NORMAL FAULT SPLAYS, RELAY RAMPS AND TRANSFER ZONES IN THE CENTRAL PART OF THE BAIKAL RIFT BASIN: INSIGHT FROM DIGITAL TOPOGRAPHY AND BATHYMETRY

RELAIS, ZONES DE DIVERGENCE ET DE TRANSFERT DANS LA PARTIE CENTRALE DU BASSIN DE RIFT DU BAÏKAL : APPORT DE LA TOPOGRAPHIE ET DE LA BATHYMÉTRIE DIGITALES

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DELVAUX, D., FRONHOFFS, A., HUS, R. & POORT, J. (1999). — Normal fault splays, relay ramps and transfer zones in the central part of the Baikal rift basin: insight from digital topography and bathymetry. [*Relais, zones de divergence et de transfert dans la partie centrale du bassin du Baïkal : apport de la topographie et de la bathymétrie digitales*] — *Bull. Centre Rech. Elf Explor. Prod.*, 22, 2, 341-358, 8 fig.; Pau, Mai 29, (1998) 2000. — ISSN : 1279-8215. CODEN : BCREDP.

A Digital Elevation Model (DEM) of the Baikal rift basin and adjacent rift shoulders has been made from 1/200.000 digitised topographic and bathymetric maps. It is used as a means for visualisation of the detailed topography and bathymetry, in morphotectonic investigation of rift basin formation in the Baikal Rift Zone. The morphology of both aerial and underwater structures is best expressed by a combination of coloured maps, according to the relative altitude and shaded relief maps with artificial illumination. The DEM is used for a detailed morphostructural and tectonic analysis of the central part of the Baikal rift basin. Relay ramps and normal fault splays of different scales are clearly shown. They illustrate rift segment interaction during rifting propagation. In addition, the structure of the large scale Olkhon - Academician Ridge, a partly underwater transfer zone between the Central and North Baikal basins, is highlighted. The digital morphology helps to visualise these structures in three dimensions and to define precisely the linking mode between fault segments and rift basins.

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Keywords: Digital Elevation Model, Morphostructures, Normal faults, Transfer faults, Relay ramps, Fault splays, Rift zones, Baikal Rift Zone

RÉSUMÉ

Un Modèle Numérique de Terrain (MNT) du bassin de rift du Baïkal et des épaules adjacentes a été réalisé à partir de cartes topographiques et bathymétriques digitalisées à 1:200.000. Ce modèle est utilisé ici comme moyen de visualisation détaillé de la topographie et de la bathymétrie, pour l'étude morphotectonique de la formation de bassins de rift dans la zone de rift du Baïkal. La morphologie des structures en surface et sous-marines est la mieux exprimée par une combinaison de cartes en couleur en fonction de l'altitude et de reliefs ombrés par illumination artificielle. Le MNT est utilisé pour l'analyse morphostructurale et tectonique de la partie centrale du bassin du lac Baïkal. Des zones de relais et des zones de divergence entre failles normales sont clairement mises en évidence. Elles illustrent le principe d'interaction entre segments de rift au cours de la propagation du rifting. De plus, la structure de la zone de transfert Olkhon–Academician Ridge, partiellement sous-lacustre est mise en évidence, entre les bassins nord et central du Lac Baïkal. La morphologie digitale aide à la visualisation des structures en trois dimensions. Elle permet de préciser les connexions entre les segments de faille et entre les bassins de rift.

Mots-clés : Modèle numérique de terrain, Morphostructure, Faille normale, Faille transfert, Zone relai, Zone divergence, Rift, Rift Baïkal

1279-8215/00/0022-0341 $ 7.40

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INTRODUCTION

In morphotectonic investigations of actively forming sedimentary basins and mountain ranges, there is a strong need for a practical and accurate visualisation of the detailed topography of the land area (e.g. HALL, 1996). Since in such environment, the presence of large and deep lakes is relatively frequent, it is also necessary to visualise the bathymetry of the lake floor. High-resolution Digital Elevation Model (DEM) combining digital topography and bathymetry is a very useful tool for all investigations based on the observation and description of the topography and bathymetry. Once the DEM is created, it can be visualised in different ways. Coloured maps according to the relative altitude and shaded relief maps, or a combination of the two, are the most frequently used in neotectonic and morphostructural analysis. Satellite images or aerial photos can be draped on the DEM, for realistic 3D displays. They can be used in quantitative morphology, for extraction of topographic cross sections, slope computation, etc. Shaded relief maps are also useful for referencing the microstructural observations, so that they can be interpreted in their context. The quality of the model depends necessarily on the quality or scale of the topographic and bathymetric survey.

This paper presents an example of the application of DEM to the structural and neotectonic investigation of the Lake Baikal sedimentary depression, in South-Siberia, by combining land topography and lake bottom bathymetry. Contoured elevation data from maps of different scales were used to illustrate the regional morphostructures of transfer zones and fault linkage in the central part of the Baikal rift basin. This paper does not deal with structural observations on the lake shore, nor with the results of high resolution seismic surveys. This new data, obtained during 1997 and 1998 campaigns will be presented elsewhere.

Relay ramps, normal fault splays and transfer fault zones are typical in an extensional environment (MORLEY *et al.*, 1990; NELSON *et al.*, 1992 and PEACOCK & SANDERSON, 1994). They play a major role in the development of rift basins. They result from the propagation and linkage of originally isolated fault-bounded rift segments. These kind of structures are particularly well expressed in the transition from the Central Baikal basin to the North Baikal basin (Fig. 3).

1. — STRUCTURE AND EVOLUTION OF THE BAIKAL BASIN IN THE BAIKAL RIFT ZONE

The Baikal Rift Zone (Fig. 1) initiated in the Late Oligocene, as a result of the combined influence of the India–Eurasia collision and convergence, and of the Pacific–Asia subduction (LOGATCHEV, 1993; DELVAUX *et al.*, 1997; SAN'KOV *et al.*, 1997). Rifting was controlled by the morphology of the Siberian Craton, by lithospheric scale discontinuities along its southwestern and southeastern margins, and by the combined action of intraplate compressional stress field and locally generated extensional stresses related to lithospheric destabilisation. The long pre-rift tectonic history (MELNIKOV *et al.*, 1994; ERMIKOV, 1994; DELVAUX *et al.*, 1995) maintained the margin of the Siberian Craton in a mechanically weak state. The basin of Lake Baikal itself (Fig. 2; LEVI *et al.*, 1997) developed first in a transpressional to transtensional context since the Late Oligocene (30 Ma), until the Early–Late Pliocene transition (4-3 Ma). This stage is named "slow rifting stage" by LOGATCHEV (1993) and "proto-rift stage" by DELVAUX *et al.*, (1997). Since the Late Pliocene, rifting process has accelerated, in a dominant extensional stress field. This is the "fast rifting stage" of LOGATCHEV (1993) or "active-rift stage" of DELVAUX *et al.* (1997). Sedimentation in the rift basin was controlled both by tectonic and climatic factors (KASHIK & MAZILOV, 1994).

2. — CONSTRUCTION OF THE BAIKAL DEM

The detailed Digital Elevation Model (DEM) of the Baikal rift basin and adjacent areas has been produced on the basis of 1:200 000 topographic maps and bathymetric charts. Topography is based on the maps of the Central Administration of Geodesy and Cartography at the Soviet Ministry of USSR. The sheets of the area surrounding Lake Baikal are taken from the Pribaikalie Map Album compiled by VKF, Irkutsk, and published in 1996. A total of 23 sheets have been digitised so far. Bathymetry is from the Bathymetric charts of Lake Baikal (1992).

The first, and more tedious, step in the procedure involved the manual digitisation of topographic elevation contour lines at 40 m intervals and of bathymetric contour lines at 100 m inter-

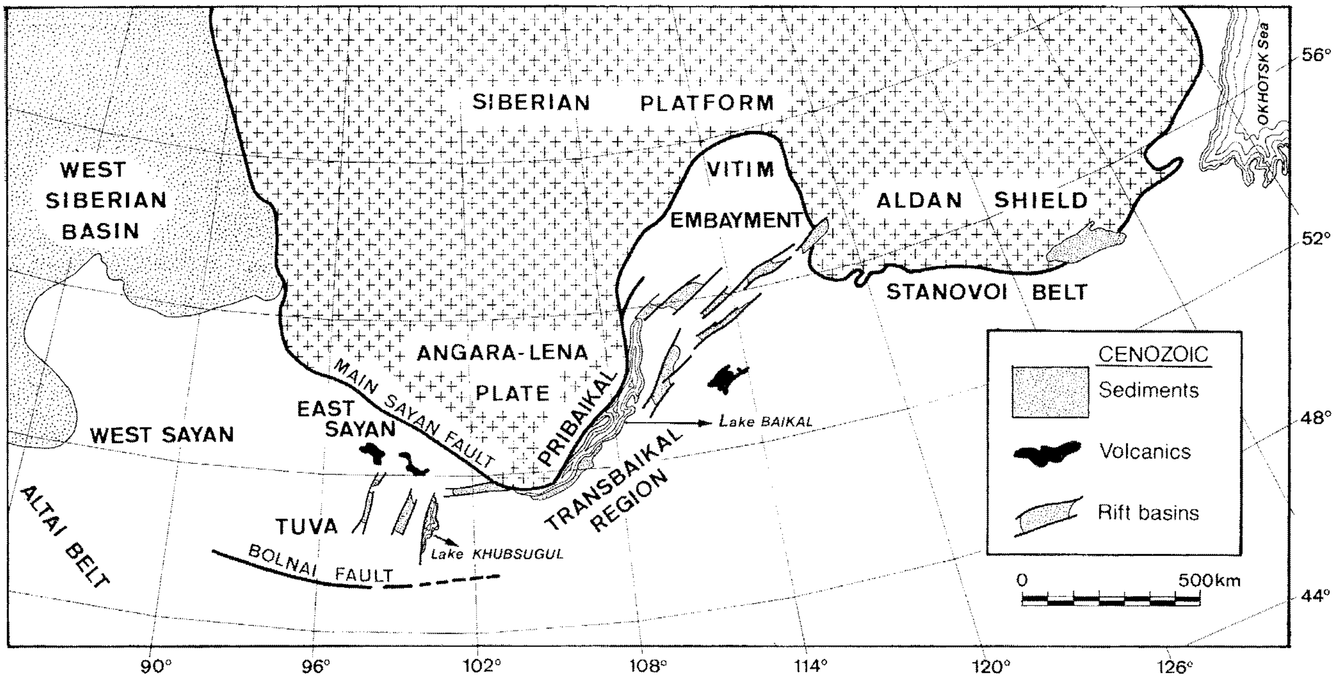


FIGURE 1
The Baikal Rift System in Central Asia (modified according to DELVAUX *et al.*, 1997).
Le système de rift du Baïkal en Asie centrale (modifié, d'après DELVAUX et al., *1997).*

vals. For this, the AUTOCAD computer system was used. Manual digitisation has been preferred to computer-aided digitisation, due to the complex and rugged topography. Both topographic and bathymetric data were merged together to constitute the input vector files, one for each 1:200 000 sheet. The data was digitised in the 1942 co-ordinate system printed in the topographic sheets, corresponding to the Gauss Krüger projection and Krasovsky Ellipsoid. In this system, the co-ordinates are nearly equivalent to UTM co-ordinates of zones 47U, 48U and 49U, with central meridians at 99°, 105° and 111° respectively. To obtain the UTM co-ordinates, an amount of 2.4 km is subtracted from the Y co-ordinate of the Gauss-Krüger 1942 co-ordinate system.

