THE SEISMICITY AND EARTHQUAKE FOCAL MECHANISMS OF THE BAIKAL RIFT ZONE

SISMICITÉ ET MÉCANISMES AU FOYER DE LA ZONE DE RIFT DU BAÏKAL

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Les épicentres des tremblements de terre dans la région de la zone du rift du Baïkal ont une répartition de genre fractal. Les variations dans le temps de cette répartition fractale pour les champs d'épicentres des dépressions du Sud-Baïkal et de Tunka montrent que la structure des champs sismiques est toujours en plein développement. Quasiment toutes les régions de la zone de rift ont des champs d'activité sismique qui sont autosimilaires à divers niveaux de la hiérarchie spatiale et pour une gamme importante d'intensité. Pourtant, l'indice de sismicité à différentes échelles varie tout au long de la zone du rift. En particulier, les parties extrêmes de la zone du rift sont caractérisées par les plus grand contrastes, pouvant afficher une différence d'un facteur 3 à 12, même pour des régions relativement petites.

L'analyse de l'orientation des axes cinématiques P et T à partir des mécanismes au foyer de plus de 3000 tremblements de terre qui se sont produits de 1950 à 1991 dans la zone de rift du Baïkal montre un champ de contrainte symétrique. La région est subdivisée en deux parties par un axe de symétrie qui recoupe la partie nord du lac Baïkal. La transition entre le champ de contrainte régional extensif de genre « rift » et le champ global compressif, typique de l'ouest de la Mongolie et du sud de la Yakoutie, est caractérisée par l'existence de deux zones asismiques localisées de façon symétrique aux deux extrémités de la zone du rift.

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Mots-clefs : Sismicité, Mécanisme focal, Structure fractale, Rift Baïkal.

ABSTRACT

Epicentres of earthquakes occurring in the region of the Baikal Rift Zone have a fractal distribution. Temporal variations of the fractal distribution of the epicentral fields of the South Baikal and Tunka depressions show that the spatial structure of the fields is still developing. For practically all regions of the Baikal Rift Zone, the seismic fields typically have clearly defined similarities at different levels of spatial hierarchy and across a wide energy range of earthquakes. The index of seismicity at various scales varies over the zone, with the rift extremities being characterized by the greatest contrast. In this case, even within relatively small areas, there are always places in which the level of seismic activity is less than in the neighbouring areas by a factor of 3 to 12.

Analysis of the orientation of the kinematic P and T axes, established from the focal mechanisms of more than 3000 earthquakes which occurred in the Baikal Rift Zone between 1950 and 1991, reveals a clear axial symmetry of the kinematic field. The axis of symmetry, which runs through the northern part of Lake Baikal, divides the area into two parts, mirror images of each other. The transition between the extensive regional kinematic field of rift style and the global compressive kinematic field typical of Western Mongolia and Southern Yakutia is characterized by the existence of aseismic zones, symmetrically located at both extremities of the Baikal Rift Zone.

Keywords: Seismicity, Focal mechanisms, Fractal structure, Baikal Rift zone.

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CONTENTS — *TABLE DES MATIÈRES*

INTRODUCTION

The Baikal Rift Zone is located in the southeastern part of the Russian Federation, just north of Mongolia and is largely occupied by the Baikal Lake (Figure 1). This rift trends NE-SW between 98°-118°E longitude, and 49°-57°N latitude (see PETIT *et al.*, 1996, fig. 1).

The rift area presents an intense seismic activity and the main structural features are shown in Figure 2. Two seismic regions are distinguished in this paper:

— the Baikal Rift Zone *s.s.* corresponding to the rift sediments depositional area between the Tunka Basin to the southwest and the Chara Basin to the northeast (Fig. 2, 7).

— the Baikal seismic zone corresponding to the depositional area of the piedmont and shallow depression sediments, and to the prolongation of the rift sediments beyond the Tunka Basin to the southwest in Northern Mongolia and beyond the Chara Basin to the northeast in Southern Yakutia (Fig. 2, 18).

In 1901, a seismic station was established in Irkutsk and equipped with three pendulums: one Milne and two Omori-Bosh. This marked the beginning of instrumental observations in Eastern Siberia. The first instruments with a galvanometric record (designed by B.B. Golitsyn), were placed at the station in March 1912. However, regional researches on the seismicity of the Baikal Rift Zone were only initiated in the late 1950s, since there were previously only discontinuous recording periods due to the often uneasy situation in 20th century Russia.

It was decided that such research was needed, to some extent, by the occurrence of two very large earthquakes: the Muya earthquake of June 25th, 1957, which took place in the northeast of the Baikal Rift Zone with a magnitude of 7.6 and the earthquake of August 29th, 1959, which took place to the northeast of Irkutsk, about 190 km away with a magnitude of 6.8. The establishment of a temporary seismic network to observe the aftershocks of this earthquake marked the beginning of regional observations in the Baikal Rift Zone (BRZ).

The present seismograph network of the Baikal Rift Zone consists of 28 stations equipped with various instruments to record local earthquakes in a wide energy band, and also large earthquakes located all over the world. The major problem with this network, apart from its rather low density, is its lack of digital recording equipment which would enable better data processing.

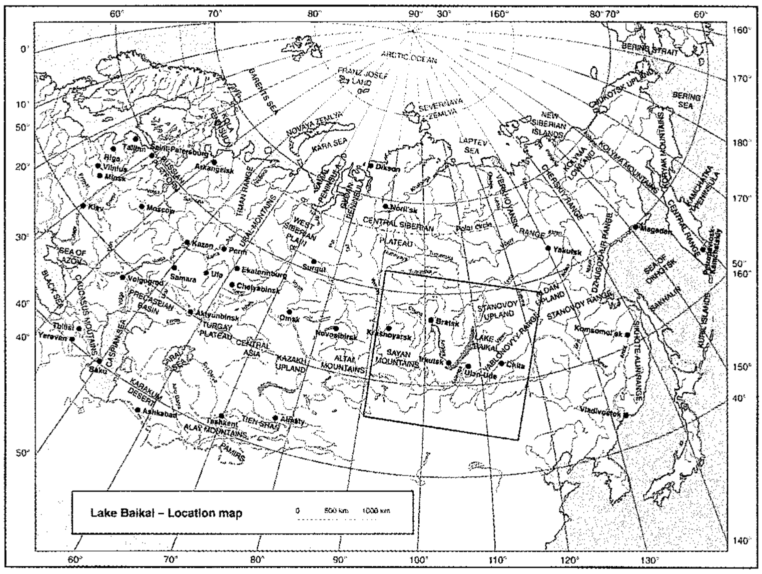
Up to 171 earthquakes with $M \geq 5.0$ have occurred in the Baikal seismic zone within the last 250 years . Among them, 34 were recorded within the Baikal rift during the period of instrumental observations (from the early 1960s). Altogether more than 70 000 shocks of $M \geq 0.5$, including more than 20 000 earthquakes with $M \geq 2.8$, have been recorded by the seismograph network. While records may be incomplete for the low magnitude earthquakes, it is believed that the record of those of magnitude above 2.8 is complete, and in some parts of the zone the records are complete down to $M \geq 1.0$.

This seismicity makes the Baikal region one of the most active seismic zones on Earth.

The epicentral map of earthquakes with $M \geq 2.2$ (Fig.3) gives an indication of the high seismic potential of the area. The data on earthquakes recorded by the regional Baikal network shows that the epicentral field has a complex mosaic structure (MISHARINA & SOLONENKO, 1990; MISHARINA & SOLONENKO, 1976; PSENNIKOV & FOMINA, 1964, and others). The key features of the distribution of earthquake epicentres in this area are their concentration in more or less wide bands trending predominantly NE-SW and a clear transverse discontinuity of the epicentral field, which is manifested by an alternation of large regions of high and low density of epicentres. In this paper, we propose to shed light on the rupture characteristics of seismogenic faults, on the spatial distribution of epicentres and on the meaning of focal mechanisms in the BRZ.

1. — AFTERSHOCK SEQUENCES AND EARTHQUAKE SWARMS

A detailed analysis of all the aftershock sequences and earthquake swarms which have occurred during the period of instrumental observation, was carried out. The difference between aftershocks and swarms is considered as the following:



A

B

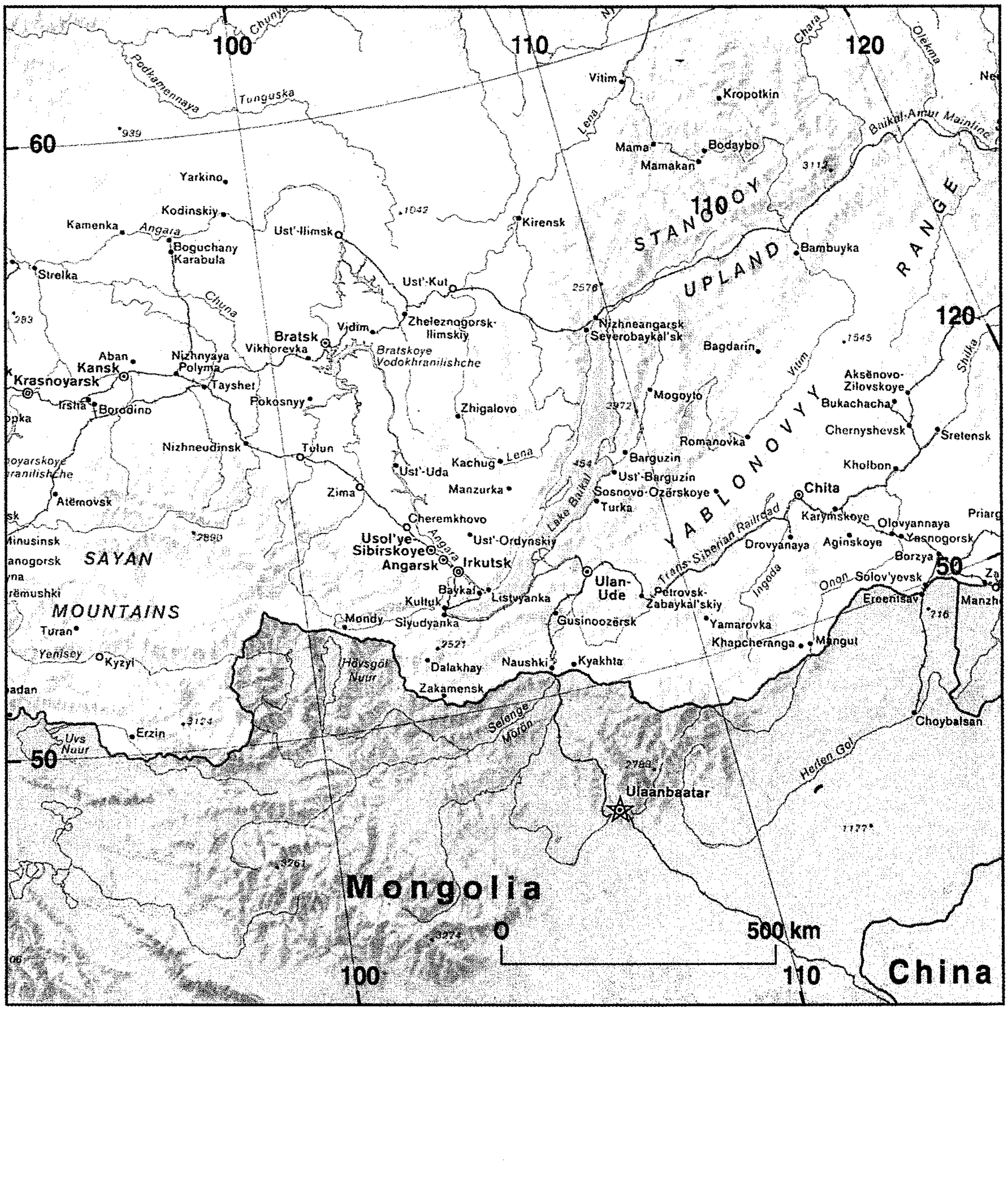


FIGURE 1

Location maps of Lake Baikal. The outline on Figure 1A shows the limits of Figure 1B.

Plans de position du Lac Baïkal. Le cadre sur la Figure 1A correspond aux limites de la Figure 1B

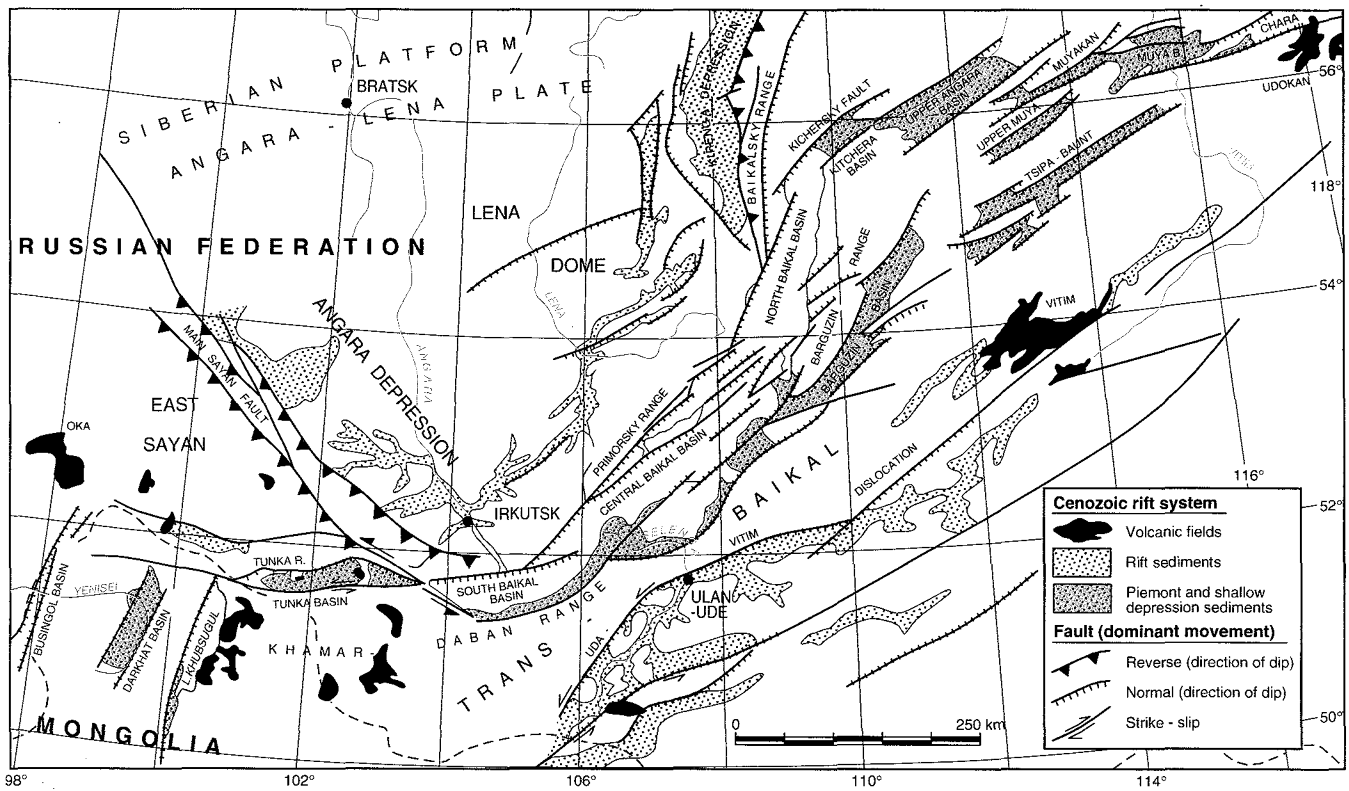


FIGURE 2

Structural sketch map of the Baikal rift zone (after DELVAUX *et al.*, 1997).

Schéma structural de la zone de rift du Baïkal

— aftershocks are shocks which follow a large event but have less magnitude. In the Baikal area, the essential series of aftershocks originate after earthquakes with M ≥ 4.2;

— swarms are groups of earthquakes of moderate magnitude which occur sporadically in space and time; among them, the main shock with much greater energy cannot be distinguished from the others. The lifetime of the swarms spans from several days to several years. The authors only analysed those swarms whose largest shock had a magnitude not less than 4.0.

