BAIKAL RIFT BASEMENT : STRUCTURE AND TECTONIC EVOLUTION

RIFT DU BAÏKAL : STRUCTURE ET ÉVOLUTION TECTONIQUE DU SOCLE

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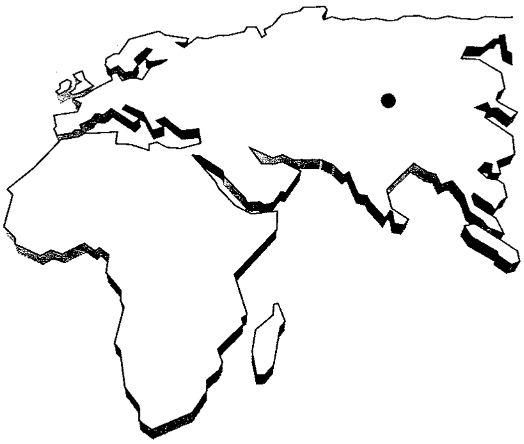

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Le système rift du Baïkal, en Sibérie orientale, possède une structure très hétérogène en raison de l'ancienneté de son histoire qui commence au Précambrien inférieur et se poursuit jusqu'au Cénozoïque. On distingue deux traits structuraux majeurs : le craton sibérien et le système orogénique Sayan-Baïkal, partie intégrante de la ceinture orogénique d'Asie centrale. Le craton sibérien est formé par les unités suivantes : les terrains métamorphiques du Précambrien inférieur, la couverture sédimentaire vendienne-paléozoïque sur laquelle les bassins paléozoïques et mézosoïques sont surimposés et une marge réactivée (suture) constituant la transition entre le craton et la ceinture orogénique. Le système orogénique Sayan-Baïkal est formé par l'assemblage des terranes Barguzin, Tuva-Mongol et Dzhida.

Les terranes du Barguzin et Tuva-Mongol sont composites; elle comportent des massifs du Précambrien inférieur, des terranes volcano-sédimentaires et carbonatées du Phanérozoïque avec des granites intrusifs; ce sont donc des super-terranes. Les unités les plus anciennes sont des ophiolites datées à environ 1,1 à 1,3 Ga. dans la terrane Barguzin et 0,9 à 1,1 Ga dans celle de Tuva-Mongol. Elles sont associées à des complexes d'arcs insulaires immatures, des prismes d'accrétion terrigènes et volcano-sédimentaires avec localement des fragments ophiolitiques et des schistes à glaucophane.

On distingue deux périodes majeures : le Précambrien inférieur comportant plusieurs phases de déformation et de métamorphisme avec diverses activités magmatiques et la période Riphéen-Phanérozoïque qui comprend :

a) l'ouverture du paléo-océan asiatique,

b) la formation au cours du Riphéen d'un système strucural péri-océanique tel que des arcs insulaires, des bassins d'arrière-arc ou inter-arc ainsi que des prismes d'accrétion,

c) au cours du Précambrien inférieur ces systèmes s'assemblent pour former les super-terranes Barguzin et Tuva-Mongol, tandis que se met en place un ensemble d'arcs insulaires qui deviendra la terrane de Dzhida,

d) la collision de ces trois terranes avec le craton sibérien au cours de Paléozoïque inférieur fut accompagnée par un métamorphisme intense et par la mise en place de l'ensemble batholitique Angara-Vitim,

e) une phase post-collision, marquée par une extension orogénique et continentale, pendant le Paléozoïque moyen, qui aura pour conséquence la mise à l'affleurement des « metamorphic core complexes »,

f) le développement d'une marge active continentale pendant le Paléozoïque supérieur.

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Mots-clefs :Tectonique socle, Terrane, Marge continentale active, Collision plaque, Antécambrien, Primaire, Rift Baïkal.

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ABSTRACT

The Baikal rift zone in East Siberia has, due to its very long history, starting in the Early Precambrian and continuing into the Cenozoic, a heterogeneous structure. Two major structural elements are distinguished : the Siberian craton and the Sayan-Baikal fold system, which is part of the Central Asian Fold Belt. Within the craton, the following units are recognized : the Early Precambrian metamorphic rocks of the basement, the Vendian-Paleozoic sedimentary cover with superimposed Paleozoic and Mesozoic basins and a reworked margin which is transitional between the craton and the fold belt.

