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Structural evolution of the Teletsk graben (Russian Altai)

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Abstract

Lake Teletskoye in the northeastern part of the Altai mountain range has attracted the attention of geo-scientists for a long time, because it fills an impressive tectonic depression. The lake is 77 km long and 4 km wide, and it has a maximum water depth of 325 m. The vertical offset of the basement surface is up to 3000 m. A multidisciplinary study of the Teletsk graben was carried out during the last few years, including satellite image and air photo analysis, bathymetric-, structural- and geomorphological mapping, high-resolution seismic profiling and seismic refraction. The structural study revealed that reactivation of preexisting weak basement zones is important in controlling the basin formation. These zones separate different tectonic terranes at the contact of which the Teletsk graben developed. This study identifies the significance of the basin in the regional neotectonic context. It shows that the major vertical movements are restricted to the basin itself, but do not characterize the whole region. Outside of the basin, recent tectonic structures have the same pattern as adjacent areas of Northeast Altai and West-Sayan. Quaternary glaciations have had no major influence on the basin formation. Two stages of faulting are identified. First, transpressive movements restricted to discrete (reactivated) fault zones controlled the opening of the basin. In the second stage, normal faulting is dominant and is responsible for the modern basin outline. An echo-sounding survey led to the recognition of several morphological characteristics of the lake bottom. In the southern part, the uppermost sediments seem slightly disturbed, whereas further north, transverse ridges and slope breaks are increasingly common. The deepest part of the lake is located in a highly disturbed zone of normal fault-bounded blocks. The structural difference between the southern and northern subbasins is supported by the interpretation of a deep seismic refraction profile which indicates a substantial increase of basement isochores in the area where the reactivated Teletsk (Paleozoic) shear zone crosses the lake. Correlation of high-resolution seismic profiles suggests that the Teletsk graben started to evolve during the Pleistocene, and that its present shape was formed in two stages. The first stage was responsible for the opening of the southern basin. It probably started in the Middle Pleistocene. A second kinematic stage induced by a sinistral reactivation of the NE striking West-Sayan fault initiated the opening of the different segments of the northern subbasin due to opposite movements between the reactivated Teletsk and West-Sayan faults. This second stage was active after the end of Late Pleistocene glaciations and during the Holocene. The recent lateral extension and the related N–S-trending normal faults result from a change in tectonic regime, with related

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extensional movements along the main reactivated fault zones. These recent movements result in the lateral escape of the lake borders and the collapse of the area between them.

Keywords: Neotectonics; Seismics; Structural basin evolution; Altai; Lake Teletskoye

1. Introduction

Active crustal deformation in Central Asia affects a wide region between the Himalayas and the Siberian craton. Major actively forming mountain ranges are the Tien Shan, Hangai, Altai and Sayan ranges (Fig. 1). Central Asia is characterized by intense strike–slip faulting (e.g. Altyn Tagh fault, Bolnai fault; Tapponnier and Molnar, 1979) and transpressional faulting (e.g. Mongolian Altai; Cunningham et al., 1996). Burov et al. (1993) proposed processes of lithospheric folding to produce the uplift of the Tien Shan and subsidence of bordering basins (e.g. Turfan depression in NW China). Doming of the crust occurs in the Hangai uplift (Schlupp, 1996; Zorin et al., 1993). The resulting ranges have summits over 3000 m high, although they are situated from 500 to 2000 km north of the Indus Suture, the closest plate boundary. The propagation of stress and strain through the lithosphere from the Himalayan orogeny towards the north is often invoked as the main driving mechanism for this large-scale mountain-building activity (e.g. Molnar and Tapponnier, 1975, 1977; Dobretsov et al., 1996). After the initiation of the Indo–Eurasian collision in the Eocene, this mountain building started in the Late Oligocene in Tien Shan (Dobretsov et al.,

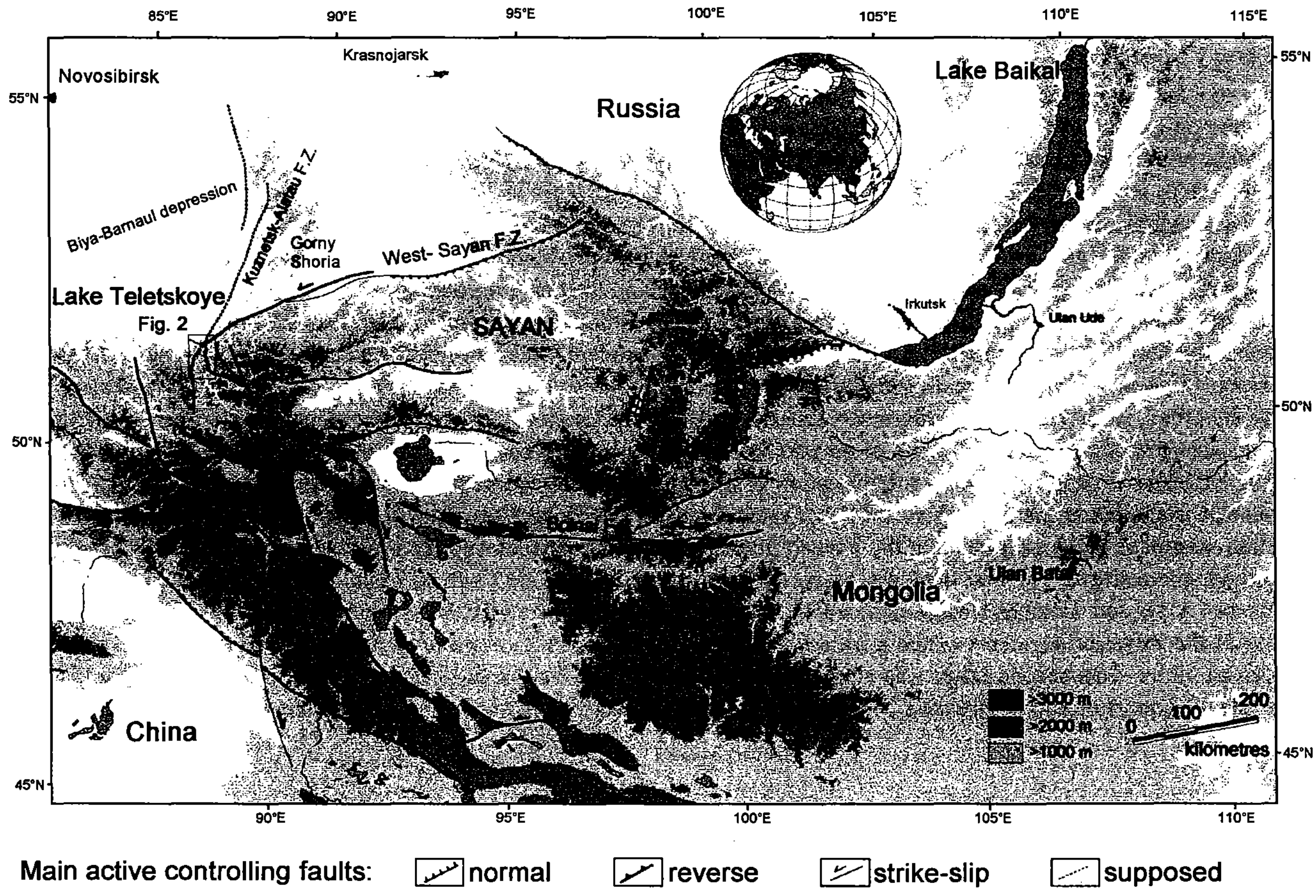


Fig. 1. Topographic map showing the Altai–Sayan region in Central Asia.

1996; Molnar and Tapponnier, 1975). Stress propagation led to the northward migration of the deformation, which reached the Altai region as recently as the Pliocene (Dobretsov et al., 1996). Apart from far field collision-induced stresses, mantle plume activity may have caused lithospheric doming and perturbations to the regional stress field (Rasskazov, 1994; Windley and Allen, 1993; Dobretsov et al., 1996). The present-day stress field in Central Asia varies from compressional in the Tien Shan to transpressional in the Altai and Sayan ranges to transtensional and tensional in the Baikal Rift Zone (Petit et al., 1996; Delvaux et al., 1997).

Regional physiography in the Altai–Sayan region consists of an alternation of high ranges with intermontane basins. The formation of the ranges is controlled by thrust, reverse and transpressional faulting on the one hand (Ufimtsev, 1990), and possibly by large-scale lithosphere folding on the other hand (Nikishin et al., 1993). This alternation reflects the rheological variations of lithospheric structures and their specific response to the imposed regional stress regime (Burov et al., 1993). Large island arc and micro-continental blocks behave more rigidly and become aseismic basins and plateaus filled with Neogene continental deposits (Cunningham et al., 1996; Dergunov, 1979). In between those blocks, inherited long-lived shear zones and Paleozoic sutures are reactivated. These movements control the formation and development of the mountainous fold-and-thrust belts (Cobbold and Davy, 1988; Tapponnier and Molnar, 1979). Topographic changes also reflect changes in crustal thickness (Cobbold et al., 1993), the absolute value of which remains debated.

The Altai is a NW-trending mountain range that fans out at its northwestern end into separate ridges trending E–W in the western part to N–S in the eastern part. They are confined by E–W-trending thrusts and NW-trending strike–slip and transpressive reactivated Paleozoic shear zones (Fig. 1). Inside the ranges, several intramontane sedimentary depressions exist, developing mostly as strike–slip to full ramp basins (Delvaux et al., 1995b; Schlupp, 1996). Only at the northern termination of the Altai, in the vicinity of the Biya–Barnaul depression (Fig. 1), are local extensional basins developed (Lukina, 1996; Dobretsov et al., 1996; Dergunov, 1972) which in some cases are successors of strike–slip basins (Dehandschutter et al., 1997). The tectonic activity of the Altai is illustrated by the high seismicity in the southern (Mongolian and Chinese) Altai, with numerous earthquakes of magnitude 4 and more (Lukina, 1996). The major earthquakes occur along the fault zones bordering the ranges (Shapshal fault zone, Tsagan fault zone, Kurai fault zone). Despite this high seismic activity of the southern Altai, the Russian part of the Altai did not undergo significant earthquakes since the beginning of this century, and currently behaves aseismic. There are only indications for numerous historical earthquakes of $M>6$ during the last 200 years (Lukina, 1996), and geological indications for paleoseismic activity (Deviatkin, 1965; Bondarenko et al., 1968; Dergunov, 1972; Delvaux et al., 1995a).

In the northeastern extremity of the Altai, at the junction between two different structural terranes, the Lake Teletskoye depression develops as an extensional basin (Fig. 2). The lake basin has a total length of 77 km. It is composed of a N–S-oriented graben 50 km long and an E–W-trending lake segment 27 km long. The average width of the N–S-trending basin is about 4 km. With its 325-m water depth and its 40 billion m^3 of water, Lake Teletskoye is the deepest natural lake in Russia after Lake Baikal. In some aspects, the geometry of the basin is similar to the Baikal-type continental rifts, but the scale is significantly smaller and it is a much younger tectonic feature (Table 1). It is bordered by steep slopes, extending the basin for 500 m in the north to over 2000 m in the southern part of the lake. Considering the water depth and the sedimentary fill reaching more than 800 m in thickness

Table 1
Dimensions and parameters of the Teletsk basin, compared to the Baikal basin

	Lake Teletskoye	Lake Baikal
Total length	70 km	600 km
Total width	4 km	40 km
Water volume	40 km^3	23,000 km^3
Maximum water depth	335 m	1637 m
Maximum sediment infill	~ 1 km	~ 10 km
Maximum aerial depth	2 km	2 km
Maximum depth to basement	>3 km	>13 km
Length/width	18	15
Width/water depth	12	25
Width/total depth	1.5	3
Total depth/sedimentary thickness	3	1.3

(Seleznev et al., 1995), the total vertical displacement of the pre-Cenozoic planation surface recognized for the whole Altai (Deev et al., 1995) ranges from 600 m in the north to more than 3000 m in the south of the lake.

Lake Teletskoye is the largest of several narrow, sub-meridionally oriented graben in the northeastern part of the Altai. The morphology and fault pattern of these basins were initially compared to rift structures like the Rhine graben (Bondarenko, 1967; Bondarenko et al., 1968). Later, the Teletsk graben was interpreted as an extension zone between two main strike–slip faults (Lukina, 1991; Delvaux et al., 1995a). In this paper, we propose a detailed model for the tectonic evolution of the basin based on new geophysical, structural and geomorphological data.

2. Geological settings

The basement geology of Lake Teletskoye is extensively discussed in several papers (Buslov and Sintubin, 1995; Sintubin et al., 1995; Buslov et al., 1993). Nevertheless, it is useful to discuss some of the major structures since they are important for understanding the Cenozoic basin development, active fault geometry and modern fault kinematics.

