Tectonic history of the Irtysh shear zone (NE Kazakhstan): New constraints from zircon U/Pb dating, apatite fission track dating and palaeostress analysis


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1. Introduction and geological setting

The NW-trending Irtysh shear zone (ISZ) (also known as Ertix or Erquis fault) represents a major tectonic boundary between the Siberian and Kazakhstan paleo-continents in the framework of the Central Asian Orogenic Belt (CAOB) (e.g. Jahn, 2004) or Altaiid tectonic collage (Sengör et al., 1993). It can be traced for more than 1000 km from NE Kazakhstan to NW China and might extend even further southwest into Mongolia (Cunningham et al., 1996; Windley et al., 2002; Briggs et al., 2007) (Figs. 1 and 2). The Siberian and Kazakhstan continents converged during the Late Palaeozoic through oblique subduction of the Ob’-Zaysan ocean floor that existed between them. The Ob’-Zaysan ocean is also known as Char or Gobi-Zaysan ocean and represents a part of the Palaeo-Asian Ocean (PAO) (e.g. Buslov et al., 2001; Windley et al., 2007). The Hercynian (late Early Carboniferous) closure of this basin provoked the final amalgamation of the ancestral CAOB (Sengör et al., 1993; Chikov and Zinoviev, 1996; Buslov et al., 2001, 2004; Vladimirov et al., 2003, 2008; Khromykh et al., 2011). This collision occurred along the Char ophiolitic suture-shear zone (CSZ) (Fig. 1) which follows a parallel NW-trend with respect to the ISZ. The CSZ separates the Zharma and Chingiz–Tarbagatai island arcs on one hand from the Rudny-Altai island arc system on the other. These volcanic arcs mark the active margins of the Kazakhstan and Siberian continents respectively. The ISZ separates the Rudny-Altai island arc from the Kalba–Narym fore-arc turbidite complex at the Hercynian active margin of Siberia (Fig. 1) (Buslov et al., 2001, 2004; Vladimirov et al., 2003; Khromykh et al., 2011).

During the Late Carboniferous – Permain, the convergence of Kazakhstan towards Siberia continued and as a consequence, the peri-Gondwanan terrane of Altai-Mongolia was transferred along the edge of Siberia towards the present day Rudny Altai (Fig. 1). The accompanying tectonic forces of oblique subduction...
(Ob'-Zaysan) in the West and collision (Altai-Mongolia) in the East (present-day co-ordinates) initiated coeval strike-slip movement along the ISZ and CSZ. Multi-mineral 40Ar/39Ar ages record two major stages of left-lateral deformation in the ISZ at /\text{C}_2 285–270 Ma and /\text{C}_2 270–260 Ma (Travin et al., 2001). It is thought that both the ISZ and CSZ accommodated more than 1000 km sinistral strike-slip displacement during this period of time (Melnikov et al., 1997; Burtman et al., 1998; Buslov et al., 2004; Vladimirov et al., 2008). The Rudny-Altai granitoids (NE of the ISZ) mainly have Devonian – Early Carboniferous crystallization ages (Fig. 2). They were emplaced during subduction and closure of the Ob'-Zaisan ocean and the collision of Siberia with Kazakhstan and Junggar. South of the ISZ, in the Kalba-Narym terrane, granitoids yield younger, Late Carboniferous – Permian ages, coinciding with the timing of major displacement along the ISZ (Fig. 2). Hence, the Kalba–Narym intrusions are thought to be emplaced in a post-collisional setting associated with ISZ activity (Vladimirov et al., 2001, 2008). The granitoids associated with the ISZ are deformed and show a ductile mylonitic fabric, indicating that the ISZ remained active after their emplacement (Chikov and Zinoviev, 1996; Melnikov et al., 1997; Buslov et al., 2004; Pirajno, 2010). Early Mesozoic (Triassic–Jurassic) granitoids are found at both
sides of the ISZ (Fig. 2) and were emplaced in an intra-plate setting, possibly related to the supposed Tarim plume activity (Vladimirov et al., 2001; Chikov et al., 2008; Pirajno, 2010).

