

## CHAPTER 9. SYNTHESIS

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This final chapter gives a synthesis of the present study. It puts the deformation observed in the different studied regions (discussed in Part II of this study) in an overall model of the deformation along the northern border of the Central Asian Deformation zone, in relation to the sedimentary basin formation. Conclusions are made about the contribution of the present study to tectonic investigations in general.

### 9.1 The study of active deformation in mountainous basement terrains

The tools for studying brittle deformation and active tectonics in heterogeneous basement terrains suffer from several inconveniences. The classical kinematic models for fault growth, propagation and interaction applicable to homogeneous and isotropic elastic media become strongly complicated by anisotropy created by pre-existing weakness zones, absorbing and guiding stress and deformation in a highly variable way. Ages of brittle faults, most commonly constrained indirectly by stratigraphic considerations, are difficult to make in crystalline basement environments where stratigraphic markers are lacking. Distinguishing between active faults related to the prevailing stress regime and inactive faults which may be inherited from past conditions is not always straightforward, and is impossible but with applying a detailed study combining techniques for assessing the surface characteristics of the structures and their characteristics at depth.

Detailed analysis of the morphological features along a supposed active fault using a wide variety of remote sensing data of different resolution and acquisition, can give indications for recent movements. This qualitative approach only provides a first indication for fault activity. It cannot be taken as a final result of the study of fault activity. Further investigations (field studies and geophysical techniques) have to be applied to provide better constrained

information. Possible techniques, applied in this study, are seismic surveys, careful brittle micro-tectonic analysis and radon activity measurements. It has to be noted that these studies cannot be considered individually, as they only give a particular part of information describing the studied fault(s), but combining all observations and results, it is possible to describe a fault in terms of kinematics and sometimes in terms of timing and movement history (chapters 2-4).

A detailed evaluation of the use of brittle micro-structural data in analysing local kinematic characteristics showed that use of fault-slip analysis for paleostress reconstruction should be treated with care. This technique has its limits in polyphase deformed zones, and misinterpretations can be made if special care is not taken for the distinction of structures related to the different phases.

If the regional (remote sensing derived) orientation of a studied structure in the examined exposure is kept in mind, and attention is paid to the (rheologically controlled) expression of the different types of kinematic indicators, as well as their mutual relations (cross-cutting, overprinting, displacing), it is sometimes possible to distinguish the (relatively) most shallow, and therefore presumably most recent micro-tectonic kinematic markers, which in some cases can give an idea about the kinematic behaviour of the macro-scale fault or fault zone. The relation between the landscape morphology and the structures can sometimes give an age constraint to the movement. If the orientation of the principal stress directions (reduced paleostress tensor) responsible for the kinematics of the latest phase of observed movements in a certain exposure can be determined in several zones along the studied structure, the kinematics of that larger scale structure can be estimated. By studying secondary fractures of a fault zone, different conjugated and co-existing fault plane orientations can give a much better constraint on the local stress conditions inherently responsible for the observed fault movements than can the macro-fault which per se has only one main orientation, from which the orientation of the driving forces cannot be deduced. These driving forces are local, and do not necessarily represent the regional stress conditions. This is because the stress state can vary quickly in space due to the absorbing effects of pre-existing structures, simple-shear non-coaxiality and the influence of fault movements in adjoining regions on the orientation of the stress ellipsoid (chapters 4 and 5).

However, it was observed that the horizontal component of the principal compression direction ( $S_{Hmax}$ , which in an Andersonian stress regime corresponds to the  $\sigma_1$  or  $\sigma_2$ , and in a non-Andersonian stress regime to a projection of this in the horizontal plane) in general remains relatively constant in its regional orientation on a km scale (Chapter 6 and 8).