The Teletsk basin developed in the contact zone between two Paleozoic blocks (Fig. 2) with specific characteristics and geodynamic significance (Buslov and Sintubin, 1995; Dobretsov et al., 1995a; Berzin et al., 1994). To the northwest of the lake, the *Gorno-Altay terrane* consists of Vendian and Cambrian volcano-sedimentary rocks. They were formed during Late Proterozoic (Vendian) island-arc magmatism, and structurally deformed during early Paleozoic accretionary wedge formation (Buslov et al., 1993). The eastern shores of the lake belong to the *West-Sayan terrane.* It consists of two units. In the southwest, the Teletsk Unit is composed of Riphean gneisses, intruded by the middle Paleozoic Altyntauss granites. The northeastern unit of the West-Sayan terrane is composed of Cambrian turbidites intruded by Devonian granite–gneiss domes. The contact between both units was established during Devonian–Carboniferous strike–slip movements along the *Shapshal* (Fig. 1) and *Teletsk* (Fig. 2) shear zones. The mylonitic structure of the Teletsk shear zone runs subparallel to the lake trend in the southern part, but bends to the west and crosses the lake in the central part. The Paleozoic significance of this shear zone is discussed by Buslov and Sintubin (1995).

The Gorno-Altay terrane was joined with the West-Sayan terrane by left-lateral movements along the West-Sayan shear zone (Fig. 2). This is a 6–8-km-wide movement zone which is supposed to be a segment of the Kurai–Sayan–Kuznetsk suture zone (Zoneshain et al., 1990; Sherman et al., 1996). It is traceable for more than 1000 km to the northeast and to the south, and underwent active collision tectonics during late Paleozoic (Dobretsov et al., 1995b). It forms one of the main terrane boundaries within the Altaid tectonic collage, and would be responsible for several hundred kilometres of lateral displacement (Berzin et al., 1994; Sengör et al., 1993). In the northwestern part of the West-Sayan terrane, the West-Sayan shear zone cuts the N30W-oriented Teletsk shear zone, indicating its younger age.

The Teletsk shear zone separates island-arc and fore-arc complexes of the West-Sayan terrane from the Altai micro-continent (Dobretsov et al., 1995b).

In the southeastern part of the lake, in the Kyga valley (Fig. 2), branches of the Shapshal shear zone reach the basin. The Shapshal shear zone forms a main Paleozoic lateral movement zone, displaying blocks of sheared eclogites, granitoids, metasediments and mylonitic ophiolites. It is believed to have experienced several stages of ductile reactivation, the last of which seems to have been late Paleozoic sinistral transpression on its northern segments. Several branches of this shear zone are presently active. The focal mechanisms of recent earthquakes on the southern part of this fault, in Mongolia, indicate dextral transpression. Field observations of the northern segment indicate a transpressive stress with compressive strain for the Quaternary movements, indicated by major reverse faults displacing moraine and cutting Late Pleistocene glacial cirques.

These three shear zones are major, long-lived continental wrench systems responsible for the most important Paleozoic tectonic movements in the region (Dobretsov et al., 1995a). As suture zones, they are supposed to cut at least the whole crust, possibly even a part of the lithospheric mantle.

Another structure which obviously affects the morphology of the Teletsk basin surroundings is

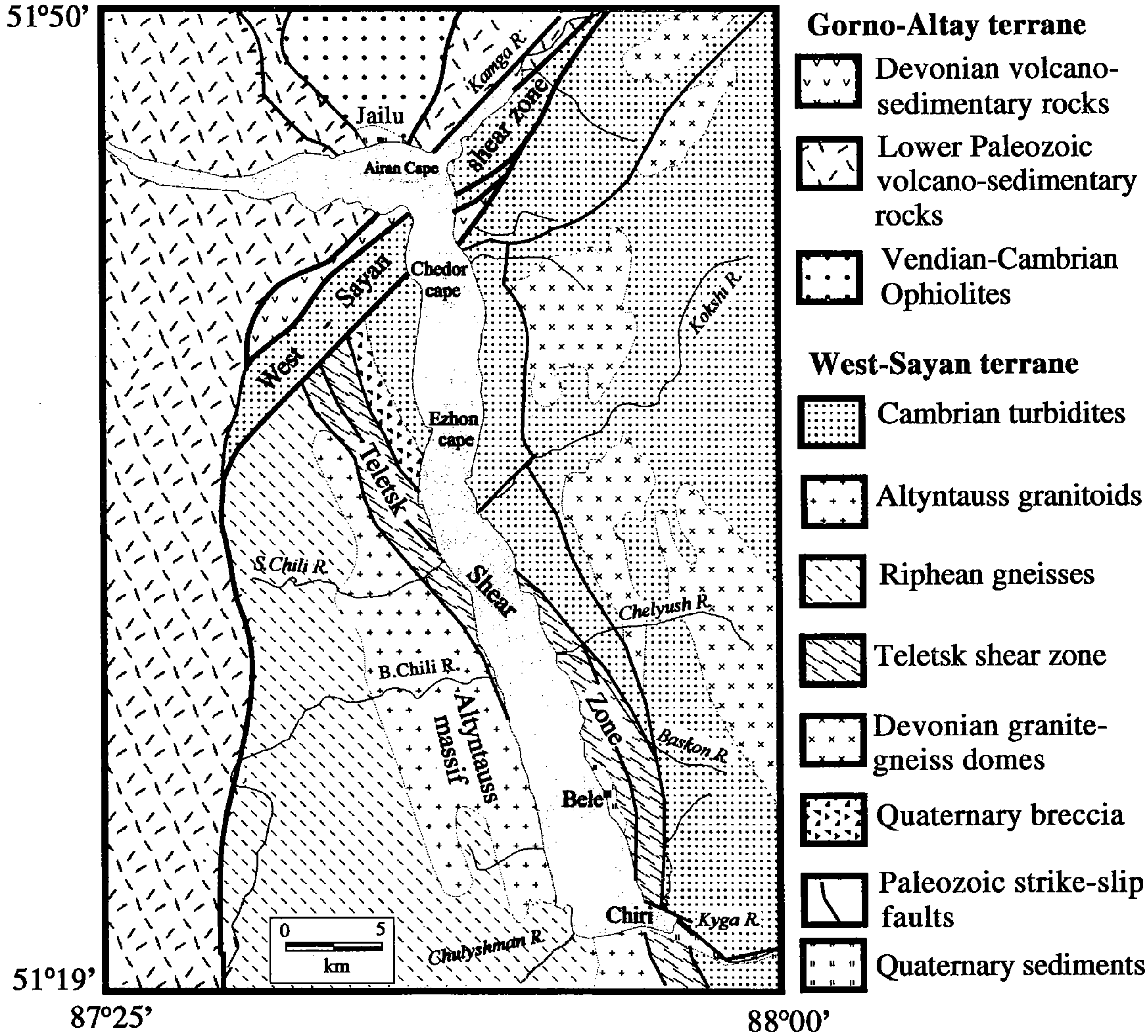


Fig. 2. Geological map of the Teletsk basin region.

the Kuznetsk–Alatau fault zone (Fig. 1). It strikes NNE, and reaches the northern end of the Teletsk basin, where it joins the West-Sayan zone. According to Dobretsov et al. (1996) and Berzin et al. (1994), this fault zone was important for Paleozoic post-Devonian tectonic movements. It is traceable from the Teletsk basin to the north for over 500 km, along the Kuznetsk–Alatau mountainous region in Siberia (Fig. 1). Its current tectonic activity as well as its importance for the formation of the Teletsk basin are debated, and will be discussed in this paper.

3. Active tectonics in the Teletsk region

3.1. Methodology

Recognition of the main morphological features related to the recent tectonic activity in the region was obtained from analysis of topographic maps (1:50,000 scale), aerial photographs (1:35,000 scale) and satellite images at different resolution (SPOT, LANDSAT MSS and Russian satellites).

Analysis of the morphology of the lake basin floor was done by bathymetric mapping. Between 1994 and

1998, a dense network of echo-sounding profiles recording the water depth was established in order to compile a detailed bathymetric map of Lake Teletskoye. In total, 345 profiles were shot, yielding an orthorhombic profile grid with an average interval of less than 1 km. These profiles were used to construct a general bathymetric map on 1:100,000 scale using a 250-m resolution grid obtained by Kriging interpolation of the irregularly distributed depth points.

Based on the image of the bottom morphology obtained from this relatively scarce grid, several zones were selected for more detailed profiling with an average interval of about 250 m. Interpolation of these profiles led to a grid with a resolution of 60 m. In this way, the general bathymetric features of the lake's bottom were highlighted. In some specific zones, a detailed grid of 30-m resolution was used to analyse and interpret gentler structural features (Fig. 6).

A general Digital Elevation Model was constructed from digitized contours of 1:100,000 scale topographic maps. A combination of the elevation models for topography and bathymetry led to a digital terrane model of the area, which was used as a basis for analysis and presentation of the results (Figs. 4–8).

A detailed field study of brittle micro- and mesostructures around the lake basin was carried out in order to determine the kinematics of fault movements responsible for basin formation. Microstructural data were analysed by the graphical and statistical computer-aided method TENSOR (Delvaux, 1993) for the investigation of brittle deformation. It mainly consists of a classification of kinematic data and of a paleostress reconstruction based on the inversion of fault slip data (Angelier, 1989, 1994; Bott, 1959). In order to obtain reliable results, it is important to use as much data with a large orientation distribution as possible (Delvaux et al., 1997).

For most outcrops, fault slip data could be grouped in classes from which the statistical mean movement plane with associated slip could be calculated. For the reconstruction of the kinematic history of fault movements, it was important to know the statistical slip on the main movement planes on micro-scale and to compare them to the structures observed on macro-scale.

A detailed seismic survey was performed over the last few years, using different techniques and resolutions. A deep seismic refraction profile provided arguments for the distinction between the different sedimentary sequences and related geological formations. The first results of this study are described in a previous publication (Seleznev et al., 1995). This work mainly determines the thickness of the sedimentary fill by means of multilayer modelling of apparent wave velocities (estimated to be up to 2 km/s for seismic wave velocities in sedimentary rocks and more than 5 km/s in crystalline basement) (Emanov and Kaptsov, 1992; Seleznev, 1977).

In total, 120-km one-channel seismic reflection profiles penetrating about 900 m were used to study the structure of the sediment load inside the basin. Preliminary interpretation of these sections was done by Seleznev et al. (1995).

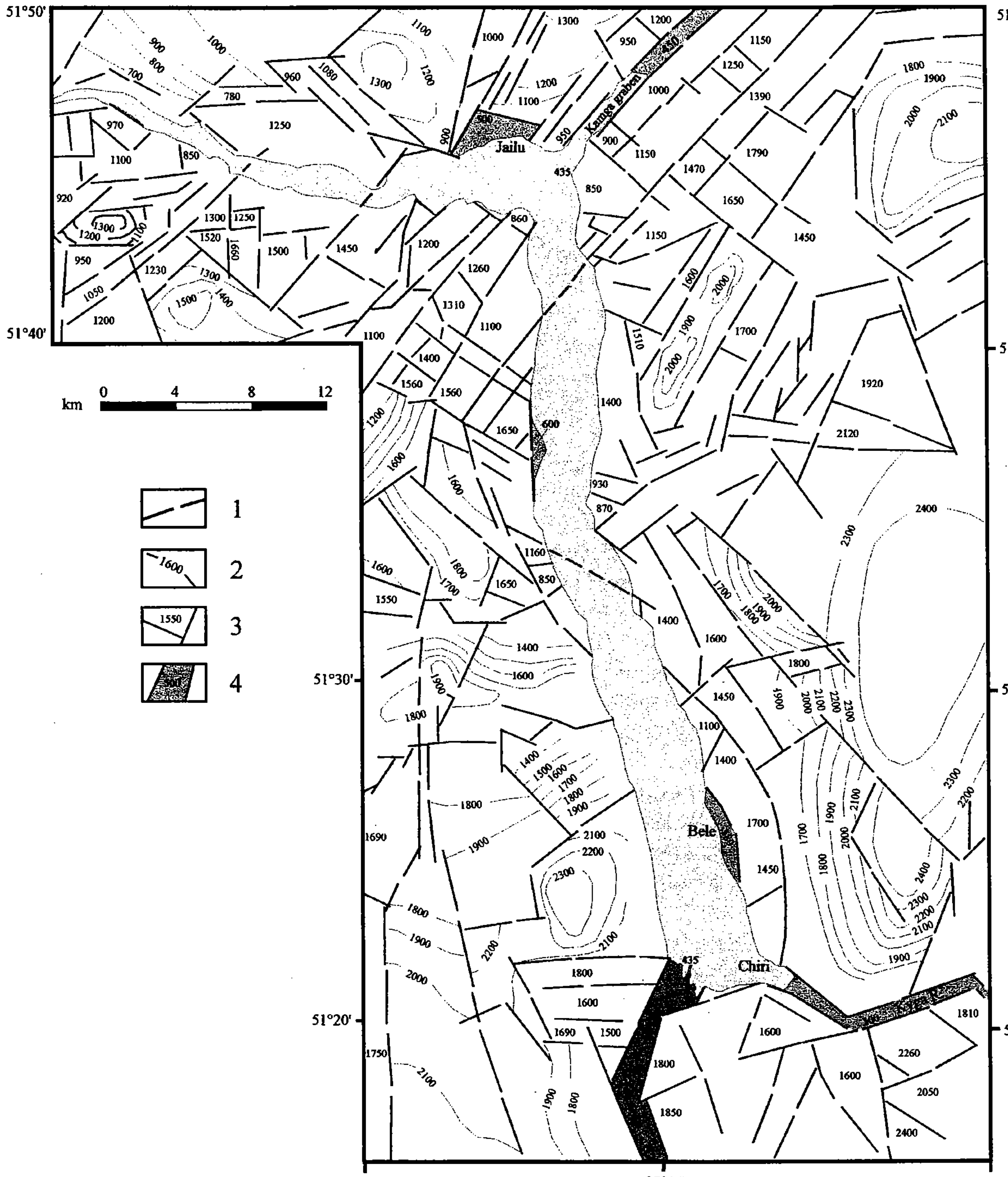
High-resolution one-channel seismic reflection profiling was carried out to study in more detail the top few hundred metres of sediments. The penetration depth reached 300 m in the southern part, but decreased towards the north. A grid of 91 profiles with a total length of 340 km was created both subperpendicular and parallel to the lake orientation. This relatively dense net allowed correlation between the observed faults and construction of a structural map of the sediments.

