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# Fault linkage in continental rifts: structure and evolution of a large relay ramp in Zavarotny; Lake Baikal (Russia)

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**Abstract**

The internal structure of a large (10×40 km) relay ramp has been described between two border faults of the Baikal Rift Zone. The relay ramp, which is located partly onshore and partly offshore, has been investigated using a dense grid of high resolution seismic profiles and a digital terrain model containing topographic as well as bathymetric data.

The structure of the relay ramp in Zavarotny is characterised by the development of secondary faults striking approximately parallel to the main faults. In combination with this, breaching occurred through the development of a new connecting fault. The breaching in Zavarotny has not lead to the destruction of the relay ramp, but a clear further evolution has been observed (e.g. a similar morphology of the lake floor and the basement inside the relay ramp, as well as the development of a second connecting fault). The strike direction of the secondary faults in the relay ramp has likely been influenced by the pre-existing basement fabric in the area.

*Keywords:* Relay ramp; Fault linkage; Fault interaction; Baikal; Baikal Rift Zone

## 1. Introduction

A property of many major faults is that they have irregular traces, showing certain jogs along their path (e.g. dePolo et al., 1991; Cartwright et al., 1996; Jackson et al., 2002). This is believed to be a result of the growth and connection of different fault segments (Segall and Pollard, 1980; Peacock and Sanderson, 1991; Davison, 1994). Such fault segments can initially be isolated structures (e.g. Peacock and Sanderson, 1991, 1994; Cartwright et al., 1996), or they can be interrelated from their initiation and for example result from the bifurcation at depth of a single fault (e.g. Huggins et al., 1995; Childs et al., 1996; Walsh et al., 2003).

In the isolated fault model, a physical connection between two off-set faults is only a final stage in the linking process (e.g. Peacock and Sanderson, 1991, 1994; Cartwright et al., 1996, amongst others). At the first stage, segments exist as isolated structures. While they are growing, segments will approach each other closely enough to allow a mechanical interaction. This interference of the stress fields of the two approaching segments starts in the underlapped geometry of the faults. Elastic fracture mechanical modelling of fault interaction suggests that segments with such an underlapped geometry will tend to grow further, whereas when segments overlap they will tend not to propagate (Aydin and Schultz, 1990; Willemse et al., 1996; Crider and Pollard, 1998).

Walsh et al. (2003) have suggested, however, that relay zones between normal faults are most commonly segments of a single kinematically coherent system. In such cases, relay zones at a free surface can be formed almost instantaneously on a geological timescale as a result of the upward propagation of for example a single bifurcated fault and not necessarily as a result of the lateral propagation of two isolated faults.

When two overlapping synthetic normal faults are linked by an area of tilted bedding, the transfer zone is called a relay ramp (Larsen, 1988; Peacock and Sanderson, 1991; Peacock et al., 2000a) or a synthetic transfer zone (Morley et al., 1990). Within a relay ramp there is a reorientation of bedding, due to the progressive increase of fault displacement gradients towards the fault tips (Peacock and Sanderson, 1994). This rotation often involves bending and the formation of minor

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faults within the relay ramp (Peacock and Sanderson, 1994; Cartwright et al., 1996; Crider and Pollard, 1998). At a certain critical limit, a through-going fault may develop to accomplish a plane-to-plane linkage (e.g. Peacock and Parfitt, 2002), or one or both of the major fault segments may propagate towards the other fault and connect to obtain tip-to-plane linkage (e.g. Peacock and Sanderson, 1991, 1994; Childs et al., 1995; Cartwright et al., 1996).

Because the main basin geometries of rift systems (half-graben or full-graben) are controlled by major faults (e.g. Morley, 1995), transfer zones associated with such faults—intra-basin transfer zones according to Gawthorpe and Hurst (1993)—have a considerable structural importance, as they are commonly responsible for changes in border fault geometry. On a larger scale, inter-basin transfer zones link major boundary faults that are located on opposite sides of rifts (Gawthorpe and Hurst, 1993) and can therefore cause variations in rift segment geometry (Rosendahl et al., 1986; Morley et al., 1990; Nelson et al., 1992; Upcott et al., 1996).

Transfer zones also have considerable influence on hydrocarbon migration and trapping in rift systems (Morley et al., 1990; Peacock and Sanderson, 1994; Coskun, 1997; Dou and Chang, 2003), as well as on basin formation and depositional patterns (Gawthorpe and Hurst, 1993; Morley, 1999; Leeder et al., 2002; Jackson et al., 2002).

Notwithstanding the importance of large relay ramps in rift basins, their internal structure has mainly been investigated from small scale (metres to tens of metres) (e.g. Peacock and Sanderson, 1994; Huggins et al., 1995) or meso scale (a few hundred metres) (e.g. Trudgill and Cartwright, 1994; Ferrill et al., 1999) examples. The internal structure of large relay ramps has only rarely been described (e.g. Peacock et al., 2000b). In this study we have investigated the internal structure of a ∼400 km$^2$ relay ramp in the northwestern border fault

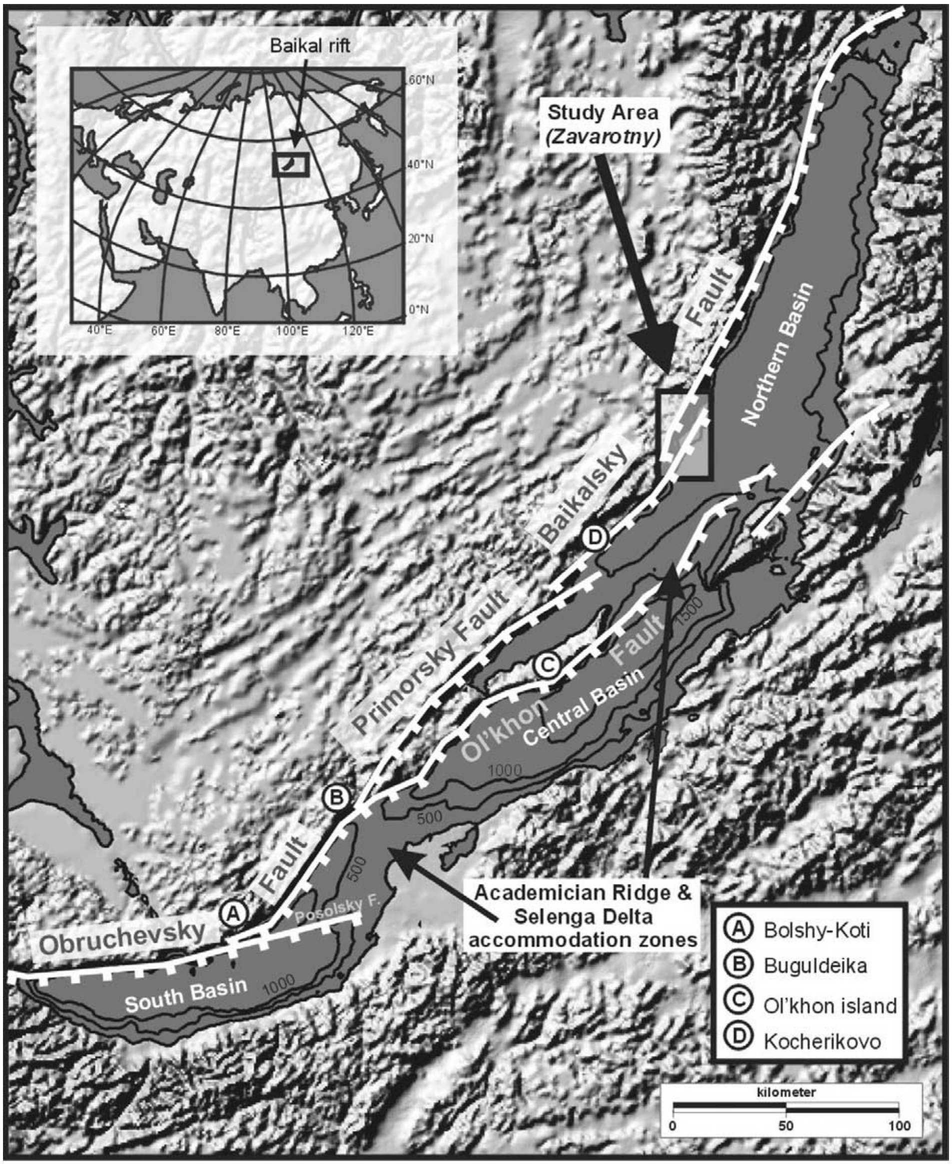

Fig. 1. Shaded relief image of Lake Baikal with major structures indicated.

