east) and the Chu Basin (west), in between which the West Kuney Range forms a physiographical boundary. In the West Kuney basement, the Boom Canyon forms a complex ramp syncline in which also a Paleogene–Neogene section is preserved (Buslov and Delvaux, personal communication; Sobel, personal communication). We must therefore consider that Paleogene sediments once covered and buried parts of the West Kuney Range, and that these sediments were subsequently stripped away during the Oligocene, in perhaps an embryonic phase of Cenozoic reactivation of the Kyrgyz Tien Shan. Burial and subsequent denudation of the West Kuney Range would account for the observed local Oligocene reheating peak. Detailed mapping and assessment of Paleogene sedimentary thickness should be carried out to test this hypothesis. Published data on Paleogene sedimentary sequences in several Tien Shan basins however shows that in most cases the thickness reaches just a few dozen meters, to a maximum of 400 m (Cobbold et al., 1994; Sobel and Arnaud, 2000; Bullen et al., 2001). This would seem insufficient to push the basement back into the APAZ temperature window when considering a normal geothermal gradient of 25–30 °C/km.

A second scenario involves the emplacement of Paleogene basaltic rocks in the western part of the Issyk–Kul Basin and the eastern tracts of the Chu Basin (including Boom Canyon). The localities of studied outcrops of these rocks (Sobel and Arnaud, 2000; Bazhenov and Mikolaichuk, 2002) correspond remarkably well with our basement sample sites. While a single Late Cretaceous K–Ar age of 84 Ma was reported by Dobretsov and Zagruzina (1977), most other ages for these igneous rocks (K–Ar and Ar–Ar) clearly fall between 55 and 20 Ma (Krillov, 1960; Dobretsov and Zagruzina, 1977; Sobel and Arnaud, 2000). This corresponds well with the age of the local Oligocene reheating exhibited in our models. Hence, a local geothermal gradient increase, accompanying emplacement of these basaltoids might have affected the surrounding Paleozoic

basement rocks, repositioning them back within the APAZ. Sobel and Arnaud (2000) attribute these basaltic rocks to the potential existence of a small plume residing underneath the area. However, Yin (personal communication) ascribes them to magmas associated with partial melting of remnant subducted slabs along the South Eurasian paleo-margin.

6.1.4. Late Cenozoic cooling

The final stage in the thermal history of the Kyrgyz Tien Shan Mountains is a Late Cenozoic cooling, displayed by all samples. Although there exists some scatter between individual samples (10–20 Ma), in general, the Miocene onset of cooling is timed at ~15 Ma ago. More recently, around 5 Ma ago, the cooling curves seem to steepen, suggesting a more intensified cooling and denudation. This latter event corresponds with the timing of the main Cenozoic cooling event observed in our thermal history models for the Siberian Altai Mountains (see next section). This intensified cooling is corroborated by the modeled t, T -paths of the Kindil Las samples, which only exhibit cooling from 4 to 6 Ma ago and do not show earlier, Mid Miocene onset of cooling. We note here that the Kindil Las Range represents the most northern of our Tien Shan sample localities. Considering the tectonic setting and history, we interpret this cooling as denudation of the modern Tien Shan orogen as a consequence of its tectonic reactivation. This reactivation is a distant effect of India–Eurasia collision and the ongoing indentation of India into Eurasia. It installed a principally dextral transpressional regime in the Tien Shan (Abdrakhmatov et al., 1996, 2002; Yin et al., 1998; Allen et al., 2001; Buslov et al., 2003a). Our data suggests that building of the modern Tien Shan began about 15 Ma ago and that an accelerated phase of denudation affected all parts of the investigated area ~5 Ma ago. This corresponds to observations of a poly-phase Late Cenozoic Tien Shan reactivation by Bullen et al. (2003) and Sun et al. (2004). Sediments produced during this denudation have been transported and deposited in the large, bordering Junggar and Tarim Basins (Metivier and Gaudemer, 1997) and in the intramontane Tien Shan basins. The Issyk–Kul Basin, for example, has accumulated over 4 km of Cenozoic (mainly post-Eocene) sediments (Cobbold et al., 1994). Moreover, this sedimentary column bears several Mio-Pliocene horizons of very coarse, molassic-type deposits, indicating erosion of the growing orogen. As shown by the modeled t, T -paths, the Late Cenozoic event is still ongoing. This is underscored by numerous active tectonic indicators. The Tien Shan form one of the world's most active intracontinental mountain belts, with historical large magnitude earthquakes and landslides outlining the tectonic hazards of the region (Abdrakhmatov et al., 2002).

Again we would like to emphasize that Late Cenozoic cooling might represent a modeling artifact. However, considering the various independent lines of geological evidence, we can state that the thermal history described by our AFT data for the Kyrgyz Tien Shan express a real

and important Neogene denudation event accompanying the building and growth of this intracontinental mountain belt. Our data shows incipient activity becoming significant around ~15 Ma ago (some samples already show some activity as early as ~20 Ma ago) with a clear intensification encompassing the entire investigated region ~5 Ma ago. This is in agreement with previously published data. Hendrix et al. (1994) found reset AFT ages of 20–25 Ma in the northern Chinese Tien Shan and the Junggar Basin. Sobel and Dumitru (1997) clearly showed that exhumation along the southern Tien Shan and the western Kun Lun occurred between 14 and 25 Ma ago. Using AFT and apatite U–Th/He data, Bullen et al. (2001, 2003) draw similar conclusions. The latter authors argue that Late Cenozoic reactivation induced pulsed deformation of the Kyrgyz Tien Shan, with main exhumation phases 10–11 Ma ago and 0–3 Ma ago.