3.2. Morphotectonics of the basin surroundings

The present-day mountain belt in the Altai began to form in the Late Pliocene (Delvaux et al., 1995b; Dobretsov et al., 1996). Fig. 3 shows the present position of the remnants of a peneplane surface. This flattened surface of planation was formed in the Altai region in the Cretaceous–Paleogene (Deviatkin, 1965). After the onset of recent tectonic movements in the Middle Pleistocene, slight folding and intensive block movements disrupted this surface. Remnants of this surface occur around Lake Teletskoye as flattened relief surfaces less than 1–2 km in size without any sediment cover.

Correlation of these surfaces allowed us to estimate recent vertical displacements between adjacent tectonic blocks. These neotectonic vertical movements reach 3 km in the southwest of the lake and range from 700 to 1200 m on the flanks of the basin. Farther away from the basin, relative vertical movements between adjacent blocks are less than 200–300 m.

Recent faults of different trends are important for the morphotectonic structure of the area. They coin-



1 - recent faults
2 - isolines of the remnants of the peneplanation surface (m)
3 - neotectonic blocks with nearly flat surface
4 - accumulative surface of downfaulted neotectonic blocks

Fig. 3. Neotectonic features in the Teletsk area.

cide with the main basement structures defined by Paleozoic shear zones. Dominant faults in the northern part of the area trend northeast, parallel to the West-Sayan fault zone. Branches of the NW-trending Shapshal fault zone dominate the southeastern part of the lake, and N–S-trending faults control the development of small ranges and drainage network to the southwest of the basin.

The reactivated West-Sayan fault zone is composed of rectangular blocks with symmetric block faulting and small graben formed along the central axis of the Kamga valley (Fig. 3). Both the morphotectonic structure of the fault zone and disrupted alluvial fans on the lakeshore provide evidence for Quaternary sinistral strike–slip movements along the West-Sayan fault zone.

To the southwest of the lake, on the Altyntauss massif, relatively large neotectonic blocks have small displacements and some borders can be confused with nonactive faults in the basement that have been eroded by strong rivers. This flank of the lake depression seems to be the most stable. Its geology is characterized by a granitic massif (Altyntauss massif, Fig. 2). The straight western flank of the southern basin has the most impressive relief: the slope of the lake is 1700 m high and the total depth of the depression (with water and sediments)—about 3 km.

Southeast of the lake, the top of the bordering range (up to 2500 m above sea level) is more or less stable, but towards the lake, the altitudes decrease dramatically due to intensive block faulting. This faulting is due to the reactivation of NW- and NNW-trending faults, which are dominant on this flank of the southern basin. The morphotectonic structure of this area was previously interpreted as resulting from eastward lateral escape of the eastern flank of the basin (Delvaux et al., 1995a).

The region which is south of the lake is more typical of the eastern Altai region: Neotectonic faulting is hardly identifiable due to small displacements between blocks. In general, the area appears as a high mountain plateau eroded by several rivers with deep canyons.

The surroundings of the EW-trending part of the lake (in the north) are less tectonically active and the block faulting occurs due to passive response to movements along the West-Sayan fault zone. NE-trending faults are most important with minor activity on N-, NW- and EW-trending faults. Besides the West-Sayan fault zone, the Kuznetsk–Alatau zone (Fig. 1) with a NNE trend is identified on the northern flank near the Jailu terrace (Fig. 3). Active tectonic activity of this fault zone is very limited, but the junction between the West-Sayan and the Kuznetsk–Alatau fault zones is situated in the middle of the lake in a highly faulted area (see further).

Recent faulting south of the EW-trending part of the lake is more intensive, while the northern flank looks morphologically like the low mountains of Gorny Shoria to the north (Fig. 1). North of the lake, intense faulting becomes rare, and the altitudes of flattened ridges are less than 1300 m.

In this general morphotectonic context, the basin can be divided into different neotectonic domains. The southern subbasin shows the most intensive vertical displacements. The northern subbasins and EW-trending part of the lake depression accommodate the sinistral strike–slip of the West-Sayan fault zone.

The observed fault planes bordering the lake basin dip towards the basin at 60–80° and morphologically occur as normal faults. It is characteristic for the area that important recent faults occur only very close to the basin. This suggests a shallow crustal deformation in the close vicinity of the Teletsk graben.

Due to the lack of onshore Cenozoic sediments in the region, the relative age of deformation events can only be estimated by analysis of the relief structure. The oldest relief elements are remnants of a peneplane surface, which existed up to the Late Pliocene when the neotectonic deformation started. The composition of sediments of the lower Biya River (flowing out of Lake Teletskoye), and of small depressions controlled by the main Shapshal fault indicates that the deformations started in the Late Pliocene. An important tectonic stage of the late Neogene—early Quaternary is marked by specific coarse sediments in other parts of the Altai. None of them are present around Lake Teletskoye, but it is probable that an initial basin already formed by this time.

Typical relief elements and glacial deposits are observed around the lake at altitudes higher than 900–1000 m above sea level. They are associated with Middle Pleistocene glaciations (Vysotsky, 1997). Close to the lake basin, the border fault scarps disrupt these deposits.

Along the Kyga valley (Fig. 2), glacial cirques of Late Pleistocene age are displaced by fault movements along ENE-trending faults. This indicates that the main stage of faulting causing the opening of the Kyga basin took place after the end of the last glacial period in this region, probably not older than 20 ka (Deviatkin, 1965).

3.3. Morphology of the border faults

The general morphotectonic structure and rift morphology of the basin can be illustrated by topographic profiles running perpendicular to the basin. Fig. 4 shows some examples of the graben morphology of the border faults. Profile 1 illustrates the symmetric graben morphology of the NE-trending Kamga graben with down-faulted border faults. It forms part of the reactivated West-Sayan fault zone. A similar picture can be observed in the NW-trending Kyga graben in the southeastern limit of the lake. It suggests extensional tectonic activity not only in the N–S-trending part of the basin, but also on the NE- and NW-trending edges. Profile 2 illustrates the morphology of the northern-, N–S-trending basins. The eastern flank is straight and steep, while the western flank is more eroded and shows more important intermediate steps. Profiles 3 and 4 crosscut the southern-, NNW-trending basin. On profile 3, a transitional situation is observed with relative intensely faulted slopes on both sides, but with a tilt of the western flank. Conversely, profile 4 shows tilting of the eastern flank.

All around the meridionally trending part of the lake, the flanks are composed of steeply dipping normal faults. The fault scarps are almost not eroded. Triangular facets, typical for erosion of normal faults, rarely develop on the slopes, and the valleys of the tributaries are very steep. The lake slopes are rectilinear only in the southwestern part of the lake. In plan view, the rest of the lake is bordered by several curvilinear fault segments, with opposite concavity on both sides of the lake. The most developed curvilinear segment delimits the southeastern part of the basin (profile 4). Fig. 5 represents a 3-D synthetic view of a satellite image towards the north. It was obtained by draping a SPOT satellite image on the DEM of the area. The eastern lake flank is formed by a basement block, down-faulted along a curved fault, and tilted towards the lake. It indicates the development of a listric fault resulting from the opening of the basin. The top of the block is 700 m lower than the adjacent mountains (Fig. 3).

3.4. Bathymetry of the lake

Lake Teletskoye occupies a sedimentary basin that can be subdivided in three first order and several second order structural zones on the basis of the bathymetric features of the lake bottom (Figs. 4, 6 and 7a). Taking into account only the depth and the shape of the basin, it can be divided into three different units (Fig. 7a). The first unit forms the southern basin, which runs from the Chulyshman mouth up to the trend break near the Kokshi river mouth (location of rivers in Fig. 2). The second unit is the northern basin, between Kokshi River and Kamga River. This basin in itself is composed of several subbasins. The third unit is the E–W-trending part of the lake, from Jailu up to the western lake limit.

At the southern extremity of the lake, the basin is completely filled by sediments mainly supplied by the Chulyshman River. The water depth slowly increases towards the north to reach the average depth of 300 m not far from the Chelyush river mouth. In the southern basin, there is no evidence for deformation of the top sediments. Except where river deltas occur, the bottom deepens gradually up to Kokshi River where the strike of the lake changes from NNW to N–S. In this area, the first topographic irregularities in the superficial sediments occur, associated with a NW-oriented ridge of about 10 m high to the north of which the basin depth increases to 320 m (Fig. 7a-i). Thus, the change in basin trend is accompanied by a change in water depth and deformation style: in the northern basin, several zones of disturbed sediments are present, between which smaller subbasins exist, increasing in depth towards the north. Between Ezhon and Chedor capes, a highly deformed structural zone exists (Figs. 2, 6a and 7a-ii). Inside this zone, the central part of the sediments subside along N–S-trending faults. Oblique to perpendicular to these faults are two ridges, about 50 m high, delimiting gradually deepening subbasins. The southern ridge is more or less WNW oriented (Fig. 6a). The basin depth gradually increases towards the north along several steps parallel to the ridge.