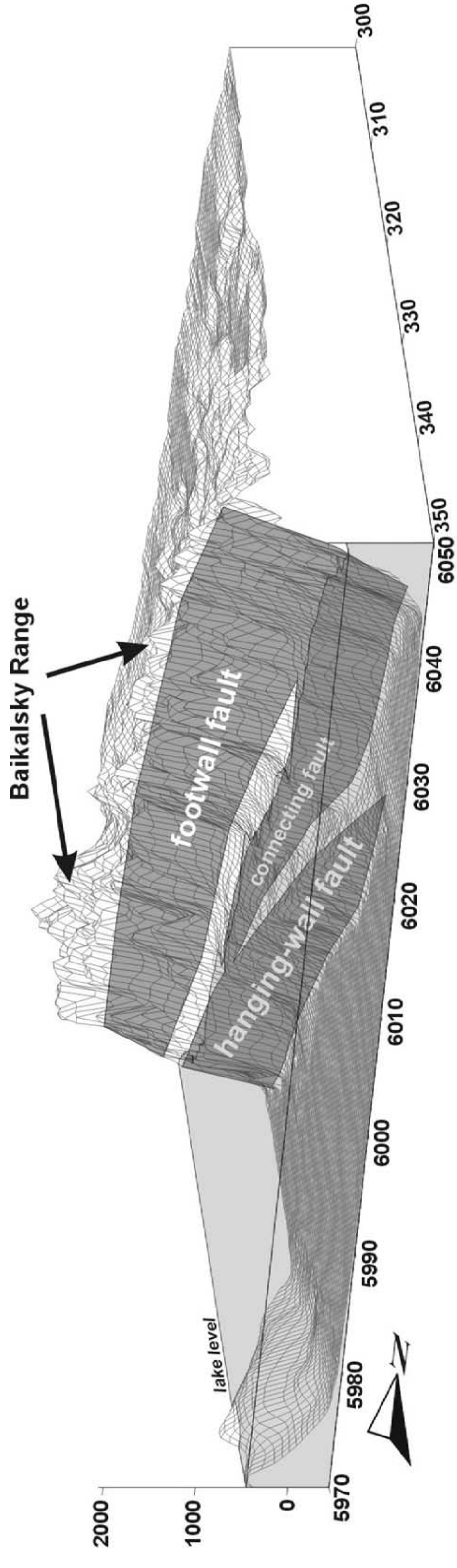

Fig. 2. Three dimensional representation of the relay ramp between two segments of the Baikalsky Fault. Definition of the terms used.

system of Lake Baikal, near the village of Zavarotny (Figs. 1 and 2). Because the relay ramp is situated partly onshore and partly offshore, it could be investigated with different research techniques. The present study is based on the interpretation of a dense grid of high resolution seismic profiles and digital terrain models.

With this study we wish to discuss the process of linkage between two major synthetically dipping fault segments, and thus provide additional insight in the evolution of border fault systems in rifts. This study will highlight the complexity of the internal structure of a large relay zone, including the formation of smaller basins within the relay ramp. Because we have determined the internal structure and evolution of a large relay ramp, our observations can be compared with those made on smaller scale to evaluate further whether the internal structure of relay ramps depends on scale (Peacock et al., 2000b) or not (Peacock and Sanderson, 1994).

### *1.1. Available data and applied research techniques*

The data available for the offshore part of Zavarotny were acquired during different campaigns between 1993 and 1995 by the Royal Museum of Central Africa (RMCA), Tervuren (Belgium) and the Renard Centre of Marine Geology (RCMG), Gent (Belgium). These data consist of a very fine grid of bathymetric data, obtained by echo-sounding profiling (Matton and Klerkx, 1995) and a total of 300 km of high-resolution single-channel seismic profiles, covering the whole area (Fig. 3) (De Batist and Vanhauwaert, 1995). The seismic data were shot using a 'Centipede' sparker source (frequency range of 400–1500 Hz when operated at 500 J) and a single-channel streamer as receiver. The incoming signal was filtered using a bandpass filter (400 Hz high-pass; 2000 Hz low-pass) and digitally recorded on an Elics Delph2 system. After processing with ProMax software (frequency filtering, spiking deconvolution), all the data were loaded and interpreted using the KINGDOM Suite software from Seismic Micro-Technology. The seismic sections have a theoretical resolution of approximately 0.5 m and the penetration is deep enough to allow the detection of the basement reflector in this area (up to 120 ms sub-bottom depth).

For the onshore part of the relay ramp, topographical maps (scale: 1:50,000) were digitised in the Royal Museum of Central Africa and the results were merged with the echo-sounding data. This allowed for the construction of a digital terrain model (DTM) that provides a link between onshore and offshore structures (Fig. 2). In this paper we present the results of the interpretation of these data sets.

## 2. The Baikal Rift Zone: geological setting

The Baikal Rift Zone (BRZ) is a good example of an active continental rift system. It has evolved since the Late Oligocene along a weakened part of the Baikal–Sayan mobile belt at the eastern border of the Siberian Craton (e.g. Mats, 1993). In the central part of the rift zone, three large basins formed that are currently occupied by the world's most voluminous fresh water

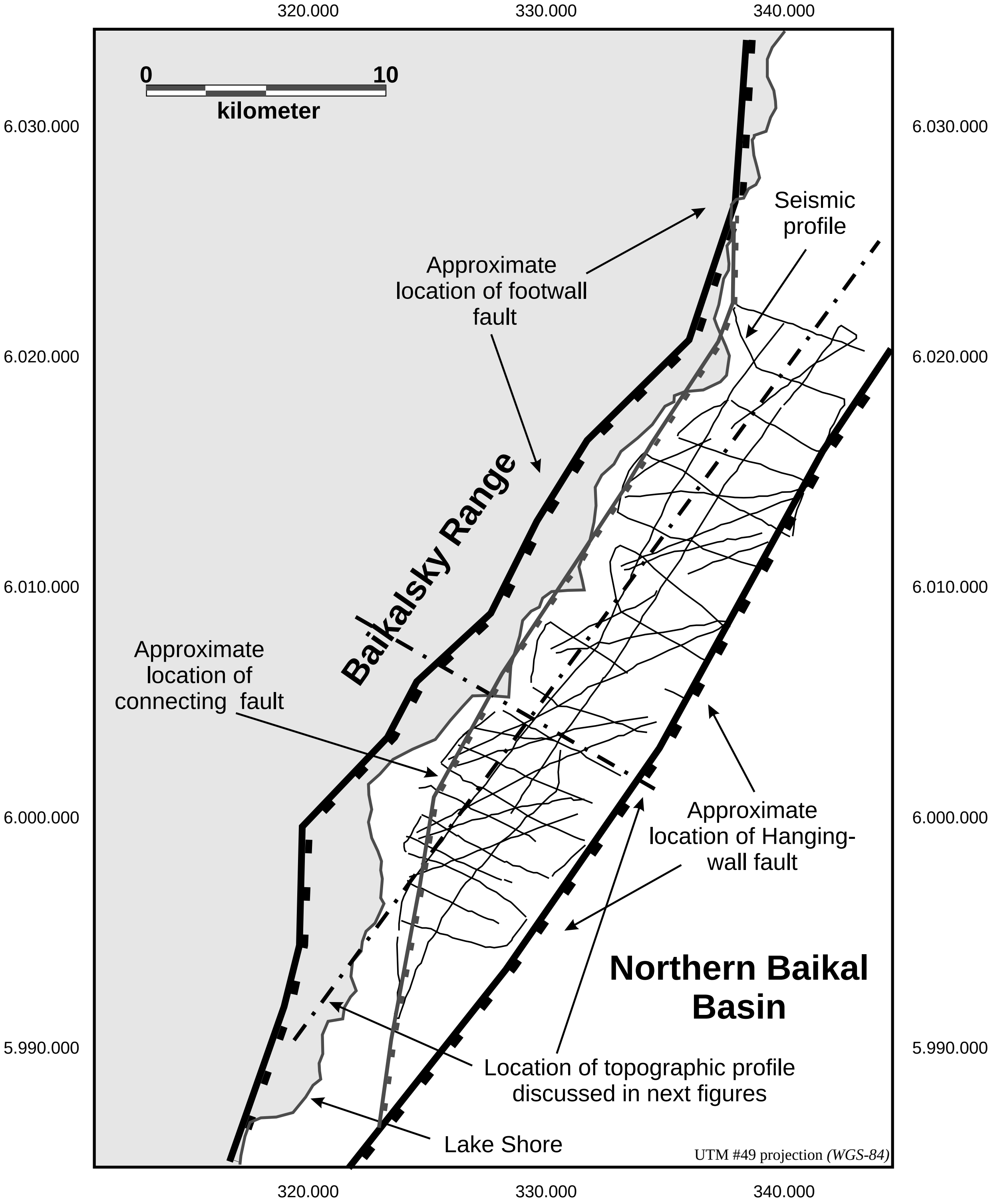

Fig. 3. Grid of high-resolution seismic sparker profiles in the area of Zavarotny. The approximate locations of the faults bordering the relay ramp are included. The total length of the profiles is 300 km. The dashed lines show the location of the topographic profiles in Fig. 4.

body: Lake Baikal. The three basins are separated from each other by two basement highs: the Academician Ridge Accommodation Zone between the northern and the central basins and the Selenga Delta Accommodation Zone between the central and the southern basins (Fig. 1). The relative position and orientation of these sub-basins has resulted in the segmented geometry of Lake Baikal, a property that is also recognised in other extensional terrains like the East African Rift System (e.g. Bosworth, 1985; Rosendahl et al., 1986) and the Basin and Range Province (e.g. Faulds and Varga, 1998). Despite its long history (about 35 Ma) the Baikal Rift Zone is currently at a rather young stage in the classification of

Rosendahl (1987); this is mainly due to the small stretching factor $\beta = 1.15$–$1.20$ (Zonenshain et al., 1992).