The Sayan-Baikal fold system comprises the Barguzin, Tuva-Mongolian and Dzhida terranes.

The Barguzin and Tuva-Mongolian terranes are composite, consisting of separate Early Precambrian massifs, volcanic-sedimentary and carbonate Phanerozoic terranes, impregnated by granites. They are thus super-terranes.

The oldest units are ophiolites, dated around 1.1 - 1.3 Gy in the Barguzin terrane and 0.9 - 1.1 Gy in the Tuva-Mongolian terrane. They associate with complexes of immature island-arc accretionary wedges of mainly terrigenous or terrigeno-volcanic composition with occasional slices of ophiolite and glaucophane schists.

Two major periods are distinguished : the Early Precambrian period which comprises several phases of deformation and metamorphism with diverse magmatic activity, and the Riphean-Phanerozoic period which includes :

a) the opening of the paleo-Asian ocean,

b) the formation, during the Riphean, of peri-oceanic structural systems such as island arcs, fore-arc and inter-arc basins and accretionary wedges,

c) the amalgamation of these systems, during the Late Precambrian, to form the Barguzin and Tuva-Mongolian super-terranes. At the same time, a system of island arcs was formed which became the Dzhida terrane,

d) the collision of all three terranes with the Siberian craton, in the Early Paleozoic, with accompanying high-grade metamorphism and the formation of the huge Angara-Vitim batholith,

e) a post-collision phase, marked by orogenesis and continental extension which, in the Middle Paleozoic, resulted in the tectonic exposure of the metamorphic core complexes, and

f) the development of an active continental margin during the Late Paleozoic.

Key words : Basement tectonics, Terrane, Active margins, Plate Collision, Precambrian, Paleozoic, Baikal rift zone.

CONTENTS

INTRODUCTION

The geological setting of the southern part of South East Siberia, where the Cenozoic (*Editor's note : Logatchev (1993) argues that the subsidence of the Lake Baikal basin could have started in the Late Cretaceous.*) Baikal Rift zone (Logatchev, 1993) is located (Fig. 1), is very complicated. The territory includes the Siberian platform, one of the largest ancient platforms on Earth, and the essentially Paleozoic or Caledonide Sayan-Baikal fold system which is the north-eastern segment of the Central Asian Fold Belt (Fig. 2). Both are composed of structural complexes which range in age from the Early Precambrian to the Cenozoic. Intensive multiphase deformation, polymetamorphism, (in the Precambrian and Paleozoic) and a long-lived magmatic history have resulted in a heterogeneous structural assemblage in which the primary boundaries between the complexes are seldom preserved. Consequently, the interpretation of this region is still a matter for intense debate.

During the last decades the range of problems studied has increased considerably. This paper covers recent reassessments of regional stratigraphy, correlation between the complexes, the tectonic-metamorphic evolution, (including the petrologic characteristics and P-T conditions), and, where possible, isotopic geochronology which helps to establish the origin of the crust in the earliest stages of the earth's history.

Concepts on the Precambrian and Phanerozoic structural development are revised in the light of recent tectonics hypotheses.

When studying the evolution of the Precambrian platform part of the Baikal rift basement, one of the main problems is reconstructing its paleogeodynamic setting. Numerous regional and detailed investigations have been carried out on the substratum of the platform, made up of ancient complexes (Sharyzhalgay, Aldan, etc.). Many of these studies have been carried out within the framework of multidisciplinary projects such as the International Lithosphere Program, and IGPC among others. This paper is a review of the most recent results.

FIGURE 1
Location map of Lake Baikal.

Among the many question marks remaining on the geology and tectonics of the Sayan-Baikal Fold Belt, the most important concerns the age and structural setting of some of the granulite complexes (Slyudyanka see § 3.1.3., and Olkhon, etc.). The age and origin of the strongly metamorphosed rocks in the Barguzin super-terrane remain the subject of discussion, unlike the unambiguous cases of the Precambrian granulites of the Siberian Platform basement and of paleomicrocontinents such as those in the Tuva-Mongolian and Barguzin super-terranes. In most cases, the available isotopic ages, though scarce, only indicate a Paleozoic age for the metamorphism but these ages often contradict the geological data. Nevertheless, many researchers, including geochronologists, believe that these very high grade complexes probably originated in the Early Precambrian.