The largest shocks (M ≥ 4.2) of the BRZ during the instrumental observational period (1962-1991) are presented in Table I. The number of aftershocks, the name of the largest aftershock sequences and the main shocks of the swarms are also indicated. Brief characteristics of the swarms are given in Table II, in particular, the time and the area of maximum concentration of earthquake epicentres, and the total number of swarm earthquakes. Epicentral areas of all 21 swarms and aftershock sequences are given in Figure 4. The analysis of the spatial distribution of aftershock sequences and earthquake swarms on a regional scale leads to several observations:

— large earthquakes are generally not typical of the regions where swarms are dense;

— large shocks, each accompanied by a considerable number of aftershocks, took place to the northeast of the BRZ in a region where swarms had been absent;

— in regions where earthquakes (in the considered energy range) are rarely accompanied by aftershocks, swarm populations, when they occur, are not very dense.

This suggests that swarms and aftershock sequences are different in nature, reflecting different physical and mechanical properties of the crust.

The magnitude-frequency relation for aftershock sequences and earthquake swarms, presented in Figure 5, shows that the slope of the regression lines is very similar: 0.83 ± 0.04 for the earthquake swarms and 0.92 ± 0.04 for the aftershock sequences(2.2 ≤ M ≤ 4.5). While the magnitude-frequency relationship is linear and inverse for earthquakes up to magnitude 4.5, for magnitudes above 5.0 the relationship changes in that a possibly exponential increase in the number of aftershocks occurs (see dotted line in Figure 5). This suggests that the earthquakes grouped in a swarm could only be triggered (no matter what the magnitude) by external effects. Thus, ruptures at all hierarchical levels (see § 3.2) occur as a function of the fundamental deformation of the Earth (SADOVSKY *et al.*, 1982).

Aftershocks due to large earthquakes appear to be caused by a redistribution of the stresses in the Earth's crust induced by the initial major event of the sequence. The same explana-

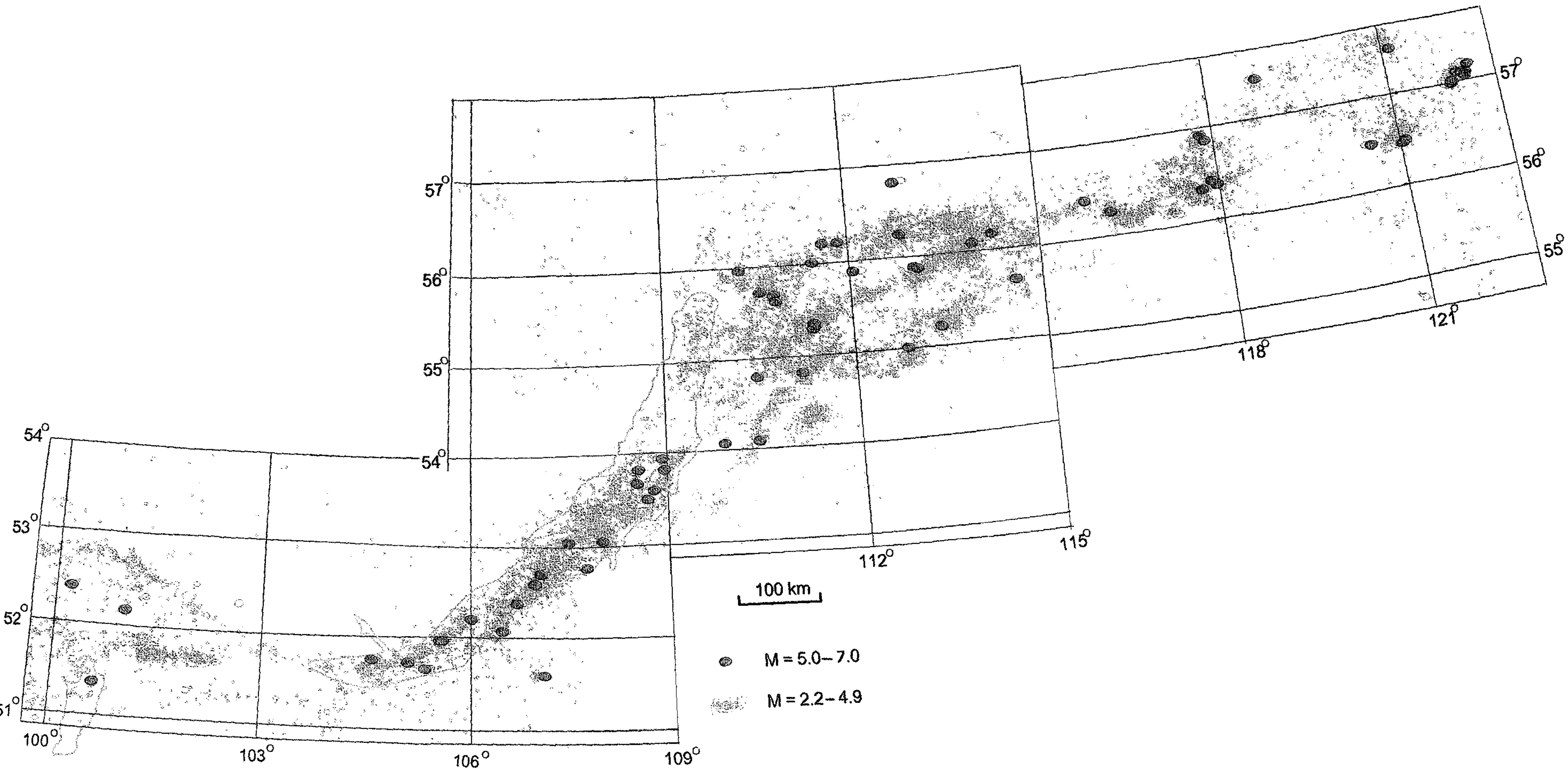


FIGURE 3
Earthquake epicentres (M=2.2 - 4.9 and 5.0 - 7.0) in the Baikal seismic zone 1960-91).
Épicentres des tremblements de terre d'intensité M=2.2 - 4.9 et 5.0 - 7.0 dans la zone sismique du Baïkal (1960-91).

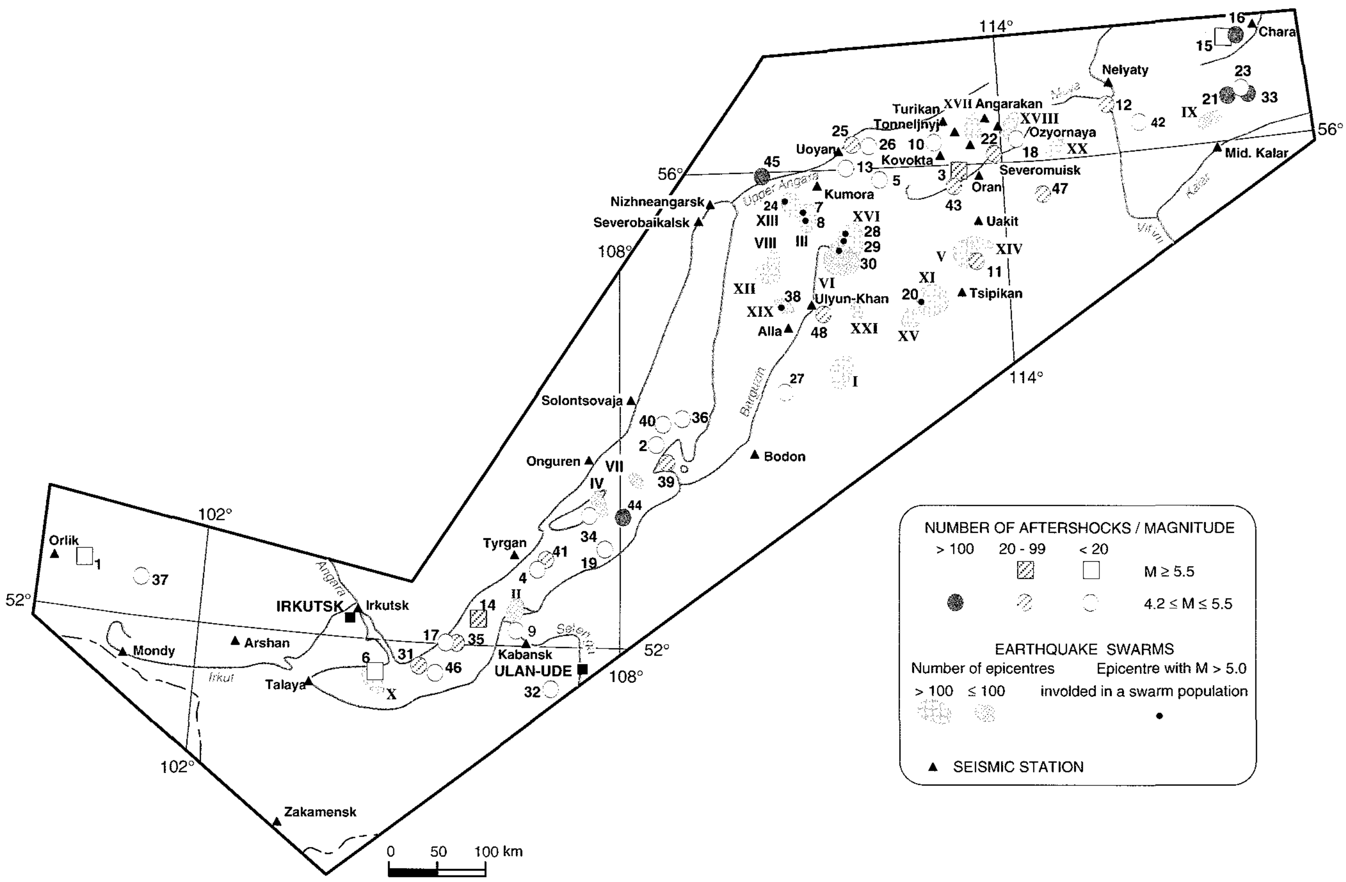


FIGURE 4

Large shocks, aftershock sequences and earthquake swarms of the Baikal Rift Zone (1962-1991).

Secousses importantes, répliques et essaims sismiques de la zone de rift du Baïkal (1962-1991).

1-48: Numbering of epicentres of large earthquakes corresponding to the one of Table I.

1-48 : Numérotation des épicentres des grands séismes correspondant à celle du Tableau I.

I - XXI: Earthquake swarms corresponding to those in Table II.

I - XXI : Essaims de séismes correspondant à ceux du Tableau II.

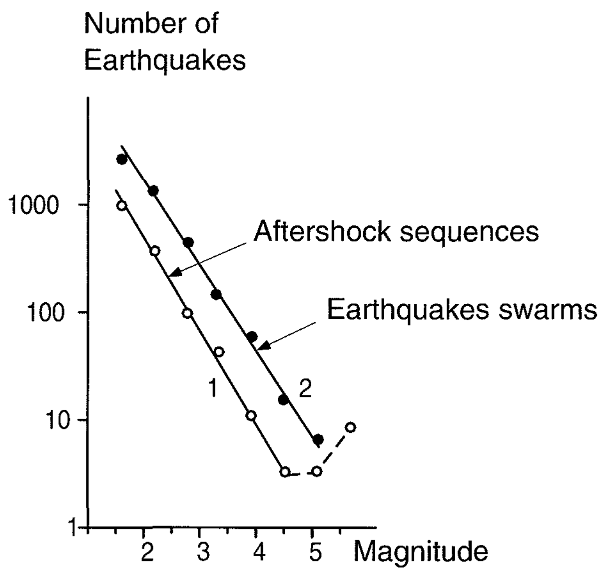


FIGURE 5

Magnitude-frequency relationship of (1) aftershock sequences and (2) earthquake swarms in the BRZ (1962-1991).

Relation magnitude-fréquence des séquences de répliques (1) et des essaims de tremblements de terre (2) dans la zone de rift du Baïkal (1962-91).

TABLE I
Major earthquakes in the Baikal Rift Zone and number of aftershocks (1962-1991)
Tremblements de terre majeurs dans la zone de rift du Baïkal avec le nombre de répliques (1962-1991)

N°	Year	Month Day	Hour Min.	Lat. °N	Long. °E	Magnitude	Name	Number of after-shocks
1	1962	01 22	07 26	52.40	100.20	5.5		7
2	1962	08 13	20 11	53.68	108.53	5.2		18
3	1962	11 11	11 31	55.92	113.26	5.7	Muyakan	67
4	1963	02 10	06 48	52.60	106.90	5.0		17
5	1963	12 01	04 26	55.87	112.05	4.9		7
6	1966	08 30	06 10	51.76	104.61	5.5		4
7	1966	12 31	00 29	55.70	110.80	5.1	1st main shock of Kumora swarm	
8	1967	01 15	19 58	55.63	110.82	5.2	2nd main shock of Kumora swarm	
9	1967	02 11	09 27	52.09	106.46	5.3		15
10	1967	08 22	23 12	56.21	112.88	5.0		0
11	1968	07 21	01 41	55.18	113.45	5.0	Baunt	56
12	1968	08 31	18 06	56.40	115.80	5.0	Ust-Muya	30
13	1968	11 26	18 31	56.00	111.40	5.3		4
14	1970	03 28	09 44	52.23	106.01	5.5	Verkhnegoloust	64
15	1970	05 15	20 50	56.93	117.78	5.5	1st Kodar earthquake	
16	1970	05 18	14 36	56.87	117.87	4.8	2nd Kodar earthquake	407
17	1970	08 13	19 26	51.95	105.53	4.9		2
18	1971	12 18	22 23	56.19	114.21	5.0		7
19	1972	08 09	19 42	52.80	107.73	5.2		0
20	1973	06 16	12 12	55.00	112.77	5.1	Main shock of Tsipikan swarm	
21	1974	06 21	20 56	56.35	117.70	5.1	1st Kalar earthquake	266
22	1974	07 01	05 21	56.09	113.81	5.0		27
23	1975	02 06	21 26	56.41	117.89	4.7	2nd Kalar earthquake	
24	1976	09 23	09 50	55.75	110.54	5.0	Main shock of Swetlinsk swarm	
25	1976	11 02	14 55	56.19	111.59	5.2	1st Uoyan earthquake	54
26	1977	06 04	15 00	56.20	111.82	4.7	2nd Uoyan earthquake	
27	1977	08 24	10 14	54.12	110.44	5.0		15
28	1979	01 10	07 30	55.43	111.44	5.0	1st main slock of Amut swarm	
29	1979	01 10	09.54	55.40	111.43	5.0	2nd main shock of Amut swarm	
30	1979	12 05	00 54	55.32	111.39	4.5	3rd main shock of Amut swarm	
31	1980	02 06	16.35	51.74	105.14	4.9		24
32	1980	10 02	01 12	51.62	107.04	5.1		13
33	1981	01 17	11 23	56.39	117.98	5.1	Udokan earthquake	467
34	1981	02 19	01 48	53.09	107.45	5.0		2
35	1981	05 22	09 51	51.96	105.52	5.4	Goloustninsk	55
36	1981	05 27	21 26	53.94	108.92	5.2		6
37	1981	12 01	21 42	52.18	101.00	5.0		0
38	1982	01 14	07 35	54.81	110.42	4.9	Main shock of Shagnanda swarm	
39	1982	01 28	13 11	53.49	108.69	4.6		38
40	1984	12 09	22 06	53.83	108.59	4.8		2
41	1985	03 10	03 37	52.70	106.98	4.8		44
42	1986	05 26	03 34	56.26	116.19	4.2		19
43	1988	06 04	07 24	55.87	113.18	4.3		68
44	1990	05 20	13 42	53.07	108.02	4.6	Turka	105
45	1990	10 26	18 17	55.95	110.25	5.1	Kichera	133
46	1991	05 12	16 17	51.68	105.39	5.1		3
47	1991	08 22	21 15	55.69	114.58	5.4		35
48	1991	09 12	00 33	54.82	111.15	5.3		21

tion holds good for shocks of magnitude ≥ 5.0 which are part of an aftershock sequence.

The rupture propagation velocities and the directions of aftershock sequences and earthquake swarms have been determined using a procedure developed by A.V. SOLONENKO (SOLONENKO & SOLONENKO, 1987). A set of histograms (left side in Figure 6) shows that the rupture propagation velocities (U) of aftershocks in opposite quadrants (NW-SE and NE - SW) differ in the two directions. The velocities (U) vary not only within each population, but also from one sequence to another. The range of variation is between U = 0.45Vs and U = 1.4Vs, where Vs is equal to the velocity of S-waves. In the case of swarms (right side in Figure 6), the variation is much less (0.2Vs) and does not vary with rupture direction. The reasons for these differences are not clearly understood. They could be due to the scale of ruptures in aftershocks being greater than those of swarms, the former being more affected by regional scale inhomogeneities. However, the further accumulation of data on all parameters of these types of earthquakes and their spatial characteristics (particularly with respect to the specific geological structures involved) is required in order to reach a complete understanding of these phenomena.