The intermediate basin is separated from the northern one by a NW-oriented zone (Fig. 6a). This zone is

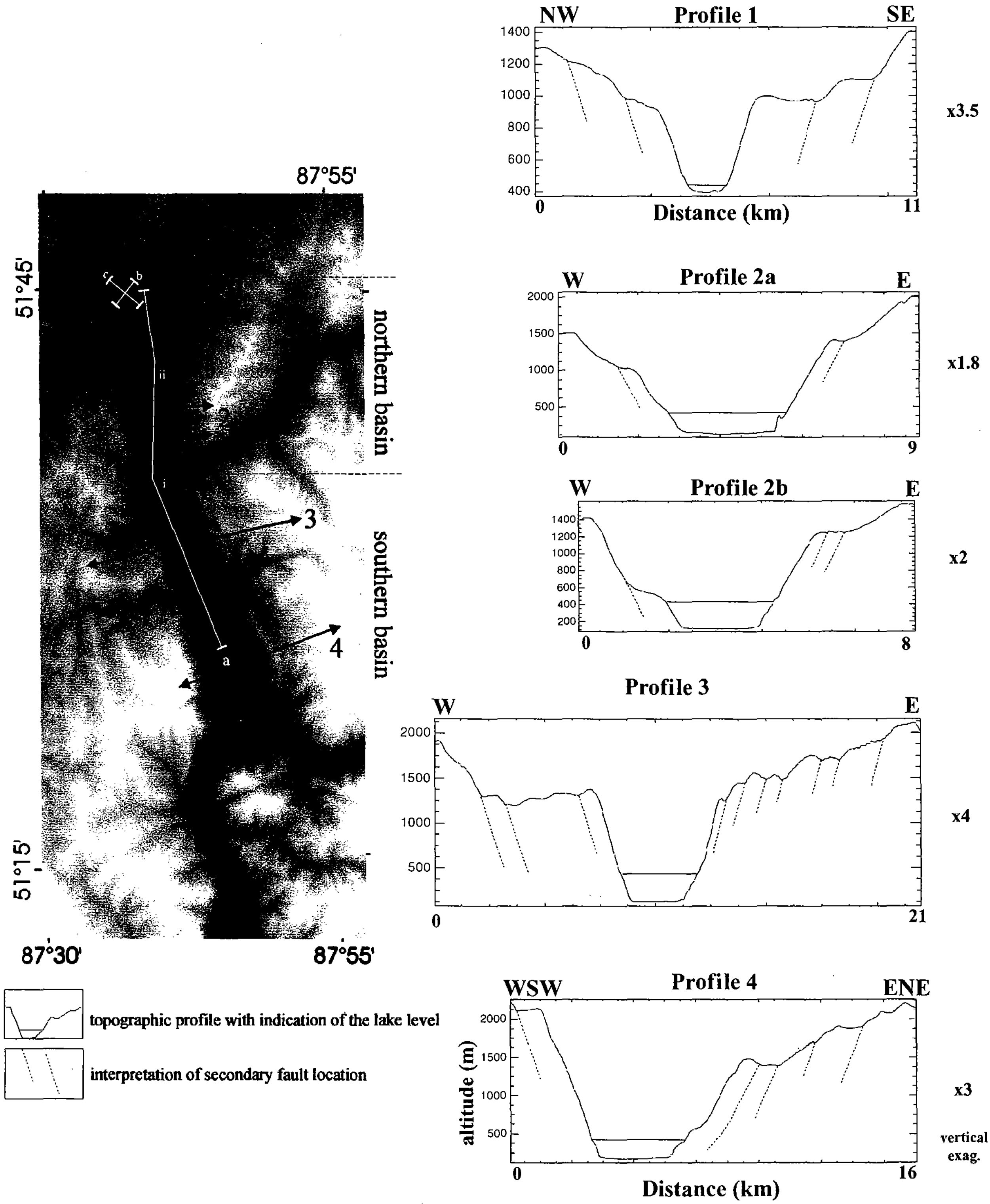


Fig. 4. DTM of the Teletsk basin showing locations of profiles. Black numbers indicate topographic profiles, white characters indicate the bathymetric profiles (Fig. 7). Profiles are vertically exaggerated.

Fig. 5. Artificial 3-D perspective of the Teletsk area from a SPOT image. View towards the north.

situated near the Chedor cape. It forms an intensively faulted and deformed ridge 20–40 m high. To the north of this transverse zone, the deepest subbasin of Lake Teletskoye is situated. It has a flat surface and a depth of 325 m. In the north, this basin is bounded by a 200-m-high NE-trending ridge called the Lepnyov Ridge (Figs. 6b and 7b,c). This ridge is situated in the continuation of the Kamga river valley, and follows the trend of the West-Sayan fault zone. It separates the northern basin from the E–W-oriented basin.

The E–W-trending basin segment shows a very complex pattern of horst and graben trends. There is a combination of E–W-trending, NE-trending and NW-trending basins, separated by ridges (Fig. 6b). The main ridge is the Lepnyov Ridge. It forms a horst structure, separating the main meridional depression from the Jailu graben in the north. It has an asymmetric shape along its trend, gradually shallowing towards the northeast and an abrupt cliff along a steep northeastern edge (Fig. 7b and c).

Although the bathymetry indicates the location and direction of structural deformation within the uppermost sediments along with changes in sedimentation patterns, the kinematic evolution of these deformed zones is unclear from bathymetric data alone.

3.5. Brittle tectonics of the basin surroundings

It is not always easy to distinguish fault movements of different tectonic phases inside polyphase-reactivated basement faults. However, a detailed field study classified more than 650 faults on the basis of deformation style (related to the depth of faulting), kinematic style (direction and sense of movement), orientation of the computed paleostress axes, cross-cutting relations of fault striations and stratigraphic

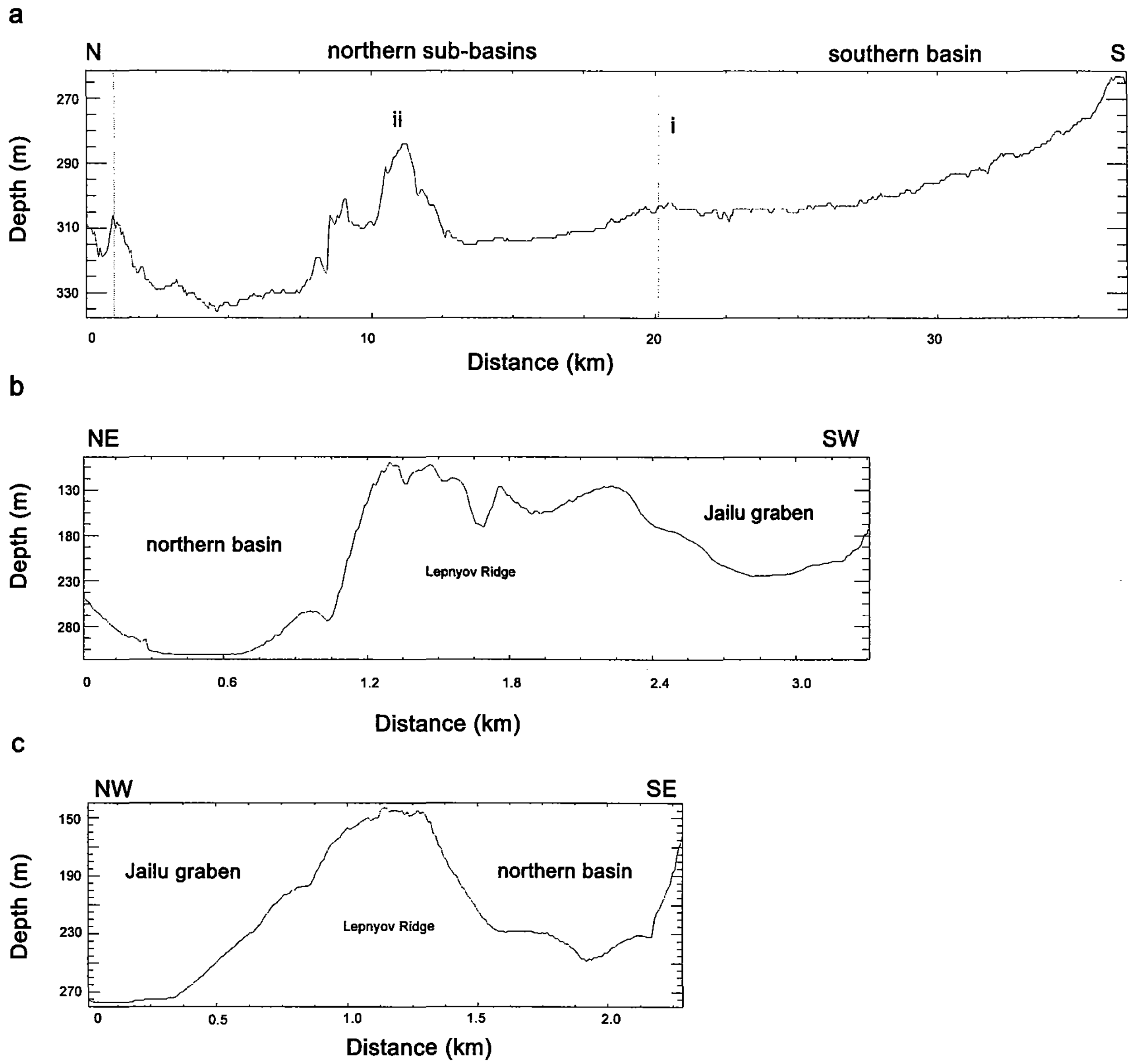


Fig. 7. Bathymetric profiles. Location of the profiles in Fig. 4, white lines. (a) N–S-trending profile, showing the different basins. (b) Asymmetric shape of Lepnyov Ridge, parallel to the West-Sayan fault zone. (c) Shape of Lepnyov Ridge and the E–W-trending basin.

epidote–chlorite striae or coating on their planes. Sometimes, quartz lineations occur. Cataclasite planes are also formed in these deep brittle environments. Faults displaying only these types of slickenside are clearly transected by the recent morphology, and they do not displace the Late Pliocene–Quaternary surfaces. Paleostress reconstructions derived from such slickensides mostly produced strike–slip paleostress tensors with σ_1 oriented at east–west. Observed fault movements in this tectonic regime are incompatible with the east–west opening of the basin. The few fault movements in this deep brittle environment which are kinematically competent to open the basin, repeatedly are overprinted by the previously discussed incompatible striae, indicating their older age. These slickensides are attributed to deep brittle movements in a preextensional tectonic context.

Often, these striae are overprinted by younger striae which have movements conforming to basin opening kinematics. These shallow structures are well represented around the basin, and they control directly the recent morphology. They are grouped into two kinematic phases which are related to Cenozoic tectonics. They were determined by means of stratigraphic correlation with fault movements and related stress tensors in Quaternary sediments, crosscutting relations with the older phases and slickenside style. Table 2 shows the location of the measurements, the results of slip inversion (paleostress reconstruction) and the statistical mean of the orientation of the principal stress axes for the two phases.

Many of the active faults are long-lived, polyphase-deformed structures which were reactivated several times. Hence, we were able not only to determine the modern kinematics of the major faults, but also the style of faulting of the major structures in the geological past.

The general stress situation for the Altai region expressed by the direction of maximum horizontal compression (S_{Hmax}) can be found on the world stress map (Zoback, 1992), and in some publications dealing with seismicity and movements of Quaternary faults in Central Asia (Zhalkovskii et al., 1995; Delvaux et al., 1995b). These studies show that the contemporary regional direction of horizontal compression is quite stable over the area, with an average N–S to NNE–SSW maximal horizontal compression direction (S_{Hmax}). Nevertheless, there is a high variability in tectonic regimes ranging from locally pure compressional to pure tensional regimes in other regions. The dominant tectonic regime for Altai, however, seems to be strike–slip and transpressional (Dehandschutter et al., 1999).

Around the Teletsk basin, all faults having red iron-coated (hematite) slickensides fit in the model of the youngest stress field for the region: they correspond in their orientation of principal stress directions to the paleostress tensors derived from movements in Quaternary sediments, as well as to the stress trajectories derived from earthquake movements (Zhalkovskii et al., 1995). Also, paleostress tensors derived from faulting in Quaternary sediments in adjacent regions of the Altai (Delvaux et al., 1995b) correlate well to those of the last phases in the Teletsk area.

Striae on clay- or sand-coated fault planes are relatively abundant, and typically superficial. They too are all kinematically compatible with the recent regional stress field for the northeast Altai derived from

Table 2
Paleostress tensors for the Teletsk region, Cenozoic tectonic phases

Site	Latitude	Longitude	Description	n	n_t	σ_1	σ_2	σ_3	R	α	Q	R'
Phase Q1												
Tel089	51 77	87 06	Jailu village	21	25	13/359	01/089	77/182	0.42	07.81	A	2.42
Tel093	51 41	87 68	Altyntauss massif, dextral faults	18	28	09/165	80/012	05/256	0.49	15.23	B	1.51
AL172	51 36	87 85	Chiri	42	65[1]	14/174	76/360	01/264	0.04	11.07	A	1.96
AL172	51 36	87 85	Chiri	12	65[1]	22/334	20/073	59/202	0.48	6.38	B	2.48
Tel122	51 48	87 41	Kamga Bay, NE Teletskoye	13	28[2]	25/183	60/037	15/280	0.12	16.08	C	2.12
AL05	51 75	87 67	Airan Cape, Devonian sandstones	27	32	12/183	10/090	75/323	0.03	7.18	A	2.03
AL05	51 75	87 67	Airan Cape, Quaternary breccia	46	86	06/180	18/088	71/287	0.17	12.14	A	2.17
Tel117	51 35	87 83	Kyga bay	27	37	01/207	64/117	26/298	0.10	10.8	A	1.90
Tel 058	51 25	87 44	Altyntauss massif	11	50	01/036	83/134	07/300	0.48	4.81	B	1.47
Weighted mean: nine tensors				217		04/194	70/093	20/285	0.23	11.4		2.23
Phase Q2												
AL02	51 50	87 15	Arty-Bash, sand querry	18	20	83/198	03/317	06/048	0.73	9.40	A	0.73
AL03	51 30	87 45	Bele Quaternary terrace	13	13	87/087	03/202	06/292	0.10	0.8	A	0.10
Tel122	51 48	87 41	Kamga bay, NE Teletskoye	14	28[2]	63/168	24/016	11/281	0.50	11.49	B	0.50
Weighted mean: three tensors				45		78/158	09/022	08/291	0.45	7.2		0.55

Coordinates are given in decimal degrees. n is the number of geological structures used to calculate the reduced paleostress tensor. n_t is the total number of measured kinematic structures. σ_1, σ_2 and σ_3, respectively, are the maximal, intermediate and minimal compression directions of the stress ellipsoid (dip/dip direction). $R=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$ is the ratio of principal stress differences. It is indicative of the state of stress corresponding to a tensor. α describes the mean deviation between theoretical and observed fault movement. It is a measure of the accuracy of the calculated tensors. Q is the quality of the calculated tensor, taking into account n, n_t and α. R' is the fault index. It varies gradually between 0 (radial extension) and 3 (radial compression). For $0.25<R'<0.75$, the regime is pure extensive; for $0.75<R'<1.25$, it is transtensive; for $1.25<R'<1.75$, it is pure strike–slip; for $1.75<R'<2.25$, it is transpressive and for $2.25<R'<2.75$, the stress regime is pure compressive.

focal mechanisms. Therefore, we included all faults with iron-coated slickensides, clay gouge and breccia fill to the data set of the youngest movement phase in the region, and used them to derive the paleostress tensors corresponding to the Quaternary tectonic regime.