6.2. Altai region

6.2.1. Mesozoic cooling

Mesozoic cooling of the Altai basement in the Late Jurassic–Cretaceous was driven by an important denudation event in the Jurassic–Cretaceous, as recorded in the sediments of intramontane Altai basins and larger orogen-adjacent basins (Fig. 3). We therefore interpret the Mesozoic cooling observed in the thermal histories as due to the denudation of the Altai basement. Considering different sample elevations and considering a normal geothermal gradient of 25–30 °C/km, the Siberian Altai area experienced at least 1–3 km of denudation as recorded by the AFT system.

Sediments derived from the orogen were transported to large adjacent basins (Mongolian basins, WSB, Junggar Basin), as well as to smaller fault-controlled, intramontane depressions (Fig. 3; e.g., Dobretsov et al., 1996; Surkov et al., 1997; Graham et al., 2001; Johnson, 2004). Mesozoic clastic sediments, mainly Jurassic and Early Cretaceous sediments, overlie the Paleozoic basement of these basins unconformably. Mesozoic sediment thickness reaches several kilometers in the large adjacent basins, in the smaller intramontane basins it can reach over 2 km (Dobretsov et al., 1996). In these intramontane basins, Mesozoic sediments are commonly molassic type deposits. The relationship between Altai basement denudation and (molassic) sediment accumulation within depressions in the Altai orogen itself, points to a reactivation of this orogenic system. This is further underscored by the Jurassic Kuznetsk–Alatau Thrust and thrust-related basins at the northern edge of the Altai orogen (Fig. 3), at the Kuznetsk Basin interface (Buslov et al., 2003b).

Accumulation of thick Mesozoic deposits in large adjacent basins probably indicates active extension, and subsidence within these basins. This is the case for the WSB (Aplonov, 1988) and for the Mongolian–Baikal basins (Ermikov, 1994; Delvaux et al., 1995; Graham et al., 2001; Johnson, 2004). Therefore, basement cooling as

observed in our models could be a complex interplay of base-level drop due to active extension in large adjoining basins on one hand, and reactivation of the orogen on the other.

Mesozoic tectonic reactivation of the Altai Mountains is contemporaneous with the final stages of closure of the Mongol–Okhotsk (MO) Ocean, and the ensuing MO orogeny. The geological and tectonic history of this area, however, remains poorly constrained (Graham et al., 2001). Convergence and eventual collision of the Siberian and North Chinese (Sino–Korean)/Mongolian continents resulted in the development of the MO orogenic belt in the Late Jurassic–Early Cretaceous (Xu et al., 1997; Zorin, 1999; Wang et al., 2004; Liu et al., 2005). The collision zone ran from the current Okhotsk Sea, through Mongolia, to its western extension, southwest of the Baikal rift zone. Incipient collision occurred in the west at the Early–Middle Jurassic transition (170–180 Ma ago) (e.g., Zorin, 1999). Oblique and thus diachronous collision and associated compressive tectonics lasted until final closure in the east in the Early Cretaceous (110–140 Ma ago) (e.g., Van der Beek et al., 1996; Zorin, 1999). Deformation was not solely confined to the collision zone proper, but migrated through the hinterland and affected the Mongolian Altai (Dobretsov et al., 1996), the Baikal area (Van der Beek et al., 1996; based on AFT models from the Trans-Baikal Mountains) and even reached the Siberian cratonic rim (Ermikov, 1994; Zorin, 1999). Our AFT data suggests that the Siberian Altai region might also have experienced the far-field effects of the MO orogeny. These effects induced reactivation and deformation of the ancestral Altai orogen, leading to an important phase of denudation as discerned from the Mesozoic t, T -cooling paths in our models. Van der Beek et al. (1996) also interpreted their AFT results of Mesozoic denudation in the Baikal area in terms of distant effects of the MO orogeny. Their models show a Late Cretaceous cooling, which is generally somewhat younger than our results. This is in agreement however with the oblique collision model (Zorin, 1999), where initial collision and orogeny affected the western area (Altai) earlier with respect to the central (Baikal) and eastern part of the MO belt.

6.2.2. Late Cretaceous–Paleogene stability

Here also, the Late Cretaceous–Paleogene is characterized by near-horizontal modeled t, T -paths, similar as those for the Kyrgyz Tien Shan area. We assign a similar interpretation and discussion to this feature here. Regional peneplanation in a long-lasting regime of tectonic quiescence produced no or only moderate cooling of the Siberian Altai basement, resulting in the near-horizontal t, T -paths.

6.2.3. Late Cenozoic cooling

The Late Cenozoic cooling inferred by the thermal history models for the Siberian Altai Mountains is associated with the tectonic reactivation of the region and the building and denudation of the modern Altai orogen. This reactivation, of mainly transpressional deformation, is thought to

be a far-field effect of the India–Eurasia collision and the still ongoing indentation of the Indian Plate into the Eurasian Continent. We relate the observed cooling to denudation of the reactivated mountain belts. According to our models, cooling commenced somewhat 5 Ma ago and still continues. This corresponds well with other indicators that point towards Late Neogene initiation of transpressional reactivation and clear intensification in the Plio–Pleistocene (Cunningham et al., 1996; Dobretsov et al., 1996; Dehandschutter et al., 2002).