If the region of investigation is included in a single UTM zone, the previous treatment is sufficient. For larger regions, or for regions situated at the boundary between two different UTM zones, it was necessary to convert the geographic co-ordinates into a single co-ordinate system. This is the second step of the referencing procedure. The UTM co-ordinates were converted first into latitudes and longitudes, then the vectorial data was set in a single Lambert Conic Conform (LCC) projection, equivalent to the projection used in the Operational Navigation Chart of the Defence Mapping Agency of the United States of America as in Figure 3.

Finally, gridded heights were computed using the vectorial data (in UTM or LCC coordinates). In this work, the DEM was produced by the Kriging method in MICROSOFT SURFER for Windows.

3. — MORPHOSTRUCTURAL INTERPRETATION OF TOPOGRAPHIC FEATURES

The combination of topography and bathymetry offers a common visualisation of landforms and lake bottom morphology. This allows us to follow the underwater continuation of active fault scarps known on land, and helps to relate basin structures interpreted from seismic profiling and lake shore morphostructure. The DEM can also be used to draw topographic and bathymetric sections. The land and lake bottom morphology of the Baikal Rift Zone is presented here as a shaded relief map. This is one of the most efficient and natural ways to illustrate the tectonic structure, landform fabric and erosion-deposition features.

In this paper, the Baikal DEM is used to illustrate the morphology of secondary basins developed between normal faults in relay ramps and fault splays along the major rift border fault systems of Central Baikal (Fig. 3). The geological structure of this part of the Baikal rift basin has been studied by various authors, combining land surveys (MATS, 1993; AGAR & KLITGORD, 1995; DELVAUX *et al.*, 1997); seismic profiling (HUTCHINSON *et al.*, 1992; SCHOLZ *et al.*, 1993; KAZMIN *et al.*, 1995) and underwater studies by means of a submarine (BUKHAROV, 1996). Detailed examination of particular areas along the major fault systems reveals several complications, like relay-ramps between two overlapping fault segments and fault splays. These structures controlled the development of secondary basins and participated in the propagation of the Baikal rift basin development towards the North.

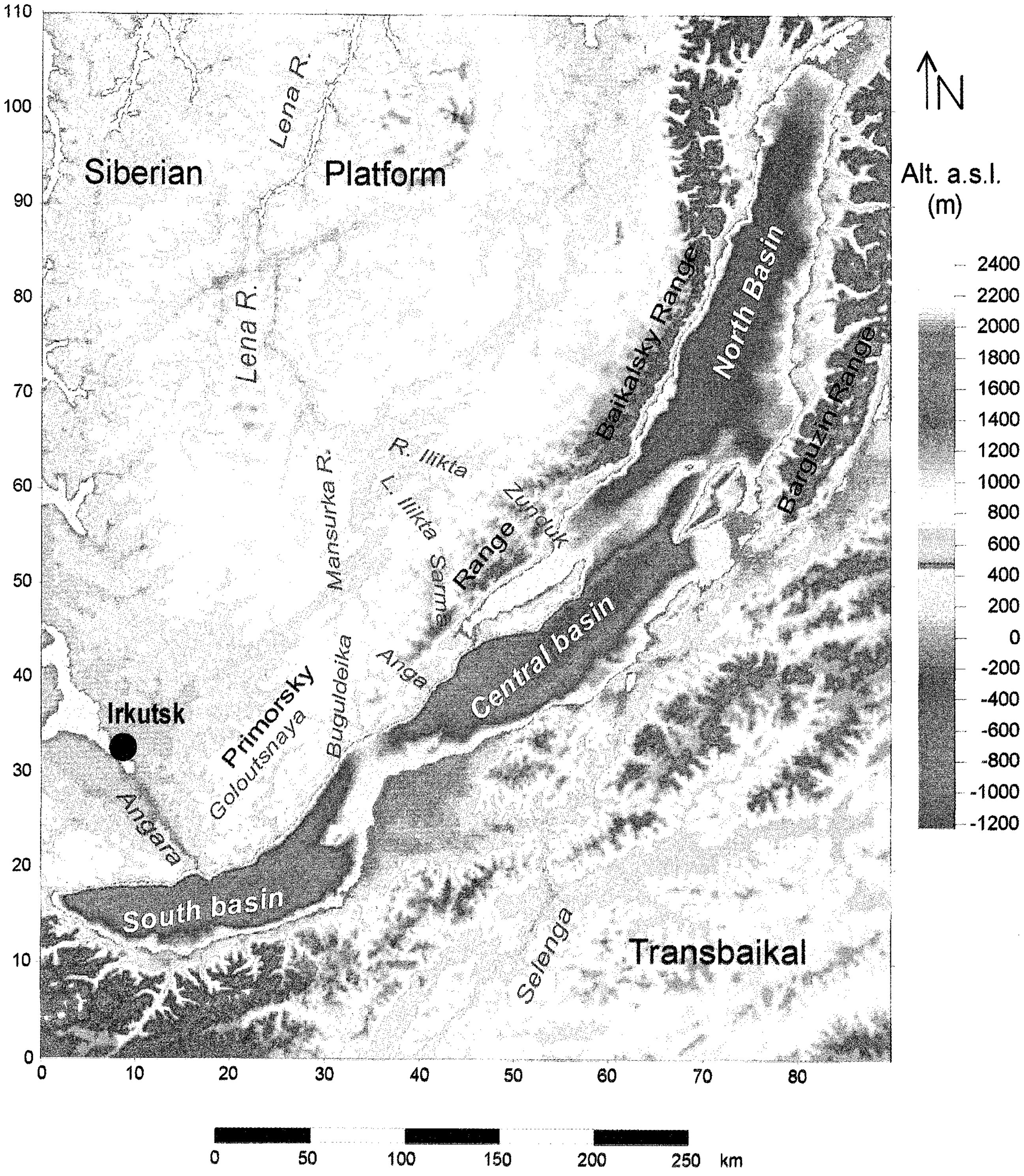


FIGURE 2

Digital Elevation Model (DEM) of the Lake Baikal rift basin and surrounding area, from 1:500 000 topographic and bathymetric maps. Arbitrary co-ordinates (km).

Modèle Numérique de Terrain (MNT) du bassin de rift du lac Baïkal et de la région environnante, d'après cartes topographiques et bathymétriques à 1:500 000. Coordonnées arbitraires (km).

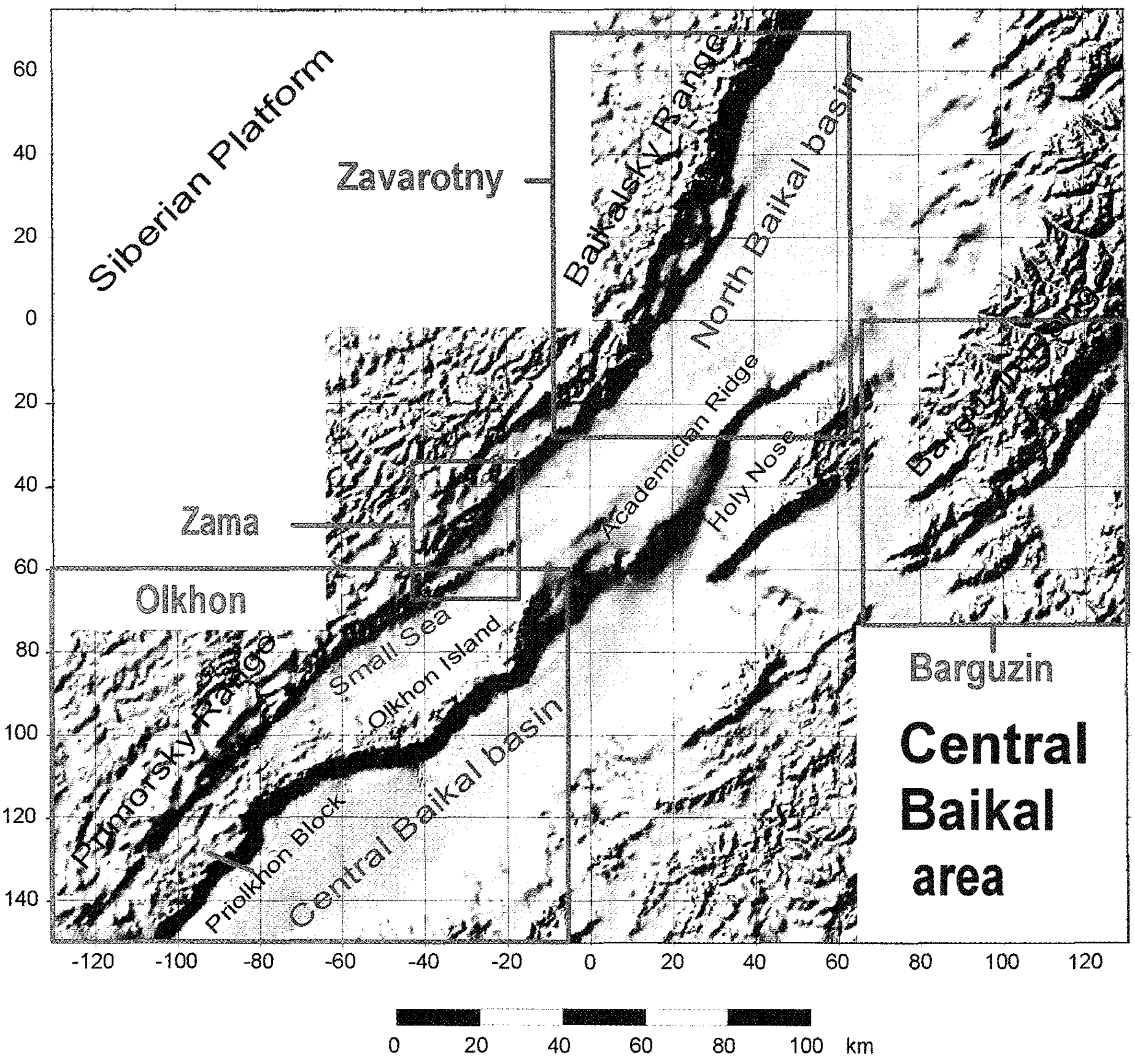


FIGURE 3

Digital Elevation Model (DEM) of Central Baikal from 1:200 000 topographic and bathymetric maps, produced by Kriging, with artificial illumination from the NW, inclined at 45°. Illustration of the Olkhon Island–underwater Academician Ridge transfer zone between the Central and North Baikal basins, and location of areas for detailed investigation (Fig. 4-7). Lambert Conic Conform projection (km) centred at 53°N, 108°E.