The tectonic structure of the fold belt is characterized by a zonation which is controlled by the geometry of the margin of the platform with formations which become younger with distance from the platform and are affected by multiphase zonal metamorphism. However, this simple pattern is modified by a number of major block-bounding faults.

1. — MAJOR STRUCTURAL ELEMENTS OF THE BAIKAL RIFT BASEMENT

The Baikal rift zone was formed at the junction of the ancient Siberian platform and the Sayan-Baikal Fold Belt and these major tectonic domains and the suture zone between them constitute the pre-rift basement (Fig. 2).

A

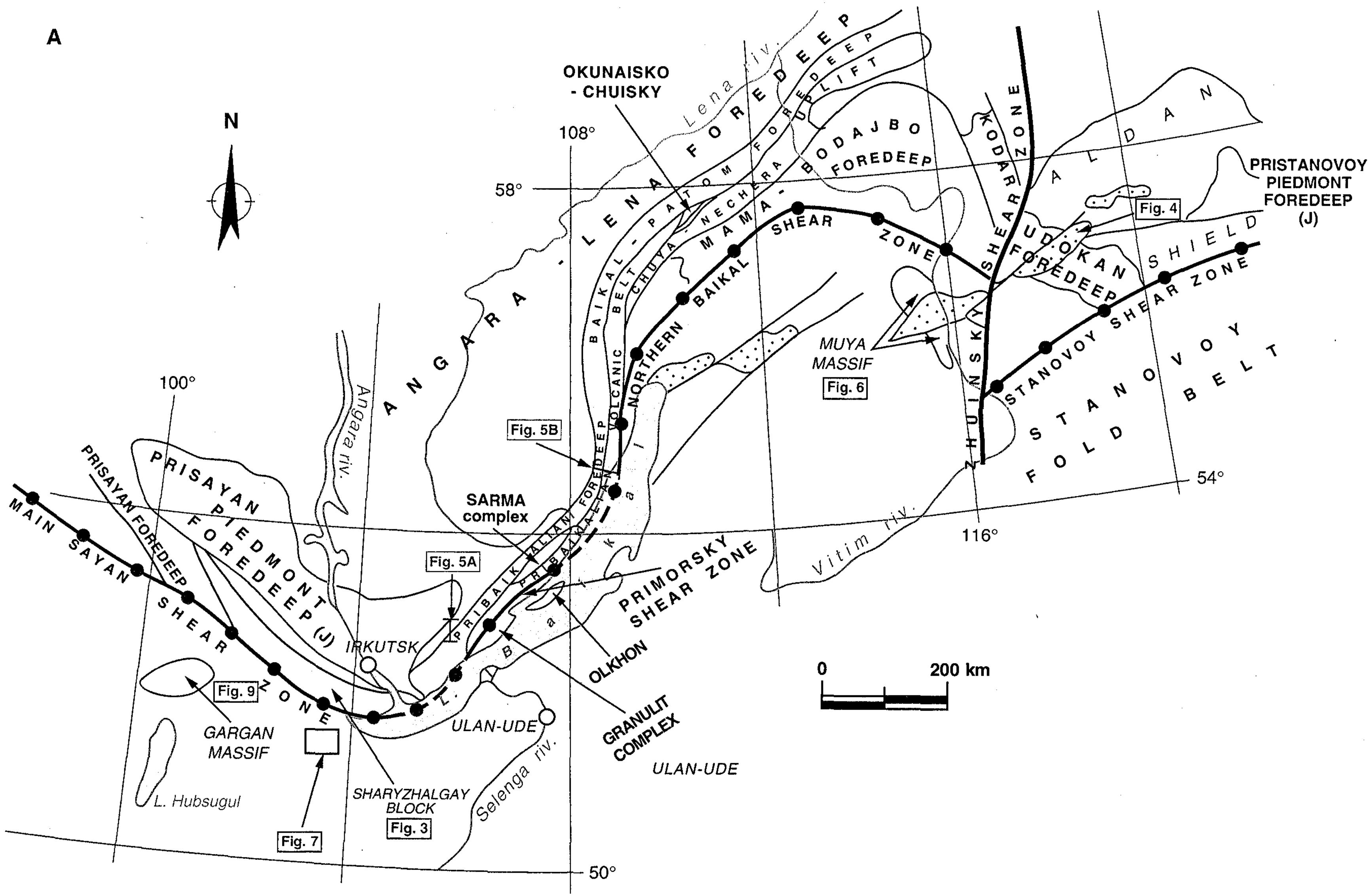
N
OKUNAISKO
- CHUISKY
108°
58°
100°
54°
116°
50°
Lena riv.
ANGARA - LENA FOREDEEP
BAIKAL - PATOM FOREDEEP
BAIKAL - PATOM UPLIFT
CHUYA - NECHERA FOREDEEP
BELT - VOLCANIC
MAMA - BODAJBO FOREDEEP
NORTHERN BAIKAL SHEAR ZONE
KODAR SHEAR ZONE
ALDAN
ALDAN SHIELD
PRISTANOVOY
PIEDMONT
FOREDEEP
(J)
Fig. 4
UDOKAN FOREDEEP
ZHUINSKY SHEAR ZONE
STANOVOY SHEAR ZONE
STANOVOY FOLD BELT
MUYA
MASSIF
Fig. 6
Vitim riv.
Angara riv.
Fig. 5B
SARMA
complex
PRIBAIKALIAN FOREDEEP
PRISAYAN PIEDMONT FOREDEEP (J)
PRISAYAN FOREDEEP
MAIN SAYAN SHEAR ZONE
Fig. 5A
IRKUTSK
L. Baikal
PRIMORSKY SHEAR ZONE
OLKHON
GRANULIT
COMPLEX
0
200 km
Fig. 9
GARGAN
MASSIF
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Fig. 7
SHARYZHALGAY
BLOCK
Fig. 3
ULAN-UDE
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ULAN-UDE