Sediments produced by the denudation of the modern Altai orogen are deposited in the large adjacent basins (WSB, Mongolian basins, Junggar–Zaisan Basin) in a more or less analogous setting as during the Mesozoic (Fig. 3). Also reminiscent of Mesozoic denudation, formation of Cenozoic, fault-controlled basins within the orogen itself accommodate part of the Late–Cenozoic clastics derived from the growing orogen as well. The Teletskoye Graben, and the Dzhulukul and Chuya–Kurai basins are examples of the latter (Figs. 3 and 6). Within these basins, several horizons of coarse clastics dating to the Late Neogene to Quaternary can be observed (Dobretsov et al., 1996; Buslov et al., 1999). For example, the sediment thickness in the Teletskoye Basin reaches at least 800 m (Seleznnev et al., 1995), while the basin formed less than 2 Ma ago (Dehandschutter et al., 2002), clearly indicating active denudation in the Siberian Altai Mountains in the last few million years.

In addition, Late Cenozoic reactivation is demonstrated by uplift, break-up, and displacement of the Late Cretaceous–Paleogene peneplain. In comparison to the low-lying inactive hinterland, remnants of the peneplain are vertically displaced by 2 km or more in some parts of the Siberian Altai Mountains (Dehandschutter et al., 2002). Within the mountains, adjacent blocks capped with remnants of the lateritic peneplain show vertical offsets of several hundred meters relative to each other. The preservation of the Late Cretaceous–Palaeogene peneplanation surface however, puts an upper limit to the extent of denudation that can have taken place and on the magnitude of concomitant cooling observed in our thermal history models. Yet, preservation is local and not regional, indicating that some of the uplifted blocks were indeed subjected to considerable denudation. In addition, all samples were collected at the surface and along vertical profiles situated well below the estimated position of the peneplanation surface.

In summary, tectonic as well as sedimentary evidence indicates a Late Neogene–Quaternary episode of intense tectonic activity with rapid uplift and sedimentation. Although to some extent the AFT evidence may overestimate the amount of denudation associated with this event (Late Cenozoic artifactual cooling), the Late Neogene–Quaternary event itself and its timing are accurately reflected in the modeled t, T -paths. We hence interpret the young rapid cooling as observed in the thermal history models of the Siberian Altai Mountains to be related to Late Neogene–Quaternary denudation in a still active transpressional tectonic regime. If we consider a direct relationship

between the timing of cooling/denudation as observed in our models on one hand and onset of mountain building and rock uplift on the other, we can conclude that reactivation and building of the modern Altai orogenic edifice is largely constrained to the last 5 Ma.

7. General tectonic implications and conclusions

7.1. Mesozoic reactivation

Our AFT data and models show that the interior part of the Eurasian continent experienced important Mesozoic activity. After the Paleozoic assembly of Eurasia and its Permo-Triassic consolidation, growth and accretion of the continent continued throughout much of the Mesozoic. Convergence between northward drifting peri-Gondwanan fragments and the southern Eurasian margin, produced a large-scale subduction-accretion belt, ranging from the Okhotsk Sea in far eastern Siberia, all the way to the European Alpine zone. Subduction underneath the active tracts of the south Eurasian margin consumed several oceanic basins, and pulled various tectonic units into the active margin, effectively accreting them to Eurasia. In the Central Asian–Siberian area, closure of the Paleo-Tethys and Mongol–Okhotsk oceans, respectively, resulted in the docking of the Cimmerian blocks of present-day Tibet (Qiangtang and Lhasa) with Tarim–Eurasia in the Late Triassic–Early Cretaceous and of the amalgamated North Chinese–Mongolian continent with South Siberia in the Jurassic–Early Cretaceous. This gave rise to the Cimmerian orogeny on one hand, and the Mongol–Okhotsk orogeny on the other. Both orogenies not only affected the respective collision zones, but propagated deformation to the interior of Eurasia by reactivation of the pre-existing Paleozoic structural fabric. Both the Tien Shan and the Altai area experienced far-field effects of these accretion-collision events that took place at the distant continental margins. In this way ancestral Central Asian and Siberian mountain belts were reactivated and consequently were subjected to denudation. The denudation produced sediments that were deposited in adjoining, large and long-lived basins (e.g., Junggar, Tarim, West Siberian Basin) and in newly forming and evolving fault-controlled intramontane depressions. The denudation also induced cooling of the Paleozoic basement underlying both the Tien Shan and Altai Mountains. This cooling of the upper kilometers of the crust, brought apatite-bearing rocks under the AFT accumulation and retention threshold temperatures and the cooling events were subsequently recorded in the AFT system as apparent Mesozoic AFT ages and steep modeled t, T -cooling paths.

These Mesozoic events can be viewed as a continuation of the Paleozoic accretionary history that shaped the complex blocky-mosaic architecture of Siberia and Central Asia. These events were able to reactivate the region as a consequence of that complex inherited structural network that crosscuts the entire region. In this light, the Mesozoic events can alternatively or equally be seen as precursors to Cenozoic

reactivation. Distant effects of large-scale India–Eurasia collision and ongoing convergence between them, once again propagated deformation to the interior of Eurasia, often along the same structural pathways as in the Mesozoic. Thus again the complex Central Asian Deformation Zone (CADZ) was subjected to intracontinental reactivation.

7.2. Late Cretaceous–Paleogene stability

After Mesozoic tectonic reactivation, activity subdued and regional tectonic quiescence and stability was imposed throughout Late Cretaceous–Paleogene times. The entire CADZ experienced a long period of peneplanation under predominantly tropical conditions and a regional Late Cretaceous–Paleogene lateritic erosion surface matured. Remnants of this peneplain are found in many parts of the CADZ and attest to its widespread areal dimensions. Under these conditions moderate denudation transpired at most and relaxation of the isotherms occurred, developing a stable temperature profile in the CADZ crust. Consequently, basement rocks remained at the APAZ temperatures and depths where Mesozoic denudation and exhumation had positioned them. This resulted in only slow cooling of the basement and AFT length shortening. These conditions are reflected in the AFT system: broad, negatively skewed AFT length-frequency distributions and near-horizontal t, T -paths in the thermal histories models.