Modèle Numérique de Terrain (MNT) de la partie centrale du bassin du Baïkal, d'après cartes topographiques et bathymétriques à 1:200 000, produit par krigeage, avec illumination artificielle du NO, inclinée à 45°. Illustration de la zone de transfert entre les bassins nord et central du Baïkal, formée par l'île d'Olkhon et la ride sous-lacustre Academician. Localisation des régions d'étude détaillée (Fig. 4-7). Projection Lambert Conique Conforme (km), centrée à 53°N, 108°E.

First, the general morphostructure of the Olkhon–Academician Ridge transfer zone is discussed (Fig. 3). After that, four different areas are detailed, illustrating relay ramps and fault splays linking normal fault segments. The Olkhon and Zama areas are examples of sub-basin development between two splaying faults, respectively the Olkhon–Primorsky and the Primorsky–Zunduksky faults (Figs 4, 5). The Zavarotny and Uliun areas are examples of sub-basins controlled by a relay ramp between two overlapping segments of the same normal fault system, the Baikalsky and Barguzin faults respectively (Figs 6, 7). These structures are of different scales, but they display similar morphologies.

4. — OLKHON–ACADEMICIAN RIDGE TRANSFER ZONE

The Central Baikal basin is separated from the North Baikal basin by a transfer zone formed by a system of horsts bounded by normal faults (Fig. 3). They include the Priolkhon block, the Olkhon Island and the underwater Academician Ridge, in prolongation of each other. The north extremity of the Central Baikal basin is closed by an *en échelon* right-stepping horst system, formed by the northern extremity of the Academician Ridge, the Holy Nose (Svyatoi Nos) Peninsula and the Barguzin

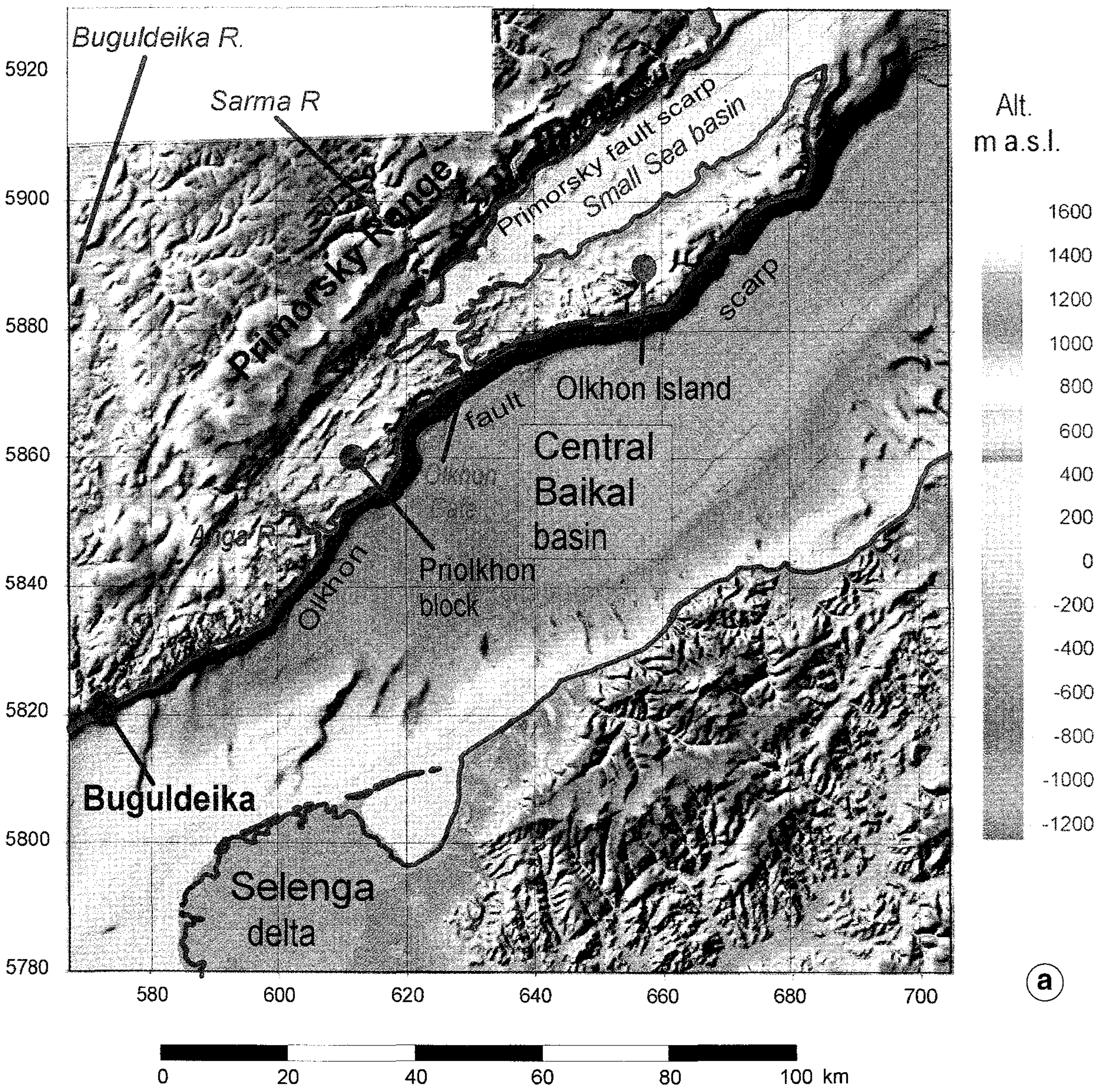
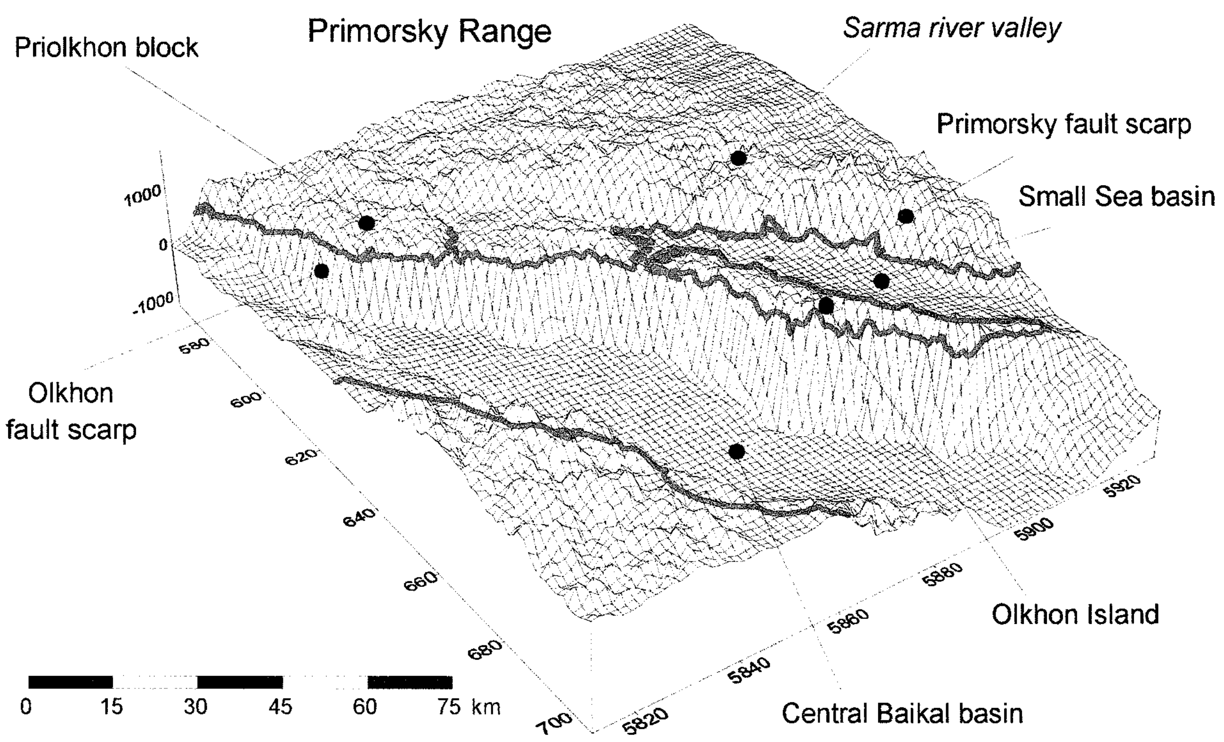