The present mountainous morphology of the Altai is thought to have formed during reactivation of inherited structures such as Late Palaeozoic faults, of which the ISZ is a prime example (Allen and Vincent, 1997; Yuan et al., 2006; Briggs et al., 2007; Buslov, 2011). As a response to ongoing left-lateral displacements during the Late Permian–Early Triassic, the Junggar basin opened as a large intracontinental pull-apart basin along the southern edge of the ISZ (Allen et al., 1995). The Zaysan basin in fact forms the large intracontinental pull-apart basin along the southern edge of the Late Permian–Early Triassic, the Junggar basin opened as a

2. Sample locations and methodology

2.1. Zircon LA-ICP-MS U/Pb dating

Two granitic intrusions in the Kalba–Narym terrane were sampled for zircon U/Pb (ZUPb) analysis. Sample KZ-23 comes from the main Kalba–Narym batholith at the shores of the Buktharma artificial lake (a branch of Lake Zaysan), while KZ-36 was sampled in a small granitic pluton from the Kaldjir plateau, close to the Kazakh–Chinese border (Table 1, Fig. 2). Zircon separates were embedded and polished for LA-ICP-(SF)-MS (Laser Ablation-Inductively Coupled Plasma-(Sector Field)-Mass Spectrometry) U/Pb (ZUPb) dating. Using this technique, the zircon crystallization ages (closure-T = 800–1000 °C) of the sampled intrusives were determined in order to constrain the timing of pluton emplacement (Cherniak and Watson, 2003). The U/Pb analyses were carried out at the LA-ICP-(SF)-MS facility of the Department of Analytical Chemistry at Ghent University, using identical analytical procedures as those described in Glorie et al. (2011b) and De Grave et al. (2011). The internal structure of the zircon crystals was investigated and mapped by cathodoluminescence (CL) imaging, using a JEOL JSM-6400 SEM (Scanning Electron Microscope). Reference zircon GJ-1 (Jackson et al., 2004) was used as primary standard and Plešovice zircon (Sláma et al., 2008) for validation purposes (Glorie et al., 2011b). Data reduction was performed using the PepiAGE-software (Dunkl et al., 2009) and the age results were plotted on a Wetherill concordia diagram using the Isoplot program (Ludwig, 2003).

2.2. Apatite fission track thermochronology

In order to reconstruct the post-emplacement thermal history, four basement apatite samples were analyzed using the apatite fission track (AFT) method (Wagner and Van den haute, 1992). The resulting AFT ages are cooling ages that can be linked to movements in the upper crust corresponding to exhumation and denudation of the sampled intrusions (e.g. De Grave and Van den haute, 2002; Glorie et al., 2010; De Grave et al., 2011; Jolivet et al., 2011). In this study, we followed the analytical procedures described by De Grave et al. (2011) and Glorie et al. (2011a). KZ-06 and KZ-18 were sampled in sheared granitoids along the ISZ (Table 1, Fig. 2). KZ-23 and KZ-36 come from the Kalba–Narym batholith and as mentioned were also analyzed with the ZUPb dating method. Spontaneous fission tracks in apatite were etched with a 2.5% HNO₃ solution for 70 s at 25 °C, induced tracks in mica with 40% HF for 40 min at 20 °C. Irradiation was carried out in the Belgian Reactor 1 (BR1) facility of the Belgian Nuclear Research Centre in Mol (channel X26), with a thermal neutron fluence of 2.17 × 10¹⁵ cm⁻². Both Q-ages (based on the calculated absolute thermal neutron fluence) and conventional Q-ages (calibration factor based on IRMM 540 dosimeter glass) were calculated.

AFT lengths were measured on horizontal confined fission tracks using an identical experimental setup as described in Glorie et al. (2010). Where possible 100 natural confined tracks were measured to construct an AFT length-frequency distribution, a number that was not always attained. Subsequent AFT thermal history modeling was carried out using the HeFTy software (Ketcham, 2005) using identical settings as in Glorie et al. (2010) and Glorie et al. (2011a). One time–Temperature (TT)-constraint was introduced, reflecting the apparent AFT age of the sample. More geological constraints were not available to aid the modeling process. Dₐ (Donelick et al., 1999) values were found to be identical to the obtained values for Durango apatite (~1.5–1.9 μm) in our laboratory conditions and therefore a fixed μ parameter of 15.95 μm was used for the initial AFT length (Glorie et al., 2010, 2011a).