TABLE II
Earthquake swarms in the Baikal Rift Zone (1962-1991)
Tremblements de terre en essaim de la zone de rift du Baïkal (1962-1991)

N°	Time interval (years)	Region of maximum concentration		Name	N=Number of earthquake
		Lat. (°N)	Long. (°E)		
I	1962-1969	54.10-54.50	111.10-111.50	Ikat	621
II	1964	52.10-52.40	106.30-106.60	Ust-Selenga	15
II	1966-1967	55.50-55.70	110.70-111.00	Kumora	370
IV	1968	53.10-53.30	107.50-107.80	Olkhon	30
V	1969	55.10-55.40	113.10-113.50	Baunt	177
VI	1969	55.10-55.40	111.10-111.60	Barguzin	32
VII	1970	53.30-53.50	108.10-108.30	Central Baikal	76
VIII	1971	55.10-55.40	110.20-110.40	Upper Tompudinsk	103
IX	1972	56.10-56.25	117.10-117.50	Udokan	54
X	1973	51.50-51.70	104.30-104.70	South Baikal	156
XI	1973-1974	54.70-55.00	112.50-113.00	Tsipikan	459
XII	1975	55.00-55.25	110.00-110.40	Central Tompudinsk	309
XIII	1976-1978	55.60-55.85	110.40-110.80	Svetlinsk	196
XIV	1978	55.20-55.40	113.30-113.70	Uakit	276
XV	1979	54.65-54.80	112.20-112.55	Gorbylok	302
XVI	1979-1981	55.20-55.55	111.20-111.70	Amut	736
XVII	1979-1983	56.20-56.45	113.40-113.70	Angarakan	1454
XVIII	1981-1982	56.20-56.45	114.00-114.30	Amnunda	215
XIX	1982	54.80-54.95	110.30-110.60	Shagnandinsk	282
XX	1984-1991	56.00-56.20	114.70-114.90	Mudirikan	1148
XXI	1989-1991	54.75-54.90	111.55-111.70	Upper Tsipikan	430

2. — CHARACTERISTICS OF EARTHQUAKE EPICENTRAL FIELDS

Variations in the distribution of earthquake epicentres reflect the internal structure of the region and its state of stress. In order to understand this distribution, as much as possible must be known about the laws governing seismic processes, as well as about the external factors which control it.

2.1. STATE OF DEVELOPMENT OF THE EPICENTRAL FIELDS

The reliability of quantitative estimates of seismic hazard from seismological data depends on whether the available data on the distribution of past epicentres is sufficient to predict the development of future seismic activity. In particular, it is important to know whether the development of epicentral fields is complete or not. The criteria to enable the prediction of the future development of the epicentre distribution in the Baikal region are presently unknown. Since these criteria are not available, any calculation of average long-term parameters of the seismic regime of the area could induce significant errors, which in turn, would distort any estimation of the true seismic potential in the region. The theory of fractal multitudes (MANDELBROT, 1982) currently has a wide application in the study of spatial heterogeneity of seismic fields. Investigation of temporal variations of the spatial fractality of epicentre distribution seems to clarify the problem of evaluating its state of development.

A completely developed epicentral field is a field in which the new seismic events are located within its previously determined structure. In other words, no essential change is made to its outline. Conversely, if new earthquakes make a significant change to the structure of the epicentral field, its development is considered to be incomplete.

In view of the fractal structure of a fully developed epicentral field, any subsequent shocks will, most probably, occur in areas of the field where seismic events have been observed before. Thus, the fractal dimension of the field will not vary with time. On the other hand, an incompletely developed epicentral field will have a dimension which varies with time.

In practice, the estimation of the dimension of the earthquake epicentral field involves the following operations (NICHOLIS & PRIGOZHIN, 1990). In the first stage, the studied area is divided into equal parts, four in this particular case (Ns=4). The average number of earthquakes in each area and the standard deviation from the average number of earthquakes is estimated. Then the number of areas (Nx) in which the number of earthquakes exceeds the standard deviation is calculated. Thus "the background noise" of epicentral field dependent, in particular, on errors in estimation of earthquake coordinates, is precluded. At the second stage, the size of the areas is decreased and the estimation procedure is repeated. The reduction in the small area size continues until the area size equals the positioning errors. The dimension of epicentral field Ds is determined by the slope of the plot lg Nx(lgL), where $L=(1/Ns)^{1/2}$ is a similarity coefficient, in other words, a scaling coefficient (FEDER, 1991).

To estimate the epicentral field dimensions of the Baikal Rift Zone, the following values of numbers of equal parts (Ns) have been tested: 4, 9,16,25,36,49, 64.

To analyse the epicentral fields in various parts of the Baikal Rift Zone, 12 regions as large as 0.8° latitude by 1.6° longitude were chosen (Fig. 7). The symbols of the regions and their geographic coordinates are given in Table III where N is the number of earthquakes of $M \geq 2.2$ recorded between 1962 to

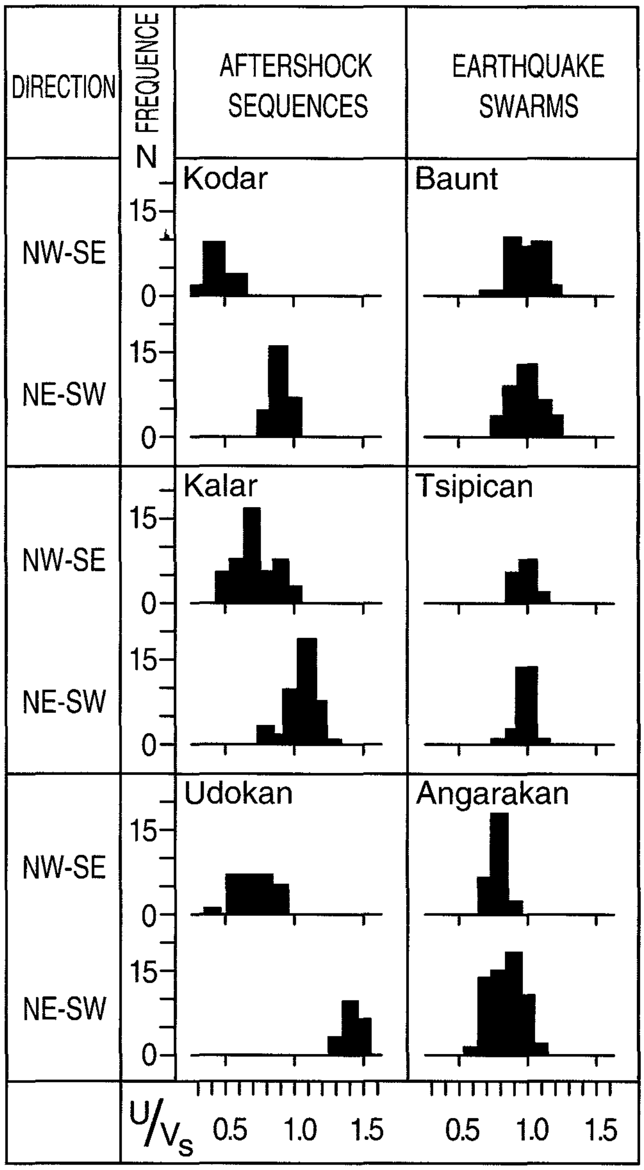


FIGURE 6

Propagation velocities of ruptures of various directions (NE-SW and NW-SE), in foci of aftershock sequences (left) and earthquake swarms (right).

U = Rupture propagation velocity; V_s = S-wave velocity.

Vitesses de propagation des ruptures dans les foyers de séquences de répliques (à gauche) et d'essaims de tremblements de terres (à droite) dans les directions NE-SW et NW-SE.

1991.The last two columns (Ds and k) are discussed below. Almost all earthquakes of M ≥ 2.2 recorded within the area of study were analysed, with the exception of certain ones, which are specifically mentioned by GOLENETSKY (1985).

The estimation of the fractal dimension of earthquake epicentral fields is illustrated on Figure 8 by the Central Baikal and Muyakan regions (5 and 10 in Fig. 7). Earthquake epicentral fields in these two regions have fractal dimensions (Ds) of 1.91 and 1.60 respectively (Table III). They represent a self-similar structure to the Serpinsky cover type as defined by FEDER (1991), having a regular hole structure in a wide range of structural hierarchy. The epicentral fields of the remaining 10 regions also have fractal dimensions which range from 1.53 to 1.89 (Table III).

The successive summations of earthquake epicentral fields over two - year observational periods given on Figure 9, show that for each region, the Ds(t) curves became practically asymptotic in the 1980s. There is reason to believe that the main structure of earthquake epicentral fields in these regions has been essentially completed. In the Kultuk, Central Baikal, South Barguzin and, to a lesser degree, North Barguzin regions, the process of epicentral field structure formation appears to be still in progress. In this respect, extreme care is required in predicting the development of the seismic process in these regions, as the probability of earthquakes occurring in them is low. This is particularly the case in regions where earthquakes have not yet been recorded. It is possible that in the future, earthquakes will occur in areas where they have not yet been observed. It is thus reasonable to assume that, in the cases where seismologists have to make predictions based on insufficient data, large unforeseen earthquakes may occur in areas of underestimated seismic risk. For example, the largest earthquake in the last 30 years in the Baikal seismic zone (the Kyakhta earthquake of 13.05.1989, M=5.8), occurred in a region of extremely low seismic activity where shocks of such intensity are not typical.

2.2. SELF-SIMILARITY OF EARTHQUAKE EPICENTRAL FIELDS

Some publications (GOLUBEVA, PISARENKO & SHNIRMAN, 1987; SADOVSKY & PISARENKO, 1991) suggest that an essential feature of the earthquake epicentral fields of seismic zones is their self-similarity in the case of fully developed epicentral fields (as mentioned above, this means that the fractal dimension of the field will not vary with time). The aims of the present study are to determine the seismic zones that are heterogeneous in seismic activity, seismic potential and stress field, and to determine the characteristic features of hierarchical self-similar systems of earthquake distribution, in terms of both area and energy.

The analysis of self-similarity in the structure of local seismicity in the BRZ followed the procedure developed by SADOVSKY & PISARENKO (1991), using the catalogue of earthquakes compiled in the Institute of the Earth's Crust between 1962 and 1991. Each of the previously defined regions (Fig. 7, Table III) was divided into trapezia of decreasing size: four of 0.40 longitude by 0.80 latitude, sixteen of 0.20 by 0.40, and sixty four of 0.10 by 0.20. The choice of minimum dimension was determined according to the average errors in the determination of the position of earthquake epicentres over the studied area study. The investigation was limited to the two dimensional distribution of epicentres due to the inherent inaccuracy of focal depth determinations.

For each trapezium at each spatial scale, the index of seismicity, relative to that of the trapezium of the previous level, was estimated as in SADOVSKY & PISARENKO (1991). If the number of earthquakes in the first scale trapezia are n(1), n(2), n(3), n(4) then the indices of relative seismicity are estimated by the formulae (SADOVSKY & PISARENKO, 1991): p(1)= n(1)/N, p(2) = n(2)/N, p(3) = n(3)/N, p(4) = n(4)/N, where N = n(1) + n(2) + n(3) + n(4). The indices p(1), p(2), p(3) p(4) are plotted in decreasing order. Similar calculations are performed at the next scale, with, at the second level, the indices being aver-

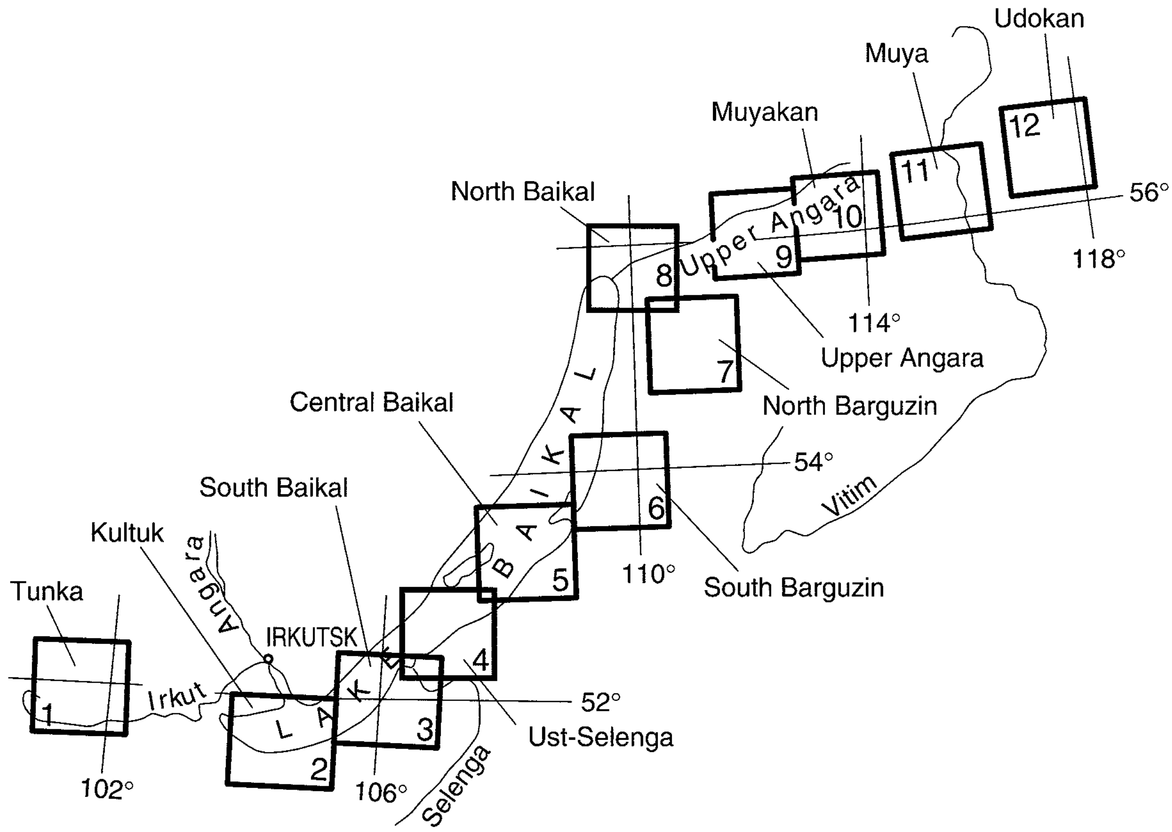


FIGURE 7

Location of regions for the analysis of development completion and self-similarity of earthquake epicentral fields. Regions coordinates are given on Table III.

Position des régions analysées pour l'état de développement et l'auto-similarité des champs d'épicentres de tremblements de terre. Les coordonnées des régions sont données sur le Tableau III.

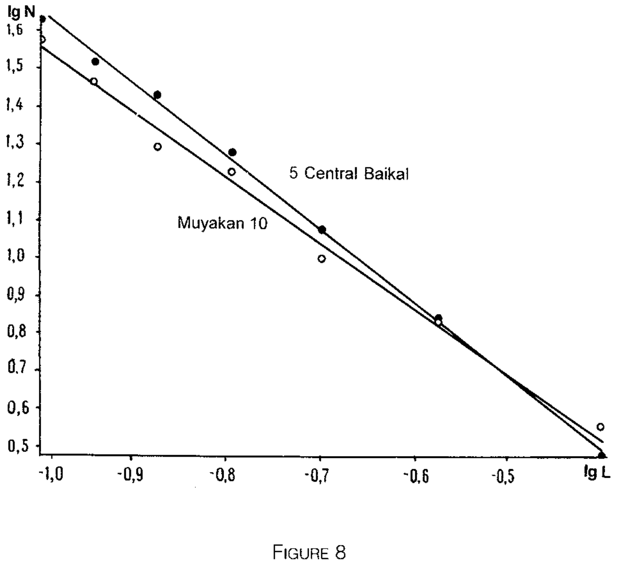


FIGURE 8

Determination of the fractal dimensions of Central Baikal (5) and Muyakan (10) earthquake epicentral fields in the Baikal Rift Zone (see § 2.1. for definition of L and N).