By investigating the different structures related to the latest movements in the area, it appeared that a subdivision can be made, resulting in two different stages of Quaternary faulting and tectonic movements, Q1 and Q2.

Most of the iron-coated movement planes yield a paleostress tensor which is transpressional. These faults are generally restricted to the northern and southern edges of the basin, in the regions of the reactivated West-Sayan and Shapshal shear zones. In the West-Sayan region, the stress regime is mainly derived from sinistral–oblique movements on ENE-oriented planes. In the Shapshal area, dextral transpression and reverse movements of NW-trending faults express this stage of faulting (Fig. 8a). The transpressional stress regime derived from these movements initiated the opening of the basin by lateral slip along the Shapshal-related faults and the West-Sayan fault zone. It is called phase Q1 (Fig. 8b).

In the N–S-trending part of the lake, these strike–slip movements are less abundantly observed. In contrast, several small-scale normal faults with hematite coating indicate the local extension related to the basin formation as an extensional duplex in between two strike–slip faults.

Apart from these iron-coated structures which are related to subsurface faulting, much evidence for superficial faulting was found. Most breccia-filled and clay-gouged fault planes from micro- to mesoscale were found along the meridionally trending part of the basin. Here, normal faulting is the dominant style. The orientations of the normal faults bordering the lake also indicate an east–west extension direction. In several places (e.g. tel122, Al02, Fig. 8a), crosscutting of strike–slip faults by normal faults indicates the temporal relationship between the respective tectonic regimes. At Airan Cape (AL05-97, Fig. 8a), Devonian sedimentary rocks have quartz lineations, mainly dip–slip, crosscut by strike–slip hematite slickensides. Angular fragments of these Devonian sediments inside a sandy matrix comprise an unconsolidated tectonic breccia almost vertically exposed against the basement. Inside this breccia, the same hematitic striae as on the Devonian rocks indicate sinistral strike–slip. Zones of lacustrine sediments occur, chaotically mixed with the breccia layers. This means that the breccia was formed during the opening of the basin. Large normal faults with clay gouge, running parallel to the lake's strike, cut the whole sequence.

Apart from these geological indications, the morphology of the lake bottom and the interpretation of the seismic profiles (below) indicate that the strike–slip movements are no longer active, and the region is presently characterized by pure extension. Therefore, we attribute these pure extensional structures to a second Quaternary kinematic and tectonic phase Q2 (Fig. 8b).

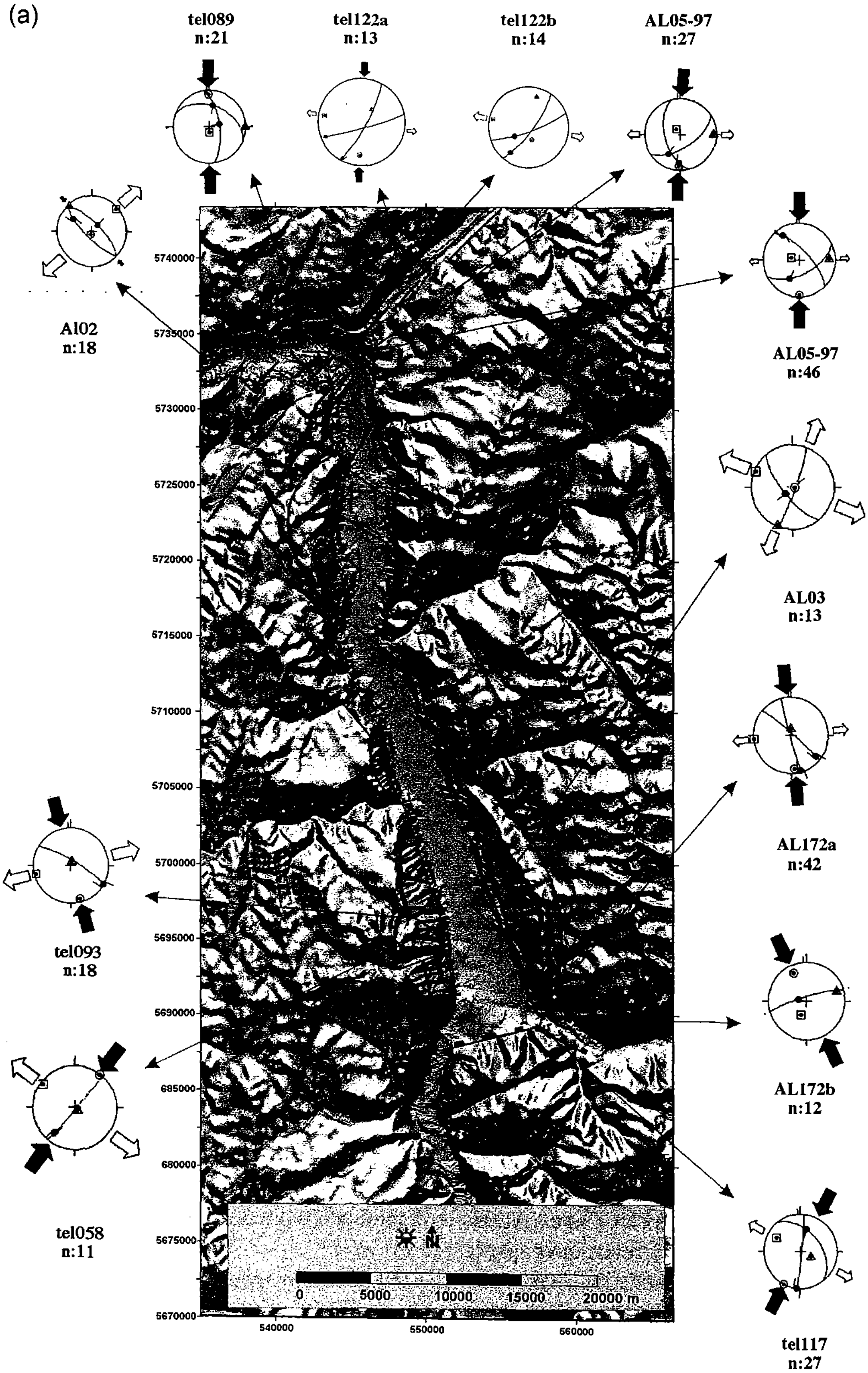
Brittle reactivations of the weak basement structures in the Teletsk region play a very important role in the development of the Cenozoic basin. The West-Sayan shear zone underwent reactivation during the Quaternary due to intensified regional tectonic activity. It actively controlled the opening of the northern part of the Teletsk basin and also defined the main mountain front of the West-Sayan range. The latter extends up to the Sayan fault zone which is connected to the Baikal Rift Zone (Fig. 1).

The Teletsk shear zone (Fig. 2) forms the mylonitic weak zone on which the southern basin was formed by transtension. Cenozoic reactivation of the Paleozoic structure accommodated the main strike–slip and tensional stresses by opening the southern basin.

The Shapshal fault is one of the most seismically active deformation zones in the area controlling the present structure of the Altai (Zhalkovskii et al., 1995). It is part of the NNW-trending fault system that forms the boundary between the Great Lake Depression in Mongolia, and the Altai range (Fig. 1). Dextral strike–slip is observed along NE and ENE faults in the Kyga valley (Fig. 2). These movements are induced by the reactivation of the Shapshal shear zone, transferring compressional stress from the south to the north. Movements on these branches also facilitate the reactivation of the Teletsk shear zone.

3.6. Seismic sections

The study of a seismic refraction profile running parallel to the lake trend revealed that the sedimentary


(a)
tel089
n:21
tel122a
n:13
tel122b
n:14
AL05-97
n:27
Al02
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AL05-97
n:46
AL03
n:13
AL172a
n:42
tel093
n:18
AL172b
n:12
tel058
n:11
tel117
n:27
5740000
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(b)

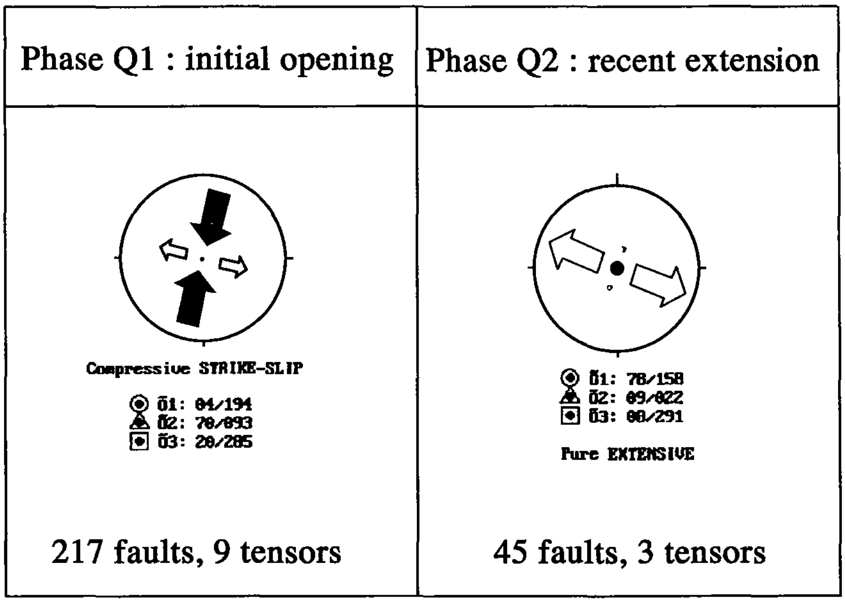

Fig. 8. Orientation of principal stress axes for the Cenozoic deformation phases. (a) Fault kinematics and related stress fields for phases Q1 and Q2. Stereoplots show the statistical fault planes with associated lineation. Smith projection on lower hemisphere. Black arrows indicate the direction of principal compression; white arrows show principal extension direction. Stress symbols in stereoplots: circle: σ_1, triangle: σ_2, square: σ_3. (b) Graphic representation of the statistical mean of the calculated paleostress tensors corresponding to the two main tectonic phases responsible for the Quaternary opening and development of the Teletsk graben.

fill of the Teletsk basin exceeds 800 m in the southern basin (Seleznev et al., 1995). In the area of the lake's trend break, near the Kokshi river mouth, there is an abrupt decrease in depth of the wave velocity discontinuity layer of several hundreds of metres. More to the north, this suggested basement-sediment boundary gets deeper again and is lost towards the north. This rise in basement isochores in the middle of the lake implies an important structural discontinuity. This is also supported by seismic reflection profiles (Fig. 9a and b). The northern segment of the profile in Fig. 9a shows how the upper 400 m of sediments are disturbed and forms an uplift which can be interpreted as a transfer zone of strike–slip movement or another type of accommodation zone. In the southern basin (for location, see Fig. 4), we can distinguish several zones of apparently folded sediments in the N–S-trending profiles (Fig. 9a). These zones most probably correspond to transverse (oblique to the profile direction) zones of deformation. Unfortunately, the lack of several parallel profiles makes extrapolation and determination of fault trends impossible. One can observe that the upper 100–150 m of sediments is hardly disturbed (Fig. 9a,c,d). On the contrary, they are characterized by very regular horizontal layering. This indicates that the main tectonic activity in the southern basin ceased before the deposition of the top 100–150 m of sediments.