FIGURE 4

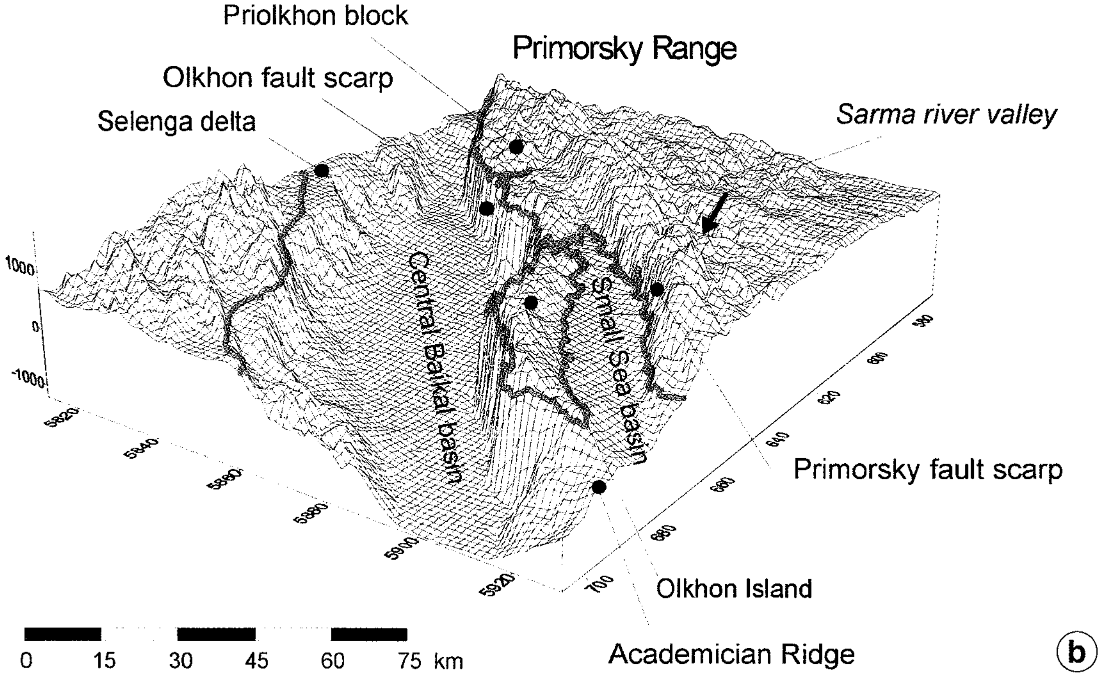
DEM of the Primorsky–Olkhon fault splay between the Central Baikal basin and the Small Sea, from 1:200 000 topographic and bathymetric maps. UTM co-ordinates, zone 48U.
a: Combination of shaded relief and coloured altimetry.
b: 3-D block diagrams.

MNT de la zone de divergence de faille de Primorsky–Olkhon entre le bassin central du Baïkal et la Small Sea, d'après cartes topographiques et bathymétriques à 1:200 000. Coordonnées UTM, zone 48U.
a : Combinaison du relief ombré avec les couleurs en fonction de l'altitude.
b : Blocs diagramme 3-D.

Range. The normal faults controlling this structure mostly reactivate Early Paleozoic ductile shear zones and Late Paleozoic–Mesozoic brittle faults. The top of basement of the Academician Ridge is covered by a thin basal layer of deltaic sediments of probable Middle–Late Miocene age, then by finely stratified diatom-rich lacustrine sediments (KAZMIN *et al.*, 1995). It was the site of several boreholes drilled through the ice during the winter, by the Baikal Drilling Project. The BDP-96-1 drill hole penetrated 300 m of sediments on the Academician Ridge, and the core base corresponds to ca. 5 Ma (BDP-Members, 1998), indicating that the ridge has remained in an underwater position since at least the Early Pliocene.



Perspective view towards NW (N305°E), inclination 35°



Perspective view towards SW (N235°E), inclination 25°

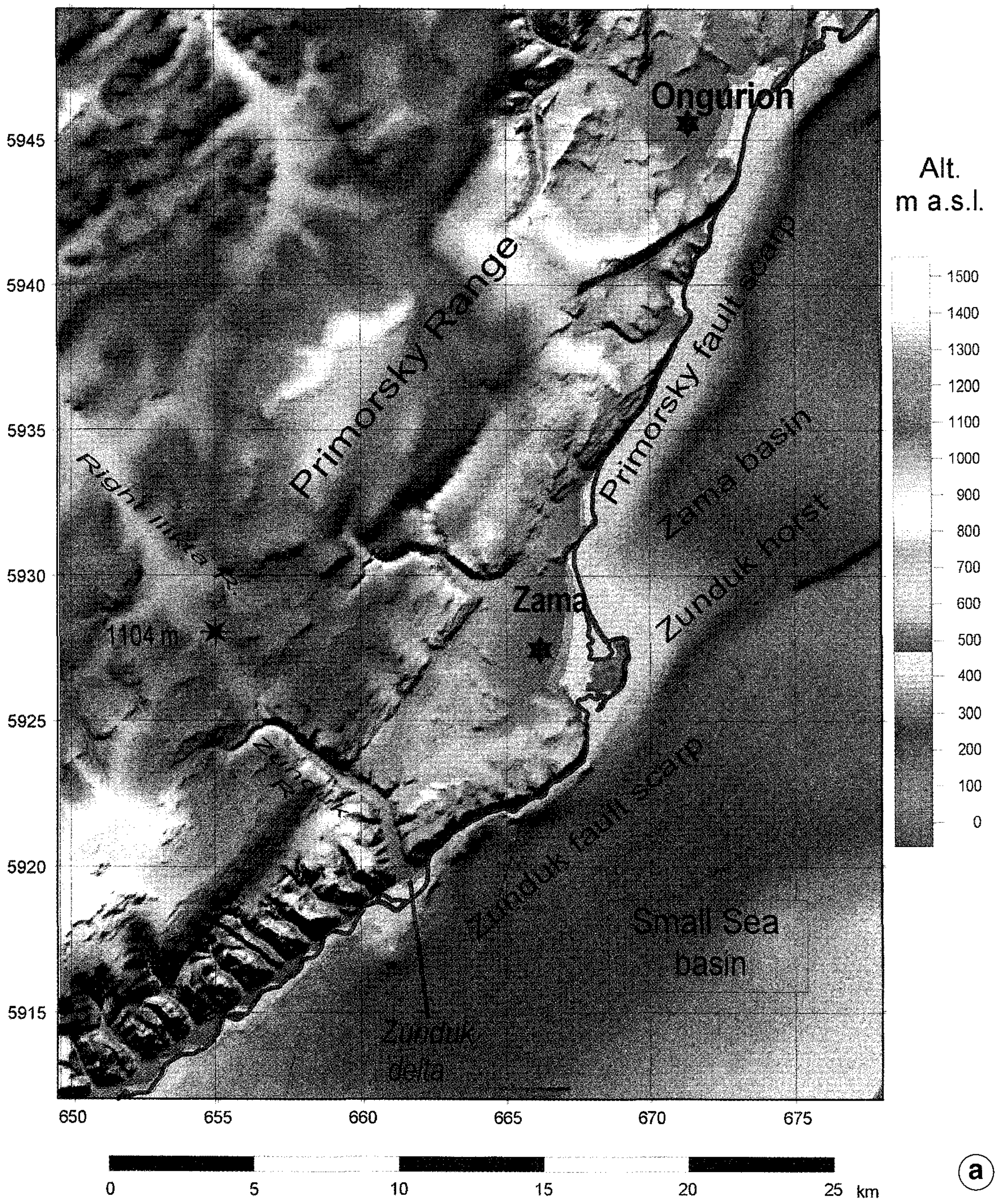
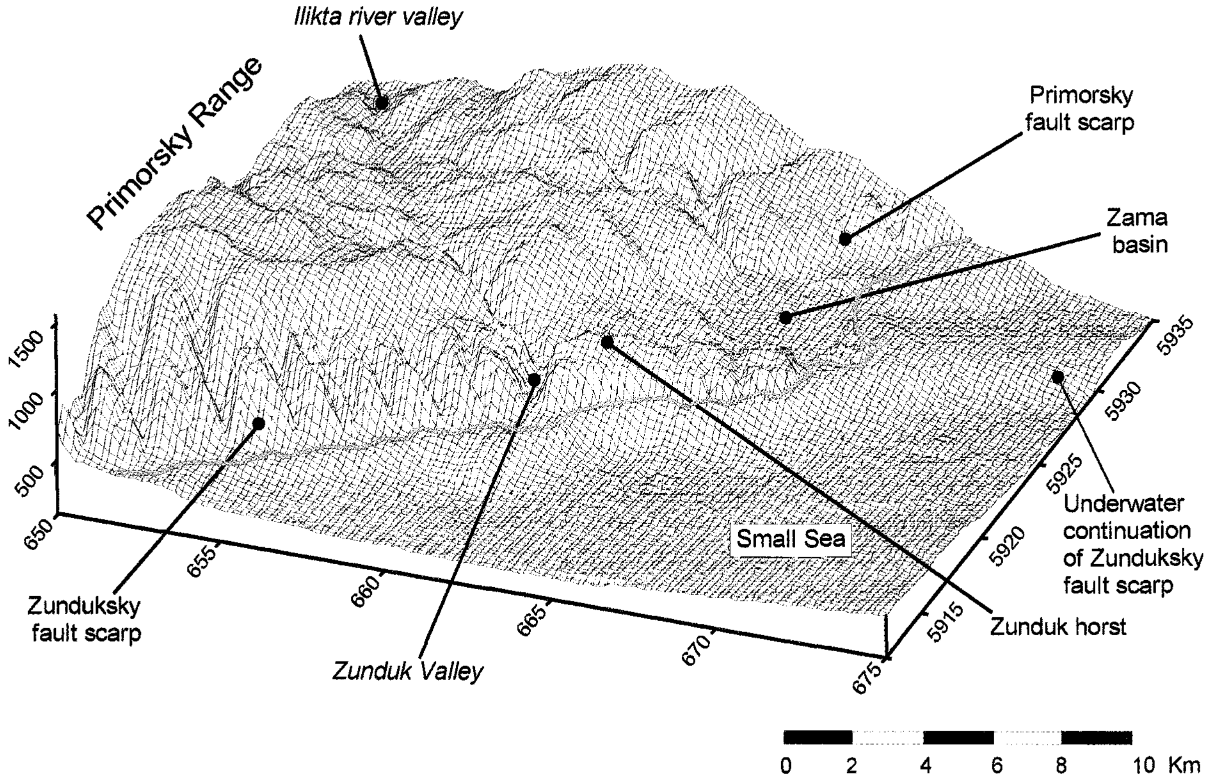