Détermination des dimensions fractales des champs d'épicentres de tremblement de terre de Baïkal Central (5) et Muyakan (10).

aged in all four trapezia, and at the third level, the indices being averaged in the 16 trapezia.

Various plots for the regions delineated on Figure 7 and listed on Table III were established (Fig. 10, 11, 12, 13). The numbers of trapezia of the 1st spatial scale are plotted along the abscissae axes and the values of relative index of seismicity are plotted along the ordinate axes, on figures 10, 11, 12 and 13 (as explained above). To keep these figures from becoming too involved, the numbers of trapezia of the 2nd and 3rd spatial scales, which are obtained by dividing the trapezia of the first scale into 4,16,64 and so on, are not plotted along the abscissae axes. To correlate the results, obtained for trapezia of three scales, the indices of seismicity P for trapezia of 2nd and 3rd levels were averaged. All above figures show a unique relation between the relative index of seismicity P and the trapezium scale, but the conditions are different:

— Figure 10 shows the relation Pf(N) for various regions;

— Figure 11 gives the relation Pf(N) with aftershocks and without them (for this purpose the highly seismic Udokan region was chosen);

— Figure 12 gives Pf(N) depending on magnitude range (for this purpose the Muyakan region is chosen);

— Figure 13 gives Pf(N) depending on time periods (the Muyakan region is again chosen).

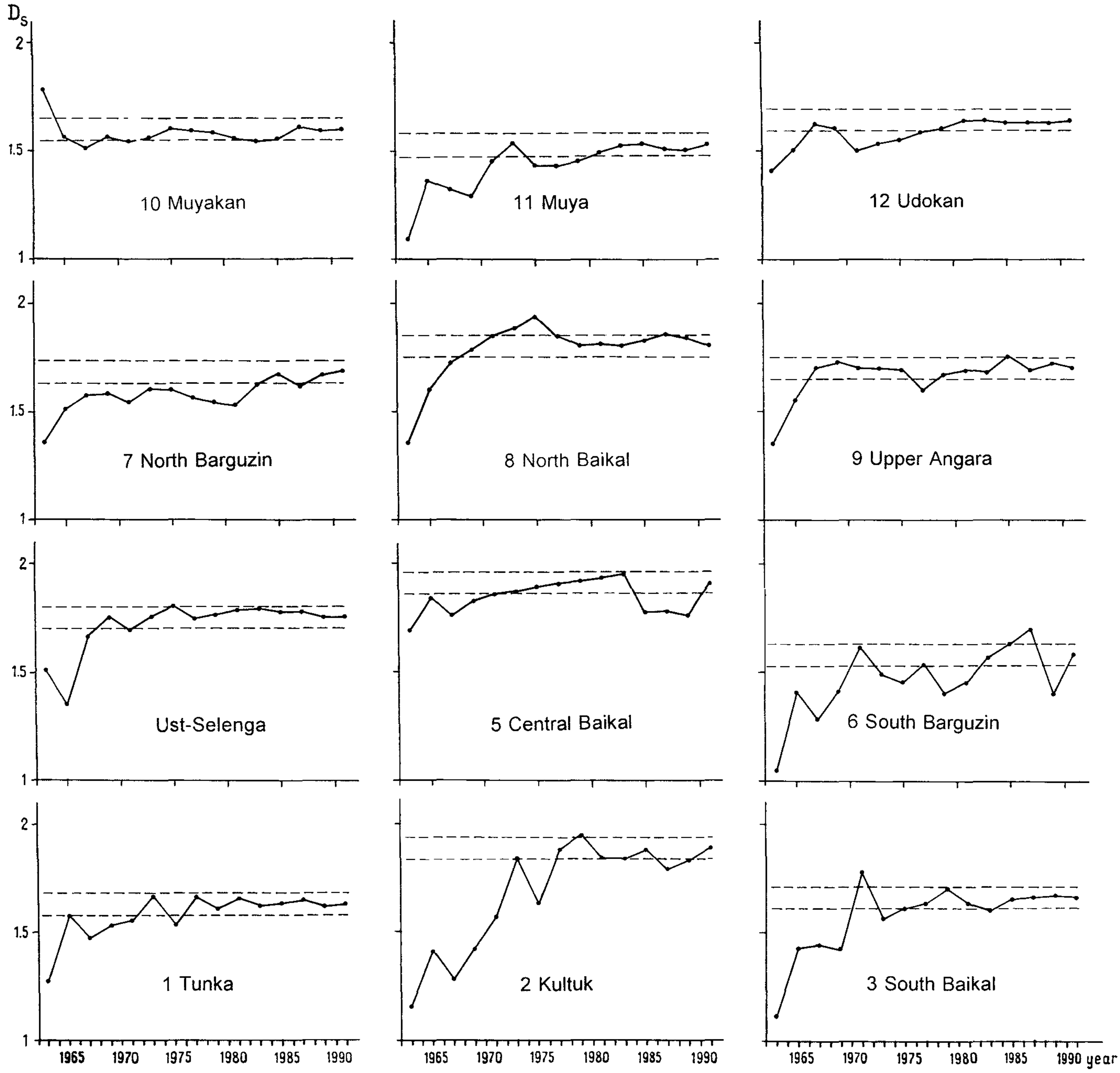


FIGURE 9

Variation with time of the fractal dimension (Ds) of earthquake epicentral fields in various regions of the Baikal Rift Zone. See Table III and Figure 7 for location of the regions.

Variation dans le temps de la dimension fractale (Ds) des champs d'épicentres de tremblements de terre dans diverses régions de la zone de rift du Baïkal.

Usually aftershocks of large earthquakes are not taken into account in the earthquake catalogue (SADOVSKY & PISARENKO, 1991). The Udokan region which is characterized by numerous recurrent shocks (SOLONENKO & SOLONENKO, 1987), was chosen to estimate the effect of aftershock sequences on the nature of the spatial distribution of earthquakes at various scales. In a first step, calculation was made for the whole 30 - year period of observation. In this case, each earthquake of $M \geq 2.2$ was taken into account (Fig. 11.1). In a second step, calculation was made for the periods in which the effect of aftershock sequences on the proportionality of spatial distribution of seismicity was minimal (Fig. 11.2). The period up to 1965, during which aftershocks of the 1957 Muya earthquake (M=7.6) could still be recorded, was eliminated. For the remaining three earth-

TABLE III
Completely developed seismic regions of the Baikal Rift Zone and their selfsimilarity (1962-1991)
Régions sismiques « complètement développées » de la zone de rift du Baïkal et leur autosimilarité(1962-1991)

N°	Region	Location		N	DS	k
		Lat. (°N)	Long. (°E)			
1	Tunka	51.5-52.3	100.8-102.4	518	1.63	7.3
2	Kultuk	51.2-52.0	103.8-105.4	531	1.89	10.2
3	South Baikal	51.6-52.4	105.4-107.0	805	1.66	10.3
4	Ust-Selenga	52.2-53.0	106.2-107.8	1237	1.75	8.1
5	Central Baikal	52.9-53.7	107.4-109.0	1819	1.91	3.2
6	South Barguzin	53.5-54.3	109.0-110.6	624	1.58	5.9
7	North Barguzin	54.7-55.5	110.2-111.8	2211	1.68	3.0
8	North Baikal	55.4-56.2	109.3-110.9	780	1.80	6.6
9	Upper Angara	55.6-56.4	111.4-113.0	850	1.70	5.0
10	Muyakan	55.7-56.5	112.9-114.5	2364	1.60	5.0
11	Muya	55.8-56.6	114.6-116.2	659	1.53	12.4
12	Udokan	56.1-56.9	116.6-118.2	1391	1.64	8.5

No= region number,
N = the number of earthquakes with M ≥ 2.2,
Ds = the fractal dimension,
k = the ratio of the seismicity in the most active trapezium to that in the least active (see § 2.2).

quakes (Kodar, 1970; Kalar, 1974; Udokan, 1981; each with M ≥ 5.1), earthquakes which were accompanied by appreciable aftershock sequences, the two years after the main event of each sequence were eliminated. The almost complete coincidence of the curves for all scales (with correlation coefficients of 0.978, 0.998 and 0.990 for the first, second and third scales respectively) suggests that aftershock sequences do not essentially affect the proportionality of seismicity for various levels of hierarchy, at least in the Udokan region of the BRZ.

As can be seen in Figure 10, a relatively stable level of proportionality at various scales is maintained in all regions except in the Muyakan region, where the earthquake distribution at the first scale is significantly different from that at the 2nd and 3rd scales. This phenomenon is probably related to the fact that two highly seismic structures (Upper Angara and Upper Muya, which behave independently at the first level) fall within the initial trapezium. Further division of the area shows that parts of single seismic structures fall within smaller trapezia and the self-similarity of the seismicity field becomes more prominent.

In order to correlate the degree of contrast of the seismicity field in various regions of the BRZ, an averaging of data on the proportionality of seismicity at three successive scales, was performed. In the case of Muyakan, this was restricted to the two smallest size of trapezia (again to minimise the effect of the Upper Angara and Upper Muya structures - see above). In Table III, where N is the number of earthquakes with M ≥ 2.2 recorded in the seismic regions of the BRZ between 1962 and 1991, k (the ratio of the seismicity in the most active trapezium to that in the least active) varies between 3 and more than 12. This variation is represented on Figure 14. The maximum k values are typical of the terminations of seismic zones in the region of transition between the rift stress field and the regional or global stress field (SOLONENKO, 1993). In the central part of the rift the seismic field shows less contrast. Nevertheless, even there, the level of seismic activity can vary locally by a factor of 3 to 6.

The analysis of self-similarity of the seismic field raises the question as to what extent the above conclusions apply to the energy level. In an attempt to address this question, the data at four energy levels were analysed using data from the Muyakan region, where all shocks with M=1.1 have been recorded. As shown in Figure 12, there is a good similitude between the curves for different magnitudes which, in turn, supports the conclusion of SADOVSKY & PISARENKO (1991) that a straight-line law of earthquake recurrence is valid for very small areas (about 10 by 10 km), though the level of seismicity can vary significantly from area to area.

In order to follow the variability of relative seismicity with time, four calculations were made to describe relative seismicity in the Muyakan region. This region was chosen because a large earthquake swarm, with more than 3500 shocks with 0 < M ≤ 4.7, of which 95% took place within an area of about 30 sq. km occurred there in the period from 1979 to 1987 (KOCHETKOV *et al.*, 1987). The local seismograph network in this region allows the estimation of epicentre coordinates, in most cases, within 3 km. The occurrence of this swarm only slightly influences the proportionality of seismicity at a high scale. At lower scales, even such a prominent event has little effect on the contrast of the seismic field. In other words, the spatial structure of the epicentral region of the swarm fits well with the general self-similarity of the seismic field.

The problem of the stability through time of the relationship of seismic activity within individual trapezia of various sizes, is of practical importance in terms of seismic prediction. If seismic activity within the individual trapezium of any scale (1st, 2nd or 3rd) does not vary during some time, it is believed that we deal with "the completed" epicentral field. This information may be used in earthquake prediction. The estimations of the stability of the seismic intensity range made over 10-year periods for the Muyakan region (Fig. 13) show that, at the first spatial scale, the stability of the seismic intensity range is relatively low at 66.6%. At low levels of spatial scale, which are of the greatest interest in the estimation of local activity, the stability is significantly higher. At the second level, it reaches 100% for the most seismically active trapezia.

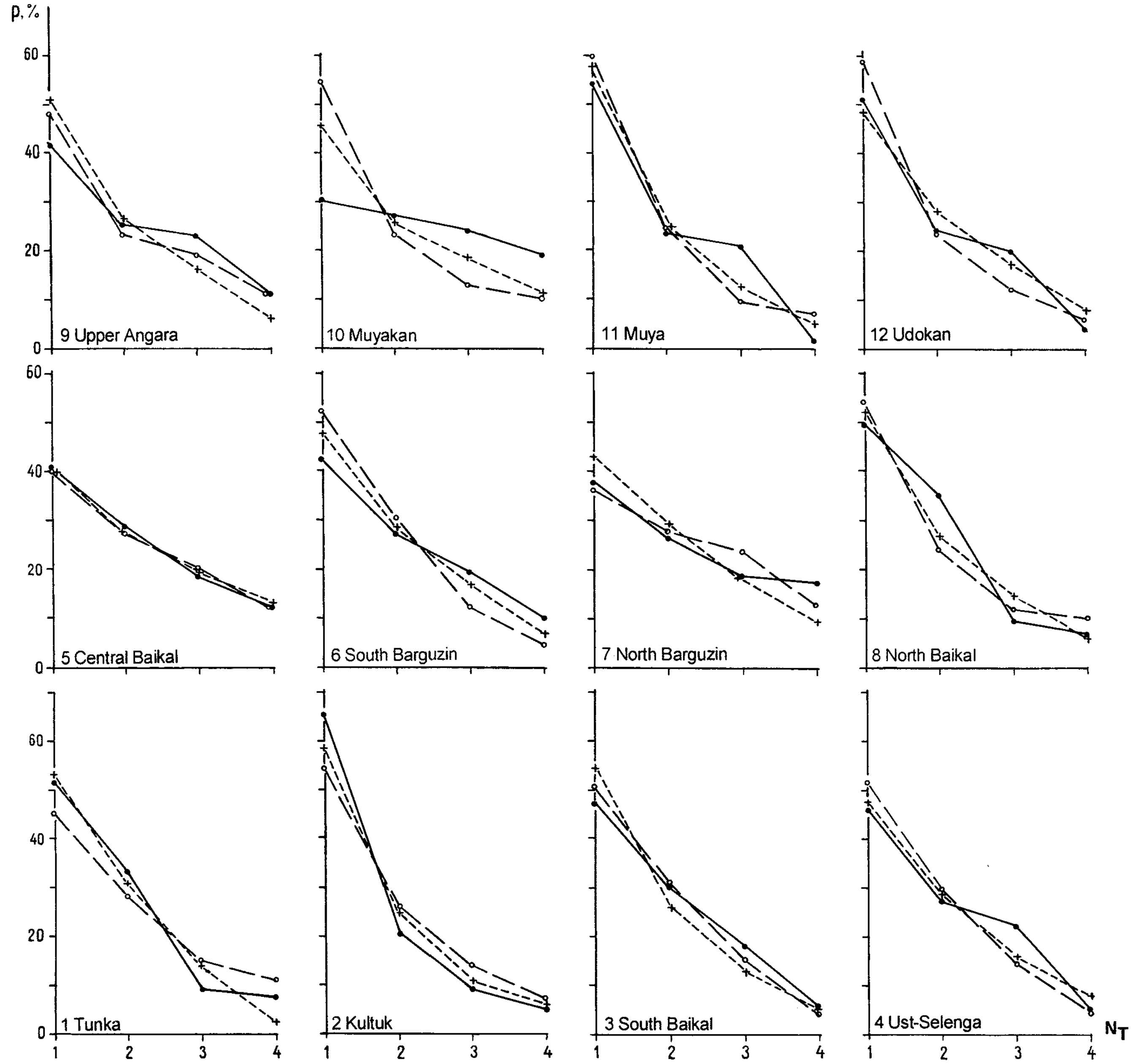


FIGURE 10
Index of seismicity (p%) for different spatial scales in various regions of the Baikal Rift Zone (See Figure 7 for location of the regions).
Indices de sismicité (p%) pour différentes échelles spatiales dans diverses régions de la zone de rift de Baikal. (Voir Figure 7 pour la localisation des régions).

——— Percentage of earthquakes in trapezia of 1st spatial scale.
– – – – Average percentage of earthquakes in trapezia of 2nd spatial scale.
- - - - - Average percentage of earthquakes in trapezia of 3rd spatial scale.
NT = Trapezia number.