Passing into the northern basin, the picture changes and the whole sedimentary sequence seems to be affected by intense tectonic activity, although restricted to discrete regions (Fig. 9b). The northern basin can be regarded as being composed of several subbasins, divided by transfer zones often expressed as flower structures that affect the whole sedimentary package. These zones of transverse deformation form positive relief accommodation zones (expressed as horst structures) in between the different subbasins. The tectonic activity in the northern basin affects the whole sedimentary sequence, indicating its present-day activity, in contrast to the southern basin.

Rejuvenation of fault activity towards the north is indicated by upward migration of the fault top (Fig. 9c and e). The seismic profiles of the southern basin also show clearly the very steep and deep continuous nature

(a)

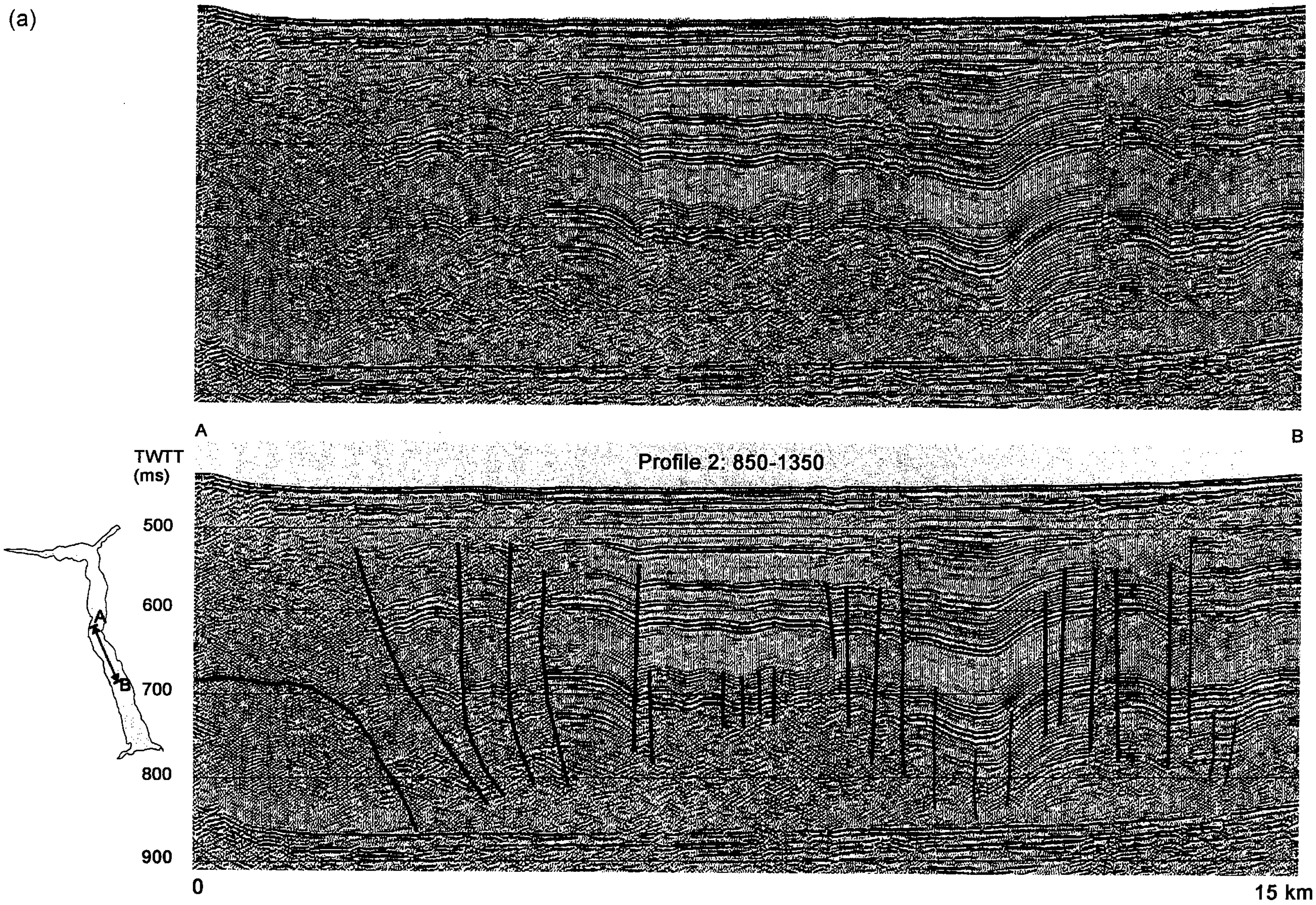

Fig. 9. Seismic sections of the N–S-trending basins. (a) Transverse structures in the southern basin. (b) Surface faulting and accommodation zones in the northern basin. (c) Regular sedimentation in the southern basin, border fault shapes. (d) Steepening of the border faults towards the north and shallowing of the deformation. (e) Highly faulted sediments near Ezhon cape.

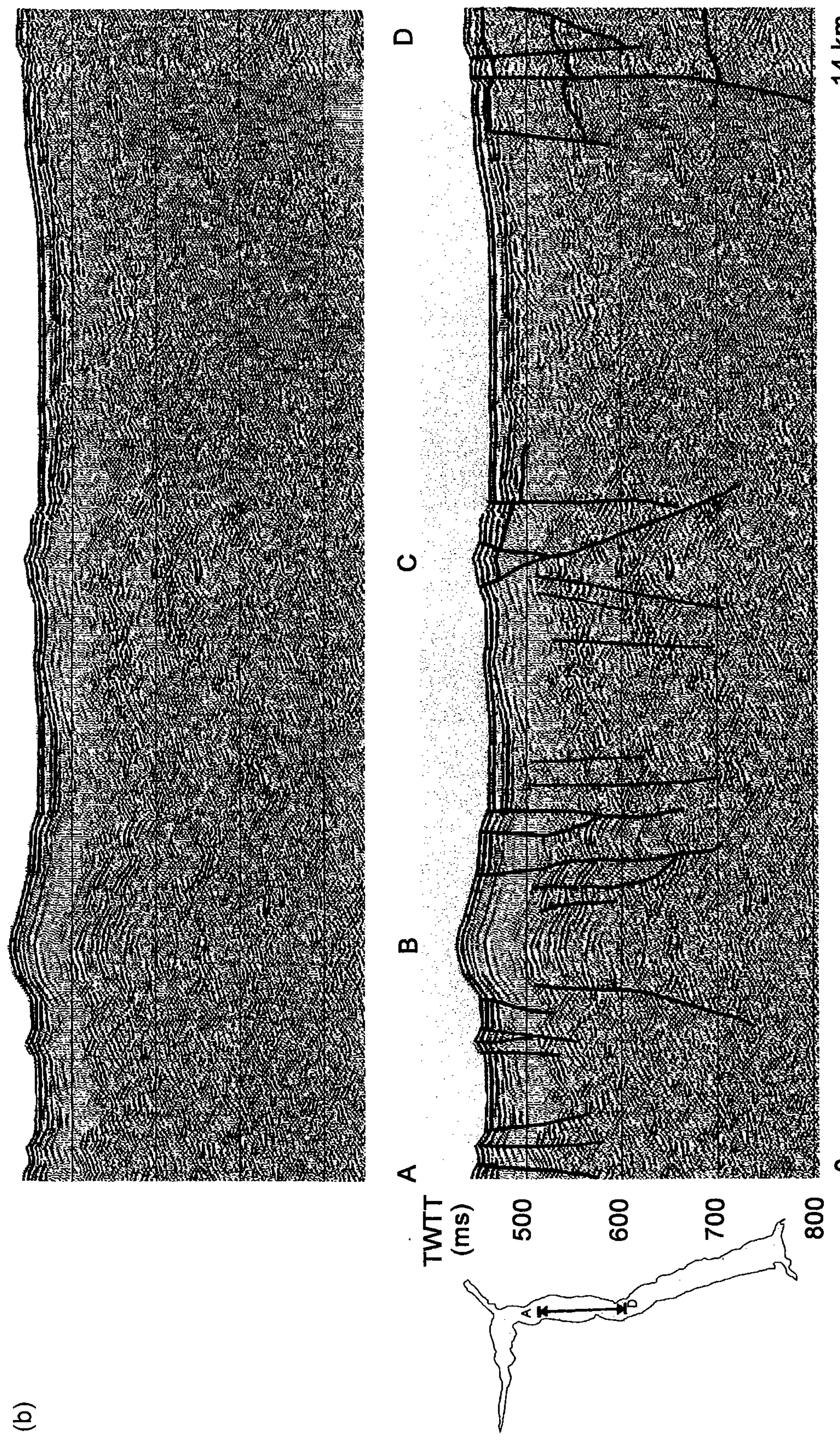

Fig. 9 (*continued*).

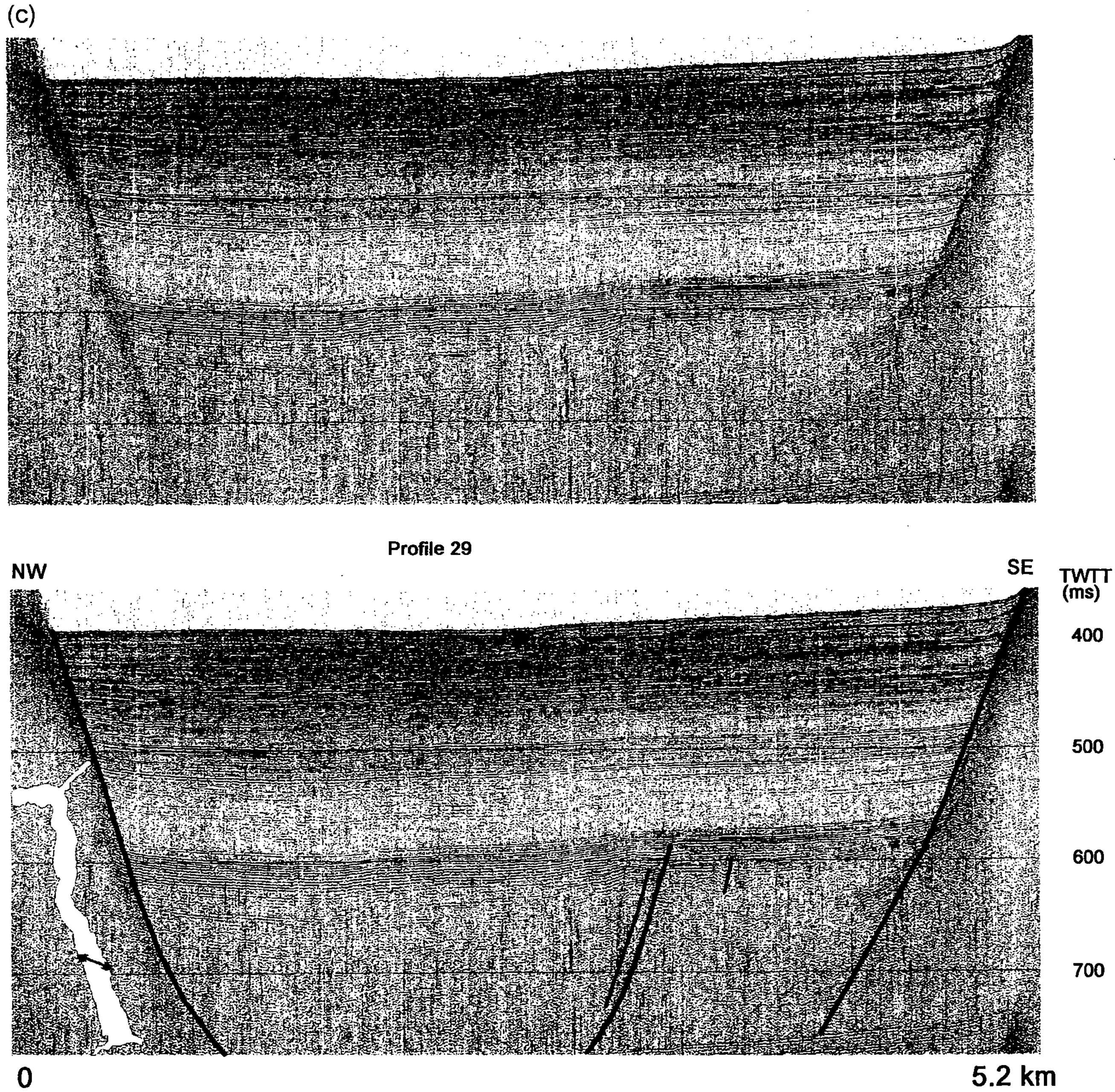

Fig. 9 (*continued*).

of the border faults, which directly link with the air-free border faults. Fig. 9c shows how the western border fault is straighter at depth than the eastern one. This was already suggested by the interpretation of the land morphology (Figs. 4 and 5). The south-eastern border fault has a slightly concave shape at depth suggesting a listric form. Profiles more to the north (Fig. 9d and e) show that the asymmetric graben style of the southern basin is not typical of the whole basin. Generally, a relatively symmetric full-graben morphology with rectilinear border faults characterizes the different subbasins.