FIGURE 5

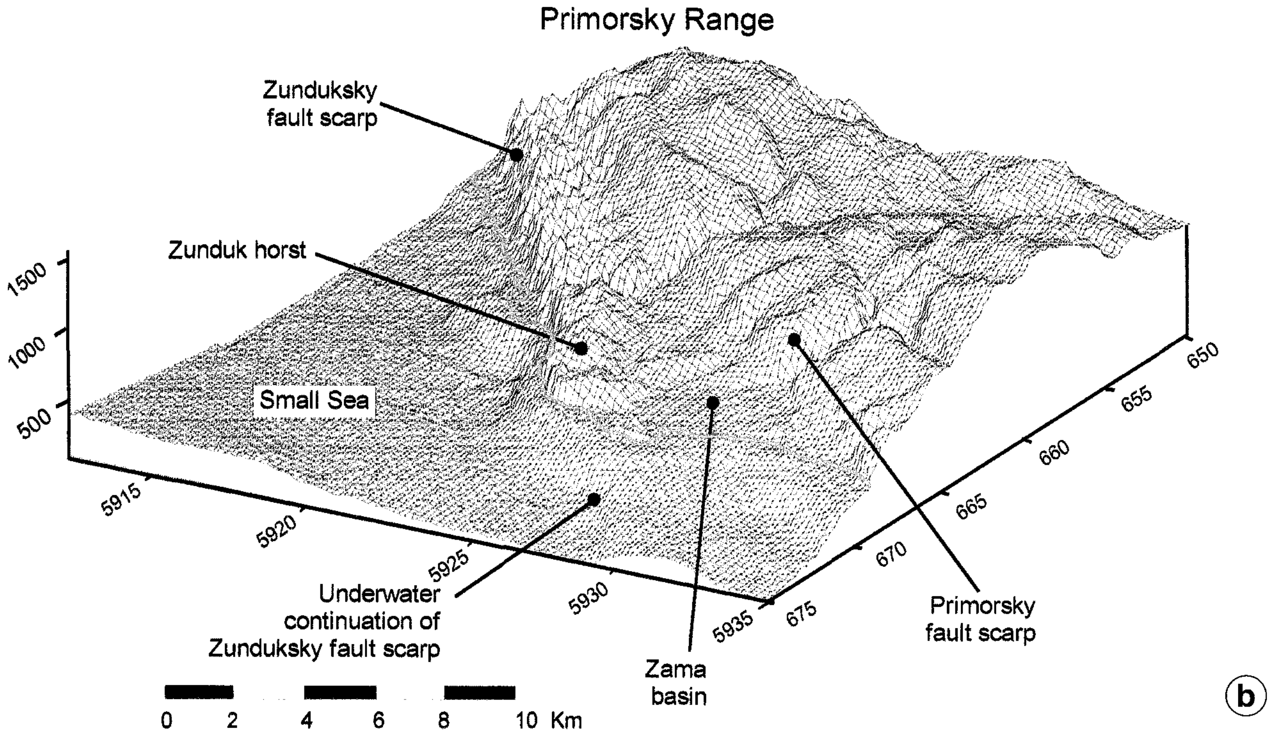
DEM of the Zama fault splay between the North Baikal basin and the Small Sea, from 1:50 000 topographic and 1:200 000 bathymetric maps. UTM co-ordinates, zone 48U.
a: Combination of shaded relief and coloured altimetry.
b: 3-D block diagrams.

MNT de la zone de divergence de faille de Zama entre le bassin de Nord Baïkal et la Small Sea, d'après cartes topographiques à 1:50 000 et cartes bathymétriques à 1:200 000. Coordonnées UTM, zone 48U.
a : Combinaison du relief ombré avec les couleurs en fonction de l'altitude.
b : Blocs diagramme 3-D.

Perspective view towards NW (N339°E), inclination 26°



Perspective view towards SW (N240°E), inclination 20°



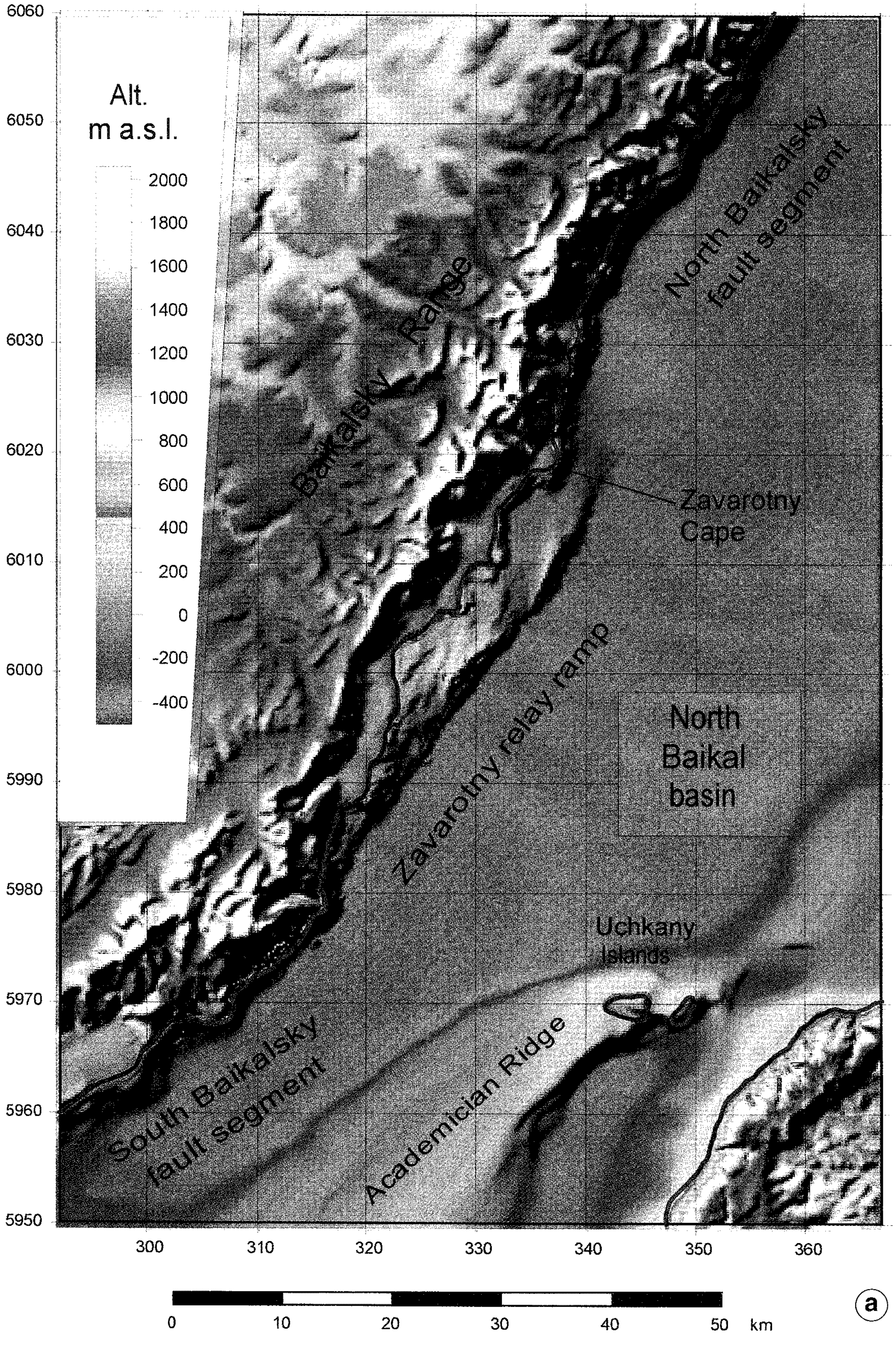
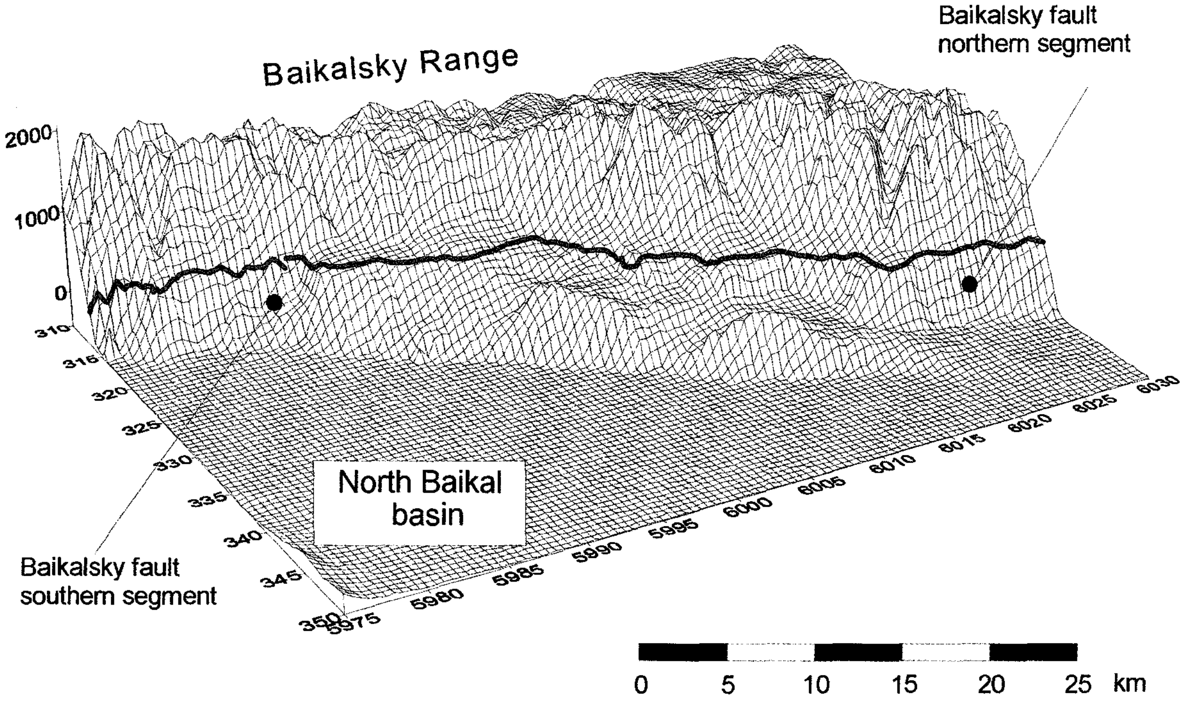