All three of the Baikal basins are delimited at their western border by major, large displacement faults, sharply contrasting with the morphology of the eastern side that resembles a smooth bend of the basement, occasionally cut by small normal faults (Logatchev, 1993; Mats, 1993). The result of this is a clear asymmetrical geometry of the basins (Hutchinson et al., 1992; Scholz et al., 1993; Logatchev, 1993, amongst others). Field investigations indicate that the western border faults have oblique movements (Mats, 1993; Delvaux et al., 1997), which is also confirmed by the study of earthquake focal mechanisms (Doser, 1991). However, it is clear that the character of these main faults was not constant during the whole evolution of Baikal (Scholz et al., 1993; Delvaux et al., 1997).

### *2.1. Recent tectonic evolution*

Generally it is agreed that the BRZ evolved in at least two major stages: a slow and a fast rifting phase (Hutchinson et al., 1992; Logatchev, 1993). The slow rifting stage lasted from ca. 30 Ma till about 3.5 Ma (e.g. Mats, 1993) or 2.5 Ma (Kuzmin et al., 2000) and led to the formation of large depressions, mainly as a result of a relatively slow subsidence and an unimportant uplift of the rift shoulders (Mats, 1993). The fast rifting stage, from 3.5–2.5 Ma to present, started with an increased rate of subsidence of the basins and the uplift of especially the western rift flank. All three Baikal basins started to evolve in the slow rifting phase, but due to a difference in syn-rift sediment thickness between the south and central basins (ca. 10 km) compared with the northern basin (ca. 4 km), the latter is believed to be considerably younger (Hutchinson et al., 1992; Mats et al., 2000).

### *2.2. Western border deflection*

The orientation of the border faults along the western side of Lake Baikal changes from an ENE direction along the southern basin to an approximately NNE orientation in the northern basin. This deflection reveals the different distinct segments of the western border fault system.

The Obruchevsky Fault is the northwestern border of the southern Baikal basin. Despite its sharp bend near Bolshy-Koti and a split of the fault with an eastern segment prolongating in the basin as the Posolsky Fault, it is usually traced to the mouth of the Buguldeika River. Here it splays into an eastern branch, the Ol'khon Fault, and a western branch, the Primorsky Fault, the main boundary of the central Baikal Basin (Fig. 1). The Ol'khon Fault (or Morsky Fault according to Agar and Klitgord (1995)) cross-cuts Lake Baikal, delimiting the southern side of the Ol'khon Island and the submerged Academician Ridge, two major blocks of the Academician Ridge Accommodation Zone (Mats et al., 2000). Farther to the north, near Kocherikovo, the Primorsky Fault dies out and is replaced by the Baikalsky Fault, which has a slightly different orientation and borders the northern basin.

Within these major fault segments, a smaller scale segmentation can be identified, see for example Agar and Klitgord (1995) for a description of the Primorsky Fault. For the northern Baikalsky Fault, a relay structure is found in the area of Zavarotny (Matton and Klerkx, 1995; Delvaux et al., 2000). Here a southern segment dies out in Lake Baikal and its displacement is transferred to an onshore segment to the north. Both segments partly overlap and a clear relay ramp structure has developed in between (Matton and Klerkx, 1995) (Fig. 2).

## 3. Morphology of the Zavarotny Area

The area of Zavarotny is a ∼40 km × 10 km tilted relay ramp structure between two fault segments of a major large displacement rift boundary fault (Baikalsky Fault). The segment of the Baikalsky Fault in the south of Zavarotny has a different orientation from that in the north (respectively, N45°E and N15°E), but they are almost parallel within the zone of overlap (N35°E). The southern segment (hanging-wall fault) terminates in the lake where it dies out towards the north after 35 km. The main fault on land (footwall fault) corresponds to the leading border fault farther to the north. Both faults dip towards the southeast.

A topographical cross-section (Fig. 4a) shows the 10-km-wide platform that formed between the two main faults. The surface of the platform is slightly tilted towards the hanging-wall fault. The cross-section also reveals the presence of a topographic step inside the platform (at a distance of around 7000–8000 m in the profile), which is small compared with the main faults. This topographic step corresponds approximately to the present-day lake border (Fig. 2) and connects the footwall fault with the hanging-wall fault.

A longitudinal elevation profile shows that the highest part of the relay ramp (∼50 m above the lake level) is located at its southwestern limit (Fig. 4b). The depth of the relay ramp gradually increases towards the northeast, where it eventually reaches a value of ∼800 m below lake level (Fig. 4). The longitudinal profile can be roughly subdivided into four zones, characterised by slightly different average slope values. As seen in Fig. 4, average elevation gradients are lowest in the southwestern part of the relay ramp (1.7%) and they increase towards the northeast (respectively, 3.4, 4.9 and 8.8%). On a smaller scale, local topographic variations are superimposed on the overall elevation change and this results in a rough surface morphology of the relay ramp.

As a result of the onshore deposition of coarse clastic sediments, derived from the nearby Baikalsky Range, the morphology of the onshore part of the relay ramp is more smoothed than that of the offshore part. During field investigations in this onshore area, small surface breaks have been reported, which are caused by movements on faults with orientations oblique to the main faults of the Zavarotny relay ramp (Matton and Klerkx, 1995).

## 4. Structural interpretation

Although the actual shape of the topographic step that connects the hanging-wall and the footwall faults in Zavarotny is determined to a large extent by sedimentary processes,

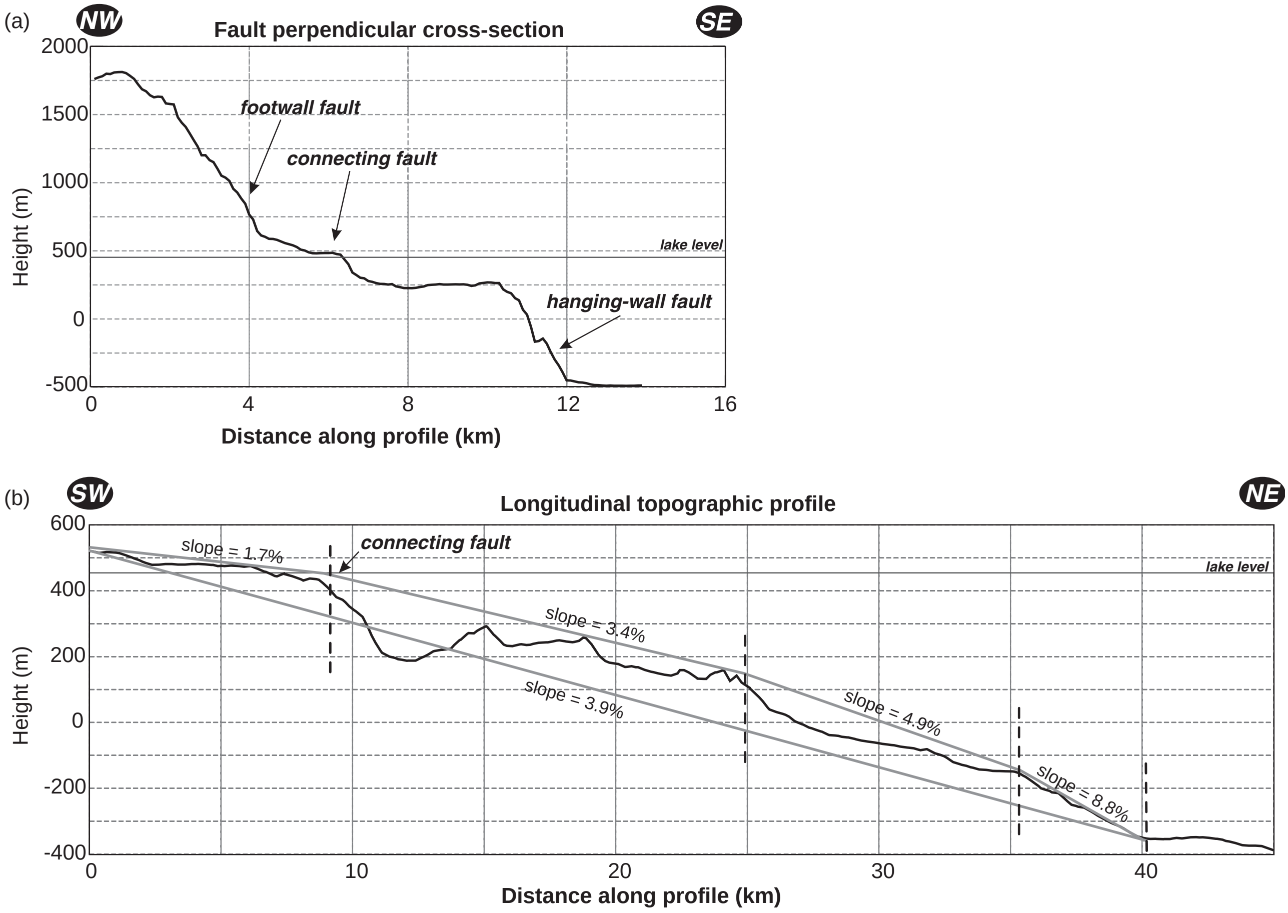

Fig. 4. Topographic profiles through the Zavarotny Relay Ramp (see Fig. 3 for their locations). (a) Fault perpendicular cross-section. (b) A longitudinal topographic section, illustrating the average slope variations in different parts of the relay ramp: lowest values for the slope are found in the upper part of the structure, and the values increase towards the lower parts.

an underlying fault has been inferred from a consistent small slope variation in the onshore part of the relay ramp, as well as from occasional small surface breaks observed on a RESURS satellite image. This fault has a N25°E strike and forms an angle of 10–15° with the main faults.