B

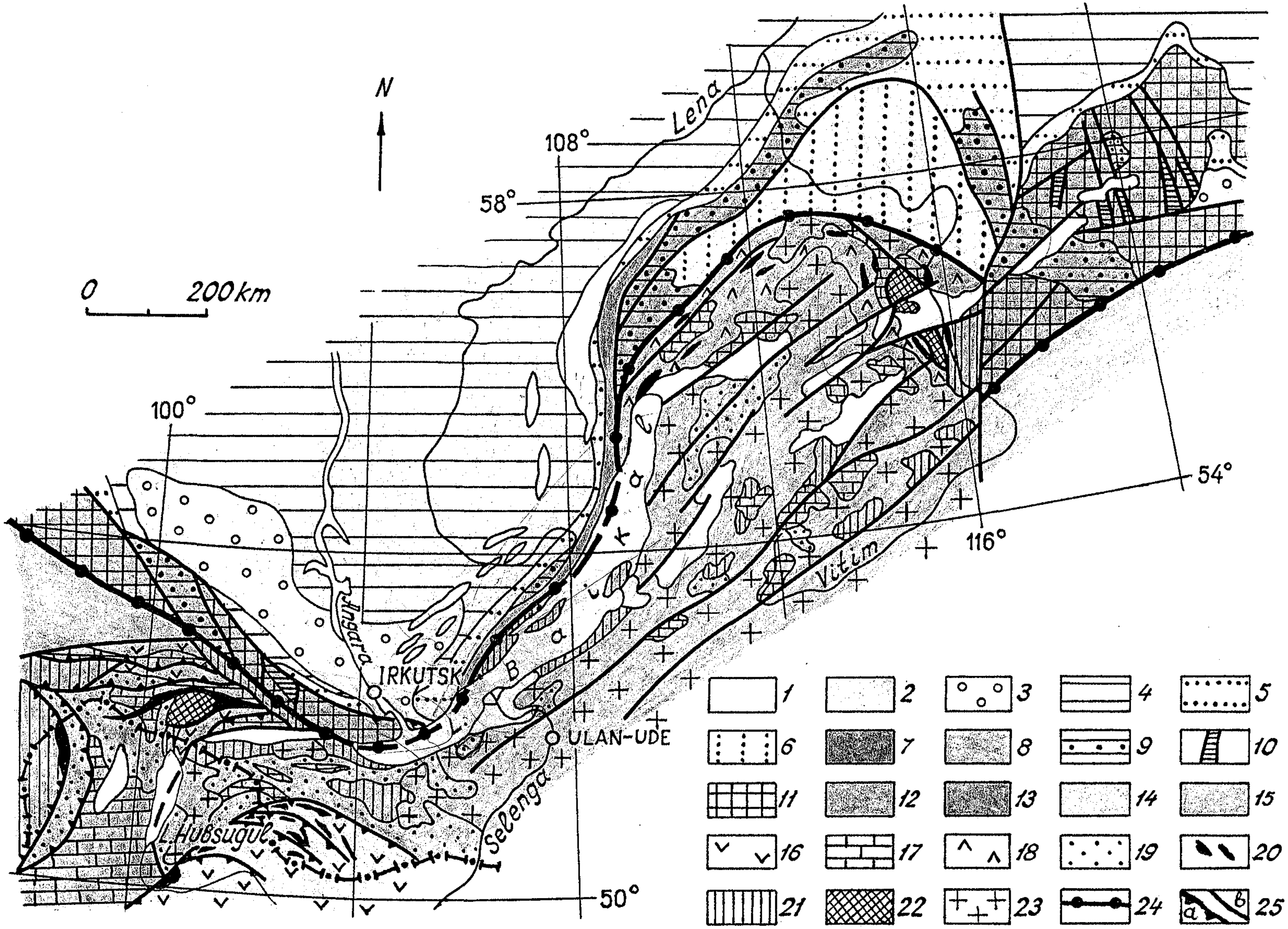

FIGURE 2 : The Baikal rift basement.
A : Geographical location of main structures of the Baikal rift basement.
B : Reconstruction of the Pre-Mesozoic basement of the East Siberian Rift System. SIBERIAN PLATFORM : 1 : Cenozoic sediments of rifts and piedmont basins; 2 : Riphean-Phanerozoic sedimentary cover; 3 : Mesozoic sediments; 4 : Paleozoic sediments; 5 : Riphean sediments of Pribaikalian and Baikal-Patom foredeeps; 6 : Riphean sediments of Mama-Bodajbo foredeep; 7 : Pribaikalian volcano-plutonic belt; 8 : Early Precambrian platform basement; 9 : Early Proterozoic foredeeps; 10 : Late-Middle Archean greenstone belts; 11 : Early Archean granulite-grey gneiss basement. SAYAN-BAIKAL FOLD BELT : 12 : Barguzin super-terrane; 13 : Tuva-Mongolian super-terrane; 14 : Dzhida terrane; 15 : East Sayan and Stanovoy super-terranes; 16 : Cambrian-Silurian island arc complexes; 17 : Vendian-Cambrian shelf formations; 18 : Riphean volcanic-plutonic island-arc complexes; 19 : Riphean and Vendian-Cambrian ophiolites; 20 : Early Precambrian relicts; 21 : Baikalian metamorphic massifs; 22 : Early Precambrian rocks – Gargan and Muya blocks; 23 : Riphean-Paleozoic granitoids (main areas); 24 : Marginal suture of the Siberian platform; 25 : thrust (a) and other faults (b).

Marginal Suture Zone : the Siberian platform is sutured with the fold belt (ZAMARAEV, 1967) by a major system of large ancient strike-slip faults which have been subjected to multiphase reactivation. The marginal suture has three segments each with differing orientations. The first segment, made up of the Main Sayan and Primorsky shear zones, borders the southern edge of the platform. The second forms the Baikal-Patom arc and consists of the Northern Baikal and Zhuinsky shear zones. The third, bordering the south-western termination of the Aldan shield, is the Stanovoy shear zone. The orientation of the marginal suture controls the orientation of the linear folding in the adjacent parts of the platform and in the fold belt. Similarly the suture influences the trends of the marginal sedimentary basins superimposed on the platform and also that of adjacent volcano-plutonic belts which are of varying age and style. It should be emphasised that the marginal suture is, in fact, a wide zone which is characterized by :

• obvious structural discordance with both the internal structure of the platform and that of the fold belt,
• the common occurrence of dynamo-metamorphic effects,
• abrupt changes in lithofacies, and
• faults with large vertical and horizontal throws.

The marginal suture represents an abrupt boundary between two completely different lithosphere units (ZAMARAEV, 1967; ZAMARAEV *et al.*, 1979).