7.3. Late Cenozoic reactivation

The period of stability was disturbed by the India–Eurasia collision at the Meso-Cenozoic transition and by effects of the ongoing indentation of India into Eurasia. At first, this major collision induced lateral extrusion of lithospheric fragments along major shear zones north of the collision zone (mainly in Tibet and SE Asia) with peak activity between about 40 and 20 Ma ago. Around 20 Ma ago crustal thickening and large-scale construction of the Himalayan fold-and-thrust arc became a significant mechanism for the accommodation of additional indentation of India. From the Late Miocene onwards, starting some 20–15 Ma ago, another important shift in accommodation mechanism occurred. Further convergence and accompanying strain and stress accumulation was also partitioned through propagation of this stress through the interior of the Eurasian Plate, especially by penetration of the Pamir indenter and by underthrusting of the rigid Tarim Plate under the Tien Shan. This mechanism is corroborated by the evidence from our and previously reported AFT data sets. By the Late Miocene, approximately 15 Ma ago, after possible initial movements around 20 Ma ago, the Tien Shan area experienced an important deformation stage. Inherited structures became reactivated and building and growth of the modern Tien Shan orogen was initiated. Reactivation style was predominantly dextral transpressional. Strike-slip and thrust movements are responsible for developing the characteristic morphology of E–W

trending ranges with intermittent intramontane basins. Thrust sheets once again flexurally loaded the Tarim and Junggar basin margins. Denudation of the orogen generated clastic sediments that were deposited in the Tarim and Junggar basins as well as in intramontane depressions in between the growing Tien Shan ranges. This denudation and exhumation displaced the Paleozoic basement vertically upwards in the crust, resulting in cooling of the basement rocks. This cooling and denudation episode is ongoing and brought the rocks to ambient surface temperatures and to their present outcrop positions. This is preserved and recorded in the AFT system and is revealed by our thermal history models.

The northward propagation of deformation was further transmitted through the stable Kazakhstan and Junggar plates to the Altai Belt that is bordered to the north by the vast and rigid West Siberian Basin and the Siberian Craton. The underthrusting of the Junggar Plate in the south act as a sort of indenter, while the unyielding terrains in the north can be considered a backstop. This configuration has caused the Altai Mountains to be reactivated as a distinct transpressional mobile belt wedged in between these rigid blocks. After early signs in the Miocene, reactivation and deformation has intensified manifestly since the Pliocene. Denudation of the young and growing orogen has brought about sedimentation in large adjoining basins as well as in Cenozoic intramontane basins. Some of these basins, like the Teletskoye Graben, are very young systems, formed as recent as 2 Ma ago as a result of active differential movements of adjacent tectonic blocks. Given the fact that hitherto no reset AFT ages have been found in the Altai realm, and the fact that in many places, especially atop plateau-like uplifts, the Late Cretaceous–Paleogene peneplanation surface is preserved, denudational response to the young tectonic movements in the area has not been sufficient for complete registration in the AFT system. However, modeling of our data suggests that recent cooling began to affect the Altai basement since ~5 Ma ago, which is in agreement with other geological observations.

This implies that the age of reactivation as a consequence of continued indentation of India into Eurasia, seemingly became younger towards the north: ~15 Ma in the Tien Shan and ~5 Ma in the Altai. This observation would support the hypothesis that ongoing India–Eurasia convergence is partly accommodated by propagating stress northward through intracontinental Central Asia via an inherited structural network of zones of weakness in the crust and lithosphere. In this way the vast Central Asian Deformation Zone is developing as an extensive system of intracontinental mountain belts with intermittent large basins accumulating much of the sedimentary load stripped off of these growing mountain chains.

Acknowledgements

We wish to thank Dr. R. Jonckheere, Prof. F. De Corte and A. De Wispelaere for help at various stages in the

AFT research. Drs. B. Dehandschutter, D. Delvaux, R. Hus, J. Klerkx, L. Smirnova, K. Theunissen, E. Vassilieva, E. Vysotsky, and others are acknowledged for assistance during fieldwork and sampling. A critical review and comments by Dr. Mark Allen were greatly appreciated. Review comments by Dr. C. Johnson undoubtedly enhanced the quality of both contents and form of this paper. This research was supported by the Flemish Institute of Innovation by Science and Technology. J.D.G. is currently postdoctoral fellow of the Fund for Scientific Research – Flanders (Belgium). The CARS center and their researchers contributed valuable resources and inspiring discussions for which we are extremely grateful.