2.3. IMPLICATIONS

The above results have several implications:

— the data for the 30 years of regional seismological observations shows that the structure of the earthquake epicentral fields of the BRZ is still developing with its configuration changing from year to year,

— a clearly defined selfsimilarity of the seismicity field at various scales and over a wide energy range is typical for practically all the regions of the Baikal rift, and does not appear to

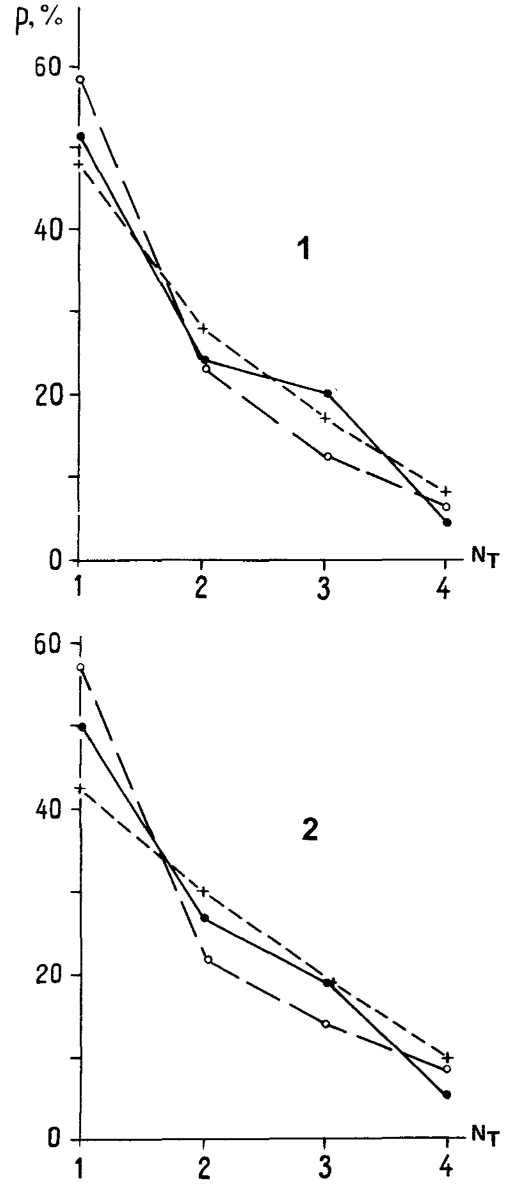


FIGURE 11

Index of seismicity (p%) of the Udokan region for different spatial scales with (1) aftershock sequences included and (2) aftershock sequences excluded.

——— Percentage of earthquakes in trapezia of 1st spatial scale.

- - - - Average percentage of earthquakes in trapezia of 2nd spatial scale.

- - - - - Average percentage of earthquakes in trapezia of 3rd spatial scale.

NT = Trapezia number.

Indice de sismicité (p%) de la région de Udokan pour différentes échelles spatiales avec (1) les séquences de répliques incluses, et (2) les séquences de répliques exclues.

be affected by important aftershock sequences and earthquake swarms,

— the index of seismicity shows strong changes at various spatial scales over the BRZ, with the rift sides being characterized by the greatest contrast,

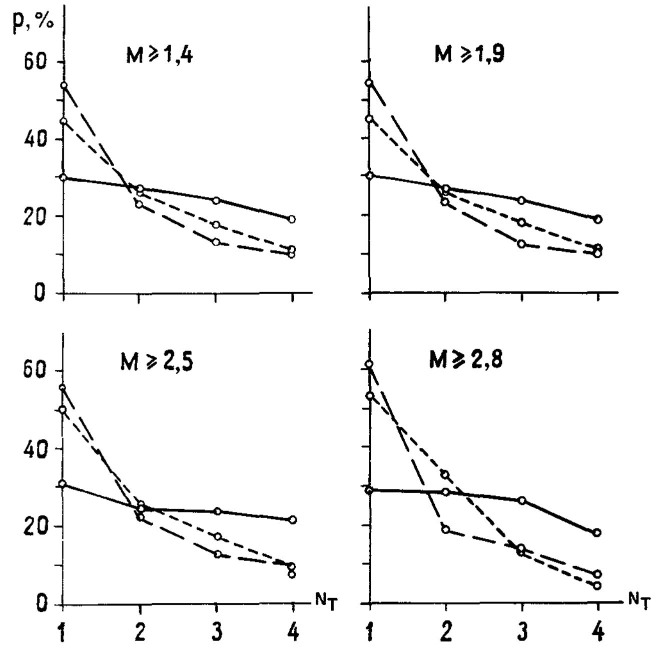


FIGURE 12

Index of seismicity (p%) for different spatial scales in the Muyakan region (1962-1991) at various intensity ranges.

Indice de sismicité (p%) pour diverses gammes d'intensité à différentes échelles spatiales dans la région de Muyakan (1962- 1991).

——— Percentage of earthquakes in trapezia of 1st spatial scale.

- - - - Average percentage of earthquakes in trapezia of 2nd spatial scale.

- - - - - Average percentage of earthquakes in trapezia of 3rd spatial scale.

NT = Trapezia number.

— even within small areas, strong local variations are encountered and the level of seismic activity between neighbouring regions can vary by a factor between 3 and 12. These results are of first importance in the planning of the industrial development of the region when predicting levels of seismic activity. However, it must be emphasised that for each specific case, a special study of the local spatial distribution of earthquake epicentres through time should be conducted.

3. — EARTHQUAKE FOCAL MECHANISMS AND KINEMATIC REGIME

As the Baikal Rift Zone is characterized by a rather high seismic potential, earthquake focal mechanisms have been much studied here. Focal mechanisms of more than 3000 earthquakes in the Baikal region over a wide energy range, during the period 1950-1990, have been determined by soviet institutions. The orientation of the compressional P and tensional T axes of selected focal mechanisms is shown in Figures 15 and 16.

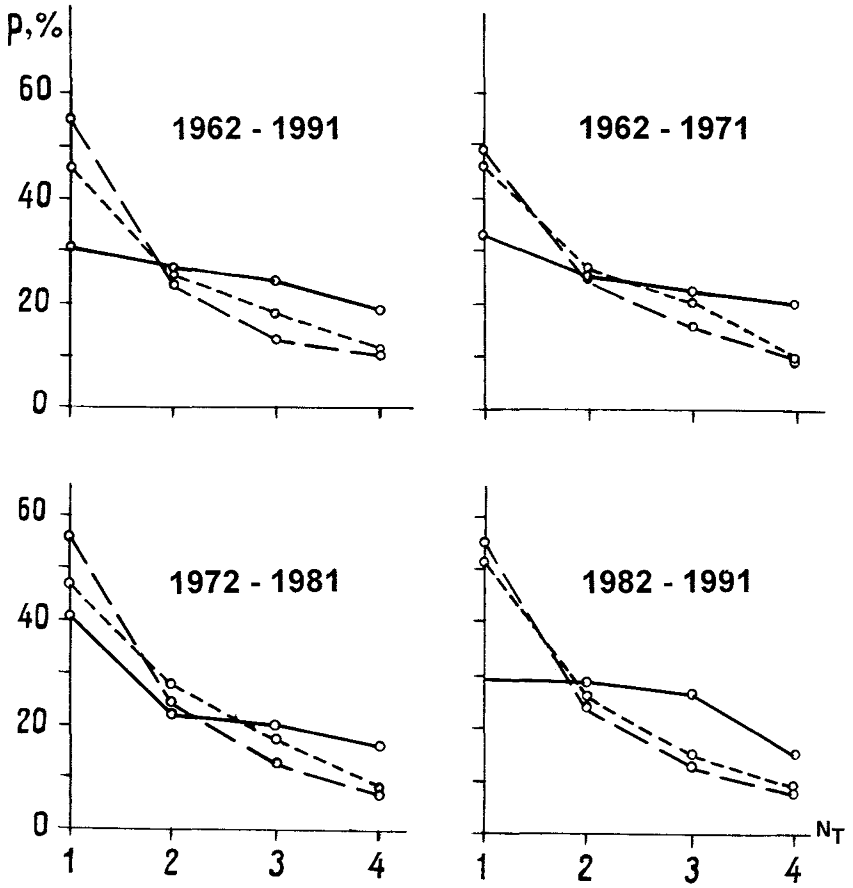


FIGURE 13

Index of seismicity (p%) for different spatial scales in the Muyakan region over different periods.

——— Percentage of earthquakes in trapezia of 1st spatial scale.

– – – – Average percentage of earthquakes in trapezia of 2nd spatial scale.

- - - - - Average percentage of earthquakes in trapezia of 3rd spatial scale.

NT = Trapezia number.

Indice de sismicité (p%) pour différentes échelles spatiales dans la région de Muyakan pendant diverses périodes.

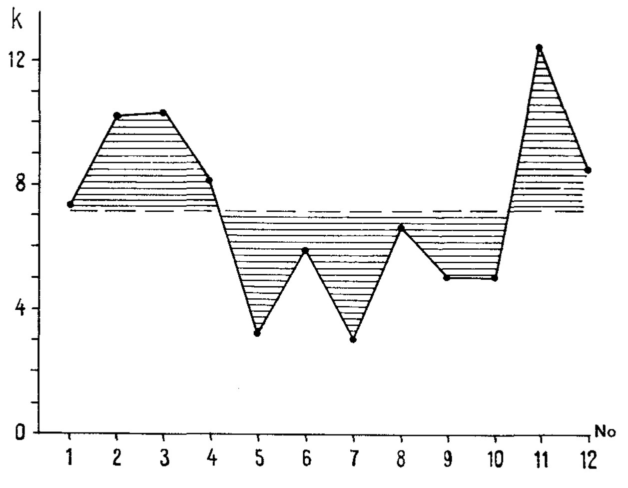


FIGURE 14

Variation of k (the ratio of the seismicity in the most active trapezium to that in the least active) for regions in the Baikal Rift Zone. No = Region number. See Table III for region names.

Variation du rapport de sismicité dans le trapèze le plus actif avec celle du trapèze le moins actif) pour des régions de la zone de rift du Baïkal. No = Numéro de région. Voir Tableau III pour les noms de régions.

In addition to the focal mechanisms determined by soviet institutions, new focal mechanisms have been determined from relocated earthquakes in the North Baikal area (DÉVERCHÈRE *et al.*, 1991) and in the Muyakan area (DÉVERCHÈRE *et al*, 1993).

3.1. DETERMINATION OF FOCAL MECHANISMS

The history of focal mechanism determination in the BRZ is closely related to the installation of a regional seismograph network which provides the greater part of the information. In addition, local seismograph networks have occasionally operated in the central and northeastern regions of the BRZ. Data from seismic stations of the neighbouring areas of the Altai-Sayan zone, Mongolia and Yakutia, have also played an important part in the determination of focal mechanisms in the BRZ. Data from teleseismic stations and from seismographic bulletins have also been used.

The initial stage of investigation of earthquake focal mechanisms in the BRZ, dating back to the 1950s, was characterized by the examination of the most important events in the region using observations mainly from teleseismic stations (VVEDENSKAYA & BALAKINA, 1960). In the 1960s, it became possible to study intermediate shocks with $M > 4.0$ (MISHARINA, 1972). Earthquake focal mechanisms were determined with the first motions of longitudinal waves, using the procedure of A.V. VVEDENSKAYA (1969).

About 50 000 shocks with $0.0<M<3.0$ required a procedure which allows the "grouping" of information from several earthquakes to obtain a mean focal mechanism. These composit

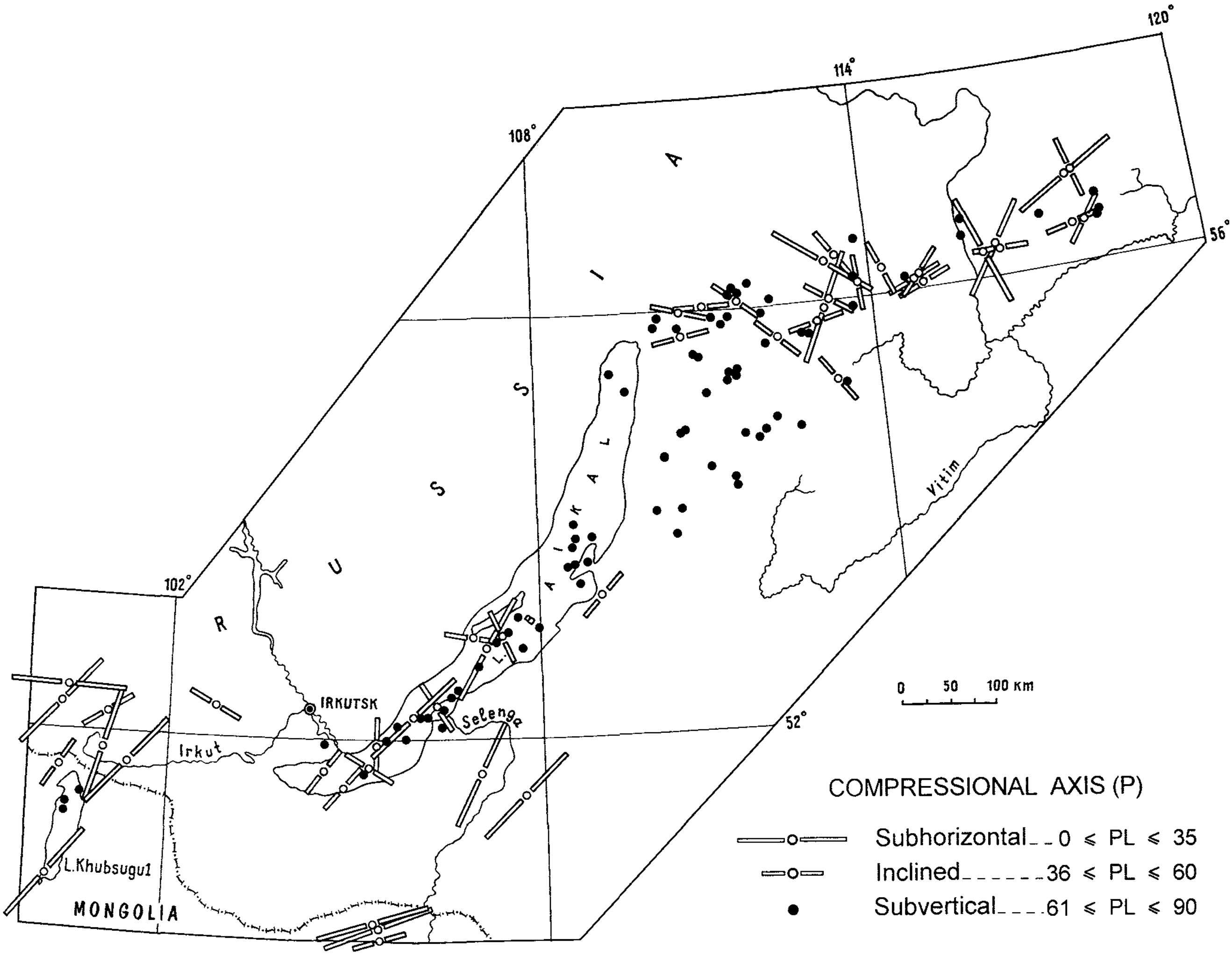


Figure 15A

Orientation of the compressional P axis referring to a horizontal plane (PL) for individual earthquakes in the Baikal Rift Zone.

Orientation de l'axe de compression P par rapport à un plan horizontal (PL) pour des tremblements de terre individuels dans la zone de rift du Baïkal.

solutions are realized according to the proximity of epicentres, the similarity of the orientation of their kinematic axes and the similarity of the P-wave first motions signs (Misharina *et al.*, 1975, 1985; Misharina & Solonenko, 1981a and b). The resulting mean focal planes, established for the whole group, must be consistent for all the earthquakes of each group. If the first motions of a given group of shocks cannot be divided into compressional and dilatational quadrants by the same system of nodal planes, then the population of earthquakes is divided into two or more subgroups, each being characterized by the stability of recurrence of first motions. In this way, 135 groups of earthquakes have been distinguished in the BRZ and have been used to map the regional kinematic field.