In many cases, however, it was observed that the use of paleostress reconstructions is obstructed by polyphase deformation, block rotations, local stress deviations and other restricting and obscuring parameters. Especially in the high simple-shear environment of northeastern Altai, we observed that local kinematic markers were highly variable and rarely yielded a consequent and stable stress tensor, even if the simultaneity of the faults was probable. The strong strain partitioning and effects of block rotation has a very strong limiting effect of the stress-strain relations in simple-shear conditions. Therefore, it is recommended always to bear in mind the boundary conditions in which to apply paleostress reconstructions, and to evaluate the hypothesis of coaxiality for the study-region (chapter 7).

## 9.2 Kinematics and dynamics of the studied regions

This work contributes to comprehend the active tectonic processes in the northern and poorly studied parts of the Central-Asian Deformation Zone. This zone forms an actively deforming heterogenous and anisotropic region. Remote sensing, structural field mapping and brittle micro-structural fault analysis led to the structural characterisation of the main active fault zones in the northeastern Altai, Sayan and Tuva deformation zones, and their contribution in formation and evolution of sedimentary basins in the transpressional tectonic settings. The structural and kinematic characteristics of several studied Tertiary (Tuva) and Quaternary (Altai) sedimentary basins allowed us to constrain the deformation styles in these regions for these periods, completing the surface observations with information of the sub-surface structure.

The northern part of the Central Asian Deformation Zone is characterised by an overall transpressional deformation with a sub-meridionally trending shortening direction. In dynamic terms, the  $S_{Hmax}$  has a fan shape with a trend ranging from northwesterly to northeasterly. There is a propagation of active tectonism towards the north, expressed by a northward rejuvenation of the faults, a decrease in seismic activity and in qualitative tectonic expression of deformation, expressed by morphology.

These observations indicate that the deformation in this region is driven from the south, as suggested by several authors for other regions (chapter 1). The link between the tectonic activity in the Himalayan collision zone and its foreland belts such as the Tien-Shan is widely accepted. The direct relation between deformation 2500 km into the foreland and the collision zone is less obvious. However, the kinematic indications regarding timing and fault movements in the studied area suggest this relation. It also seems that the exact disposition of the main morphotectonic elements could be influenced by lithospheric and even asthenospheric processes, as suggested by seismic velocity information (§ 1.3.6). A decoupling between the crust and the mantle could account for lithospheric and crustal buckling at different wavelengths, explaining the observed basin-mountain range alteration.

Although the crustal shortening, resulting in a sub-meridional  $S_{Hmax}$ , is the driving mechanism for the observed upper crustal deformation, we showed how the local tectonic regime can vary rapidly in time and space. In other words, the deformation is partitioned over the region, resulting in a high variable tectonic style, occurring even over a small zone, such as the study area. The various expressions of the shortening will be briefly discussed now.

### 9.2.1 Wrench deformation

Strike-slip and oblique-slip faulting affected the area since the onset of Cenozoic deformation in the region, in the Late Pliocene-Pleistocene. Figure 9.1a shows the main faults which were active during the earlier phase of deformation in the region, resulting in inversion of the basins in the south and transpressional movements in the Teletsk region. The initial opening of the southern Teletsk basin was directly controlled by pull-apart along a releasing bend in the northwesterly trending Teletsk-Bashkauss right-lateral reactivated strike-slip fault. This structure dies out against the northeasterly trending reactivated West-Sayan left-lateral

oblique-slip fault, forming the frontal zone of active deformation in the Himalayan foreland (chapter 6 and chapter 8).

The main active movements directly related to the contemporaneous seismicity occur in Mongolian Altai, as indicated by earthquake epicentre locations, remotely sensed geomorphology and ages of sedimentary depocentres. The northern terminations of these transpressional strike-slip faults are located in the Shapshal region and the Chulyshman plateau. We showed how the main part of strike-slip accommodation in northeastern Altai occurs along northwesterly reactivated fault systems (Teletsk-Bashkauss and Chulyshman fault) and sub-latitudinal trending sinistral faults, delimiting rotating blocks in a simple-shear setting (chapter 7 and figure 9.1b).