FIGURE 6

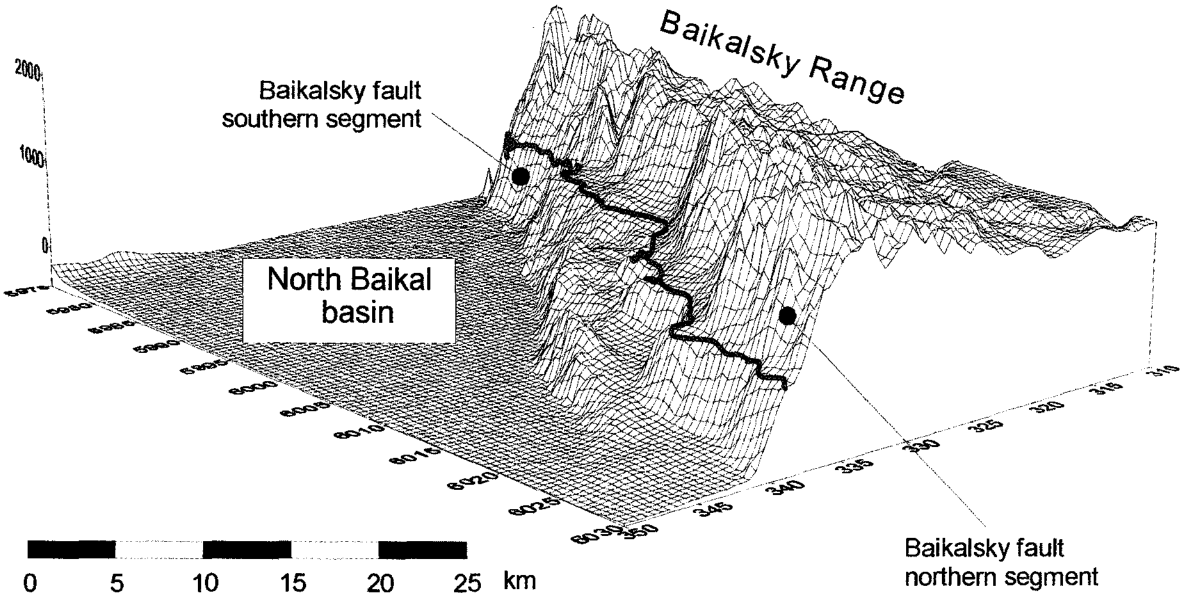
DEM of the Zavarotny relay ramp along the western coast of the North Baikal basin, from 1:200 000 topographic and bathymetric maps, and detailed echosounding data. UTM co-ordinates, zone 49U.
a: Combination of shaded relief and coloured altimetry.
b: 3-D block diagrams.

MNT de la zone de relais de Zavarotny le long de la côte ouest du bassin de Nord Baïkal, d'après cartes topographiques et bathymétriques à 1:200 000, et données d'échosondage. Coordonnées UTM, zone 49U.
a: Combinaison du relief ombré avec les couleurs en fonction de l'altitude.
b: Blocs diagramme 3-D.

Perspective view towards NW (N300°E), inclination 25°



Perspective view towards SW (N220°E), inclination 15°



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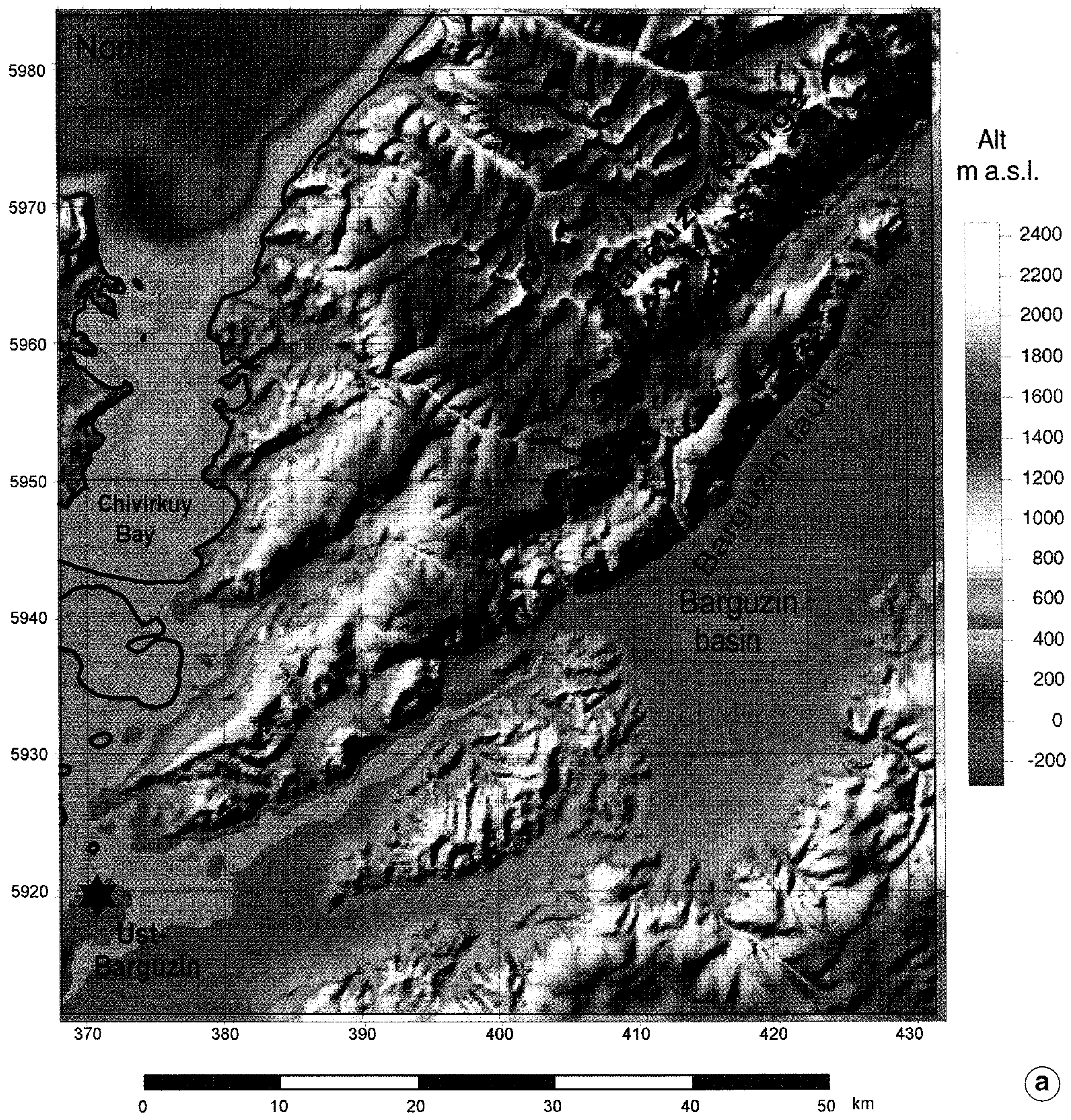


FIGURE 7

DEM of the Uliun relay ramp along the northwestern margin of the Barguzin basin from 1:200 000 topographic map. UTM co-ordinates, zone 49U.
a: Combination of shaded relief and coloured altimetry.
b: 3-D block diagrams.

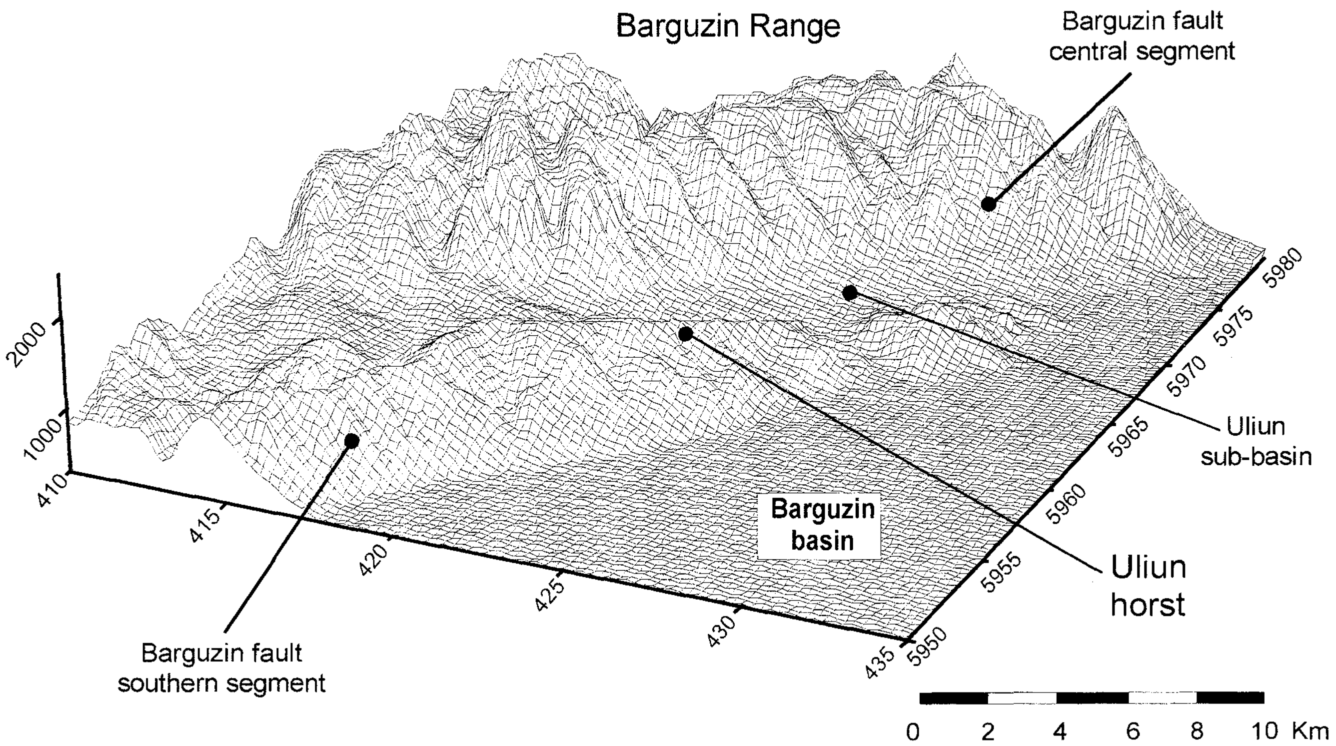
MNT de la zone de relais d'Uliun le long de la bordure nord-ouest du bassin de Barguzin, d'après cartes topographiques et bathymétriques à 1:200 000. Coordonnées UTM, zone 49U.
a: Combinaison du relief ombré avec les couleurs en fonction de l'altitude.
b: Blocs diagramme 3-D.