References

- Abdrakhmatov, K.Ye., Aldazhanov, S.A., Hager, B.H., Hamburger, M.W., Herring, T.A., Kalabaev, K.B., Makarov, V.I., Molnar, P., Panasyuk, S.V., Prilepin, M.T., Reilinger, R.E., Sadybakasov, I.S., Souter, B.J., Trapeznikov, Yu.A., Tsurkov, V.Ye., Zubovich, A.V., 1996. Relatively recent construction of the Tien Shan inferred from GPS measurements of present-day crustal deformation. *Nature* 384, 450–453.
- Abdrakhmatov, K.Y., Djanuzakov, K.D., Delvaux, D., 2002. Active tectonics and seismic hazard of the Issyk–Kul basin in the Kyrgyz Tian-Shan. In: Klerkx, J., Imanackunov, B. (Eds.), *Lake Issyk–Kul: Its Natural Environment*. Kluwer Academic Publishers, Dordrecht, pp. 147–160.
- Allen, M.B., Vincent, S.J., 1997. Fault reactivation in the Junggar region, northwest China: the role of basement structures during Mesozoic–Cenozoic compression. *Journal of the Geological Society, London* 154, 151–155.
- Allen, M.B., Windley, B.F., Zhang Chi, 1992. Palaeozoic collisional tectonics and magmatism of the Chinese Tien Shan, Central Asia. *Tectonophysics* 220, 89–115.
- Allen, M.B., Windley, B.F., Zhang Chi, 1994. Cenozoic tectonics in the Urumqi–Korla region of the Chinese Tien Shan. *Geologische Rundschau* 83, 406–416.
- Allen, M.B., Vincent, S.J., Wheeler, P.J., 1999. Late Cenozoic tectonics of the Kepingtage thrust zone: interactions of the Tien Shan and the Tarim Basin, northwest China. *Tectonics* 18, 639–654.
- Allen, M.B., Alsop, G.I., Zhemchuzhnikov, V.G., 2001. Dome and basin refolding and transpressive inversion along the Karatau fault System, southern Kazakhstan. *Journal of the Geological Society, London* 158, 83–95.
- Apionov, S., 1988. An aborted Triassic ocean in West Siberia. *Tectonics* 7, 1103–1122.
- Avouac, J.P., Tapponnier, P., Bai, P., You, H., Wang, G., 1993. Active thrusting and folding along the northern Tien Shan, and Late Cenozoic rotation of the Tarim relative to the Junggar and Kazakhstan. *Journal of Geophysical Research* 98, 6755–6804.
- Bachtadse, V., Pavlov, V.E., Kazansky, A.Y., Tait, J.A., 2000. Siluro–Devonian paleomagnetic results from the Tuva terrane (southern Siberia, Russia): implications for the paleogeography of Siberia. *Journal of Geophysical Research* 105, 13509–13518.
- Bazhenov, M.L., Mikolaichuk, A.V., 2002. Paleomagnetism of Paleogene basalts from the Tien Shan, Kyrgyzstan: rigid Eurasia and dipole geomagnetic field. *Earth and Planetary Science Letters* 195, 155–166.
- Bullen, M.E., Burbank, D.W., Garver, J.I., Abdrakhmatov, K.Ye., 2001. Late Cenozoic tectonic evolution of the northwestern Tien Shan: New age estimates for the initiation of mountain building. *Geological Society of America Bulletin* 113, 1544–1559.
- Bullen, M.E., Burbank, D.W., Garver, J.I., 2003. Building the Northern Tien Shan: integrated thermal, structural and topographic constraints. *Journal of Geology* 111, 149–165.