2.3. Stress inversion of fault-slip data

Fault-slip measurements were performed in several sites along the ISZ to reconstruct Palaeostress tensors with the program Win_Tensor (Delvaux, 2011). The same procedure was used as

<table>
<thead>
<tr>
<th>Sample</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Alt. (m)</th>
<th>Locality</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>KZ-06</td>
<td>N49°53'29&quot;</td>
<td>E082°37'49&quot;</td>
<td>340</td>
<td>Irtyszh, near Us'-Kamenogorsk</td>
<td>Granite-gneiss</td>
</tr>
<tr>
<td>KZ-18</td>
<td>N49°06'22&quot;</td>
<td>E084°33'34&quot;</td>
<td>1500</td>
<td>Irtyszh, near Kok-Terek village</td>
<td>Granodiorite</td>
</tr>
<tr>
<td>KZ-23</td>
<td>N48°14'29&quot;</td>
<td>E084°58'30&quot;</td>
<td>580</td>
<td>Kalba–Narym, near lake Buktharma</td>
<td>Granite</td>
</tr>
<tr>
<td>KZ-36</td>
<td>N48°16'26&quot;</td>
<td>E085°01'18&quot;</td>
<td>1100</td>
<td>Kaldjir plateau</td>
<td>Granite</td>
</tr>
</tbody>
</table>

Table 1: List of sample locations along the ISZ.
3. Results

3.1. Zircon LA-ICP-MS U/Pb dating

The obtained ZUPb data are summarized in Table 2, listing the results for each analyzed zircon crystal (excluding common-Pb polluted analyses; <10% for both samples). Concordia plots are presented in Fig. 3 and the resulting ZUPb ages are compared with published data in Fig. 4 (discussed further in Section 4.1). Sample KZ-36 yields within error identical (common Pb-corrected) 206Pb/238U and 207Pb/235U results for all analyzed grains, defining a U/Pb concordia age of 338 ± 5 Ma (Fig. 3). This Early Carboniferous (Visean) age is interpreted to represent the time of crystallization of the Kaljirdi granitoids at the northern margins of the Zaysan basin. For sample KZ-23, 206Pb/238U and 207Pb/235U ages range from ~300 to 1125 Ma, defining a discordia line in the Wetherill concordia diagram. This discordia exhibits an upper intercept of 1187 ± 83 Ma and lower intercept of 310 ± 36 Ma with the concordia curve. Ten out of seventeen analyses cluster around the lower intercept, defining a concordia age of 320 ± 5 Ma (Fig. 3). This late Early Carboniferous (Serpukhovian–Bashkirian) transition age is interpreted to represent the time of the emplacement of the Kalba–Narym intrusion. The older, Mesozo–Proterozoic ages probably represent partially retained inherited ZUPb ages (discussed further).

3.2. Apatite fission track dating and thermal history models

AFT results are presented in Table 3. For all samples, within error identical Late Cretaceous ε and Q-AFT ages were obtained. The oldest ages fall at the boundary between the Early and Late Cretaceous. Interestingly, samples KZ-06 (87 ± 6 Ma) and especially KZ-18 (71 ± 4 Ma) from within the ISZ yield a slightly younger AFT age than the samples from the bordering Kalba–Narym intrusions (KZ-23 and KZ-36). The latter samples yield AFT ages of 95 ± 5 Ma and...
Fig. 3. Zircon 206Pb/238U versus 207Pb/235U concordia plots. All data-point error ellipses were calculated at the 2σ level. Concordant ages are indicated by the central bold ellipses. Discordant ages (KZ-23) are arranged along a discordia line (bold dashed) and define upper- and lower-intercept ages with the concordia.

Fig. 4. Compilation of published zircon U/Pb data along the ISZ in the Kazakh and Chinese Altai. Star symbols refer to our new ages. Diamonds refer to published ZUPb studies in the Kazakh Altai (Vladimirov et al., 2001; Kuibida et al., 2009; Dokukina et al., 2010; Pirajno, 2010), squares to ZUPb studies in the Chinese Altai (Yuan et al., 2007; Wang et al., 2009; Chen et al., 2010 and references therein).

Table 3
Apatite fission track (AFT) results.