### *4.1. Interpretation of digital terrain models*

In the offshore part of the relay ramp three relatively large basins can be recognised, which slightly change their orientation throughout the relay ramp, from a NE–SW orientation in the southern part to an approximately N–S orientation in the north (see inset in Fig. 5).

Inside the southern basin three topographic steps can be identified that locally delimit smaller sub-basins. From the interpretation of the seismic profiles, it is clear that the genesis of the different basins in Zavarotny is not the same everywhere in the relay ramp (see Section 4.2).

By drawing height profiles from a digital terrain model of Zavarotny, we measured the throw along the two segments of the Baikalsky Fault (Fig. 6). We were only able to use the height difference between the lake floor level on either side of the faults because, due to the particular sedimentation environment in a relay ramp, other horizons could not be correlated with reflections outside (e.g. deposits from local river input near the relay ramp). Using these topographic values underestimates the actual throw values; however, a fission track study has estimated that the amount of footwall erosion is not more than a few tens of metres (Van Der Beek et al., 1996). This implies that the uncertainty in the throw profiles would be around 5–10%.

### *4.2. Interpretation of seismic profiles*

By picking the acoustic basement reflector on the high-resolution seismic profiles it has been possible to visualise the basement surface of the relay ramp. Although sediments have been deposited in the small basins described above (e.g. see the seismic profiles in Figs. 7 and 8), there is still a strong resemblance between the morphology of this basement surface and that of the lake floor (compare Fig. 9a and b). This suggests that the relay ramp is still actively deforming and that the sedimentary infill has not smoothed out the basement morphology. The seismic profiles also provide evidence that the basins in the relay ramp are bordered by a series of faults (e.g. Figs. 7 and 8), which reflect secondary faulting inside the relay ramp. The fault map (Fig. 9d) shows the areal correlation

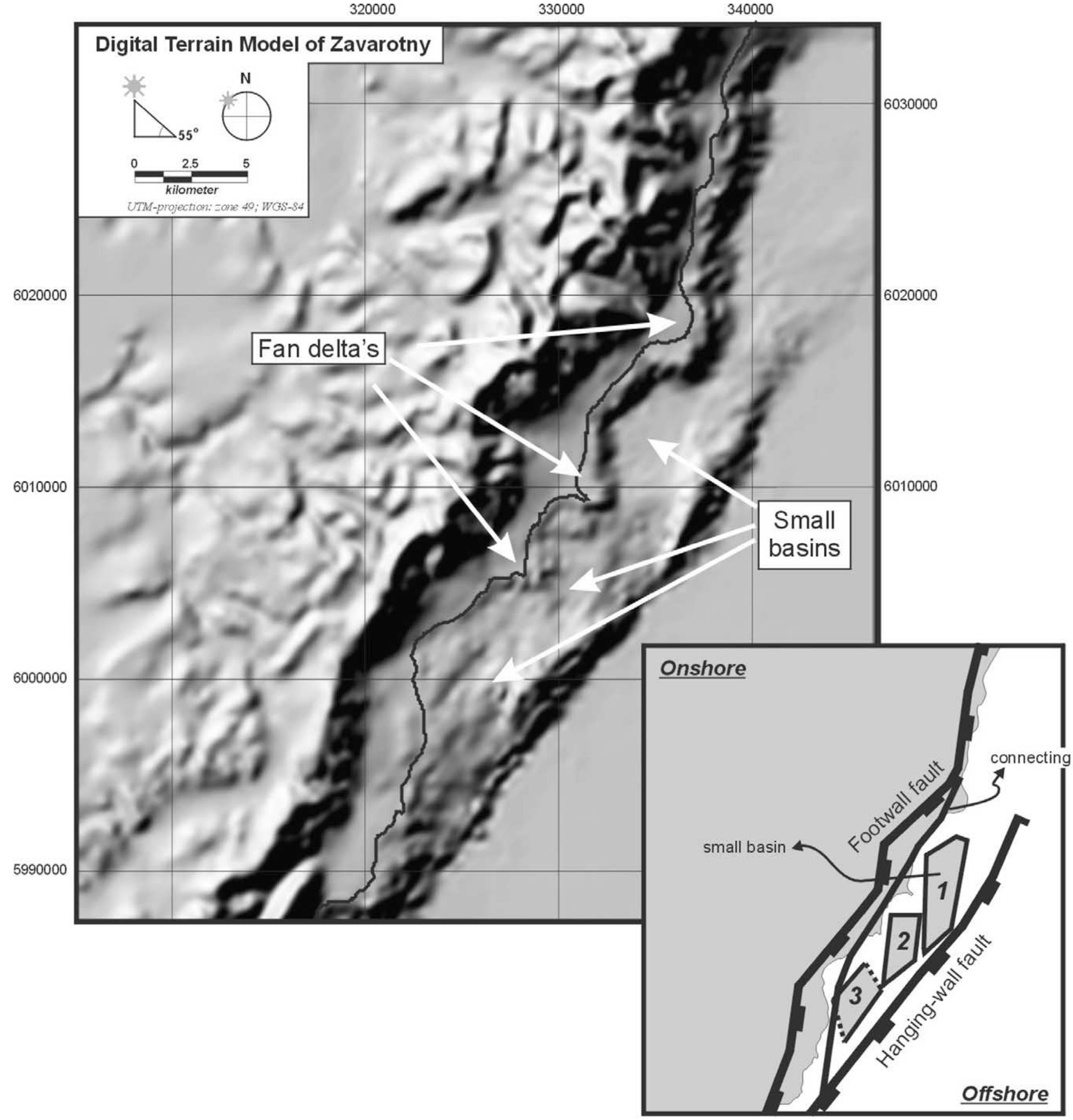

Fig. 5. Shaded relief representation of the digital terrain model in Zavarotny. The model was constructed by combining bathymetric data from echo-sounding profiles with digitised topographic maps (1:50,000). The inset illustrates the general structural interpretation of the area.

of the most important faults that displace the basement in the relay ramp. Many of these faults have a lake floor expression.

In the northern part of the relay ramp, a topographic step is produced by a NS-oriented fault, dipping towards the east (Fig. 9d). This fault links up with the major hanging-wall fault in the south, whereas towards the north it dies out, not revealing any linkage with the footwall fault. The fact that it splays from one of the major faults, and propagates towards the other, strongly suggests that it is a developing breaching fault, but has not yet caused the final hard linkage stage of the relay ramp. The largest 'embryonic' basin of the relay ramp is bordered in the west by this fault. The eastern limit of the basin is formed by an elevated basement-high near the hanging-wall fault.

On seismic profile number 49, which strikes normal to the major faults in the southern part of the relay ramp, a graben structure is observed, which is bounded by multiple conjugate faults (Fig. 8). In the eastern half of the profile these faults cause a clear tilted block geometry. This block tilting is responsible for the formation of the small sub-basins in this part of the relay ramp (as described in Section 4.1). The strike of these faults (being approximately NNE) corresponds to a pre-existing basement fabric observed onshore on satellite