- Burbank, D.W., McLean, J.K., Bullen, M., Abdrakhmatov, K.Y., Miller, M.M., 1999. Partitioning of intramontane basins by thrust related folding, Tien Shan, Kyrgyzstan. *Basin Research* 11, 75–92.
- Buslov, M.M., Zykin, V.S., Novikov, I.S., Delvaux, D., 1999. Cenozoic history of the Chuya depression (Gorny Altai): structure and geodynamics. *Russian Geology and Geophysics* 40, 1687–1701.
- Buslov, M.M., Saphonova, I.Yu., Watanabe, T., Obut, O.T., Fujiwara, Y., Iwata, K., Semakov, N.N., Sugai, Y., Smirnova, L.V., Kazansky, A.Yu., 2001. Evolution of the Paleo-Asian Ocean (Altai–Sayan region, Central Asia) and collision of possible Gondwana-derived terranes with the southern marginal part of the Siberian continent. *Geosciences Journal* 5, 203–224.
- Buslov, M.M., Klerkx, J., Abdrakhmatov, K., Delvaux, D., Batalev, V.Yu., Kuchai, O.A., Dehandschutter, B., Muraliev, A., 2003a. Recent strike-slip deformation of the northern Tien Shan. In: Storti, F., Holdsworth, R.E., Salvini, F. (Eds.), *Intraplate Strike-Slip Deformation Belts*. Geological Society London, Special Publication 210, pp. 53–64.
- Buslov, M.M., Watanabe, T., Smirnova, L.V., Fujiwara, I., Iwata, K., De Grave, J., Semakov, N.N., Travin, A.V., Kiryanova, A.P., Kokh, D.A., 2003b. Role of strike-slip faults in Late Paleozoic–Early Mesozoic tectonics and geodynamics of the Altai–Sayan and East Kazakhstan folded zone. *Russian Geology and Geophysics* 44, 49–75.
- Carroll, A.R., Graham, S.A., Hendrix, M.S., Ying, D., Zhou, D., 1995. Late Paleozoic tectonic amalgamation of northwestern China: sedimentary record of the northern Tarim, northwestern Turpan and southern Junggar basins. *Geological Society of America Bulletin* 107, 571–594.
- Chen, C., Lu, H., Jia, D., Cai, D., Wu, S., 1999. Closing history of the southern Tianshan oceanic basin, western China: an oblique collisional orogeny. *Tectonophysics* 302, 23–40.
- Chung, S., Lo, C., Lee, T.-Y., Zhang, Y., Xie, Y., Li, X., Wang, K.-L., Wang, P., 1998. Diachronous uplift of the Tibetan plateau starting 40 Myr ago. *Nature* 394, 769–773.
- Cobbald, P.R., Sadybasov, E., Thomas, J.C., 1994. Cenozoic transpression and basin development, Kyrgyz Tianshan, Central Asia. In: Roure, F., Ellouz, N., Shein, V.S., Skvortsov, I. (Eds.), *Geodynamic Evolution of Sedimentary Basins*. International Symposium, Moscow, pp. 181–202.
- Coutand, I., Strecker, M.R., Arrowsmith, J.R., Hilley, G., Thiede, R.C., Korjenkov, A., Omuraliev, M., 2002. Late Cenozoic tectonic development of the intramontane Alai Valley, (Pamir–Tien Shan region, central Asia): an example of intracontinental deformation due to the India–Eurasia collision. *Tectonics* 21 (1053), 19.
- Cunningham, W.D., Windley, B.F., Dorjnamjaa, D., Badamgarov, J., Saandar, M., 1996. Late Cenozoic transpression in south-western Mongolia and the Gobi Altai–Tien Shan connection. *Earth and Planetary Science Letters* 140, 67–81.
- De Corte, F., Bellemans, F., Van den haute, P., Ingelbrecht, C., Nicholl, C., 1998. A new U doped glass certified by the European Commission for the calibration of fission-track dating. In: Van den haute, P., De Corte, F. (Eds.), *Advances in Fission-Track Geochronology*. Kluwer Academic Publishers, Dordrecht, pp. 67–78.
- De Grave, J., 2003. Apatite fission-track thermochronology of the Altai Mountains (South Siberia, Russia) and the Tien Shan Mountains (Kyrgyzstan): relevance to Meso–Cenozoic tectonics and denudation in Central Asia. PhD. Thesis, University of Gent, Gent, 289 pp.
- De Grave, J., Van den haute, P., 2002. Denudation and cooling of the Lake Teletskoye region in the Altai Mountains (South Siberia) as revealed by apatite fission-track thermochronology. *Tectonophysics* 349, 145–159.
- Dehandschutter, B., Vysotsky, E., Delvaux, D., Klerkx, J., Buslov, M.M., Seleznev, V.S., De Batist, M., 2002. Structural evolution of the Teletsk graben (Russian Altai). *Tectonophysics* 351, 139–167.
- Delvaux, D., Moeys, R., Stapel, G., Melnikov, A., Ermikov, V., 1995. Paleostress reconstructions and geodynamics of the Baikal region, Central Asia, Part 1. Palaeozoic and Mesozoic pre-rift evolution. *Tectonophysics* 252, 61–101.