The determination of focal mechanisms is mainly based on the first motions of longitudinal waves. For earthquakes whose epicentral distances are greater than 180 km, records involve two arrivals of longitudinal waves, the first corresponding to the waves refracted at the base of the crust (Pn-waves) and the second to the direct P-waves (Pg). The Pg-waves were followed for distances of 600-700 km, but first arrivals of Pn-waves are very difficult to detect, since they appear against a background of other oscillations (P-waves, refracted from the crust or reflected waves). Thus, motions used for focal solutions have generally been determined for epicentral distances not exceeding 180 km. Epicentre coordinates were taken from the Earthquake bulletin of Pribaikalia. Hypocentral depths of individual earthquakes have been determined in the Baikal Rift Zone but with relatively poor accuracy. However, in most cases, they may be assigned to the upper half of the Earth's crust (Golenetsky, 1990). If the depth cannot be determined, it is assumed as 15 km. Focal depth variation of 5-10 km, as indicated by observations, does not significantly affect the focal mechanism determination. Angles of incidence of p-waves are derived using wave propagation velocities of 6.1 km/s in the crust and 8.0 km/s in the mantle (Golenetsky *et al.*, 1978). Under these conditions, angles of incidence of Pn-waves are about 40 degrees. When epicentral distances are more than 10 degrees, the relations between angle of incidence and the epi-

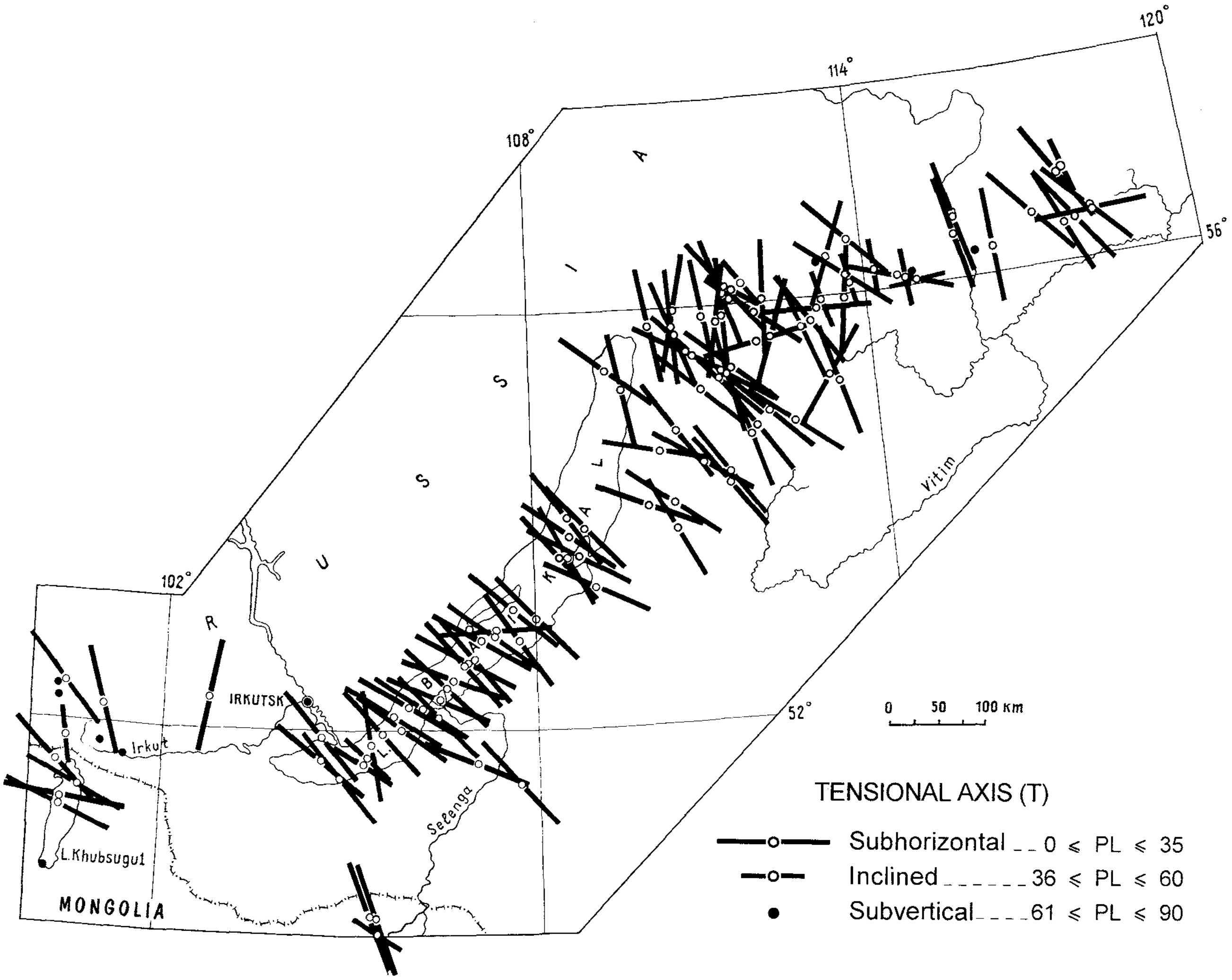


FIGURE 15B

Orientation of the tensional T axis referring to a horizontal plane (PL) for individual earthquakes in the Baikal Rift Zone.

Orientation de l'axe d'extension T par rapport à un plan horizontal (PL) pour des tremblements de terre individuels dans la zone de rift du Baïkal.

central distance (MALINOVSKAYA, 1954) are used to derive the angles of incidence of refracted waves. For proximal earthquakes (at ten to hundreds of kilometres) the angle of incidence of direct waves are derived using geometrical constructions based on available seismic profiles. For epicentral distances exceeding 1000 km, plots of relation between angles of incidence and epicentral distances constructed for various depths are used (MALINOVSKAYA, 1954).

Accuracy parameters for focal mechanisms determination are fixed as follows: Class A corresponds to mechanisms for which the orientation of kinematic axes is determined within 10 degrees and all three axes are defined. In Class B the three axes are defined, but with an uncertainty greater than 10 degrees. Class C contains solutions in which the orientation of one, two or all three axes is ambiguous (MISHARINA, 1972). Orientation of P, B and T axes is expressed by the azimuth (Az) and the angle to the horizontal plane (PL). Axes are conventionally referred to one of the three following types: subvertical ($61 \leq PL \leq 90$) degrees, inclined ($36 \leq PL \leq 60$) degrees or subhorizontal ($0 \leq PL \leq 35$) degrees.

3.2. DISTRIBUTION OF FOCAL MECHANISMS

In order to analyse the earthquake focal mechanism distribution, the vast and tectonically complex area of the BRZ is divided into 7 seismic regions: Tunka, Central Baikal, Barguzin, Upper Angara, Baunt, Muya and Udokan (Fig. 17). The results of individual determination of earthquake focal mechanisms in the BRZ with $M \geq 2.8$, between 1950 and 1990, are shown in Table IV.

In the Tunka region which includes the Tunka depression, the Tunka ridge and the Main Sayan Fault Zone (east of 101°), 14 earthquake groups are distinguished. Contrasting movement types are recognized, with predominantly normal dip-slip movements in the depression (subvertical P axes) and thrust

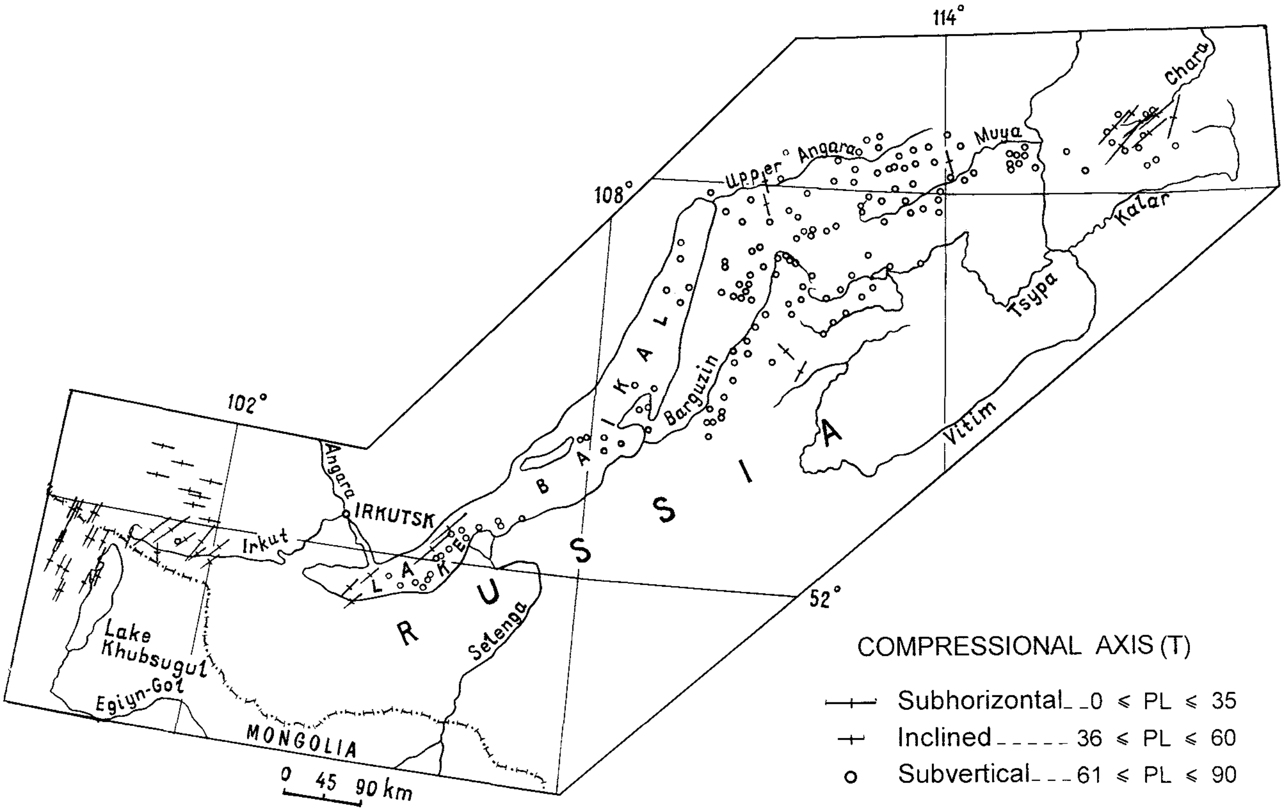


FIGURE 16A

Orientation of the compressional P axis referring to a horizontal plane (PL) for groups of earthquakes in the Baikal Rift Zone.

Orientation de l'axe de compression P par rapport à un plan horizontal (PL) pour des groupes de tremblements de terre dans la zone de rift du Baïkal.

movements in the Tunka ridge (subvertical T axes). For the three largest earthquakes in this region, two had inclined P axes and one, a subvertical T axis. NW-trending seismic rupture planes predominate over NE-trending ones.

The Central Baikal depression is characterized by a highly stable orientation of kinematic axes for both large and small earthquakes. Most of them result from a typical rift normal faulting regime, with horizontal T and B axes and subvertical P axes. Fault planes generally trend NE.

In the Barguzin region, which includes the Barguzin depression and a large portion of the Barguzin and Ikat ranges, earthquakes yield various types of focal mechanisms. In the Barguzin depression and the northern parts of the Barguzin and Ikat ranges, a normal dip-slip faulting regime is typical, whereas in the Ikat range some cases of oblique- to strike slip occur. Most of the rupture planes are NE-trending.

The Upper Angara region includes the Upper Angara depression and range, the lower part of the Upper Angara river, the northern termination of the Barguzin and North Muya ranges and the area between the Ikat and South Muya ranges. In the Upper Angara region, 18 groups over 21 reflect normal dip-slip faulting, the remaining ranging between oblique-slip and thrust faulting. An extensional "rift" regime predominates within large earthquakes. Fault planes of the Upper Angara region trend either ENE or E-W, indicating two structural directions.

In the Baunt region, involving the Tsipa-Baunt depression and the surrounding uplifts, the typical regime is normal faulting, with most faults trending NE.

The Muya region is bordered by the Delyun-Uran range to the north, by the South Muya range to the south and by the Upper Angara region to the west. Eastwards, it extends to 117° E, involving the western part of the Muya-Chara interdepressional uplift. Over the whole Muya region, including 24 groups of earthquakes and individual large earthquakes, normal rift -type faulting predominates. However, some earthquakes show strike-slip movement, with inclined P and T axes. NE-trending planes predominate but NW-trending planes exist in the western part.

The Udokan region involves the southern slopes of the Kodar range, the southwestern part of the Chara depression, the eastern part of the Muya-Chara interdepressional uplift and the northern slopes of the Udokan range. In this region, there are considerable strike -slip motions in addition to normal ones. Some earthquakes even show thrust regime. A wide range of rupture plane strikes is observed in this region, with NE-trending planes predominating over NW-, NS- and EW-trending ones.

Finally, the majority of earthquakes of the BRZ, both large and small, display rift-type mechanisms, where tensional T axes are horizontal and perpendicular to the strike of geological structures (Fig. 15a,b and 16a,b). Movement planes, whose

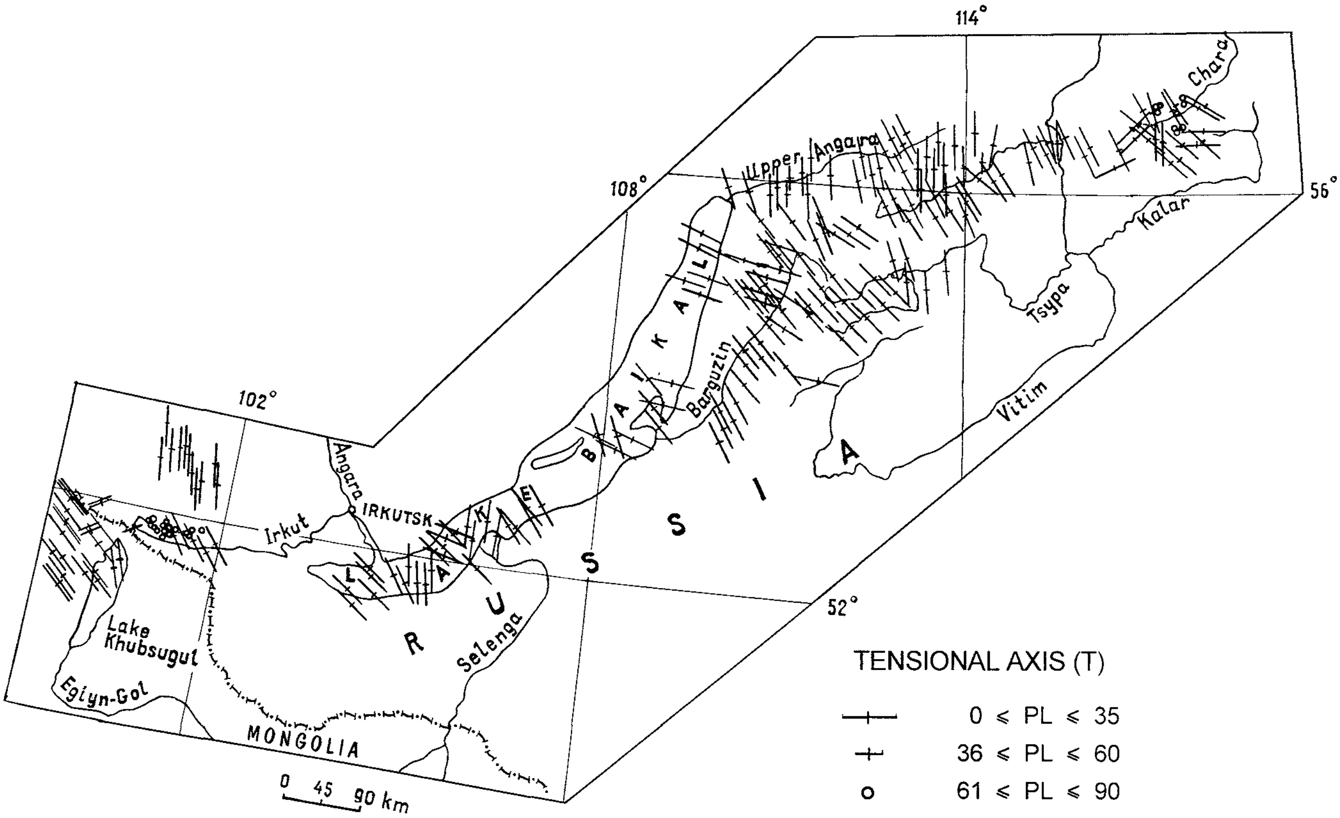


FIGURE 16B
Orientation of the tensional T axis referring to a horizontal plane (PL) for groups of earthquakes in the Baikal Rift Zone.
Orientation de l'axe d'extension T par rapport à un plan horizontal (PL) pour des groupes de tremblements de terre dans la zone de rift du Baïkal.

strike is consistent with the strike of major faults at the surface, are predominantly of dip-slip type. This pattern is relatively uniform over the BRZ, especially in the Baikal region itself, with the exception of the Tunka and Udokan regions at the extremities of the rift zone.