The Early Precambrian crystalline basement of the Siberian platform is mainly composed of highly metamorphosed and intensely deformed complexes. Much of the basement is hidden under Phanerozoic sediments. The basement rocks are well exposed only at the margins in the Sharyzhalgay block, on the western side of Lake Baikal, and on the Aldan shield (Fig. 2). The internal structure of the platform is heterogeneous. At the edge of the craton, large foredeeps were formed in the Early Proterozoic and filled with terrigeno-volcanic rocks – the Sarma, the Okunaisko-Chuisky and the Kodar-Udokan foredeeps (Fig. 2). The platform's larger marginal depressions – Prisayan and Baikal-Patom – were formed in the Middle and Late Proterozoic. The sedimentary sequences thicken markedly towards the suture to a maximum of several thousand metres (ZAMARAEV *et al.*, 1975).

In the southern part of the Siberian platform, Early Paleozoic structures – represented by the Prisayan and Angara-Lena foredeeps – are structurally superimposed on the Late Proterozoic marginal depressions. The foredeeps, initiated in the Vendian, developed a sediment thickness of about 5 000 m, including up to 2 000 m of evaporates, and ended in the Silurian. The sedimentary rocks of the Precambrian marginal depressions and the Paleozoic foredeeps are linearly folded with fold trains up to 300 km long whose trend parallels that of the marginal suture. After the Silurian, foredeeps only developed locally on the southern part of the Siberian platform. The Prisayan and Pristanovoy foredeeps were filled with coal-bearing molasses during the Jurassic (Fig. 2).

The Sayan-Baikal Fold Belt borders the southern wedge of the Siberian platform (Fig. 2). It is a segment of the Central Asian Fold Belt and has a very complicated structure. It comprises a set of terranes of different age, which differ both in metamorphism and deformation and which are set in large granitoid massifs of varying composition and age. Early Precambrian blocks within the belt are now considered to be fragments of the basement of paleomicrocontinents which are compatible in age with the crystalline basement of the Siberian platform (BELICHENKO *et al.*, 1990).

The central part of the Cenozoic Baikal rift zone in East Siberia, namely the Lake Baikal basin, coincides with the Primorsky segment of the marginal suture. The flanks of the rift zone deviate from the general strike of the suture but often follow the ancient structural discontinuities. For example, the south-western flank coincides with the south-eastern boundary of the Tuva-Mongolian paleomicrocontinent which is a Paleozoic collision zone. The ages of these discontinuities have not yet been reliably established and thus remain subject to discussion. The lack of reliable geochronological data leads to various and often contradictory views on the origin and evolution of the Sayan-Baikal Fold Belt.

2. — SIBERIAN PLATFORM

In the region of the East Siberian rift system, the Siberian platform is represented by a system of marginal structures which formed at different stages of tectonic evolution. The system includes the Sharyzhalgay wedge and the Aldan shield, the Pribaikalian and Kodar-Udokan foredeeps, the Pribaikalian marginal volcano-plutonic belt, the Baikal-Patom marginal depression, the Angara-Lena foredeep, and the Prisayan piedmont foredeep (Fig. 2).

2.1. PRECAMBRIAN BASEMENT

The most ancient complexes of the Siberian platform basement are exposed on both flanks of the Baikal rift zone, within the Sharyzhalgay block and in the western part of the Aldan shield (Fig. 3 and 4).

2.1.1. Early Archean and Proterozoic marginal blocks

The Sharyzhalgay block in the south-western Pribaikalye extends 300 km north-westwards from the Angara river outlet at the western end of Lake Baikal (Fig. 2 and 3). To the north-east, the block is either transgressively overlain by the Paleozoic or Upper Proterozoic sediments of the platform cover or it overthrusts onto these sediments. Its south-eastern boundary is the Main Sayan fault of the marginal suture separating the Siberian platform from the adjacent terranes of the fold belt. The block is generally subdivided into four large domains, which are separated by sub N-S trending faults in the marginal suture system. The blocks differ in lithology, structural style and intensity of deformation (GRABKIN & MELNIKOV, 1980).

Generally, the Early Precambrian block is composed of mafic crystalline schists – amphibolites, gneisses of varying composition, granitoids and locally ultrabasic rocks with minor highly aluminous and ferruginous rocks and slices of carbonates. All are metamorphosed in either granulite or amphibolite facies. The nature of metamorphic processes of this complex is still a matter for debate (KRYLOV & SHAFEEV, 1969; KUZNETSOVA, 1981; PETROVA & LEVITSKY, 1984). The best preserved granulite assemblages are found in the south-