<table>
<thead>
<tr>
<th>Sample</th>
<th>n⁴</th>
<th>nsp (±1σ)⁷</th>
<th>Nsp</th>
<th>Nsi (±1σ)⁷</th>
<th>Nsi</th>
<th>Nq</th>
<th>P</th>
<th>t⁸</th>
<th>t⁹</th>
<th>L⁹</th>
<th>n</th>
<th>d⁹</th>
</tr>
</thead>
<tbody>
<tr>
<td>KZ-06</td>
<td>60</td>
<td>2.431 (0.096)</td>
<td>636</td>
<td>1.546 (0.076)</td>
<td>409</td>
<td>4.272 (0.105)</td>
<td>1640</td>
<td>1.589 ± 0.101</td>
<td>1.00</td>
<td>87.4 ± 6.0</td>
<td>87.6 ± 6.1</td>
<td>–</td>
</tr>
<tr>
<td>KZ-18</td>
<td>25</td>
<td>12.846 (0.374)</td>
<td>1183</td>
<td>10.050 (0.332)</td>
<td>918</td>
<td>4.269 (0.105)</td>
<td>1639</td>
<td>1.299 ± 0.057</td>
<td>0.61</td>
<td>71.4 ± 3.7</td>
<td>71.6 ± 3.7</td>
<td>13.4</td>
</tr>
<tr>
<td>KZ-23</td>
<td>30</td>
<td>13.128 (0.276)</td>
<td>2263</td>
<td>7.647 (0.211)</td>
<td>1318</td>
<td>4.268 (0.105)</td>
<td>1639</td>
<td>1.722 ± 0.060</td>
<td>0.98</td>
<td>94.5 ± 4.2</td>
<td>94.7 ± 4.2</td>
<td>13.5</td>
</tr>
<tr>
<td>KZ-36</td>
<td>40</td>
<td>5.800 (0.162)</td>
<td>1276</td>
<td>3.248 (0.121)</td>
<td>716</td>
<td>4.265 (0.105)</td>
<td>1638</td>
<td>1.813 ± 0.085</td>
<td>0.99</td>
<td>99.4 ± 5.4</td>
<td>99.6 ± 5.4</td>
<td>13.4</td>
</tr>
</tbody>
</table>

⁴ n is the number of analyzed grains.
⁷ nsp, nsi, and nq are the density of spontaneous, induced tracks and induced tracks in an external detector (ED) irradiated against a dosimeter glass (IRM-540). nsp, nsi, and nq are expressed as 10⁵ tracks/cm².
⁸ Nsp, Nsi, and Nq are the number of counted spontaneous, induced tracks and induced tracks in the ED (Nh is an interpolated value).
⁹ P is the chi-squared probability that the dated grains have a constant P/q-ratio.
¹⁰ t(1−α) and t(Q) give the resulting ages, expressed in Ma.
¹¹ AFT length data are reported as a mean track length (L±) with standard deviation σ (in μm), obtained from the measurement of a number (n) of natural, horizontal confined tracks. See text for more details.
pect of unconsolidated breccias were detected, which were in... until... faults with a markedly different as-
toids contain numerous and well-expressed fracture planes, often
tonic and/or magmatic NW-trending foliation (Fig. 7, KZ-13-23).

tic mylonitic foliation, including subhorizontal mineral lineations
shear fabric of the ISZ is characterized by a WNW-trending subver-

right-lateral reactivation of the ISZ along the Bukhtarma lake,
and correspond to thrust movements in the Narym range.
The stress tensors were separated into three palaeostress stages
(Figs. 7 and 8), based on the field settings, crosscutting relation-
ship and fault-rock characteristics as summarized above. The first
stage (four tensors, 86 fractures, 49 slip lines) corresponds to an
average E–W \( S_{\text{max}} \) in a strike-slip regime (\( R' = 1.4 \)), with three ten-
sors showing transtension and one transpression. The second stage
(eight stress tensors, 154 fractures, 125 slip lines) exhibits a ENE-
WSW \( S_{\text{max}} \), in an average strike-slip to transpressional context
(\( R' = 1.73 \)) with individual transtensional to pure compression-

left-lateral displacement were recognized (Figs. 7 and 8). The Bukhtar-
ma granitoids are often massive, but may contain subvertical tec-
tical mylonitic foliation obliquely (Sites KZ-01-09). The Kalba–Narym grani-
toids contain numerous and well-expressed fracture planes, often
affected by chlorite-epidote alteration. They can occur as large con-

Most of the brittle fault-slip data seem to be related to the ISZ,
and are attributed to the brittle-ductile transition zone or later
movements. The brittle faults that affect the ductile fabric of the
ISZ are related to later brittle movements that crosscut the mylon-
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affected by chlorite-epidote alteration. They can occur as large con-
ąreas of 13.4–13.5 \( \mu \)m, are relatively narrow (\( \sigma = 1.1–1.4 \) \( \mu \)m) and slightly negatively skewed (Fig. 5).