In the northern subbasin, the upper sequence of sediments is composed of several structural domains of full graben which are separated from each other by transfer zones or accommodation zones of high relief

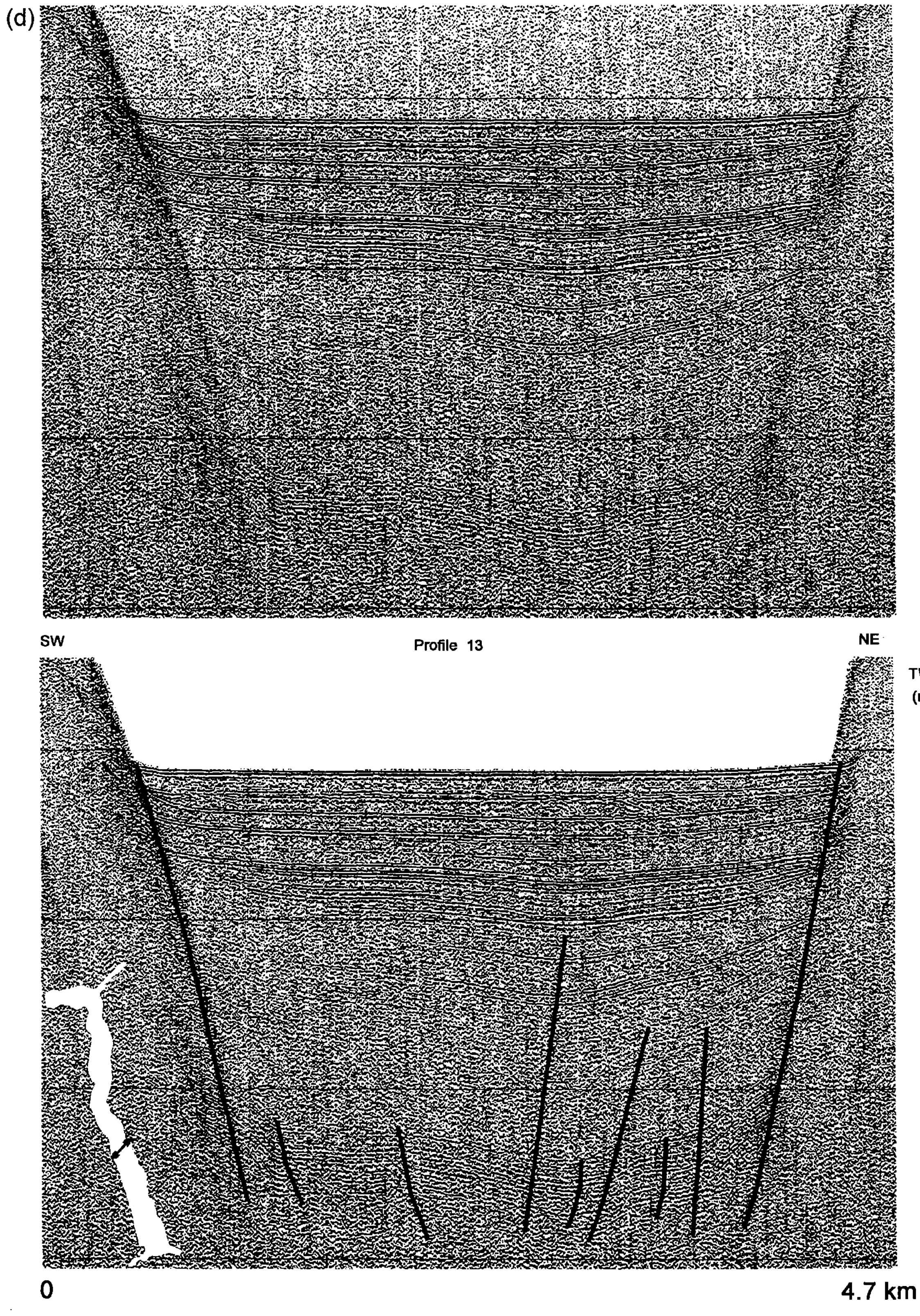

Fig. 9 (*continued*).

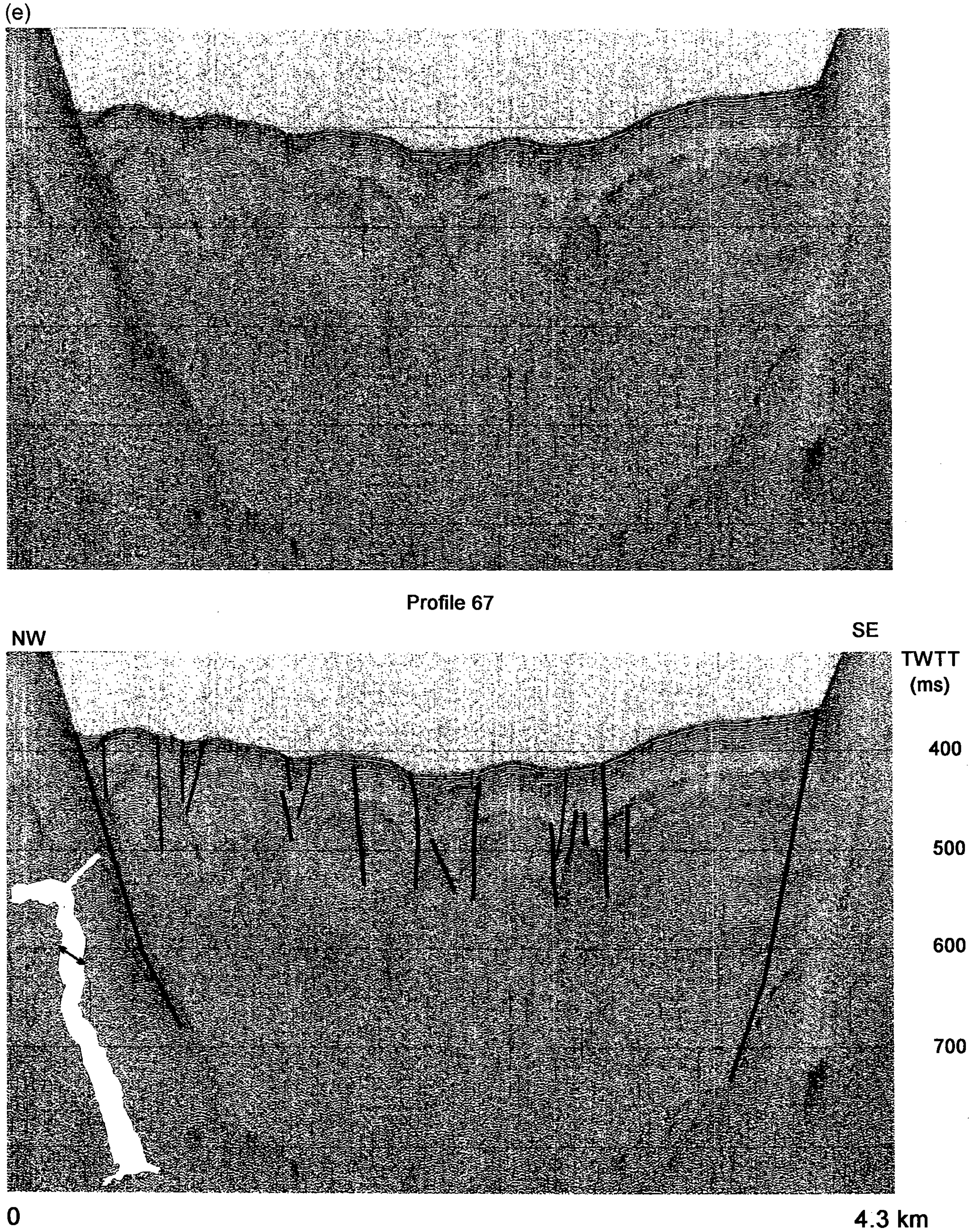

Fig. 9 (continued).

(Figs. 7 and 9b). Generally, these zones are intensely faulted (Fig. 9e). They trend perpendicular to the subbasins in the southern part, and oblique (WNW–NW) more to the north (Fig. 6a). In between these transfer zones, full graben with predominant normal faulting are developed.

The E–W-trending part of the basin is composed of a complex structure of full graben delimited by normal faults and interleaving horst structures, as was reported in the section describing the bathymetric features of the basin. The high-resolution seismic profiles confirm the idea that these (morphological) depressions are fault-bounded tectonic graben, subsiding between basement uplifts. The network of seismic profiles allowed us to map the trend and depth of these micro-basins and the basement highs. The results are shown in Fig. 10. NE-trending normal and transtensive faults form the horst structure parallel to the West-Sayan fault zone (Lepnyov Ridge, Fig. 6b). They are cut by NW-trending normal faults. Those NW-trending faults are overprinted by N–S normal faults delimiting the northern basin. North of the Lepnyov Ridge, another deep basin subsides along northeast to E–W-trending normal faults (Jailu graben, Fig. 6b).

3.7. Interpretation of the seismic profiles

The shape of the southern basin partly corresponds to the structures of half-graben, as similarly described

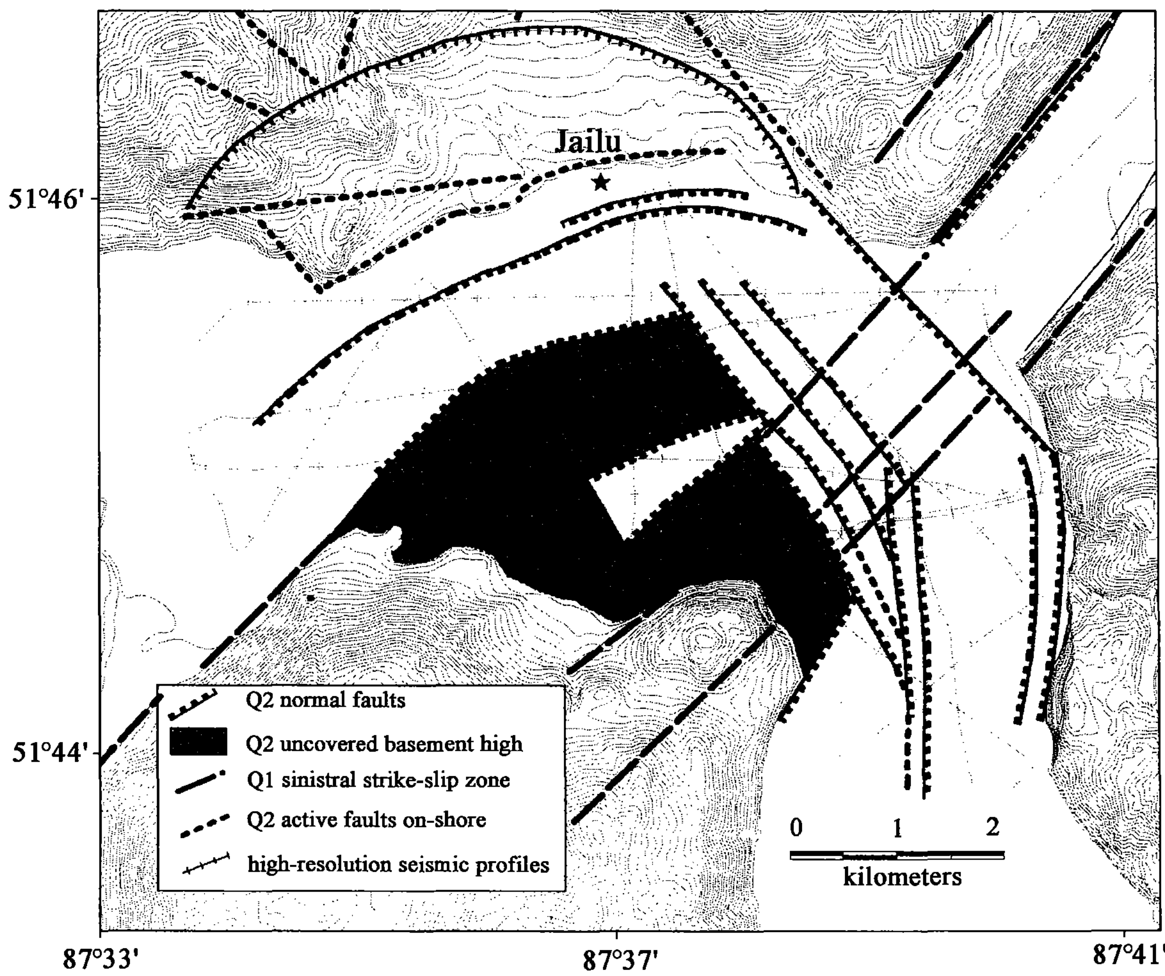

Fig. 10. Topographic map of the northern part of Lake Teletskoye (the E–W-trending Lepnyov zone) with structural interpretation derived from seismic lines. Note that Q1 strike–slip faults are cut by Q2 normal faulting.

for deep rift basins of the western branch of the East African Rift System (Rosendahl et al., 1992; Scott et al., 1992). There is an asymmetry between the border faults, but there is no real tilting of layers towards the leading fault. Due to the very immature (young) nature of the Teletsk basin and its controlling structures, the southern basin can be regarded as a half graben in its initial stage, where the leading border fault only starts to develop along the southeastern spoon-shaped 'Chiri-loupe'.