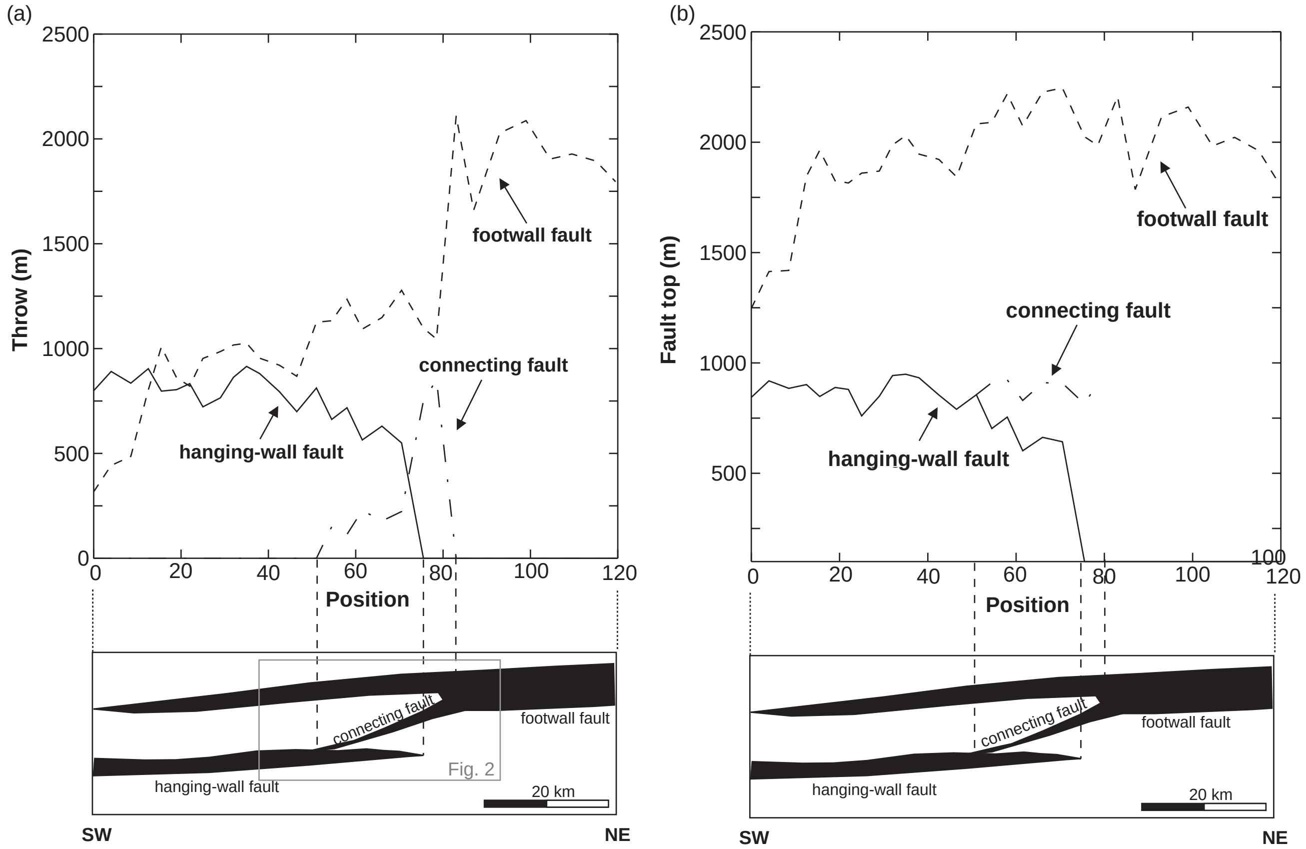

Fig. 6. Topographic difference between the top and the base of the main fault scarps in Zavarotny (a) and the height of the top of the different fault scarps (b). The scheme under the graphs should be considered as an illustration only; here the thickness of the black area is proportional to the throw.

images. The 'half-graben' structures form sub-basins in the larger basin of the southern part of the relay ramp (as interpreted in Figs. 5 and 9d). In the other relay ramp basins the same type of half-graben geometry is not observed.

The detailed sedimentary infill of the small basins shows alternating periods of deposition and non-deposition. For this reason the short gravity cores that are available from the Zavarotny area are insufficient to construct an age model for the whole sedimentary sequence. Moreover, due to the specific sedimentation environment of a relay ramp (see above), no age information could be obtained by correlating units from inside the relay ramp with units outside. Therefore the different

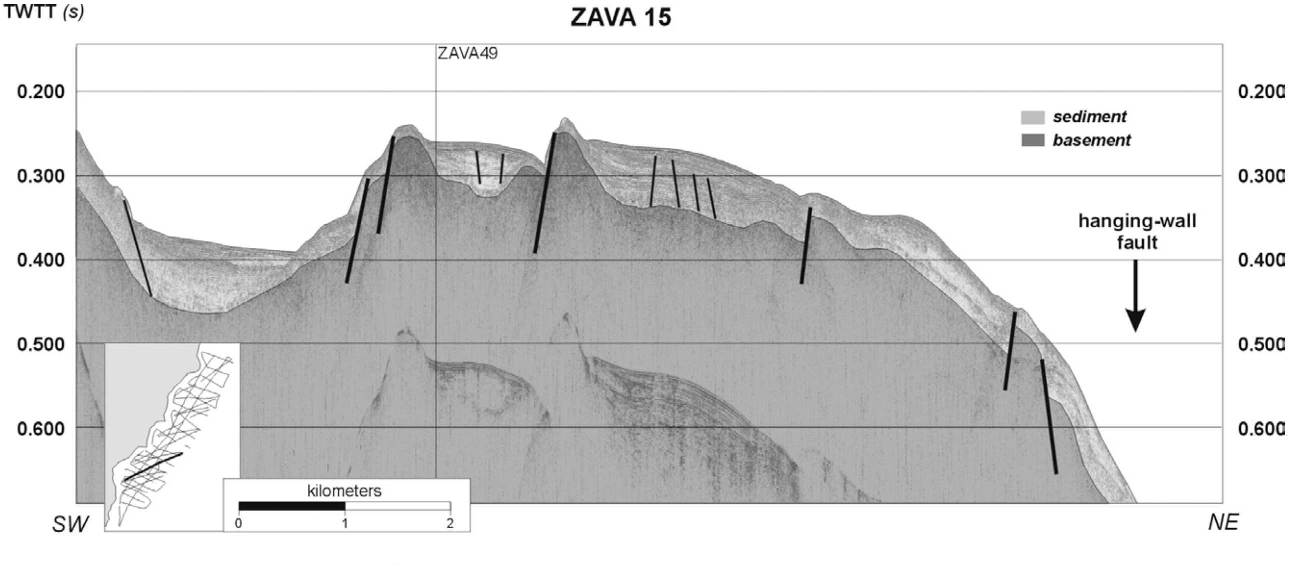

Fig. 7. High-resolution seismic profile (ZAVA015) showing some of the fault bounded basins within the relay structure. Also from this profile the strong correspondence between the lake-floor morphology and the basement morphology can be seen.

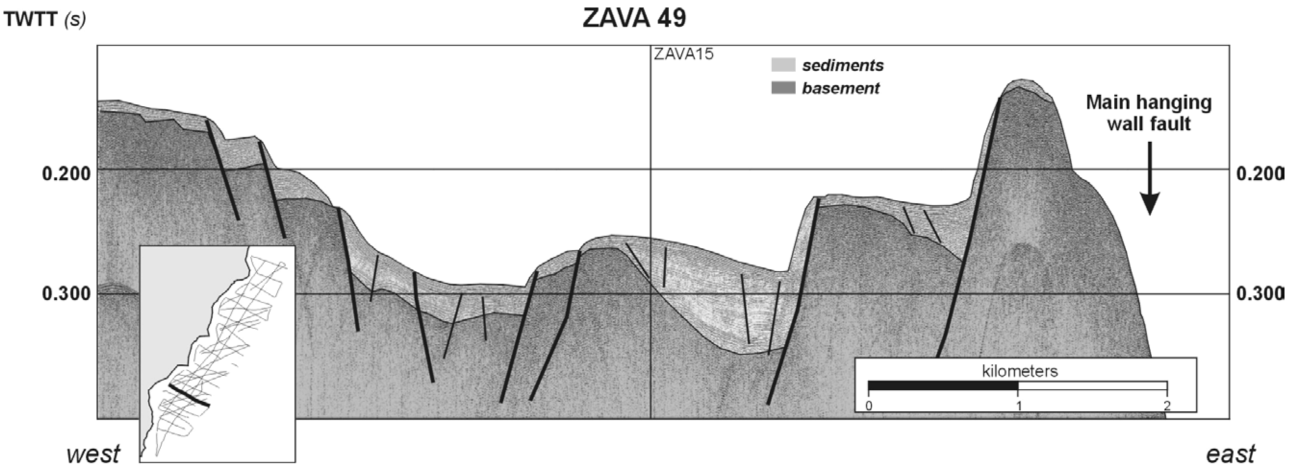

Fig. 8. Seismic profile ZAVA049, showing the tilted block geometry of the southern sub-basin.

deformation stages of the relay ramp could not be dated (absolutely or relatively), nor correlated to other events in the evolution of the Baikalsky Fault Zone.

## 5. Discussion

### 5.1. Determining fault interaction in Zavarotny

In Fig. 6 we presented the throw profiles of the main faults in Zavarotny. Drawing such throw profiles along the strike of faults is an effective technique to visualise fault interaction (Peacock and Sanderson, 1991; Dawers and Anders, 1995). Peacock and Sanderson (1991, 1994), for example, noticed that the displacement gradient of a fault increases in the zone where it overlaps with another fault and that the displacement maximum is no longer in the centre of the trace, but rather located closer to the zone of overlap. Moreover, increasing displacement gradients seem to occur with increasing fault interaction (Peacock and Sanderson, 1994; Gupta and Scholz, 2000).

Studies of displacement profiles in natural fault systems have revealed that only a small portion of the faults is completely unrestricted (e.g. 2% from a study in the Timor Sea (Nicol et al., 1996) and 4% from a study in Afar (Manighetti et al., 2001)). Such fault restriction results from a fault tip that does not propagate laterally, whereas fault displacement increases further (Nicol et al., 1996). From the strong decrease of displacement of the main faults in Zavarotny in the area of the relay ramp we can conclude that their throw profiles are at least ’tip restricted’ and that this is most likely the result of their mutual interaction.

In some studies also the separation between faults and the degree of overlap were used to evaluate a possible interaction (e.g. Huggins et al., 1995; An, 1997). For Zavarotny the distance of overlap is 40 km and the separation distance is 10 km, with a ratio of 4 we can assume fault interaction in this case (e.g. Willemse, 1997).