- Dobretsov, N.L., Vladimirov, A.G., 2001. Continental growth in the Phanerozoic: evidence from Central Asia. *Geology, magmatism and metamorphism of the western part of Altai–Sayan Fold Region*. IGCP-420 3rd Workshop, Field Guide, Novosibirsk, 139 p.
- Dobretsov, G.L., Zagruzina, I.A., 1977. Young basaltoid igneous activity in the eastern Tien Shan Academy of Science USSR. *Doklady Earth Science Section* 235, 67–70.
- Dobretsov, N.L., Berzin, N.A., Buslov, M.M., 1995. Opening and tectonic evolution of the Paleo-Asian Ocean. *International Geology Review* 37, 335–360.
- Dobretsov, N.L., Buslov, M.M., Delvaux, D., Berzin, N.A., Ermikov, V.D., 1996. Meso- and Cenozoic tectonics of the Central Asian mountain belt: effects of lithospheric plate interaction and mantle plumes. *International Geology Review* 38, 430–466.
- Dupont-Nivet, G., Guo, Z., Butler, R.F., Jia, C., 2002. Discordant paleomagnetic direction in Miocene rocks from the Central Tarim Basin: evidence for local deformation and inclination shallowing. *Earth and Planetary Science Letters* 199, 473–482.
- Ermikov, V.D., 1994. Mesozoic precursors of the Cenozoic rift structures of Central Asia. *Bulletin des Centres Recherches Explorations–Productions, Elf Aquitaine* 18, 123–134.
- Fielding, E.J., 1996. Tibet uplift and erosion. *Tectonophysics* 260, 55–84.
- Fu, B., Lin, A., Kano, K., Maruyama, T., Guo, J., 2003. Quaternary folding of the eastern Tien Shan, northwest China. *Tectonophysics* 369, 79–101.
- Garzanti, E., Le Fort, P., Sciunnach, D., 1999. First report of Lower Permian basalts in south Tibet: tholeiitic magmatism during break-up and incipient opening of Neotethys. *Journal of Asian Earth Sciences* 17, 533–546.
- Gleadow, A.J.W., Fitzgerald, P.G., 1987. Uplift history and structure of the Trans-antarctic Mountains: new evidence from fission track dating of basement apatites in the Dry Valley area, southern Victoria Land. *Earth and Planetary Science Letters* 82, 1–14.
- Green, P.F., Duddy, I.R., Gleadow, A.J.W., Tingate, P.R., Laslett, G.M., 1986. Thermal annealing of fission tracks in apatite. I. A qualitative description. *Chemical Geology (Isotopes Geoscience Section)* 59, 237–253.
- Graham, S.A., Hendrix, M.S., Johnson, C.L., Badamgarav, D., Badarch, G., Amory, J., Porter, M., Barsbold, R., Webb, L.E., Hacker, B.R., 2001. Sedimentary record and tectonic implications of Mesozoic rifting in southeast Mongolia. *Geological Society of America Bulletin* 113, 1560–1579.
- Grimmer, J.C., Jonckheere, R., Enkelmann, E., Ratschbacher, L., Hacker, B.R., Blythe, A.E., Wagner, G.A., Wu, Q., Liu, S., Dong, S., 2002. Cretaceous–Cenozoic history of the southern Tan-Lu fault zone: apatite fission-track and structural constraints from the Dabie Shan (eastern China). *Tectonophysics* 359, 225–253.
- Harrison, T.M., Copeland, P., Kidd, W.S.F., Yin, A., 1992. Raising Tibet. *Science* 255, 1663–1670.
- Hendrix, M.S., 2000. Evolution of Mesozoic sandstone compositions, southern Junggar, northern Tarim, and western Turpan basins, northwest China: a detrital record of the ancestral Tien Shan. *Journal of Sedimentary Research* 70, 520–532.
- Hendrix, M.S., Graham, S.A., Carroll, A.R., Sobel, E.R., McKnight, C.L., Schulein, B.J., Wang, Z., 1992. Sedimentary record and climatic implications of recurrent deformation in the Tien Shan: evidence from the Mesozoic strata of the north Tarim, south Junggar, and Turpan basins, northwest China. *Geological Society of America Bulletin* 104, 53–79.
- Hendrix, M.S., Dumitru, T.A., Graham, S.A., 1994. Late Oligocene – Early Miocene unroofing in the Chinese Tien Shan: an early effect of the India–Asia collision. *Geology* 22, 487–490.
- Hurford, A.J., 1990. Standardization of fission track dating calibration: Recommendation by the Fission Track Working Group of the I.U.G.S.. Subcommission on Geochronology. *Chemical Geology (Isotope Geoscience Section)* 80, 171–178.
- Hurford, A.J., Green, P.F., 1983. The zeta age calibration of fission-track dating. *Geoscience* 1, 285–317.
- Johnson, C.L., 2004. Polyphase evolution of the East Gobi basin: sedimentary and structural records of Mesozoic–Cenozoic intraplate deformation in Mongolia. *Basin Research* 16, 79–99.