In the classification of MORLEY *et al.* (1990), the Olkhon–Academician Ridge transfer zone is of synthetic overlapping type. It links two NE-trending asymmetric grabens with the major border fault on the northwestern side, and a secondary border fault on the opposite side.

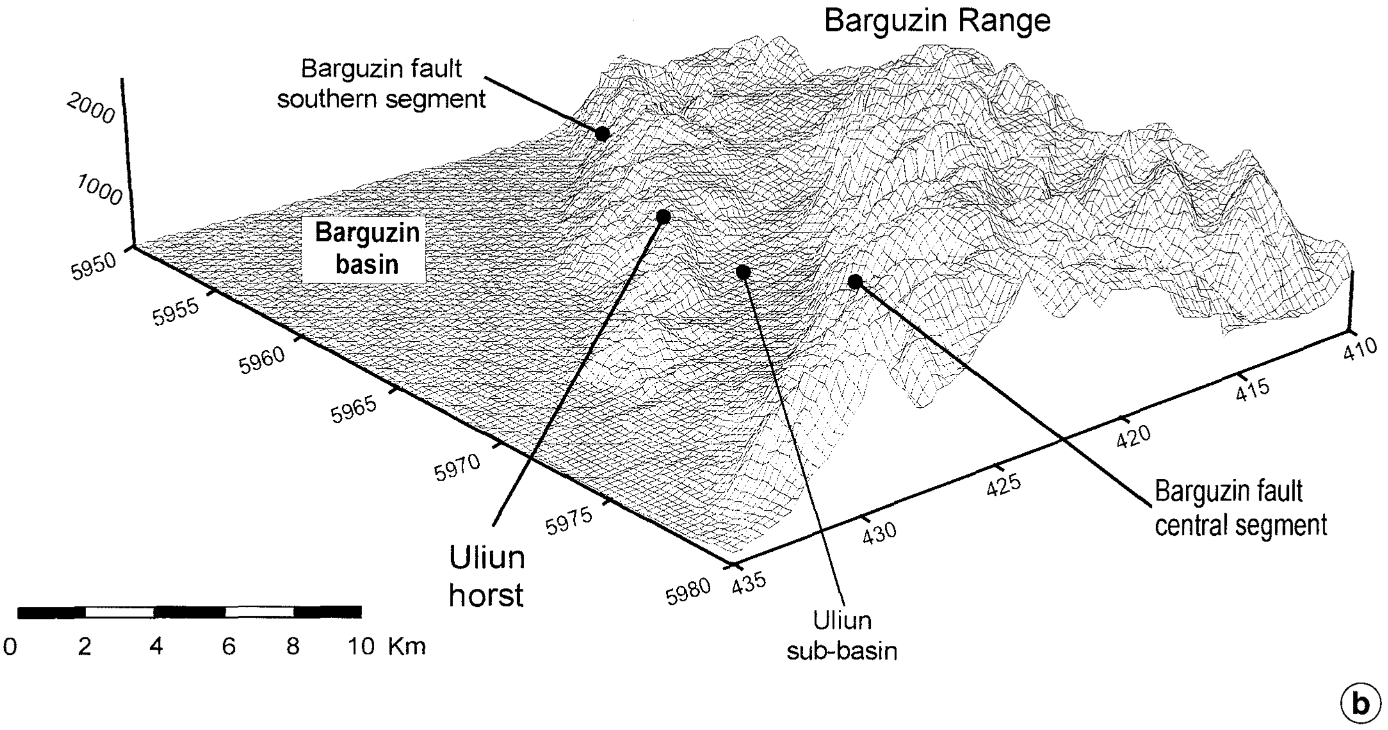
5. — OLKHON AND ZAMA FAULT SPLAYS

The Olkhon and Zama fault splays correspond to the branching of two diachronic faults, progressively diverging from

Perspective view towards NW (N335°E), inclination 21°



Perspective view towards SW (N220°E), inclination 20°



each other (Fig. 4, 5). In both cases, the youngest fault developed in the footwall of the oldest one. They were initiated at different times, probably related to different kinematic conditions. A system of horsts and grabens forms between the two splaying faults in relative parallelism with the general trend. Both faults have a different basement control, the oldest ones reactivating the gneissic structure of the Paleoproterozoic Olkhon Shear Belt and the youngest ones reactivating the Early Paleozoic mylonitic texture of the Primorsky Shear Zone (see MELNIKOV *et al.*, 1994 and DELVAUX *et al.*, 1995, for the basement structures in this area).

The sub-basin development between diachronic fault splays appears to be a major process in the broadening of the rift basin and its propagation from the Central Baikal basin to the North Baikal basin. By this way, the hangingwall of the oldest fault is transformed into the footwall of the newest fault, in a mechanism already suggested by AGAR & KLITGORD (1995).

5.1. **OLKHON FAULT SPLAY AND PRIMORSKY RANGE UPLIFT**

The Central Baikal basin is bordered on its north-western side by the Olkhon fault and its footwall is formed by the Priolkhon Block and Olkhon Island (Fig. 4a, b). The deepest part of Lake Baikal (1640m) is located at the foot of the Olkhon Island. From the interpretation of multichannel seismic profiles (HUTCHINSON *et al.*, 1992), the Olkhon fault has been active during all the development of the Central Baikal basin, which probably started in the Late Oligocene (POPOVA *et al*, 1989). At Buguldeika (Fig. 4a), a new fault (Primorsky fault) is branching to the northwest, separating the Priolkhon Block from the Primorsky Range. The trace of this fault is rectilinear, slightly curved, as opposed to the Olkhon fault. Its amplitude of normal displacement increases gradually to the northeast. Movement is predominantly normal, as shown by morphological evidence and fault-slip indicators (DELVAUX *et al.*, 1997). Along trend, the structure of the hanging wall changes from a half-graben (Priolkhon Block), to full graben (Olkhon Island), although still asymmetric, with the progressive individualisation of the Small Sea basin (Fig. 4b).

The footwall of the Primorsky fault, the Primorsky Range, gradually rises in altitude as the vertical throw of the Primorsky fault increases (Fig. 4a, b). The age of activation of the Primorsky fault is intimately related to the development of the Small Sea basin and the Primorsky Range. AGAR and KLITGORD (1995) estimated the age of formation of the Small Sea at less than 1 Ma, based on sedimentary thickness and sedimentation rate. The age of the Primorsky Range uplift cannot be determined precisely, but it profoundly influenced the drainage pattern out of Lake Baikal. Presently, the waters from Lake Baikal overflow through the Angara river, to the Yenissei (Fig. 1, 2). It has been shown by MATS (1993), MALAEVA *et al.* (1994) and TROFIMOV *et al.* (1995) that during the Middle Pleistocene, Lake Baikal was flowing through the Manzurka valley, to the Lena river. The Manzurka valley was connected to Lake Baikal across the present Primorsky Range, through the Upper Buguldeika river. The latter was connected successively to the Anga, Lower Buguldeika and Goloutsnaya valleys. All these valleys are larger than needed for their present drainage. TROFIMOV *et al.* (1995) describe alluvial deposits with cross bedding, dated between 390±80 Ka and 115±30 Ka. Alluviums of the lower terrasses of the Buguldeika, Manzurka and Lena rivers are dated between 133±30 Ka and 78±20 Ka. When observing the DEM, it appears that older outlet channels across the Primorsky Range might even have existed more to the northwest, via the Anga–Buguldeika, Sarma–Left Ilikta and Zunduk–Right Ilikta river valleys (Fig. 2, 4), but their alluviums are probably concealed under Late Pleistocene glacial deposits. The Goloutsnaya, lower Buguldeika and Anga valleys were probably all connected to the upper Buguldeika valley, connected itself to the Mansurka valley, an affluent of the Lena river. The Left and Right Ilikta rivers are connected directly to the Lena river. All these drainage systems form large paleovalleys, crossing indifferently the footwall and hangingwall of the Primorsky fault. On the southeastern slope of the Primorsky Range, the flow of these rivers is presently reversed, towards Lake Baikal, but the dimensions of the valleys are no more in accordance with the importance of the rivers flowing in them. The isthmus between Olkhon Island and Priolkon (Olkhon Gate) likely constitutes a now underwater segment of the Sarma paleo-outlet channel (Fig. 4). Further to the northeast (Fig. 5a), the Zunduk river (flowing SE) is in the direct alignment with the Right Ilikta river (flowing NW to the Lena river). The 3D block diagrams, confirmed by field check, illustrate the presence of an elongated depression crossing the Primorsky Range, and linking these two valleys (Fig. 5b).

The altitude of the highest points along the inferred paleo-outlet systems progressively increases from the present Angara river outlet (456 m), to the Buguldeika–Manzurka divide (780 m), Sarma–Left Ilikta divide (900 m) and to the Zunduk–Right Ilikta divide (1104 m).

The evidence reviewed above suggest a progressive SW migration of the outlet of Lake Baikal as a consequence of the rising of the Baikalsky–Primorsky rift shoulder. Age determinations of the Manzurka alluvial sediments point to a recent uplift of the Primorsky Range adjacent to the Central Baikal basin during the Middle Pleistocene. In conclusion, the depressed saddle along the north-western margin of the Baikal basin, which controls its outlet, propagated southwestwards together with the diachronous uplift of the Baikalsky–Primorsky Range. This was coeval with the progressive opening of the Small Sea basin during the last 1 Ma.

5.2. **ZAMA FAULT SPLAY**

The Zama sub-basin developed along the western shore of Lake Baikal at the junction of the Small Sea and the North Baikal basin (Fig. 5a, b). It was controlled by the Zunduksky–Primorsky fault splay. It is bordered on its north-western side by the N40°E-striking Primorsky fault and on its southeastern side, by the N60°E-striking Zunduksky fault. The Zama basin and the Zunduk horst formed between these two faults. Towards the southwest, the Primorsky fault branches to the Zunduksky fault and they merge together. To the northeast, the Zunduksky fault scarp disappears in the water, while the Primorsky fault scarp determines the location of the lake shore and increases in height towards the northeast. The Primorsky fault scarp is more rectilinear than the Zunduksky one. This seems to be correlated to the fact that the Zunduksky fault reactivated Proterozoic high grade gneisses and marbles (Olkhon series), whereas the Primorsky fault reactivated the Early Paleozoic Primorsky mylonite zone.