Subsequent modeling of the AFT data reveals a similar thermal
history model for samples KZ-23 and KZ-36, showing (1) fast cool-
ing at \( \sim 110–95 \) Ma to \( \sim 80–60 \) \( ^\circ \)C followed by (2) slow cooling from
\( \sim 100–85 \) Ma to ambient temperatures. The thermal history model
for KZ-18 exhibits a slightly different, 3-step cooling curve, with (1)
fast cooling at \( \sim 85–75 \) Ma to \( \sim 60 \) \( ^\circ \)C followed by (2) slow cooling until
\( \sim 40 \) \( ^\circ \)C and (3) a final phase of fast cooling from \( \sim 25 \) Ma on-

(left-lateral reactivation of the ISZ along the Bukhtarma lake,
and correspond to thrust movements in the Narym range.
The stress tensors were separated into three palaeostress stages
(Figs. 7 and 8), based on the field settings, crosscutting relation-
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3.3. Fault kinematics and stress inversion results

The ductile and brittle kinematic data have been measured at
11 sites or site-groups near Ust-Ramenogorsk (sites KZ-01-10 in
the ISZ and KZ-11 in the Kalba–Narym granitoids), around the Buk-
htarma artificial lake (sites KZ-13-16 and KZ-21-22 in the Kalba–
Narym granitoids) and in the Narym range (sites KZ-17-20 in Rud-
nyi-Altai island arc associated rocks) (Table 4, Fig. 6). The ductile
shear fabric of the ISZ is characterized by a WNW-trending subver-
tical mylonitic foliation, including subhorizontal mineral lineations
and sheath fold axes. Furthermore, consistent indicators for left-


tents) is presented in Fig. 4. Ob'-Zaysan subduction related intru-
sives are found in the NE of the ISZ (in the Rudny Altai and
southern Altai-Mongolia terrane), yielding Devonian – Early Car-
boniferous emplacement ages (\( \sim 410–330 \) Ma) with the oldest in
the East (in the Chinese segment) (Vladimirov et al., 2001; Wang
et al., 2009 and references therein). This observation is in agree-
ment with the oblique subduction model of Ob'-Zaysan oceanic
crust under the Kazakhstan continent from the SE to the NW (pres-
ent-day co-ordinates) (e.g. Buslov et al., 2001; Yuan et al., 2007;
Vladimirov et al., 2008). South of the ISZ, the intrusives in the Kal-
ba–Narym terrane and in the Chinese Saur mountains have consis-
tent Late Carboniferous–Early Permian ages (\( \sim 330–275 \) Ma) and
are interpreted as post-collisional plutons (Vladimirov et al.,
2001; Chen et al., 2010 and references therein). Our ZUPb samples
were taken in the Kalba Narym terrane and yield emplacement
ages of \( \sim 338 \) Ma and \( \sim 320 \) Ma. These late Early Carboniferous ages
are not unexpected, given their location close to the junction zone
between the magmatic domains north and south of the ISZ. There-
fore we interpret our ZUPb results in the context of the final colli-
sion of Siberia and Kazakhstan. As mentioned earlier, the initiation
of ISZ shear is dated to the Late Palaeozoic (\( \sim 285–260 \) Ma) by multi-
ineral \(^{40}\)Ar/\(^{39}\)Ar data (Travin et al., 2001).
The origin of the older zircons in sample KZ-23, at the junction zone between the Kazakhstan and Siberian active margin terranes, is debatable. Their lower intercept age coincides with the concordant age for the other zircons, suggesting that the inherited zircons were partially reset during the Kalba–Narym granitoid magma generation. Given the observation that the inherited zircons define a single Mesozo-Proterozoic upper intercept with the concordia curve, we argue that this upper intercept age may represent the original age of an igneous protolith. An alternative theory could be that the older zircons represent exotic zircons which were incorporated in the granitoid magma during its ascent in the crust. It is however less likely that the (metasedimentary) country rock zircons yield a homogeneous U/Pb age population. Additional petrological and/or geochemical data are however necessary to determine more precisely the origin of the older zircons.