### 5.2. Comparison with existing models for relay ramp evolution

Based on the data and interpretations presented so far, a possible evolution scheme has been drawn for the Zavarotny relay ramp (Fig. 10). Because the segments of the Baikalsky Fault were formed by the reactivation of older structures, their formation might be characterised by a component of out-of-plane propagation. As a result, the initial relay ramp geometry could have formed in a relative short time period (see Section 1), and therefore the importance of the first evolution stage (Fig. 10a) in the model is unclear. In the presented evolution model, the development of the first connecting fault has been interpreted as marking the onset of the submergence below lake level of the current offshore part of the relay ramp (Fig. 10b and c). From the seismic profiles, it has been observed that sedimentation in the different sub-basins did occur during the formation of the basins, i.e. during the development of new secondary faults in the relay ramp. This implies that at that stage, the relay ramp had been submerged and as such the formation of the first connecting fault (Fig. 10b) pre-dated the development of the smaller secondary faults offshore (Fig. 10c and d), as well as the development of the second connecting fault. We do, however, have no information on the actual timing of the linkage between the first connecting fault and the hanging-wall fault of the relay ramp in Zavarotny. In Fig. 10 this connection has been drawn between stages c and d; however, it is possible that the linkage had been achieved before the formation of the secondary faults, which would imply that all observed deformation in the offshore part of the relay ramp has occurred in the post-breaching stage.

At least some of the characteristics of this relay ramp do not correspond to observations made in other, small scale, natural relay ramps (e.g. Peacock and Sanderson, 1991, 1994; Huggins et al., 1995); these are discussed below. It must, however, be said that Peacock et al. (2000b) already found some deviating structures in the large Hold With Hope relay ramp and concluded that there is not a complete scale independency for what concerns the internal structure of a relay ramp. The main

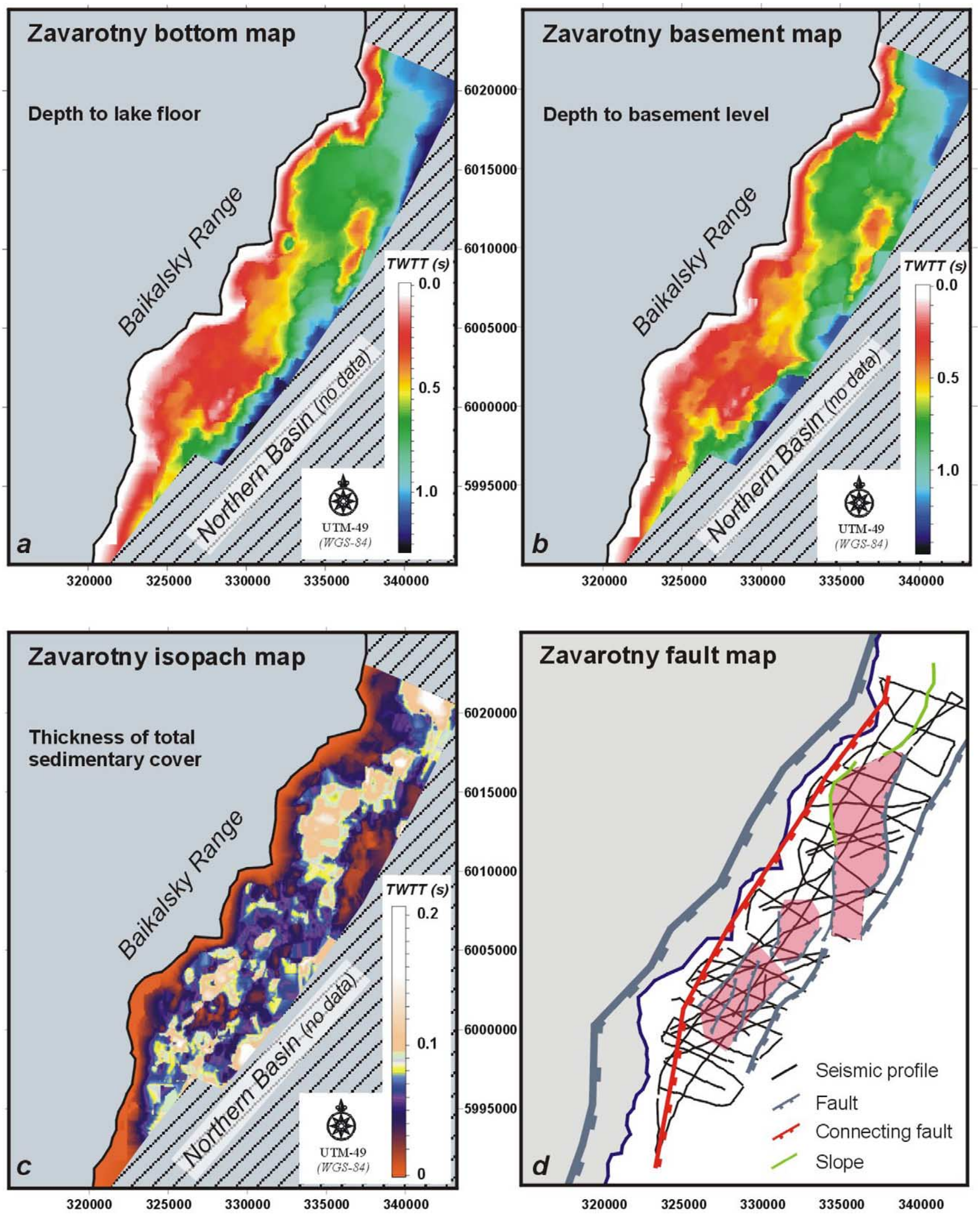

Fig. 9. Maps produced from the seismic profiles in Zavarotny: (a) depth of the lake floor, (b) depth of the acoustic basement level, (c) isopach map, and (d) fault map. Depth and thickness are expressed in two-way-travel time. The strong similarity between the lake floor morphology (a) and the basement morphology (b) indicates that the relay ramp structure is actively deforming. The fault map (d) illustrates that the basins in Zavarotny are fault-bounded structures.

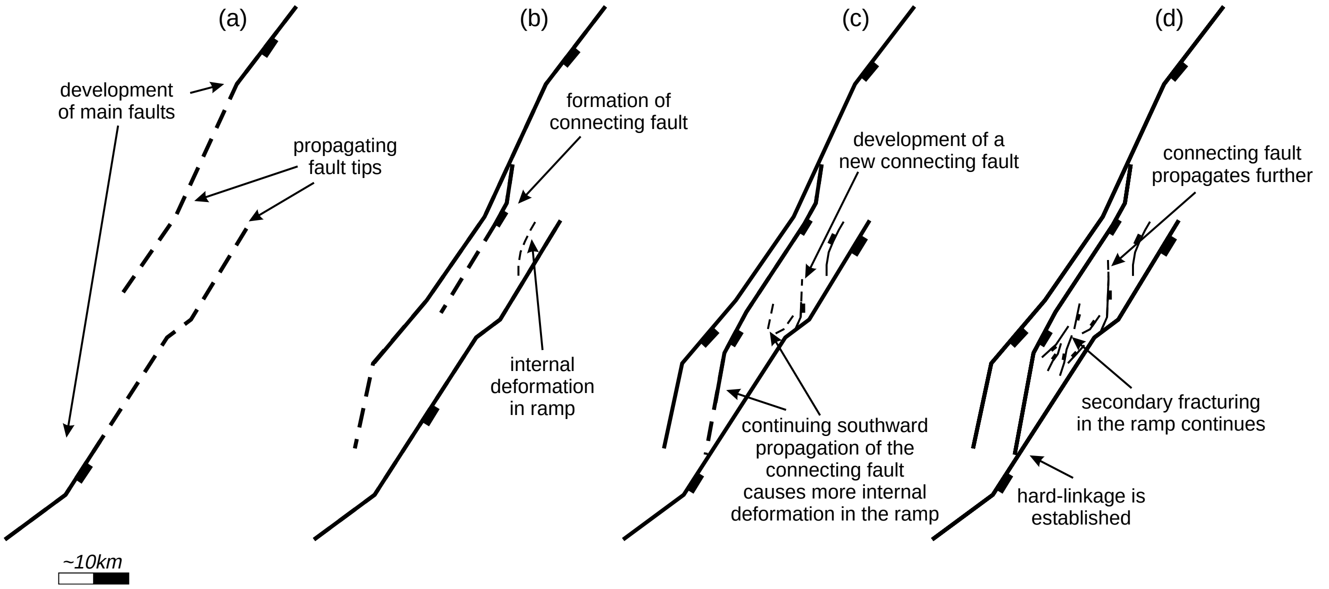

Fig. 10. Schematic illustration of the possible evolution of the Zavarotny relay ramp. (a) The main faults develop and propagate to form an overlap zone. (b) While the main faults overlap, a relay ramp forms. Deformation in this relay ramp results in the formation of the connecting fault, which splays off the footwall fault and propagates towards the hanging-wall fault. (c) The propagation of this connecting fault causes additional secondary deformation in the relay ramp between the connecting fault and the hanging-wall fault. This secondary deformation expands southward in relation to the southward propagation of the connecting fault. (d) While the relay ramp in Zavarotny has been breached by the connecting fault, a new connecting fault develops in the upper part of the relay ramp. This fault splays off the hanging-wall fault and propagates towards the first connecting fault.

geometry of relay ramps (i.e. length to width ratio), however, appears to be invariant on a wide range of scales (Peacock, 2003).