4. — DISCUSSION

4.1. SYMMETRY OF THE STRESS FIELD

Using the currently available focal mechanism data of more than 3000 earthquakes in the BRZ, together with the large amount of data from the adjacent areas of Mongolia and South Yakutia (KOZMIN, 1984; PETIT *et al.*, 1996), it is possible to present a large scale synthesis of the regularity of the stress field within that area, inferring the statistical co-axiality of S1, S2, S3 with P, B, T. Analysis of the data given in Figures 15a, b and 16a, b and in Table IV, indicates that a special feature of the stress field is its clear symmetry about a transverse axis running across the northern part of Lake Baikal (Fig. 18) and dividing the rift zone into two parts, each one being the mirror image of the other. The significance of this symmetry and relationship to the recent structure of the BRZ was indicated by UFIMTSEV (1990). On a regional scale, the central part of the rift zone, between the Vitim river valley to the northeast and the Selenga river to the southwest, is characterized by a "rift-kinematic" field. The majority of earthquakes for which fault plane solutions are available, show a normal-faulting regime, with tensional axes typically oriented perpendicular to the strike of the neotectonic structures. East of the Vitim river and southwest of the Selenga river delta, this uniformity of kinematic axis orientation is no longer observed.

In the central part of the rift zone, the mirror symmetry of the recent structure is reflected by the uniformity of kinematic axes orientations (Fig.18). In particular, the Northern Baikal and Barguzin depressions on one side, and the Upper Angara and Upper Muya depressions on the other, appear as mirror images to the main symmetry plane. Each side shows azimuths of T axes differing by 20 degrees (arrows 1-1' and 2-2' in Figure 18). The average azimuth of T axes is: N291E for the North Baikal and N311E for the Barguzin depressions; N348E for the Upper Angara and N328E for the Upper Muya depressions. In both cases, the angular difference in strike of these basin couples is also 20 degrees. The close coincidence between angular difference in strike of large structural elements of the rift zone and the azimuths of T axes from earthquake mechanisms, indicate a clear influence of the fault geometry on the kinematics of faulting - the tensional T axes tending to be perpendicular to the fault trends. This can be interpreted as a local perturbation

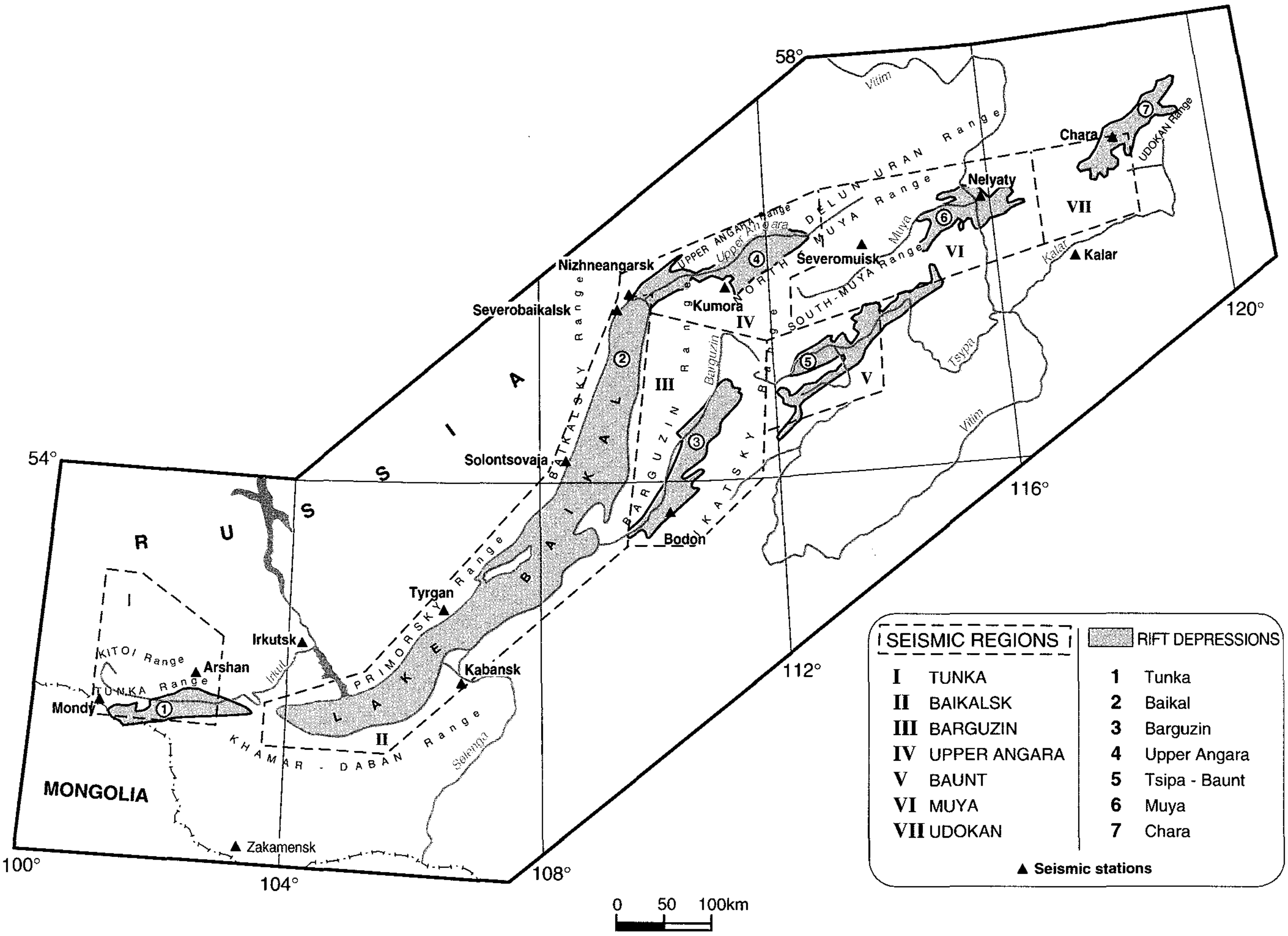


FIGURE 17

Location of seismic stations and main seismic zones of the Baikal Rift Zone.

Position des stations d'enregistrement sismiques et des zones sismiques principales de la zone de rift du Baïkal.

of the stress field in the vicinity of major crustal structural inhomogeneities.

Similar peculiarities also exist in other portions of the rift which appear as pairs of symmetrical regions: the Upper Angara basin compared with the Chivykui Bay in Central Baikal, and the region of interdepressional uplifts between South Baikal and North Baikal basins compared with that between the Upper Angara and Muya basins to the northeast. Each of these four regions is characterized by a spatial overlapping of earthquakes with two different regimes: one group with subhorizontal T axes which are perpendicular to the rift trend (rift orientation) and another with T axes oblique to the rift trend (diagonal orientation). The angular differences between the two groups of T axes is 35 degrees for the first two regions (arrows 3 and 3' in Figure 18) and 45 degrees for the remaining two (arrows 4 and 4'). It should be noted that the azimuthal difference between rift and diagonal orientations of T axes is also symmetrical relative to the North Baikal symmetry axis. The greater the distance between the region and the symmetry axis, the larger the azimuthal difference between the T axes of "rift" and "diagonal" orientations. At the extremities of the rift zone, this difference reaches 90 degrees.

4.2. TRANSITION FROM RIFT TO GLOBAL STRESS FIELDS

In the northeastern part of the rift, from the Vitim river to the eastern seismic gap (at 120°E), the characteristics of the "rift" stress field are remarkable (Fig.18). In particular the subhorizontal T axes are oriented either perpendicular or parallel to the main structural trends . This is the opposite situation as in the western extremity of the rift. In the latter, compressional axes are generally subhorizontal, but with varying orientation with respect to the strike of the major morphostructures. A large number of earthquakes in the northeast region have subvertical T axes indicating reverse faulting. In the rift territory, which extends southwest of the Selenga river delta to the western seismic gap zone (west of the south end of Lake Baikal), earthquakes show predominant subhorizontal T axes, oriented both

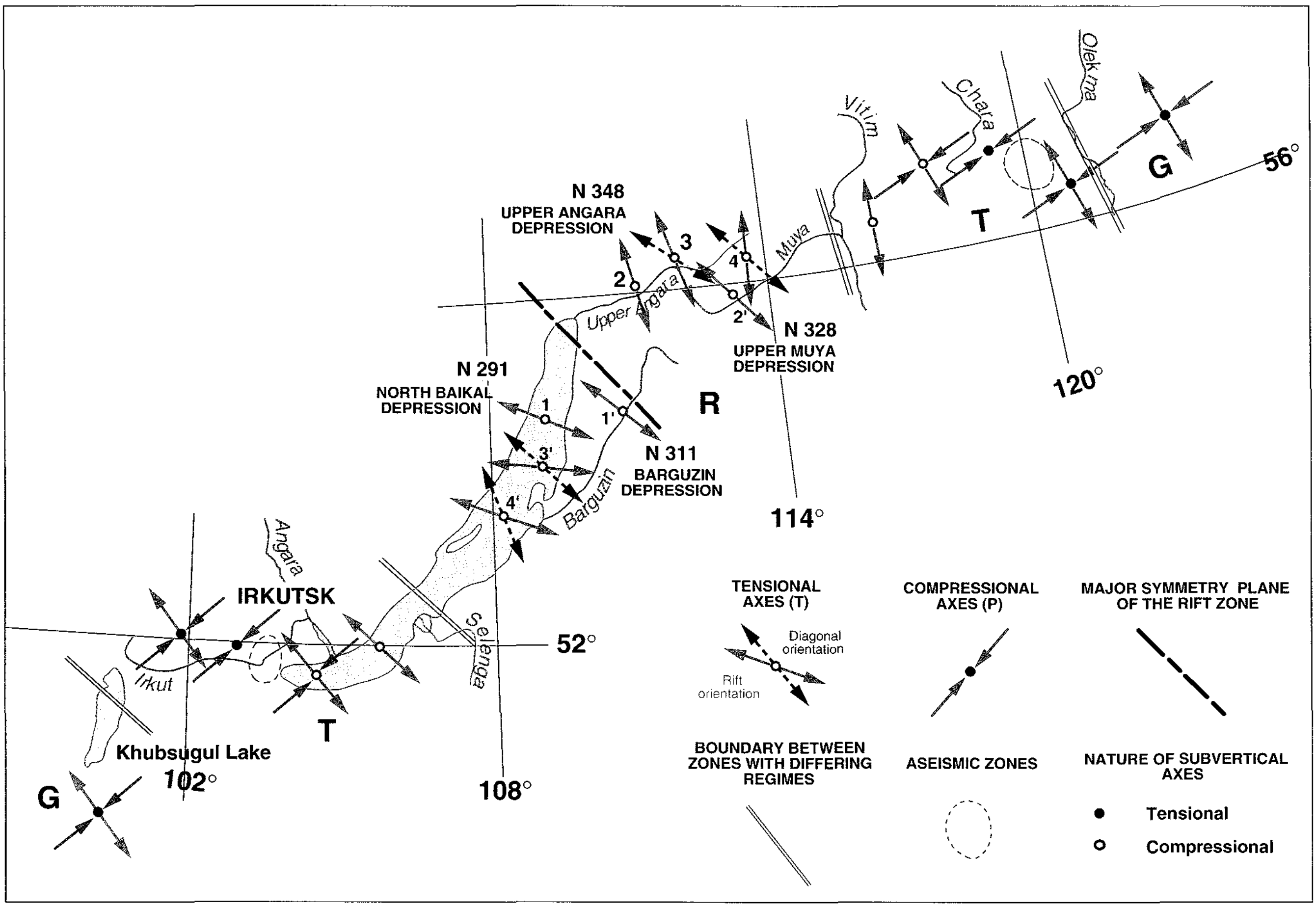


FIGURE 18

The stress field in the Earth's crust in the Baikal Rift Zone, and in adjacent areas of North Mongolia and South Yakutia. Stress axis are approximated from the orientation of P and T axes of earthquake focal mechanisms.

R) Zone of rift stress field
G) Zones with the global stress regime
T) Transitional zones.

Schéma du champ de contraintes dans la région de la zone de rift du Baïkal, et dans les régions adjacentes de Mongolie du Nord et de Yakoutie du Sud. Les axes de contrainte sont estimés à partir des données des mécanismes au foyer des tremblements de terre.

R) Zone à champ de contrainte de type rift
G) Zones à régime de contrainte global
T) Zones de transition.

perpendicular and oblique to the South Baikal depressions. The attenuation of the extensional field in the region of the South Baikal basin is particularly obvious in the Tunka depressions. The presence of both extensional rift-type focal mechanisms and compressional focal mechanisms typical of North Mongolia is clearly observed in this region. The southwestern boundary of the Baikal rift zone is drawn by MISHARINA *et al.* (1983) and KHILKO *et al.* (1985) at the northern end of Lake Khubsugul, based on the complete disappearance of Baikalian rift-type focal mechanisms.

To the northeast, the complete disappearance of the extensional rift kinematic field is observed in the area of the left bank of the Olekma river (KOZMIN, 1984). In this region, individual large earthquakes have normal-faulting mechanisms, but compressional P axes become less inclined. Further east, in the Olekma-Stanovoy seismic belt, most P axes are subhorizontal, trending in a NE-SW direction, and T axes are also subhorizontal, indicating a strike-slip faulting regime. In Mongolia, focal mechanisms attest to a significant uniformity of the stress field in that area. In most cases, they indicate a strike-slip regime, with subhorizontal P axes in a NE-SW direction (KOTCHETKOV *et al.*, 1987). Thus, the stress regime and consequently the axes orientation are broadly similar in the regions to the northeast and southwest of the BRZ. They are representative of a common global system in this part of Asia. Therefore, the rift field of the Baikal seismic zone appears as an anomaly which completely distorts the global field. Despite this change in the stress regime (from global to rift one), the orientation of the T axes is relatively stable in a NW-SE direction. The lack of significant deviation in the central part of the rift indicates that the rift T axes are oriented approximately in the same direction as the global ones.