Both faults are currently active. Multichannel (KAZMIN *et al.*, 1995) and high-resolution single channel (De Batist, pers. comm) seismic profiles show that the Zunduksky fault displaces recent sediments in the North Baikal basin, and a fresh morphological scarp is seen along the Primorsky fault. However, since the Primorsky fault is much less eroded than the Zunduksky fault, it can be supposed that the Zunduksky fault started its activity earlier.

6. — ZAVAROTNY AND ULIUN RELAY RAMPS

The Zavarotny and Uliun relay ramps developed between two contemporaneous overlapping segments of the same normal fault system, parallel to each other (Fig. 6, 7). The relay ramps appear as a complex system of basins and horsts, that might be oblique to the major fault trend.

MORLEY *et al.* (1990) defined relay ramps as synthetic overlapping transfer zones between *en échelon* normal fault segments with formation of a strike ramp between them. PEACOCK & SANDERSON (1994) examined small-scale relay ramps and compared them with larger scale ramps. They describe them as transfer zones occurring between normal fault segments having the same dip direction. In the present Baikal example, the relay ramps are complicated by the formation of an antithetic normal fault between the two overlapping synthetic faults, leading to the development of a horst and graben system.

6.1. ZAVAROTNY RELAY RAMP

The Zavarotny relay ramp developed along the Baikalsky fault, on the north-western margin of the North Baikal basin (Fig. 6a, b). This structure is partly underwater and presents a good application of the Baikal DEM, incorporating bathymetry with topography. A ramp system in the area of cape Zavarotny was suspected from the bathymetric chart, but the bathymetry was not detailed enough to investigate its structure. Therefore, a detailed echosounding survey was conducted in this area (MATTON & KLERKX, 1996). The echosounding data was calibrated and merged in the DEM with the rest of the lake bathymetry and the adjacent land topography. The resulting DEM (Fig. 6a, b) shows the complexity of the relay ramp, with the development of small secondary basins trending N-S, oblique to the general structure. The structure of the basins were further detailed by high-resolution seismic profiling (C. Matton, unpublished data).

6.2. ULIUN RELAY RAMP

The Uliun relay ramp developed along the Barguzin fault, on the northwestern margin of the Barguzin basin (Fig. 7a, b). The ramp is longitudinally segmented in a system of secondary horst and graben, separated by a synthetic normal fault. Field structural control and fault kinematic indicators confirm the dominant dip-slip character of the normal faults (DELVAUX *et al.*, 1997).

7. — REGIONAL STRESS FIELD IN CENTRAL BAIKAL

A pure extensional stress field at crustal level was inverted from 22 earthquake focal mechanism data from Central Baikal region, compiled from GOLENETSKY *et al.* (1996), PETIT *et al.* (1996) and SOLONENKO *et al.* (1997), using the TENSOR program (DELVAUX, 1993; Fig. 8). The direction of horizontal principal extension (S_{hmax}) trends N125°E ±4° and the shape factor R is 0.47. The focal planes are all dip-slip to oblique-slip, but there are no pure strike-slip mechanisms. A similar conclusion is reached from detailed fault-slip analysis in three of the areas considered, for the active rifting stage (DELVAUX *et al.*, 1997). Therefore, regional extension can be estimated to be sub-orthogonal to the modern structures of the fault splays and relay ramps considered.

The North Baikal basin trends NNE-SSW and began to form later than the NE-SW trending Central basin. The sequential development of the systems of rift basins in Central Baikal has been influenced by the reactivation of pre-existing zones of deformation related to the Paleozoic and Mesozoic history, and by the evolution of stress field during rifting. Presently, the trend of the North Baikal basin is in slight obliquity with the NW-SE direction of the horizontal minimum stress. This points to an oblique rifting mechanism, similar to that in the northern North Sea (FAERSETH *et al.*, 1997)

8. — CONCLUSIONS

This paper presents an illustration of the exploitation of a detailed DEM, combining land topography and underwater bathymetry, for the morphostructural investigation of the Baikal Rift basin. It allows to detail the morphology of recent tectonic structures, developed during the last stage of evolution of the Baikal Rift (Late Pliocene–Quaternary). The relief and lake bottom morphology well reflect the major active tectonic structures, and the DEM helps to visualise them in coloured maps with hill shading and 3D block diagrams. It also allows continuous observation from the lake shore structures to their underwater counterparts.

The DEM illustrates transfer fault zones linking the North Baikal and Central Baikal basins, and also the linking mode between different segments of the same fault zones. Nice examples of normal fault splays and normal fault relay ramps are evidenced, at different scales, some of them partly underwater. These linking modes are in accordance with the models of transfer zones defined in the literature. They show that Lake Baikal is also controlled by the development, propagation and linkage of originally isolated fault segments and rift basins.

Acknowledgements

This model has been produced entirely by computer in the Royal Museum for Central Africa, thanks to the work of Annie DIERICKS, who digitised all the maps. C. MATTON is thanked for providing the echosounding data from Zavarotny, B. DEHANDSCHUTTER, for technical help, M. DE BATIST for information on the seismic surveys and J. KLERKX for promoting the Russian-Belgian collaboration. This work has been realised in the INTAS 93-134 project "Continental Rift Tectonics and

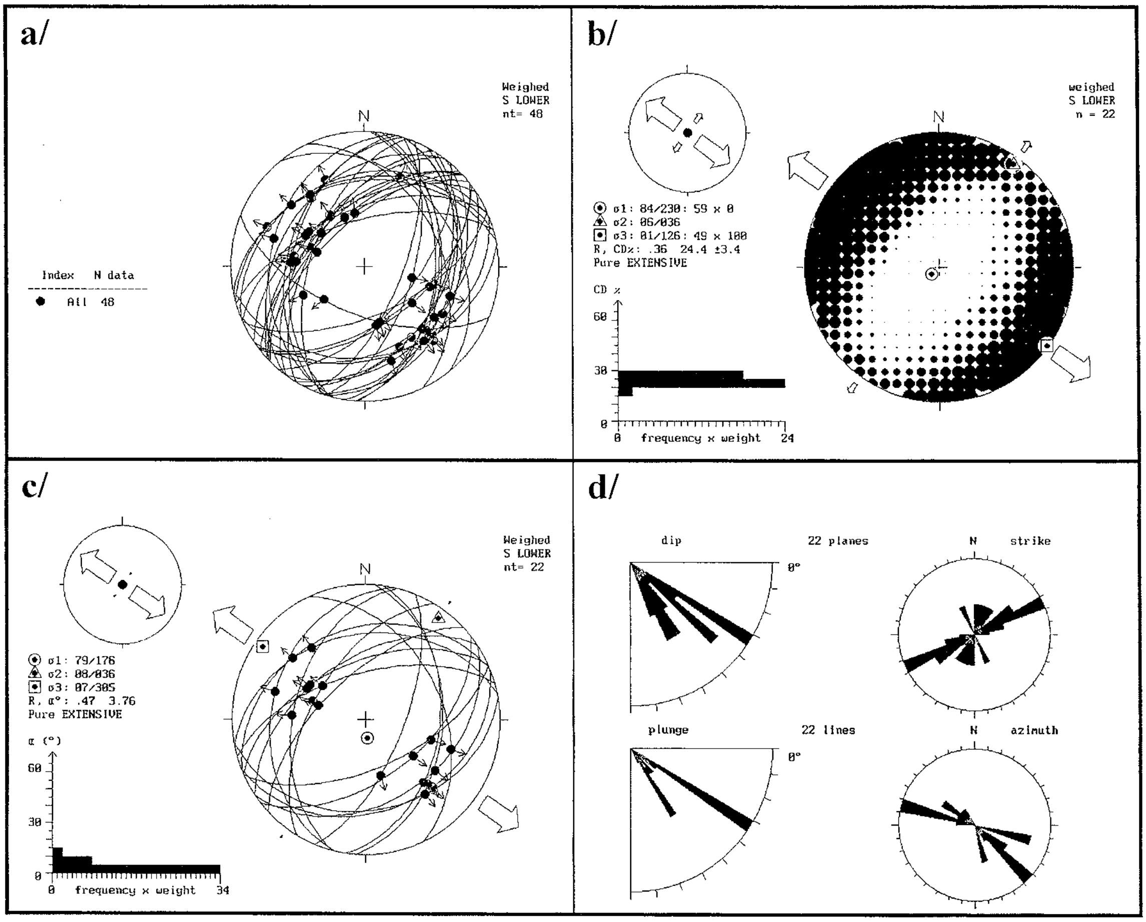


FIGURE 8

Stress tensor obtained from the inversion of 22 earthquake focal mechanisms for the Central Baikal area. Stereograms (Schmidt net, lower hemisphere) with traces of focal planes, and slip vectors, histogram of observed slip-theoretical shear deviations. – a: undifferentiated row data, before inversion and selection between movement and auxiliary planes (two focal planes for each focal mechanism); – b: preliminary stress tensor obtained by the right dihedral method; – c: final stress tensor after rotational optimisation and selection of one movement plane for each focal mechanism; – d: rose diagrams of dip and strike of selected movement planes, and of inclination and azimuth of slip vectors.

Tenseur de contrainte obtenu par l'inversion de 22 mécanismes au foyer de tremblements de terre de la région centrale du Baïkal. Stéréogrammes (Schmidt, hémisphère inférieur) avec traces cyclographiques des plans focaux, et vecteur de glissement, et histogramme des déviations entre glissements théoriques et observés. – a : données brutes non différenciées, avant l'inversion et la sélection entre les plans de mouvement et plans auxiliaires (deux plans focaux pour chaque mécanisme) ; – b : tenseur de contrainte préliminaire obtenu par la méthode des dièdres droits ; – c : tenseur de contrainte obtenu par optimisation rotationelle et sélection du plan de mouvement pour chaque mécanisme ; d : diagrammes en rose de l'inclinaison et la direction des plans mouvement sélectionnés, et de l'inclinaison et l'azimut des vecteurs glissement.

Evolution of Sedimentary Basins". This is a contribution to IGCP400 project "Geodynamics of Continental Rifting". D. DELVAUX is working in the framework of SSTC's TECTORIFT programme, Belgian State (Services du Premier Ministre - Services fédéraux des affaires scientifiques, techniques et culturelles). The first author is entirely responsible for the scientific content of this publication.

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