The termination of the Shapshal wrench fault occurs by a change in tectonic regime from strike-slip to thrust. North from the Ureg-Nuur basin, the change in orientation from NNW to WNW and back to NW results in the accommodation of shortening by mainly reverse faulting. Neotectonic deformation along the fault proper is stopped by its contact with the South-Teletsk fault, accommodating the eastwards opening of the Teletsk basin by right-lateral movement on northeast trending planes (chapter 7).

The different movements along sub-parallel faults (Shapshal and Chulyshman) result in the complex block structure in between (fig. 9.1b). Rotations inside the blocks attest for the formation of local narrow sub-meridionally trending extensional basins (chapter 1 and 7). The wrench faults also control the location of the Teletsk basin, as it lays in the direct continuation of the zone, at its contact with the West-Sayan fault zone (chapter 6). This means that local stresses strongly vary in order for the observed structures to develop coevally.

Towards the East, wrench deformation still occurs along the main fault zones, but its contribution to the overall deformation is strongly diminished, due to the different trends of the reactivated basement structure anisotropies, here forming a higher angle with the overall shortening direction (fig. 1.11).

### 9.2.2 Contractional deformation

The main contractional deformation is expressed as a component of the overall shortening, partitioned between strike-slip, reverse, and oblique-slip movements. Due to the overall transpressional settings, contractional features occur virtually all over the studied area. They are most prominent in the Tuva and West-Sayan zone, where the main sub-latitudinal to northeasterly trending neotectonic features develop as pop-up transpressional flower structures (fig. 9.1 and chapter 8).

The northern terminations of the large active NNW trending strike-slip systems in southern Altai mainly occur by a trend change and a transition from wrench to reverse faulting. An example of such a system is the Shapshal system. Other examples are the Kurai and South-Chuya systems that actively act as reverse ramp-basin bounding faults of the Chuya depression (fig. 9.1 and also figs. 1.10 and 1.12).

### 9.2.3 Extensional basin formation

The Teletsk basin on the border between the Altai and Sayan mountains, allows to conceive a deformation style which is highly variable in time and space. Quantitative indications are presented for the polyphase evolution of the Teletsk basin, with a change of transpressional to transtensional tectonics, due to a rotation of the stress tensor induced by uplift. The first phase, occurring in oblique strike-slip transpressional settings, induced uplift of the region and pull-apart opening of the sub-basins (fig. 9.1a and fig. 6.32). First, formation of the southern basin occurred in pull-apart settings by right-lateral reactivation of the Teletsk-Bashkauss shear zone, in the Pleistocene. Propagation of deformation to the north, induced by a subsequent reactivation of the West-Sayan shear zone, opened the northern basin, in the late Pleistocene. This occurred with a horizontal and sub-longitudinal oriented  $\sigma_1$ . Due to the oblique-slip related uplift, vertical stress became more important, and the strike-slip related basins currently evolve in a pure tensional stress regime with continuing extensional opening of the basin, in the Holocene (fig. 9.1b and fig. 6.32). This means that the  $\sigma_1$  turned from its original horizontal position to the current vertical position. E-W extension was possible at the locality of the Teletsk basin, because of the releasing bend in the Teletsk-Bashkauss shear zone, the occurrence of the West-Sayan sinistral fault, and because the Shapshal fault in the East, which died out as an active contractional fault, did no longer hamper the eastward escape of the eastern block of the Teletsk basin (fig. 9.1b).

This evolution model attests for the superposition of extension on transpression in a very short time (Late-Pleistocene to Holocene) induced by a rotation of the stress state due to transpressional movements on the controlling faults, and determined by the specific geometry of the regional structural grain (chapters 6 and 7).

These conclusions have been quantitatively supported by the analysis of brittle fault characteristics and the distinction of a relative chronology related to the faulting style, in combination with the analysis of high resolution seismic lines allowing for relatively confining the different deformation types in time.