If we consider the topographic step in the relay ramp to be fault related, this implies that the Baikalsky fault segments are already in the hard-linkage stage and linked by a connecting fault. In that case one would expect the unused fault-parts to be gradually eroded and finally disappear, with later displacements confined to this new fault. This would not explain the development of the young, small basins between the connecting and the hanging-wall faults, nor the development of a new, secondary, through-going fault as observed on the seismic profiles. The fact that the relay ramp continues its development suggests that either the relay ramp is not yet fully hard linked in three dimensions (Imber et al., 2004; Soliva and Benedicto, 2004) or that there is a continued post-breaching evolution. Such a post-breaching evolution of relay ramps has also been observed in scaled physical models of relay ramps and was found to be independent of the breaching type (Hus et al., 2005).

The development of the first connecting fault to breach the relay ramp could also be considered peculiar, because by far the most natural examples are characterised by one of the major fault segments that slightly bends and grows towards the other segment (e.g. Trudgill and Cartwright, 1994; Childs et al., 1995) to achieve the final connection, a property that was also observed for the linking of extensional fractures (Acocella et al., 2000). Also, in 3D distinct element models of relay evolution along normal faults, no breaching by a connection fault has been observed (Imber et al., 2004). Ferrill et al. (1999) described examples of both types of breaching and explained the linkage in terms of the displacement gradient on the main faults. Where fault throw increases disproportionately to fault-tip propagation, linkage by a connecting fault would be favoured. In this case relay ramp tilting and bending along an axis perpendicular to the strike of the main faults is increased and the associated extension results in the formation of faults striking at high angles to them. The secondary faults that we observe in the relay ramp at Zavarotny strike only slightly oblique and therefore suggest tilting and bending of the relay ramp along an axis parallel to the main faults, but this, as explained, seems to contradict the development of a new through-going connecting fault.

Another possibility for Zavarotny is that the main faults result from the reactivation of inherited basement structures and that, therefore, fault lengths were determined long before the displacement reached the limit for lateral propagation (e.g. Walsh et al., 2002; Peacock, 2002). This could explain the occurrence of both kinds of faults (striking either parallel or at high angle to the main faults). However, in our case, this explanation is not sufficient as one would expect the parallel faults to develop prior to the connecting fault.

An explanation for the small angle between the secondary faults and the main faults in Zavarotny could be that these secondary faults are segments of the same fault system that comprises the relay and not necessarily new faults that formed in the relay ramp as a result of local stresses (e.g. fig. 10 in Walsh et al., 2003).

Ferrill and Morris (2001) have described an alternative deformation path for the bounding faults of a relay ramp.

During this deformation fault tip propagation is arrested in an early stage of overlap, but fault displacement increases further. This early stage is subsequently followed by a period of rapid fault propagation. In such a deformation path, initial extension inside the relay ramp may be expressed as faults striking strongly oblique to the main faults, whereas in a later stage of overlap the faults may develop that strike almost parallel to the main faults.

In the cases explained by Cartwright et al. (1996) and Ferrill et al. (1999), the connecting fault is not a single, well expressed fault, but rather a fault system resulting from the interconnection of different fault clusters in the relay ramp. In Zavarotny, the first connecting fault—although buried by sediments—as well as the second (developing) fault seem to consist of a single, well defined, trace. Also, Young et al. (2001) observed a single, well expressed fault that links up two fault segments in the Murchison–Statfjord North Fault Zone.

Peacock et al. (2000b) noted previously that the secondary faults developed in the Hold With Hope relay ramp are mostly synthetic to the main faults and as such have an opposite dip direction compared with secondary faults in smaller relay ramps. In the Zavarotny relay ramp, the strike directions of the secondary faults are similar to the observations from the Hold With Hope relay ramp; however, they dip mainly antithetically to the main faults.

Probably the most important factor that influences the architecture of the Zavarotny relay ramp is the presence of pre-existing basement fabric in the area. Possibly this fabric limits the amount of bending in the relay ramp (along an axis parallel to the main faults) that is required to form secondary faults in the relay ramp, which strike parallel to these main faults. This mechanism could also explain the relatively small angle between the connecting fault and the main faults (10–15°), as well as the development of the well-defined connecting fault. This would imply that pre-existing basement structures can substantially complicate the internal deformation inside large relay ramps.

## 6. Conclusions

Based on the interpretation of several detailed data sets, we have described the internal structure of a relative large scale relay ramp ($\sim 10\times 40$ km) in the western border fault system of Lake Baikal and we have proposed a possible evolutionary scheme. It is the first time that the internal structure of a large relay ramp between large displacement boundary faults in a narrow rift has been described. Moreover, from the inferred evolution, it has been possible to reconstruct the linkage process between two segments of the major Baikalsky Fault in Lake Baikal.

The deformation inside the Zavarotny relay ramp has been through the development of fault controlled sub-basins. We have observed an uncommon combination of secondary fault development in the relay ramp (with fault strikes that are almost parallel or at low angle to the main faults) and breaching of the relay ramp by a newly formed connecting fault. This observation can be explained by the presence of pre-existing basement fabric in the area, which has influenced secondary fault development within the relay ramp.

We have found evidence for a post-breaching continued evolution of the relay ramp in Zavarotny, confirming earlier observations from sandbox models, which showed that relay ramp breaching is not an instantaneous process (Hus et al., 2005). From the observed continuing post-breaching deformation of the relay ramp, we conclude that the structure in Zavarotny results from a combination of soft as well as hard linked displacement transfer.

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## References

Acocella, V., Gudmundsson, A., Funiciello, R., 2000. Interaction and linkage of extension fractures and normal faults: examples from the rift zone of Iceland. Journal of Structural Geology 22, 1233–1246.

Agar, S.M., Klitgord, K.D., 1995. Rift flank segmentation, basin initiation and propagation: a neotectonic example from Lake Baikal. Journal of the Geological Society of London 152, 849–860.

An, L., 1997. Maximum link distance between strike-slip faults: observations and constraints. Pure and Applied Geophysics 150, 19–36.

Aydin, A., Schultz, R., 1990. Effect of mechanical interaction on the development of strike-slip faults with echelon patterns. Journal of Structural Geology 12, 123–129.

Bosworth, W., 1985. Geometry of propagating rifts. Nature 316, 625–627.

Cartwright, J.A., Mansfield, C., Trudgill, B., 1996. The growth of normal faults by segment linkage. In: Buchanan, P.G., Nieuwland, D.A. (Eds.), Modern Developments in Structural Geology, Interpretation, Validation and Modelling Geological Society Special Publication 99, pp. 163–177.

Childs, C., Watterson, J., Walsh, J.J., 1995. Fault overlap zones within developing normal fault systems. Journal of the Geological Society of London 152, 535–549.

Coskun, B., 1997. Oil and gas fields—transfer zone relationships, Thrace Basin, NW Turkey. Marine and Petroleum Geology 14, 401–416.

Crider, J.G., Pollard, D.D., 1998. Fault linkage: three-dimensional mechanical interaction between echelon normal faults. Journal of Geophysical Research 103, 24373–24391.

Davison, I., 1994. Linked fault systems; extensional, strike-slip and contractional. In: Hancock, P.L. (Ed.), Continental Deformation. Pergamon Press, pp. 121–141.

Dawers, N.H., Anders, M.H., 1995. Displacement–length scaling and fault linkage. Journal of Structural Geology 17, 607–614.

De Batist, M., Vanhauwaert, P., 1995. Lake Baikal 1995: Expedition Report. Internal Note of the Renard Centre of Marine Geology, Ghent University.

Delvaux, D., Moeys, R., Stapel, G., Petit, C., Levi, K., Miroshnichenko, A., Ruzhich, V., San'kov, V., 1997. Paleostress recontstructions and geodynamics of the Baikal region, Central Asia, Part 2. Cenozoic rifting. Tectonophysics 282, 1–38.

Delvaux, D., Fronhoffs, A., Hus, R., Poort, J., 2000. Normal fault splays, relay ramps and transfer zones in the central part of the Baikal rift basin: insight from digital topography and bathymetry. Bulletin des Centres de Recherches Exploration—Production Elf Aquitaine 22, 341–358.

dePolo, C.M., Clark, D.G., Burton Slemmons, D., Ramelli, A.R., 1991. Historical surface faulting in the Basin and Range province, western North America: implications for fault segmentation. Journal of Structural Geology 13, 123–136.

Doser, D., 1991. Faulting within the western Baikal rift as characterised by earthquake studies. Tectonophysics 196, 87–107.

Dou, L., Chang, L., 2003. Fault linkage patterns and their control on the formation of the petroleum systems of the Erlian Basin, Eastern China. Marine and Petroleum Geology 20, 1213–1224.

Faulds, J.E., Varga, R.J., 1998. The role of accommodation zones and transfer zones in the regional segmentation of extended terranes. In: Faulds, J.E., Stewart, J.H. (Eds.), Accommodation Zones and Transfer Zones; the Regional Segmentation of the Basin and Range Province Geological Society of America, Special Paper 323, pp. 1–45.