TABLE IV
Focal mechanisms for earthquakes with M ≥ 2.8 in the Baikal Rift Zone (1950-1990)
Mécanismes focaux des tremblements de terre d'intensité M ≥ 2.8 dans la zone de rift du Baïkal

Time			M	Location		Kinematic axes						Nodal planes						Accuracy	
Year	Month Day	Hour Min		Lat. (°N)	Long. (°E)	T pl	T azm	N pl	N azm	P pl	P azm	NP1 stk	NP1 dp	NP1 slip	NP2 stk	NP2 dp	NP2 slip	Class	Refer.
1950	04 04	18 44	7.0	51.80	101.00	68	012	00	102	22	192	282	24	090	102	65	090	C	a
1957	02 06	20 34	6.5	50.00	105.50	37	306	30	190	38	073	190	90	-120	100	30	000	A	a
1957	06 27	00 09	7.6	56.20	116.40	02	175	47	266	42	084	228	60	-147	121	62	-035	B	a
1959	08 29	17 03	6.8	52.68	106.98	00	320	18	051	72	228	033	48	-116	247	48	-066	A	a
1960	03 12	10 38	4.5	52.00	105.80	05	302	02	212	85	108	210	50	-093	032	40	-088	C	a
1960	05 19	23 20	4.0	52.10	105.70	05	302	02	212	85	108	210	50	-093	032	40	-088	C	a
1961	07 27	23 59	4.8	54.10	110.00	14	291	22	029	62	174	221	62	-064	353	38	-129	C	a
1961	08 07	21 24	4.0	52.40	106.60	04	313	31	046	58	218	015	50	-133	250	56	-052	C	a
1961	10 09	13 20	3.5	51.50	104.80	06	318	46	055	44	222	010	56	-150	262	66	-038	B	a
1961	10 28	22 45	5.5	53.60	108.80	08	297	22	030	67	189	004	42	-124	226	56	-064	A	a
1961	11 23	01 11	4.5	55.85	110.15	05	168	00	078	85	348	078	50	-090	258	40	-090	C	a
1962	01 11	14 16	2.8	54.50	111.00	05	122	07	212	81	000	204	40	-101	038	50	-081	C	a
1962	01 22	07 26	5.5	52.40	100.40	76	248	05	359	13	090	187	32	099	356	58	086	B	a
1962	04 23	21 16	3.3	56.50	117.20	03	320	22	228	68	058	210	52	-119	071	46	-059	A	a
1962	06 18	09 50	3.5	51.40	107.70	16	137	70	279	12	047	183	70	178	273	88	021	B	a
1962	08 10	08 52	3.3	56.50	113.80	05	318	08	228	80	080	221	50	-101	056	41	-079	C	a
1962	08 13	20 11	5.2	53.70	108.50	07	320	16	053	72	209	032	40	-117	244	54	-071	B	a
1962	10 28	08 29	3.5	53.60	108.60	04	298	20	030	70	196	008	44	-120	225	52	-066	A	a
1962	11 11	11 31	5.7	55.92	113.26	12	296	10	029	74	157	215	58	-078	013	34	-109	A	h
1963	01 15	09 16	3.5	55.80	112.90	12	326	33	228	54	074	210	65	-127	090	45	-038	C	b
1963	01 31	18 30	4.0	53.10	107.70	17	132	25	034	60	254	022	67	-117	254	35	-044	C	a
1963	02 05	21 56	4.0	54.30	111.40	04	136	10	046	80	248	037	50	-104	235	42	-076	A	a
1963	02 10	06 48	5.0	52.60	106.80	03	139	17	048	73	239	033	50	-114	245	45	-066	A	a
1963	02 14	21 59	3.3	54.80	111.90	05	329	11	238	77	080	228	50	-105	070	42	-074	B	a
1963	02 15	15 49	4.5	55.20	111.00	18	131	14	037	67	274	030	65	-106	242	29	-062	B	a
1963	03 12	23 07	3.5	56.10	111.50	15	158	12	064	70	297	057	61	-104	264	32	-067	B	a
1963	03 18	23 02	3.5	56.00	112.20	09	002	00	092	81	182	092	36	-090	272	54	-090	C	a
1963	04 11	17 23	3.5	54.40	111.40	03	142	16	052	74	243	038	50	-112	248	44	-068	A	a
1963	12 01	04 26	4.9	55.90	112.00	20	309	06	041	69	148	028	26	-106	223	65	-084	B	b
1966	04 03	06 13	4.5	54.00	108.60	16	330	16	065	67	197	037	33	-122	253	63	-072	C	a
1966	08 30	06 10	5.5	51.69	104.49	04	125	53	030	37	218	255	62	-026	358	68	150	A	a
1966	12 31	04 54	4.0	55.60	110.80	06	119	04	210	82	330	205	39	-097	032	51	-086	B	b
1967	01 15	19 58	5.2	55.60	110.80	05	137	26	230	63	037	200	46	-130	070	56	-058	A	b
1967	01 19	02 02	4.0	52.10	106.40	08	318	05	049	80	173	042	37	-099	232	53	-084	B	a
1967	10 16	23 19	4.0	55.90	111.10	10	174	18	080	68	292	068	58	-112	285	38	-060	B	b
1967	02 11	09 27	5.3	52.09	106.46	24	177	64	337	08	084	218	67	168	313	79	024	A	h
1968	06 17	02 55	4.5	55.96	110.58	02	190	37	099	54	282	069	56	-136	311	54	-042	A	b
1968	07 21	01 41	5.0	55.18	113.45	25	165	04	073	65	335	071	70	-095	264	20	-081	C	e
1968	08 31	18 06	5.0	56.40	115.78	14	348	15	254	70	118	245	60	-107	097	34	-063	C	b
1968	11 08	02 53	4.5	56.14	113.75	01	306	12	216	78	034	204	47	-107	049	46	-072	B	b
1968	11 26	18 31	5.3	55.90	111.49	10	355	01	265	79	171	264	55	-091	088	35	-089	B	e
1970	03 28	09 44	5.5	52.20	105.92	26	300	54	165	21	042	082	54	004	351	86	144	A	e
1970	05 15	20 50	5.5	56.84	117.74	16	150	72	294	10	057	193	72	176	283	86	018	A	b
1970	05 18	14 36	4.8	56.87	117.87	35	346	00	256	55	166	076	10	-090	256	80	-090	A	b
1970	08 13	19 26	4.9	51.95	105.53	06	322	14	054	74	206	037	40	-113	244	53	-073	A	e
1971	12 18	22 23	5.0	56.19	114.21	39	174	07	079	51	341	078	84	-097	308	09	-041	A	e
1972	01 04	13 12	4.5	55.82	110.56	07	177	08	086	80	311	080	52	-100	275	39	-079	A	b
1972	08 09	19 42	5.2	52.80	107.73	14	324	10	231	72	110	225	60	-102	068	31	-070	A	e
1973	06 16	12 12	5.1	54.85	112.58	06	126	22	218	68	021	194	44	-122	055	54	-063	A	e
1974	06 21	20 56	5.1	56.35	117.70	04	157	34	064	56	254	040	58	-133	279	50	-043	A	e
1974	07 21	05 21	5.0	56.09	113.81	53	168	03	261	37	354	262	80	088	087	10	097	C	b
1975	02 06	21 26	4.7	56.41	117.89	23	297	38	047	43	184	236	79	-051	341	41	-161	A	b
1976	04 01	19 02	4.5	50.62	100.22	76	132	14	305	02	036	293	48	072	139	45	110	C	c
1976	09 23	09 50	5.0	55.75	110.54	08	161	46	062	43	259	037	68	-140	289	54	-029	B	e
1976	11 02	14 55	5.2	56.19	111.59	00	144	25	055	65	233	032	50	-123	259	51	-057	A	e
1977	06 04	15 00	4.7	56.20	111.82	27	324	14	062	58	176	022	22	-132	246	74	-076	B	b
1977	08 24	10 14	5.0	54.12	110.44	04	123	21	214	68	024	192	46	-121	052	52	-063	B	e
1977	11 20	11 01	4.0	56.55	115.78	10	167	07	076	78	311	071	55	-099	265	36	-080	A	b
1978	10 21	15 44	2.8	56.31	113.24	61	250	22	026	18	124	017	67	066	245	33	133	C	b
1979	01 10	07 30	5.0	55.43	111.44	03	298	20	207	70	036	190	51	-116	048	46	-062	A	e
1979	01 10	09 54	5.0	55.40	111.43	17	347	01	257	73	162	257	62	-090	078	28	-089	B	b
1979	02 11	21 46	3.5	55.42	111.44	13	309	16	215	69	075	205	60	-109	060	35	-061	A	b
1979	02 21	15 38	4.0	55.84	111.31	08	189	08	097	78	322	092	53	-098	287	38	-078	A	b
1979	04 15	18 20	4.0	56.33	113.42	18	024	30	282	54	140	269	70	-121	150	38	-036	A	b

TABLE IV (SUITE)

Time			M	Location		Kinematic axes						Nodal planes						Accuracy	
Year	Month Day	Hour Min		Lat. (°N)	Long. (°E)	T		N		P		NP1			NP2				
						pl	azm	pl	azm	pl	azm	stk	dp	slip	stk	dp	slip	Class	Refer.
1979	07 01	02 41	4.0	55.66	112.30	20	016	37	271	46	128	259	74	-128	149	41	-025	C	b
1979	12 05	00 54	4.5	55.32	111.39	06	316	09	226	80	078	219	51	-102	056	40	-077	A	b
1980	02 06	16 35	4.9	51.74	105.14	35	312	05	218	55	120	217	80	-095	069	12	-059	A	e
1980	04 04	02 52	4.5	54.67	109.80	15	290	01	200	75	106	021	30	-090	200	60	-090	B	g
1980	07 23	09 55	4.5	52.32	102.63	11	194	29	097	59	300	080	62	-123	315	42	-044	A	g
1980	07 30	06 42	4.5	52.61	106.92	22	116	10	021	66	268	017	68	-101	223	26	-068	A	g
1980	09 26	15 06	4.5	51.86	105.33	29	349	05	079	61	183	068	18	-106	262	74	-085	A	g
1980	10 02	01 12	5.1	51.62	107.04	26	111	62	308	08	204	250	66	013	155	77	156	B	e
1981	01 17	11 23	5.1	56.36	117.94	11	326	32	062	56	220	021	45	-141	260	64	-054	A	e
1981	02 25	06 57	4.5	56.22	111.57	01	106	27	205	68	014	046	54	-056	178	48	-118	A	d
1981	03 03	13 30	4.2	55.73	112.88	05	159	07	070	82	288	065	50	-098	256	40	-079	A	d
1981	05 22	09 51	5.4	51.97	105.54	07	317	02	048	82	152	045	38	-095	230	52	-088	A	e
1981	05 27	21 26	5.2	53.90	108.91	20	320	16	056	64	182	024	28	-126	243	67	-073	C	e
1981	05 31	04 25	4.5	56.17	111.76	03	141	23	209	87	314	189	50	-120	051	49	-090	A	d
1981	12 01	21 42	5.0	52.18	101.00	25	163	40	276	39	050	203	40	-168	103	82	-052	A	f
1982	01 14	07 35	4.9	54.81	110.42	10	143	18	049	68	259	036	56	-112	253	40	-061	A	d
1982	01 28	13 11	4.6	53.49	108.69	10	135	07	227	78	357	052	54	-081	217	36	-102	B	d
1982	07 27	21 26	4.7	52.43	106.65	07	286	18	019	70	173	211	56	-068	356	40	-119	B	d
1982	10 03	14 51	4.5	55.98	110.91	12	334	30	235	57	084	219	64	-124	096	42	-041	A	d
1983	11 24	13 42	4.5	52.99	106.95	32	331	23	224	50	104	220	80	-114	110	26	-021	C	d
1984	02 02	23 58	4.0	55.93	113.68	00	192	08	105	83	285	096	44	-100	292	46	-078	B	d
1984	06 19	13 22	4.7	56.45	118.25	07	138	20	231	68	032	066	56	-064	206	42	-122	A	d
1984	12 09	22 06	4.8	53.83	108.59	18	306	13	041	68	161	017	30	-117	227	64	-076	B	d
1985	02 23	17 55	4.0	55.37	111.33	06	102	13	192	77	355	022	52	-074	177	42	-110	A	d
1985	03 10	03 37	4.8	52.70	106.98	17	127	14	033	67	269	025	64	-105	238	30	-061	C	d
1985	03 25	10 57	4.5	52.27	106.43	14	257	28	356	57	148	317	40	-137	191	64	-057	C	d
1985	04 06	05 32	4.8	51.36	100.61	03	123	10	034	80	220	025	48	-102	223	44	-077	B	d
1985	08 15	20 28	4.0	54.65	110.16	02	280	06	012	83	169	006	42	-097	197	48	-083	B	d
1985	08 24	22 57	4.0	51.20	100.40	06	293	24	028	64	190	000	44	-126	225	56	-060	C	g
1985	09 03	03 33	4.4	52.83	107.12	03	141	03	231	87	012	055	48	-085	228	42	-095	B	d
1985	11 11	19 01	4.2	55.63	112.01	05	077	22	344	69	179	327	54	-118	188	46	-059	C	d
1986	01 22	04 12	4.6	55.46	109.37	03	117	17	025	72	214	010	50	-114	224	44	-064	B	d
1986	05 17	07 46	3.5	56.06	114.84	06	114	44	019	43	209	51	64	-142	241	56	-030	C	d
1986	05 20	01 49	4.0	55.25	113.35	12	031	30	295	57	142	278	64	-123	156	42	-041	C	d
1986	05 26	03 34	4.2	56.26	116.19	85	305	05	125	00	215	120	46	083	311	44	097	B	d
1987	03 08	05 16	4.0	51.30	100.36	07	096	22	004	66	204	348	56	-117	208	42	-057	A	g
1987	03 29	01 25	4.0	52.19	106.20	11	305	23	210	65	058	058	40	-055	194	60	-118	C	d
1987	05 11	05 19	4.8	51.71	105.28	21	127	03	219	68	318	040	66	-086	214	25	-095	B	d
1987	10 08	21 02	4.0	55.29	109.60	13	349	29	251	58	100	112	40	-042	236	64	-123	A	d
1987	12 24	18 28	4.4	52.97	107.37	13	297	06	029	78	142	019	34	-100	212	58	-084	B	d
1987	12 24	19 29	4.5	52.96	107.40	08	270	23	003	66	162	335	42	-126	198	58	-063	A	d
1988	06 04	07 24	4.3	55.87	113.18	54	242	28	105	20	003	054	35	035	295	71	120	C	d
1988	06 21	16 14	4.0	56.07	114.68	20	284	17	020	63	148	347	29	-127	207	67	-071	B	d
1988	12 16	17 45	4.0	56.08	111.66	37	035	49	190	13	295	068	54	-020	171	74	-143	B	d
1989	05 13	03 35	5.8	50.17	105.34	12	162	66	046	22	256	031	82	-155	298	66	-006	A	g
1989	05 13	04 10	5.0	50.18	105.39	16	160	72	002	09	252	206	84	162	298	73	007	B	g
1989	07 03	08 00	4.5	53.91	110.32	04	153	12	244	77	044	229	42	-108	074	51	-074	C	d
1989	12 05	01 36	4.5	56.67	117.99	06	082	14	350	75	190	186	42	-069	338	52	-108	C	d
1990	05 20	13 42	4.6	53.07	108.02	10	136	26	230	63	027	197	42	-131	067	59	-060	A	d
1990	07 18	10 58	4.5	54.96	112.23	00	132	14	220	75	042	206	47	-111	054	46	-070	B	d
1990	10 11	10 13	4.5	54.79	111.57	03	319	21	228	69	055	210	51	-117	069	47	-061	A	d
1990	10 26	18 17	5.1	55.95	110.25	09	333	30	238	59	079	219	61	-125	094	44	-044	A	d

a MISHARINA (1972)
b MISHARINA *et al.* (1985)
c MISHARINA & MELNIKOVA *in* KHILKO *et al.* (1985)
d SOLONENKO & MELNIKOVA (1994)
e SOLONENKO & SOLONENKO (1987)
f determinations of SOLONENKO
g determinations of MELNIKOVA
h DOSER (1991a, 1991b)

pl: angle of dip of stress axes in foci (degree);
azm: azimuth of stress axes in foci (degree);
stk: azimuth of strike of the nodal plane (degree);
dp: angle of incidence of the nodal plane (degree);
slip: angle of slip of the nodal plane (degree).

Accuracy classes

A: P, B, T axes defined within 10°;
B: P, B, T axes defined within uncertainty > 10°;
C: one or more axes poorly defined.

The transition from the global stress field, with NE-SW subhorizontal P axes, to the rift stress field, with subvertical P axes is well expressed in the southeastern termination of Lake Baikal. In this area, both rift and global P axis orientations occur, indicating a change in T axes orientation from subhorizontal with a NE-SW direction to subvertical. This is explained by the spatial overlapping of the effects of the global NE-SW compression and the rift NW-SE extension. The first part of this paper shows that a special feature of the seismicity of the Baikal Rift Zone is the presence of seismic gaps or aseismic zones which are characterized by a strong deficiency in earthquakes both of low magnitude and also large shocks. These zones are located symmetrically with respect to the North Baikal symmetry axis.

These areas without large shocks are presumed to be places of very low stress where the compressive global field is neutralised by the tensional rift field.

5. — CONCLUSIONS

Recent rifting in the Baikal rift zone, as interpreted from the data for earthquake mechanisms, may be considered as resulting from the superimposition of the rift extensional regime over the global compressive regime, typical of the adjacent areas of Mongolia and Yakutia. At both rift terminations, interpenetration of both rift and global stress fields is indicated by the occurrence of earthquakes with different types of mechanisms. These areas are adjacent to zones of seismic quiescence which correspond to the transition from the global compressive stress field of Western Mongolia and Southern Yakutia, to the extensional rift stress field.

The distribution of earthquake focal mechanisms in the rift zone is characterised by a clear symmetry, explained by the combined influence of the regional stress field and the geometry of the inherited fault system.

It is believed that the global compressive stress may be produced by forces acting on plate boundaries, and, in particular, by a collision belt, which causes compression in a SW-NE direction and by the subduction zone of Kamchatka and Japan, possibly causing a NW-SE extension due to trench suction. The regional rift extension, produced by anomalous mantle and associated arched uplift, is thought to be superimposed on this global stress system.

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