A first attempt to characterise and distinguish active faults in basement terrains by their radon and mercury gas characteristics was applied to the West-Sayan fault. The results of this study showed that although uncertainties concerning the fluid circulation and fault permeability obstruct a linear correlation between fault activity and Rn and Hg activity, their characteristics in some cases can provide secondary information concerning fault activity (chapter 6).

### 9.2.4 Differences between Altai and Sayan-Tuva

The western zone of the study region (Altai) is much more affected by simple-shear related wrench deformation and associated block rotations than the eastern zone (Sayan-Tuva; chapters 7 and 8). We attribute the formation of the N-S oriented narrow graben to this tectonic style, where they form in the local zones of extension related to the block rotations. Those basins formed as late as the Pleistocene and continue their development at present (fig. 9.1b).

The eastern zone (Sayan-Tuva) bears a smaller strike-slip component in its deformation, and behaves more in a pure-shear way of range uplift between more stable basins. Basin formation started well earlier in the East (Tuva) than in the West (Altai), as attest the Tertiary lacustrine and clastic sediments. The current tectonic regime is compatible and of the same style as the Post-Neogene deformation, responsible for the uplift of the studied ranges (as observed in the field). Deformation in this area is more limited to the sub-latitudinal trend, and narrow N-S oriented graben do not develop here as they do in northeast Altai (fig. 9.1). The absence of strong wrench faulting is the reason for this difference. From the one side it prevents the transpressional pull-apart basin formation, and from the other side the block rotations, responsible for local N-S graben formation, is much more limited. In Tuva-Sayan, the basins are mainly inherited structures of tectonic quiescence, up till now resistant to uplift and deformation (chapter 8).

### 9.2.5 Early structural evolution of extensional basin

The general two-phased evolution of the Teletsk basin, as discussed in the previous paragraphs, can be regarded as a possible generality for the initiation of 'passive' rift basins, where localised upper crustal extension, driven by far-field stresses, is the first expression of rifting. Depending on whether or not extension will continue to the phase where the whole crust will be affected and lithospheric processes will take over the deformation, the presented example can be a general example for embryonic passive rifts. In that case, early strike-slip or oblique-slip reactivation of basement anisotropies in a favourable stress field generates en-echelon full-graben separated by wrench controlled transfer zones, evolving in several steps. Ongoing extension and the rotation of  $\sigma_1$  can cause one border fault to become the leading border fault, progressively getting curvilinear and listric, by alliance of wide-angle pre-existing wrench faults. The resulting separated half-graben then tend to merge and from the moment on that the whole crust is affected by the extension, a rift composed by separated basic units is born (chapter 5 and 6).

### 9.2.6 Concluding remarks

Lateral forces induced by buoyancy differences as a result of rheological diversity between the Altai lithosphere and the BRZ-Hangai lithosphere could contribute to the stress state in the crust of the study area. The (although highly uncertain) differences in crustal thickness between Altai and Sayan (60 and 50 km), could be responsible for gravitational collapse in the former (overthickened crust), contributing to the N-S graben formation, and the absence of such structures in the latter.

Upper crustal extension should not necessarily be taken as an expression of whole-crust extension. The extremely small initial width of the graben suggest that the structures are confined to the upper crust, and there are no indications for the observed extensional features to affect the whole crust. The upper-crustal extension is a result and an expression of the overall crustal shortening in the highly heterogenous area, resulting in local extensional zones. This is due to a horizontal and vertical variability in the stress field.

The variations in stress regimes between the eastern and western parts of the study area, based on fault-slip inversions, indicate a difference between both regions, more compressional in the east and more strike-slip in the west. This could be partially influenced by crustal thickness variations. However, we believe that the trend of the active structural grain, highly influenced by the basement structural grain, mostly determines the style of tectonism. The differences between both regions can be caused by the orientation of the pre-existing structural grain relative to the present shortening direction, which occurs at a much higher angle in the East than in the West.