- Ketcham, R.A., Donelick, R.A., Carlson, W.D., 1999. Variability of apatite fission-track annealing kinetics: III. Extrapolation to geologic time scales. *American Mineralogist* 84, 1235–1255.
- Ketcham, R.A., Donelick, R.A., Donelick, M.B., 2000. AFTSolve: a program for multi-kinetic modeling of apatite fission-track data. *Geological Materials Research* 2, 1–32.
- Khain, E.V., Bibikova, E.V., Salnikova, E.B., Kröner, A., Gibsher, A.S., Didenko, A.N., Degtyarev, K.E., Fedotova, A.A., 2003. The Palaeo-Asian ocean in the Neoproterozoic and early Palaeozoic: new geochronological data and palaeotectonic reconstructions. *Precambrian Research* 122, 329–358.
- Kravchinsky, V.A., Konstantinov, K.M., Cogné, J.-P., 2001. Palaeomagnetic study of Vendian and Early Cambrian rocks of South Siberia and Central Mongolia: was the Siberian Platform assembled at this time? *Precambrian Research* 110, 61–92.
- Krilov, A.Y., 1960. Absolute age of the rocks of the Central Tien Shan and application of Argon methods to metamorphic and sedimentary sediments. In: Starik, I.E. (Ed.), *Determination of the Absolute age of Pre-Quaternary Formations*. Nedra, Moscow, pp. 222–224.
- Laslett, G.M., Green, P.F., Duddy, I.R., Gleadow, A.J.W., 1987. Thermal annealing of fission tracks in apatite. 2. A quantitative analysis. *Chemical Geology Isotopes Geoscience Section* 65, 1–13.
- Liu, W., Siebel, W., Li, X.-J., Pan, X.-F., 2005. Petrogenesis of the Linxi granitoids, northern Inner Mongolia of China: constraints on basaltic underplating. *Chemical Geology* 219, 5–35.
- Lukk, A.A., Yunga, S.L., Shevchenko, V.I., Hamburger, M.W., 1995. Earthquake focal mechanisms, deformation state and seismotectonics of the Pamir-Tien Shan region, Central Asia. *Journal of Geophysical Research* 100, 20321–20343.
- Metivier, F., Gaudemer, Y., 1997. Mass transfer between eastern Tien Shan and adjacent basins (Central Asia). *Geophysical Journal International* 128, 1–17.
- Molnar, P., Tapponnier, P., 1975. Cenozoic tectonics of Asia: effects of a continental collision. *Science* 189, 419–426.
- Molnar, P., Tapponnier, P., 1977. Relation of the tectonics of eastern China to the India–Eurasia collision: application of slip-line field theory to large-scale continental tectonics. *Geology* 5, 212–216.
- Molnar, P., England, P., Martinod, J., 1993. Mantle dynamics, uplift of the Tibetan Plateau, and the Indian Monsoon. *Reviews of Geophysics* 31 (4), 357–396.
- Molnar, P., Thorson Brown, E., Burchfiel, B.C., Deng, Q., Feng, X., Li, J., Raisbeck, G.M., Shi, J., Wu, Z., Yiou, F., You, H., 1994. Quaternary climate change and the formation of river terraces across growing anticlines on the north flank of the Tien Shan, China. *Journal of Geology* 102, 583–602.
- Morley, C.K., 2001. Combined escape tectonics and subduction rollback arc extension: a model for the evolution of Tertiary rift basins in Thailand, Malaysia and Laos. *Journal of the Geological Society, London* 158, 461–474.
- Otto, S.C., 1997. Mesozoic–Cenozoic history of deformation and petroleum systems in sedimentary basins of Central Asia: implications of collisions on the Eurasian margin. *Petroleum Geoscience* 3, 327–341.
- Owen, L.A., Cunningham, W.D., Richards, B.W.M., Rhodes, E., Windley, B.F., Dorjnamjaa, D., Badamgarav, J., 1999. Timing of formation of forebergs in the northeastern Gobi Altai, Mongolia: implications for estimating mountain uplift rates and earthquake recurrence intervals. *Journal of the Geological Society, London* 156, 457–464.
- Peltzer, G., Tapponnier, P., 1988. Formation and evolution of strike-slip faults, rifts, and basins during the India–Asia collision: an experimental approach. *Journal of Geophysical Research* 93, 15085–15117.
- Philip, H., Ritz, J.-F., 1999. Gigantic paleolandslides associated with active faulting along the Bogd fault (Gobi-Altay, Mongolia). *Geology* 27, 211–214.
- Reichow, M.K., Saunders, A.D., White, R.V., Pringle, M.S., Al'Mukhamedov, A.I., Medvedev, A.I., Kirda, N.P., 2002. $^{40}\text{Ar}/^{39}\text{Ar}$ dates from the West Siberian Basin: Siberian flood basal province doubled. *Science* 296, 1846–1849.
- Ritts, B.D., Yue, Y., Graham, S.A., 2004. Oligocene–Miocene Tectonics and Sedimentation along the Altyn Tagh Fault, Northern Tibetan Plateau: analysis of the Xorkol, Subei, and Aksay basins. *Journal of Geology* 112, 207–229.
- Seleznov, V.S., Nikolaev, V.G., Buslov, M.M., Babushkin, S.M., Larkin, G.V., Evdokimov, A.A., 1995. The structure of sedimentary deposits of Lake Teletskoe according to the data of continuous one-channel seismic profiling. *Russian Geology and Geophysics* 36, 113–121.
- Sengör, A.M.C., Natal'in, B.A., Burtman, V.S., 1993. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. *Nature* 364, 299–307.
- Sobel, E.R., Arnaud, N., 2000. Cretaceous–Paleogene basaltic rocks of the Tuyon basin, NW China and the Kyrgyz Tian Shan: the trace of a small plume. *Lithos* 50, 191–215.
- Sobel, E.R., Dumitru, T.A., 1997. Thrusting and exhumation around the margins of the western Tarim Basin during the India–Asia collision. *Journal of Geophysical Research* 102, 5043–5064.
- Sun, J., Zhu, R., Bowler, J., 2004. Timing of the Tianshan Mountains uplift constrained by magnetostratigraphic analysis of molasses deposits. *Earth and Planetary Science Letters* 219, 239–253.
- Surkov, V.S., Smirnov, L.V., Gurari, F.G., Devyatov, V.P., Kazakov, A.M., 1997. Dynamics of the accumulation of the Mesozoic–Cenozoic sedimentary layer in the West-Siberian Basin. *Russian Geology and Geophysics* 38, 957–964.
- Tapponnier, P., Molnar, P., 1979. Active faulting and Cenozoic tectonics of the Tien Shan, Mongolia, and Baykal regions. *Journal of Geophysical Research* 84, 3425–3459.
- Tapponnier, P., Zhiqin, X., Roger, F., Meyer, B., Arnaud, N., Wittlinger, G., Jingsui, Y., 2001. Oblique stepwise rise and growth of the Tibet Plateau. *Science* 294, 1671–1677.
- Thompson, S.C., Weldon, R.J., Rubin, C.M., Abdrakhmatov, K., Molnar, P., Berger, G.W., 2002. Late Quaternary slip rates across the central Tien Shan, Kyrgyzstan, Central Asia. *Journal of Geophysical Research* 107 (2203), 32. doi:10.1029/2001JB000596.
- Van der Beek, P., Delvaux, D., Andriessen, P.A.M., Levi, K.G., 1996. Early Cretaceous denudation related to convergent tectonics in the Baikal region, SE Siberia. *Journal of the Geological Society, London* 153, 515–523.
- Vrolijk, P., Donelick, R.A., Queng, J., Cloos, M., 1992. Testing models of fission track annealing in apatite in a simple thermal setting: Site 800, Leg 129. In: Larson, R.L., Lancelot, Y. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results* 129, pp. 169–176.
- Wang, T., Zheng, Y., Li, T., Gao, Y., 2004. Mesozoic granitic magmatism in extensional tectonics near the Mongolian border in China and its implications for crustal growth. *Journal of Asian Earth Sciences* 23, 715–729.
- Xu, X., Harbert, W., Dril, S., Kravchinsky, V., 1997. New paleomagnetic data from the Mongol–Okhotsk collision zone, Chita region, south-central Russia: implications for Paleozoic paleogeography of the Mongol–Okhotsk Ocean. *Tectonophysics* 269, 113–129.
- Yin, A., Harrison, T.M., 2000. Geological evolution of the Himalayan–Tibetan orogen. *Annual Review in Earth and Planetary Sciences* 28, 211–280.
- Yin, A., Nie, S., Craig, P., Harrison, T.M., Ryerson, F., Qian Xianling, Yang Geng, 1998. Late Cenozoic tectonic evolution of the southern Chinese Tian Shan. *Tectonics* 17, 1–27.
- Yin, A., Rumelhart, P.E., Butler, R., Cowgill, E., Harrison, T.M., Foster, D.A., Ingersoll, R.V., Zhang, Q., Zhou, X.-Q., Wang, X.-F., Raza, A., 2002. Tectonic history of the Altyn Tagh fault system in northern Tibet inferred from Cenozoic sedimentation. *Geological Society of America Bulletin* 114, 1257–1295.
- Yue, Y., Liou, J.G., 1999. Two-stage evolution model for the Altyn Tagh fault, China. *Geology* 27, 227–230.
- Zhisheng, A., Kutzbach, J.E., Prell, W.L., Porter, S.C., 2001. Evolution of Asian monsoon and phased uplift of the Himalaya–Tibetan plateau since Late Miocene times. *Nature* 411, 62–66.
- Zorin, Yu.A., 1999. Geodynamics of the western part of the Mongolia–Okhotsk collisional belt, Trans-Baikal region (Russia) and Mongolia. *Tectonophysics* 306, 33–56.