Towards the north, this curved eastern border fault is replaced by a straighter one, in the region where the curved fault surface trace intersects with the lake (Figs. 4, 5 and 9d). To the north of the southeastern 'Chiri-loupe', the morphology of the basin has a much more full-graben shape, with two rectilinear symmetric border faults. In this region, several transverse-oriented accommodation zones delimit several subbasins. They probably reflect movements along deep-seated basement structures, controlling the initial opening of the basin. This Q1 phase of strike–slip faulting provoked the en-echelon formation of pull aparts which, in the present Q2 tectonic phase, open as pure extensional basins (Figs. 10 and 11).

This conclusion is supported by the sediment deformation observed in the north, near the intersection between N–S-trending and E–W-trending basins. Here, the West-Sayan fault definitely controlled the formation of the different graben in a sinistral strike–slip setting of the Q1 stage. However, the contemporary kinematics induce pure extensional opening with an almost radial extension direction, forming the N–S- and E–W-oriented graben, and cutting the West-Sayan fault zone. This zone by itself is reactivated as an extensive fault zone. This is shown by the Kamga graben, both morphologically and structurally (profile 1 in Fig. 4).

The modern sedimentation rate is estimated on the basis of the depth of a high-concentration ^{137}Cs layer, deposited after the 1950 nuclear tests. It is as high as 8 mm/year in the southern basin and 2 mm/year in the northern basin (Kalugin et al., 1996; Bobrov et al., 1999). Extrapolation in time of the contemporary sedimentation rate is a rough approach to estimate the age of the sediments by their depth. This is because the supply of sediments by tributaries is irregular due to climatic changes, tectonic movements, landslides and debris flows induced by climatic hazards. Nevertheless, a rough extrapolation can provide a preliminary age estimate for the onset of basin development. Taking the modern sedimentation rate for the northern basin as a reference (and a minimum for the southern basin, yielding a maximum age), this would mean that sedimentation started around 400 ka, and homogeneous sedimentation with limited tectonic movements, as observed in the upper 100–150 m of sediments, started around 50–75 ka in the southern basin assuming an acoustic wave velocity of approximately 2000 m/s (Seleznev et al., 1995). Therefore, the main active tectonic deformation in the southern basin must have occurred before 50–75 ka. After this, fault activity was reduced to minor events, observable in the top-layer sediments. However, if the modern sedimentation rate of the southern basin is extrapolated (and accepted as a maximum, yielding a minimum age), the top 150 m of sediments was deposited only during the last 20 ka, and main fault activity in the south must have ceased by this time.

4. Discussion

In and around the Teletsk graben, several domains of neotectonic activity are distinguished (Figs. 3 and 11). Their morphotectonic structure indicates the importance of reactivated Paleozoic shear zones controlling the neotectonic activity. The eastern side of the basin shows the most active deformation. Lateral escape of the southeastern flank of the lake (to the south from Kokshi River) due to E–W extension of the reactivated Teletsk shear zone was induced by dextral strike–slip of the Kyga graben and transpressive movements of the Shapshal fault zone. In the central part of the eastern side, the Kokshi valley forms a pull-apart structure accommodating the movements of the West-Sayan fault zone and the Teletsk and Shapshal fault zones. The western side of the basin is disrupted by dextral transtensional faults of the Teletsk fault zone bordering the more stable Altyntauss massif in the southwest. Pure extensional faults only occur very close to the basin.

A study of the deformation of the sedimentary fill shows that the southern basin is relatively slightly deformed, and has a regular sedimentation in the upper 150 m. This indicates the limited tectonic subsidence over this last period of deposition. The southern basin

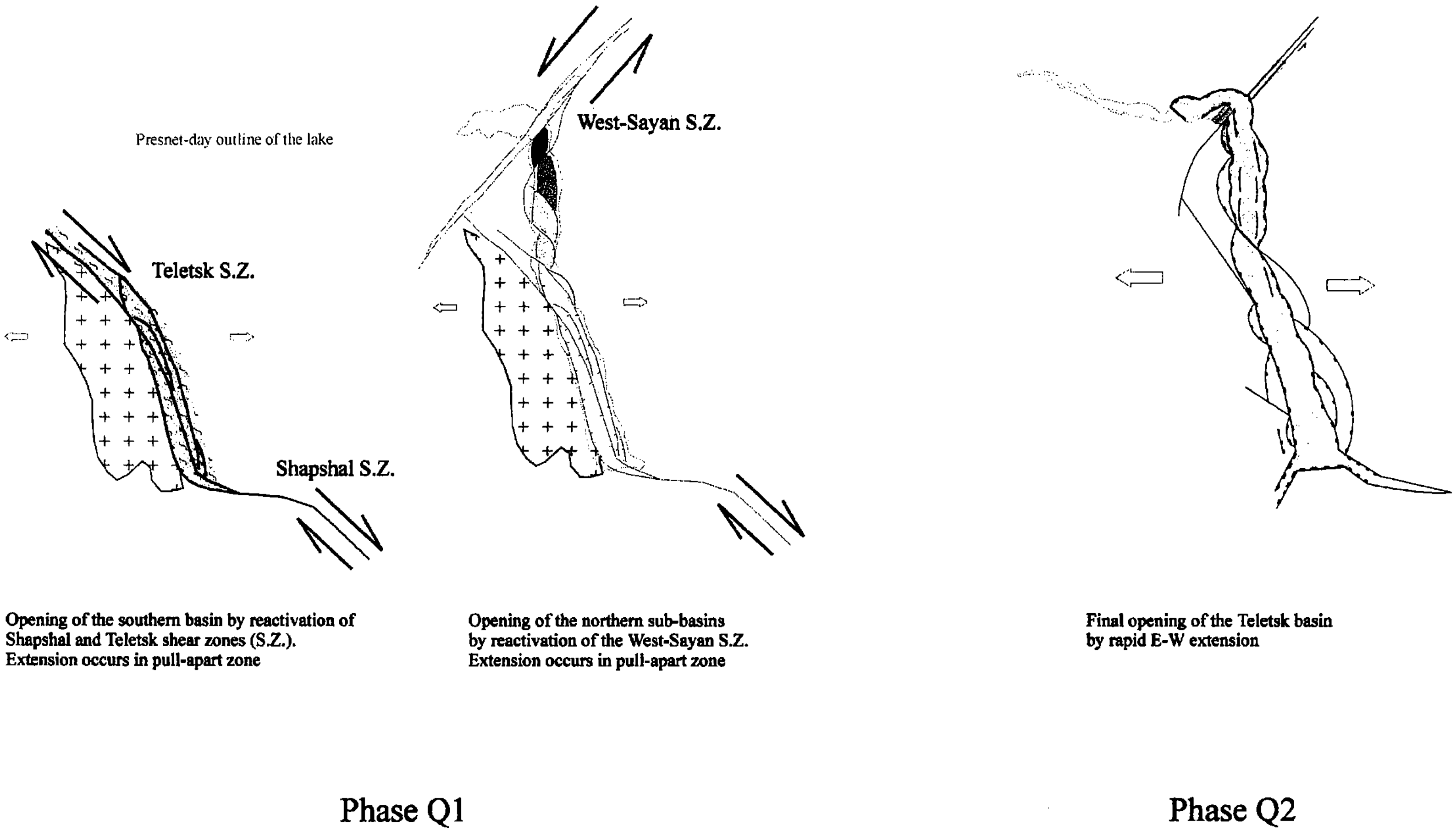

Fig. 11. Evolutionary model for two-phased development of the Teletsk graben in the Quaternary.

is the deepest basin and the lower unit was deposited in the first phase of basin formation, before the development of the northern basin.

Both onshore and offshore, the different basins are all characterized by a graben morphology with two leading border faults. The southeastern border fault has a typical curved shape in plan view and shows a general tilting of the hanging wall towards the fault, indicating its listric nature. The seismic profiles suggest such a listric shape at depth. The southern basin is the deepest, with a sedimentary fill of more than 800 m. At the lake's strike break, there is a basement uplift, to the north of which the northern subbasin is characterized by much thinner sediment fill, as suggested by seismic refraction studies.

Unlike the southern part, the northern basin is highly disturbed, even in the uppermost sediments. Along the basin, several high relief accommodation zones with complex internal faulting separate different subbasins. These are mainly full graben controlled on each side by two normal faults, slightly curvilinear in map view, but hardly listric in cross section.

At the northern termination of the lake, the bathymetry and the seismic profiles emphasize a highly deformed zone composed of several horst–graben systems. They have a relatively limited sedimentary fill. They are formed as pull-apart basins by sinistral movements along the NE-striking West-Sayan fault. In a later, more extensive phase, normal faults cut the strike–slip faults and the complex horst–graben structure was established.

The onshore outcropping segments of the faults are composed of a combination of rectilinear and curvilinear normal faults. Between those normal faults, we observe strike–slip zones of Quaternary age which do not displace the normal border faults and thus, are not involved in the latest pure extensional phase of the basin formation.

Summarizing these observations, the following model for the development of the Teletsk basin can be proposed.

In the first stage, the southern basin opened due to transpressive movements on NW-oriented faults, accommodated by extensional reactivation of the Teletsk shear zone. This is interpreted to have occurred before about 50–75 ka. In the same tectonic regime, the West-Sayan fault was subsequently reactivated as a sinistral strike–slip fault, opening the initial northern basin as a series of subbasins, delimited by oblique trending transfer zones. In a later phase, which is still active now, a change in stress regime induced a change in fault kinematics, as the N–S trending basin collapsed due to E–W extension and the formation of the present day normal faults and related graben was completed.

Investigation of the Teletsk basin offers us a unique opportunity to investigate the early tectonic development of an extensional basin. Although the tectonic settings are quite different, in a structural sense, the Teletsk basin can be regarded as a modern and premature analogue for the early stages of more established deep rifts such as those in East Africa (e.g. Tanganyika, Malawi) and Baikal. These rifts are thought to be controlled by the development of half graben, which develop along curvilinear leading border faults. Their orientation is controlled by preexisting structures (Rosendahl et al., 1992; Scott et al., 1992). These mechanisms of graben development can be applied to this young and actively forming basin. In this example, we observe the existence of curvilinear as well as linear border faults, some of which are listric in depth, others are straight.

The accommodation zones existing inside the basin form links between the different border-fault segments. Typical half graben, composed of leading faults with shallowing basement away from the fault along synthetic or antithetic faults, are not observed. Instead, the Teletsk basin is formed by full-graben units separated by accommodation zones.

Taking the Teletsk graben as an example, we can propose that the structure of the early stage of deep rifts can be dominated by full graben, developing along rectilinear or slightly curvilinear border faults, linked by transfer zones or accommodation zones, as observed in the northern part of the Teletsk basin. As extension proceeds, the main movement can be concentrated on one leading border fault, along which a major detachment develops and half graben can evolve, as is observed for the southern Teletsk basin. The influence of the amount of extension and extension rate on half-graben development should be investigated further.

5. Concluding remarks

The Teletsk graben is a good example of a very young extensional basin developing in an active orogeny. It is composed of several sub-graben which display their kinematic activity and history through their internal and surface fault morphology and fault displacement. This causes the preservation of the different stages of formation of full-graben and half-graben structures. It provides new insights into the mechanisms of the initial continental basin development.

The opening of the contemporary Teletsk basin happened over a period of less then 1 Ma. This indicates the dramatic and relatively abrupt way in which crustal extension and subsequent sedimentary basin formation can take place, even in an intracontinental tectonic setting far from any plate boundary. Although the extension cannot be regarded as orogenic collapse (Dewey, 1988) due to the limited regional uplift of less then 3000 m and the active mountain-building processes, it gives an example of extensional collapse in the sense of fast down faulting of the border faults surrounding a void created by upper crustal extension in a young and immature orogenic context. However, it can be supposed that effective continental rifts went through a similar morphological and structural early-formation stage.

Acknowledgements

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