Meso-Proterozoic ages were found at the Altai-Mongolia margin in the Charysh–Terekta–Ulagan–Sayan suture-zone (CTUSSs; Fig. 1) and are thought to be related to ancient events in the context of the Palaeo-Kazakhstan assembly (Glorie et al., 2011b). They also appear in other microcontinental terranes within the Palaeo-Kazakhstan edifice: e.g. the Tuva-Mongolia and Southern Gobi microcontinents (Kozakov et al., 1999; Demoux et al., 2009). North of the CTUSSs, in Gorny Altai, no Meso-Proterozoic ages are found at all (Glorie et al., 2011b), which indicates that the older zircons are probably related to the Kazakhstan continent, rather than to the Siberian continent.

Vladimirov et al. (2001, 2008) discussed four intrusion phases in the Kalba–Narym batholith with ZUPb ages of 307–299 Ma for the Kunush plagiogranite complex, 295–274 Ma for the Early Kalba complex, 253–245 Ma for the Late Kalba complex and 231–225 Ma for the Monastyr complex. Our results for sample KZ-23 (~320 Ma) indicate that Kalba–Narym magmatism may have started already earlier. The youngest Late Permian–Early Mesozoic crystallization ages occur throughout the entire study area and are also found further north in Gorny Altai and in the basement underneath the West Siberian basin (Vladimirov et al., 2001; Wang et al., 2009; Pirajno, 2010; Glorie et al., 2011b). These emplacement ages are interpreted to reflect intraplate magmatism, possibly related to the Siberian and/or Tarim plume activity (e.g. Vladimirov et al., 2008; Pirajno, 2010). This plume activity hypothesis however remains controversial. Alternatively, a model of slab break-off was proposed for the origin of the Late Permian – Triassic granitoids, suggesting that they are derived from mantle wedges that were metamorphosed by earlier subducting crust and magmatic arcs in the CAOB framework (e.g. Yuan et al., 2010; Glorie et al., 2011b).

4.2. Meso-Cenozoic reactivation

The Late Cretaceous AFT cooling ages, obtained in this study confirm earlier reported results in the Altai territory (De Grave and Van den haute, 2002; Yuan et al., 2006; Jolivet et al., 2007; Vassallo et al., 2007; De Grave et al., 2008, 2009). While Yuan et al. (2006) published ~30 AFT ages for the Chinese Altai, just North of the ISZ (Fig. 2), we report the first AFT data obtained for the Kazakh (Rudny) Altai. Our AFT ages range between ~100 and 70 Ma, which corroborates the Chinese Altai AFT data very well. The thermal history models show that these ages do not represent mixing ages between younger and older events, but give evidence of an episode of fast cooling in the (early) Late Cretaceous. We interpret this cooling event as the result of increased uplift and denudation of a Mesozoic Altai orogen. Various signs of Cretaceous regional compression and fault reactivation in the Junggar basin bear witness to tectonic deformation of the Central Asian crust at that time (Allen and Vincent, 1997; Vincent and Allen, 2001; Chikov et al., 2008). The AFT signal also coincides with a major stratigraphic hiatus between the Middle Jurassic and the Late
Cretaceous strata in the Zaysan basin (Delvaux et al., 1996). The driving forces that established this deformation regime are not well understood. Closure of the Mongol-Okhotsk ocean and the ensuing Mongol-Okhotsk orogeny (~140–110 Ma) (Kravchinsky et al., 2002; Cogné et al., 2005) to the East of our study area may have reactivated old fault systems and consequently induced Mesozoic intracontinental deformation in the Altai crust (Novikov, 2002; De Grave et al., 2009). Alternatively, the Cretaceous deformation in Altai can be a far-field response to Cimmerian collisions at the Mesozoic southern Eurasian margin (De Grave et al., 2007).