Ferrill, D.A., Morris, A.P., 2001. Displacement gradient and deformation in normal fault systems. Journal of Structural Geology 23, 619–638.

Ferrill, D.A., Stamatakos, J.A., Sims, D., 1999. Normal fault corrugation: implications for growth and seismicity of active normal faults. Journal of Structural Geology 21, 1027–1038.

Gawthorpe, R.L., Hurst, J.M., 1993. Transfer zones in extensional basins: their structural style and influence on drainage development and stratigraphy. Journal of the Geological Society of London 150, 1137–1152.

Gupta, A., Scholz, C.H., 2000. A model of normal fault interaction based on observations and theory. Journal of Structural Geology 22, 865–879.

Huggins, P., Watterson, J.J., Walsh, J.J., Childs, C., 1995. Relay zone geometry and displacement transfer between normal faults recorded in coal-mine plans. Journal of Structural Geology 17, 1741–1755.

Hus, R., Acocella, V., Funiciello, R., De Batist, M., 2005. Sandbox models of relay ramp structure and evolution. Journal of Structural Geology 27, 459–473.

Hutchinson, D.R., Golmshtok, A.J., Zonenshain, L.P., Moore, T.C., Scholtz, C.A., Klitgord, K.D., 1992. Depositional and tectonic framework of the rift basins of Lake Baikal from multichannel seismic data. Geology 20, 589–592.

Imber, J., Tuckwell, G.W., Childs, C., Walsh, J.J., Manzocchi, T., Heath, A.E., Bonson, C.G., Strand, J., 2004. Three-dimensional distinct element modelling of relay growth and breaching along normal faults. Journal of Structural Geology 26, 1897–1911.

Jackson, C.A.L., Gawthorpe, R.L., Sharp, I.A., 2002. Growth and linkage of the East Tanka fault zone, Suez rift: structural style and syn-rift stratigraphic response. Journal of the Geological Society of London 159, 175–187.

Kuzmin, M.I., Karabanov, E.B., Prokopenko, A.A., Gelety, V.F., Antipin, V.S., Williams, D.F., Gvozdkov, A.N., 2000. Sedimentation processes and new age constraints on rifting stages in Lake Baikal: results of deep-water drilling. International Journal of Earth Sciences 89, 183–192.

Larsen, P.H., 1988. Relay structures in a Lower Permian basement-involved extension system, East Greenland. Journal of Structural Geology 10, 3–8.

Leeder, M.R., Collier, R.E.L., Abdul Aziz, L.H., Trout, M., Ferentinos, G., Papatheodorou, G., Lyberis, E., 2002. Tectono-sedimentary processes along an active marine/lacustrine half-graben margin: Alkyonides Gulf, E. Gulf of Corinth, Greece. Basin Research 14, 25–41.

Logatchev, N.A., 1993. History and geodynamics of the Lake Baikal Rift in the context of the Eastern Rift System: a review. Bulletin des Centres de Recherches Exploration—Production Elf Aquitaine 17, 353–370.

Manighetti, I., King, G.C.P., Gaudemer, Y., Scholz, C.H., Doubre, C., 2001. Slip accumulation and lateral propagation of active normal faults in Afar. Journal of Geophysical Research 106, 13667–13696.

Mats, V.D., 1993. The structure and development of the Baikal rift depression. Earth-Science Reviews 34, 81–118.

Mats, V.D., Khlystov, O.M., De Batist, M., Ceramicola, S., Lomonosova, T.K., Klimansky, A., 2000. The evolution of the Akademichesky Ridge Accommodation Zone in the central part of the Baikal Rift, from high-resolution reflection seismic profiling and geological field investigations. International Journal of Earth Sciences 89, 229–250.

Matton, C., Klerkx, J., 1995. Basin structure in the Western part of Northern Lake Baikal: the Zavarotny Area. Russian Geology and Geophysics 36, 168–174.

Morley, C.K., 1995. Developments in the structural geology of rifts over the last decade and their impact on hydrocarbon exploration. In: Lambiase, J.J. (Ed.), Hydrocarbon Habitat in Rift Basins Geological Society Special Publication 80, pp. 1–32.

Morley, C.K., 1999. Aspects of transfer zone geometry and evolution in East African Rifts. In: Morley, C.K. (Ed.), Geoscience of Rift Systems—Evolution of East Africa AAPG Studies in Geology 44, pp. 161–171.

Morley, C.K., Nelson, R.A., Patton, T.L., Munn, S.G., 1990. Transfer zones in the East African Rift System and their relevance to hydrocarbon exploration in rifts. Bulletin of the American Association of Petroleum Geologists 74, 1234–1253.

Nelson, R.A., Patton, T.L., Morley, C.K., 1992. Rift-segment interaction and its relation to hydrocarbon exploration in continental rift systems. Bulletin of the American Association of Petroleum Geologists 76, 1153–1169.

Nicol, A., Watterson, J., Walsh, J.J., Childs, C., 1996. The shapes, major axis orientations and displacement patterns of fault surfaces. Journal of Structural Geology 18, 235–248.

Peacock, D.C.P., 2002. Propagation, interaction and linkage in normal fault systems. Earth-Science Reviews 58, 121–142.

Peacock, D.C.P., 2003. Scaling of transfer zones in the British Isles. Journal of Structural Geology 25, 1561–1567.

Peacock, D.C.P., Parfitt, E.A., 2002. Active relay ramps and normal fault propagation on Kilauea Volcano, Hawaii. Journal of Structural Geology 24, 729–742.

Peacock, D.C.P., Sanderson, D.J., 1991. Displacements, segment linkage and relay ramps in normal fault zones. Journal of Structural Geology 13, 721–733.

Peacock, D.C.P., Sanderson, D.J., 1994. Geometry and development of relay ramps in normal fault systems. Bulletin of the American Association of Petroleum Geologists 78, 147–165.

Peacock, D.C.P., Knipe, R.J., Sanderson, D.J., 2000a. Glossary of normal faults. Journal of Structural Geology 22, 291–305.

Peacock, D.C.P., Price, S.P., Whitham, A.G., Pickles, C.S., 2000b. The World's biggest relay ramp: Hold With Hope, NE Greenland. Journal of Structural Geology 22, 843–850.

Rosendahl, R.B., 1987. Architecture of continental rifts with special reference to East Africa. Annual Review of Earth and Planetary Sciences 15, 445–503.

Rosendahl, B.R., Reynolds, D.J., Lorber, P.M., Burgess, C.F., McGill, J., Scott, D., Lambiase, J.J., Derksen, S.J., 1986. Structural expression of rifting: lessons from Lake Tanganyika, Africa. In: Frostick, L.E., Renaut, R.W., Reid, I., Tiercelin, J.J. (Eds.), Sedimentation in the African Rifts Geological Society Special Publication 25, pp. 29–43.

Scholz, C.A., Klitgord, K.D., Hutchinson, D.R., Ten Brink, U.S., Zonenshain, L.P., Golmshtok, A.Y., Moore, T.C., 1993. Results of 1992 Seismic Reflection Experiment in Lake Baikal. Eos Transactions of the American Geophysical Union 74, 465–470.

Segall, P., Pollard, D.D., 1980. Mechanics of discontinuous faults. Journal of Geophysical Research 85, 4337–4350.

Soliva, R., Benedicto, A., 2004. A linkage criterion for segmented normal faults. Journal of Structural Geology 26, 2251–2267.

Trudgill, B.D., Cartwright, J.A., 1994. Relay ramp forms and normal fault linkages—Canyonlands National Park, Utah. Bulletin of the Geological Society of America 106, 1143–1157.

Upcott, N.M., Mukasa, R.K., Ebinger, C.J., 1996. Along-axis segmentation and isostasy in the Western rift, East Africa. Journal of Geophysical Research 101, 3247–3268.

Van Der Beek, P.A., Delvaux, D., Andriessen, P.A.M., Levi, K.G., 1996. Early Cretaceous denudation related to convergent tectonics in the Baikal region, SE Siberia. Journal of the Geological Society, London 153, 515–523.

Walsh, J.J., Nicol, A., Childs, C., 2002. An alternative model for the growth of faults. Journal of Structural Research 24, 1669–1675.

Walsh, J.J., Bailey, W.R., Childs, C., Nicol, A., Bonson, C.G., 2003. Formation of segmented normal faults: a 3-D perspective. Journal of Structural Geology 25, 1251–1262.

Willemse, E.J.M., 1997. Segmented normal faults: correspondence between three-dimensional mechanical models and field data. Journal of Geophysical Research 102, 675–692.

Willemse, E.J.M., Pollard, D.D., Aydin, A., 1996. Three-dimensional analyses of slip distributions on normal fault arrays with consequences for fault scaling. Journal of Structural Geology 18, 295–309.

Young, M.J., Gawthorpe, R.L., Hardy, S., 2001. Growth and linkage of a segmented normal fault zone: the Late Jurassic Murchison Statfjord North Fault, northern North Sea. Journal of Structural Geology 23, 1933–1952.

Zonenshain, L.P., Golmshtok, A.Y., Hutchinson, D., 1992. Baikal rift structure. Geotectonics 26, 396–407.