The thermal history models show that cooling slowed down from about ~90 Ma onwards in the Kalba–Narym terrane (Fig. 5). The ensuing slow cooling of basement rocks corresponds to a Late Mesozoic–Early Cenozoic period of tectonic quiescence and peneplanation in large swaths of the entire CAOB (Dobretsov et al., 1996; Cunningham, 2001). During this time, the intrusives remained approximately at the depth that they had reached after Mesozoic denudation or they slowly cooled further to ambient temperatures at their outcrop position. The thermal history model for sample KZ-18 seems to exhibit a third, subsequent Neogene fast cooling step (from ~25 Ma onwards). Although the significance of this accelerated cooling step is debatable (Ketcham et al., 1999), it is not observed in other thermal history models and might indicate a renewed period of reactivation along the ISZ. Cenozoic Altai uplift is first recorded in the Eocene (South Altai phase, 40–35 Ma) with increased tectonic activity in the middle Oligocene (Narym phase, 30–25 Ma) and in the late Miocene–Pliocene (Tarbagatai phase, 6–4 Ma) as a response to subsidence of the Zaysan basin (Borisov, 1963; Zykin, 1996). In the intramontane basins of the Mongolian Altai, an Oligocene unconformity marks the onset of deformation (Cunningham, 2001). In the Northern Junggar basin, accelerated subsidence and sediment accumulation is recorded during the Eocene–Oligocene and from the Pleistocene onwards (Chen et al., 2011). These observations testify that a Late Cenozoic Altai orogen was initially built during the Oligocene, which corresponds to the timing of the increase in cooling rate, exhibited by the thermal history model for sample KZ-18. As mentioned earlier (sample descriptions), samples KZ-06 and KZ-18 were taken from clearly sheared granites along the ISZ, while sample KZ-23 and KZ-36 were sampled in the Kalba–Narym batholith, further south of the shear zone, where no shear textures were observed. This observation might explain why only the model for sample KZ-18 exhibits increased cooling in the Late Cenozoic. Hence, the cooling signal might be a result of differential movements during a Late Cenozoic period of intensified shear.

The driving forces that triggered the Cenozoic NW-migration of the Junggar microplate and the subsequent subsidence of the Junggar basin are again open to debate but they can be related to India-Eurasia convergence at the southern Eurasian margin (De Grave et al., 2007) and block reorganization within the CAOB edifice.

4.3. Fault kinematics and tectonic stress reconstructions

The obtained stress inversion results constrain a three-step kinematic evolution for the ISZ fault (Figs. 7 and 8). The ductile fabric of the ISZ is indicative of a marked crustal-scale subvertical heterogeneity, with an ENE-WSW orientation. The first brittle palaeostress stage is observed in granitoids associated with the ISZ in the form of fault planes and tectonic breccias which are often affected by chlorite-epidote metasomatism. This specific type of fault-rock interaction is known to develop as a result of intense brittle shearing, brecciation, high fluid flow and water–rock hydrothermal alteration at temperatures between ~200 and ~400 °C (Axen, 1992; Tomita et al., 2002). These brittle stage structures can be related to detachment faulting connected to deeper mylonitic zones (Axen, 1992). They can also appear as exhumed seismogenic zones (Fujimoto et al., 2002) or even occur in fossil oceanic high-temperature fault-hosted hydrothermal vents (Barker et al., 2010). In this case, we favour the hypothesis that the ‘early brittle’ stage reflects deep brittle conditions in the granitoids that may even be contemporaneous with the ductile shear displacements along the ISZ itself.

Fractures associated with the ‘late brittle’ stage are well preserved in the Kalba–Narym granitoids and also affect the ductile fabric of the ISZ. We propose that these were produced by a similar type of stress field as those related to the early brittle stage. The $\sigma_{1max}$ orientation for the late brittle stage is however rotated anticlockwise to an orthogonal direction relative to the fabric of the ISZ and indicates a slightly more compressional regime. This could cor-

Fig. 6. Digital terrain model with indication of our obtained stress tensor data along the ISZ. Map key as in Fig. 4 and stress tensor diagrams as in Fig. 7 (oriented according to the inclined geographical north on the map).
Fig. 7. Fault-slip data and stress inversion. Lower-hemisphere Schmidt stereoplot of the fault-slip data subsets and corresponding stress tensor. Stress symbols show the horizontal stress axes ($S_{\text{Hmax}}$ and $S_{\text{Hmin}}$) in function of the stress ratio $R$. Their length and colour symbolise the horizontal deviatoric stress magnitude, relative to the isotropic stress $\sigma_i$. Orange outward arrows: $\sigma_3$ stress axis, green arrows: $\sigma_2$ stress axis (outward when extensional $\sigma_2 > \sigma_1$ and inward when compressional $\sigma_2 < \sigma_1$), blue inward arrows: $\sigma_1$ axis. The vertical stress $\sigma_v$ is symbolised by a solid circle, orange for extensional regimes $\sigma_1/\sigma_v$, green for strike-slip regimes $\sigma_2/\sigma_v$ or blue for compressional regimes $\sigma_3/\sigma_v$.

The histogram represents the distribution of the weighted misfit function. The uncertainties related to the stress axis determination are plotted as small dots (blue for $\sigma_1$, green for $\sigma_2$, orange for $\sigma_3$), and the distribution of possible $S_{\text{Hmax}}$ orientations is shown on the outer margin of the net, with 5° frequency interval (bars) and 1 σ confidence region (bold red line). fol. = foliations, f.a. = fold axes.
respond to late transcurrent displacements along the ISZ, after the cessation of ductile shearing. The reorientation of the $S_{\text{max}}$ tensor at a higher angle to the ISZ and the change towards a more compressional regime probably reflects rheological strengthening. The resulting more rigid lithosphere along the ISZ is not surprising, given the cessation of ductile shearing, intensive granitoid emplacement and subsequent cooling of the crust at that time. As shown in an extensional context by Morley (2010), $S_{\text{max}}$ trajectories effectively tend to deflect towards parallelism with a relatively weak vertical rock body and they align perpendicular to zones of relatively rigid material. For continental transforms at their early stage of evolution, displacement is commonly distributed over a wide zone (Platt et al., 2008). In the case of the Irtysh shear zone, the large size of the central ductile shear zone and its close association with the granitoids bears witness that if formed within a locally hot crust.

In a later stage, the crust cooled down and deformation became more brittle, focusing on narrow zones that were kept weak due to the presence of fluids. The frequent observation of chlorite-epidote metasomatism along the brittle fault planes, the presence of large base-metal mineralized bodies along the Irtysh shear zone and the widespread magmatic intrusions are clear indicators for high fluid flow in the principal displacement zone. Hence, as for the present-day lithospheric stress along the San-Andreas fault system (Zoback et al., 1987), the horizontal principal compression could have been re-oriented at a high-angle to fault zones that are characterized by very low shear strength. This could explain the apparent anticlockwise rotation of the $S_{\text{max}}$ orientations with time, at the vicinity of the shear zone (near-field stress). In addition, a change in regional far-field stress as a response to a slightly more convergent relative movement between the two fault planes could have happened. This can however not be demonstrated with the data presented here.

The final brittle stage that was observed postdates ISZ related displacements and is compatible with the main (Late Plio-Pleistocene) phase of mountain building in the Altai (De Grave et al., 2009; Chen et al., 2011). The faults observed in the Narym range correspond to Late Cenozoic northward thrusting along the southern Altai belt. Along the ISZ however, a discrete and focused dextral strike-slip reactivation was observed which took place under shallow brittle conditions (unconsolidated breccias, iron-oxide coating). The transpressional regime and NNW–SSE to N–S direction of $S_{\text{max}}$ correspond to existing palaeostress results for the Chuya depression (Delvaux et al., 1995) and Lake Teletskoye (Dehandschutter et al., 2002) further north in the Siberian Altai.

5. Conclusions

Based on the chronology and palaeostress data-sets, presented in this work, the following conclusions can be drawn regarding the tectonic history of the ISZ with emphasis on its formation and reactivation episodes:

1. Carboniferous (~338 Ma and ~320 Ma) zircon U/Pb ages, obtained for the syn- and post-collisional Kalba–Narym intrusives along the edge of the ISZ were interpreted in the

Fig. 8. Synthesis of ductile fabric and fault-slip data subsets with related stress tensors.
framework of the final collision of Siberia with Kazakhstan. The occurrence of older, discordant zircons indicate a limited framework of the final collision of Siberia with Kazakhstan.

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