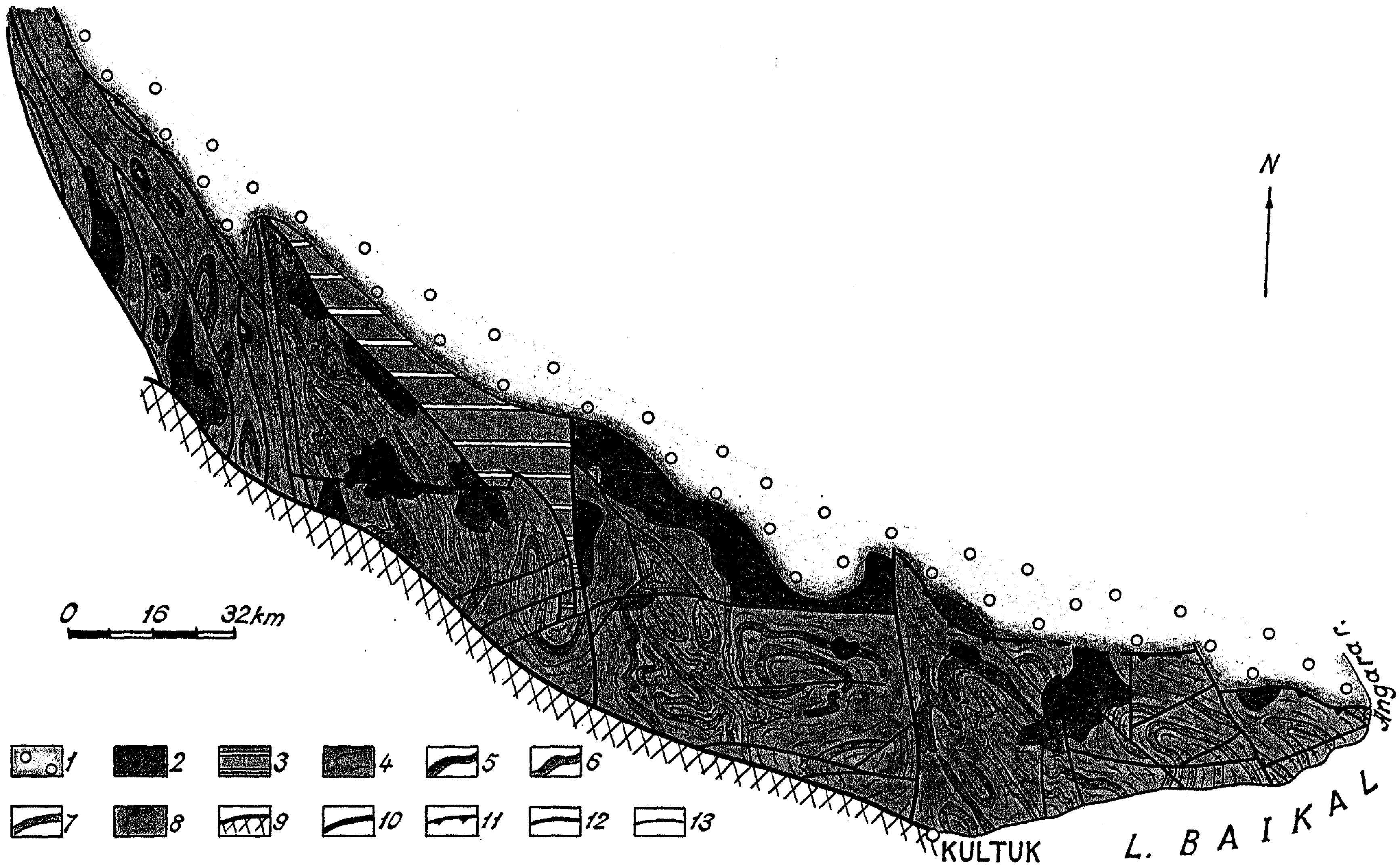

FIGURE 3

Geological map of the Sharyzhalgay block (for location map, see Fig 2 A).

1 : platform cover; 2 : Late Proterozoic rocks of near-fault grabens; 3 : Late Archean Onot greenstone belt; 4 : Early Archean rocks of the Sharyzhalgay complex with; 5 : crystalline schists and amphibolites; 6 : garnet-bearing gneisses; 7 : carbonate rocks; 8 : Sayan-complex granitoids; 9 : main Sayan fault; 10 : large interplate faults; 11 : thrust faults; 12 : undifferentiated faults; 13 : geological boundaries.

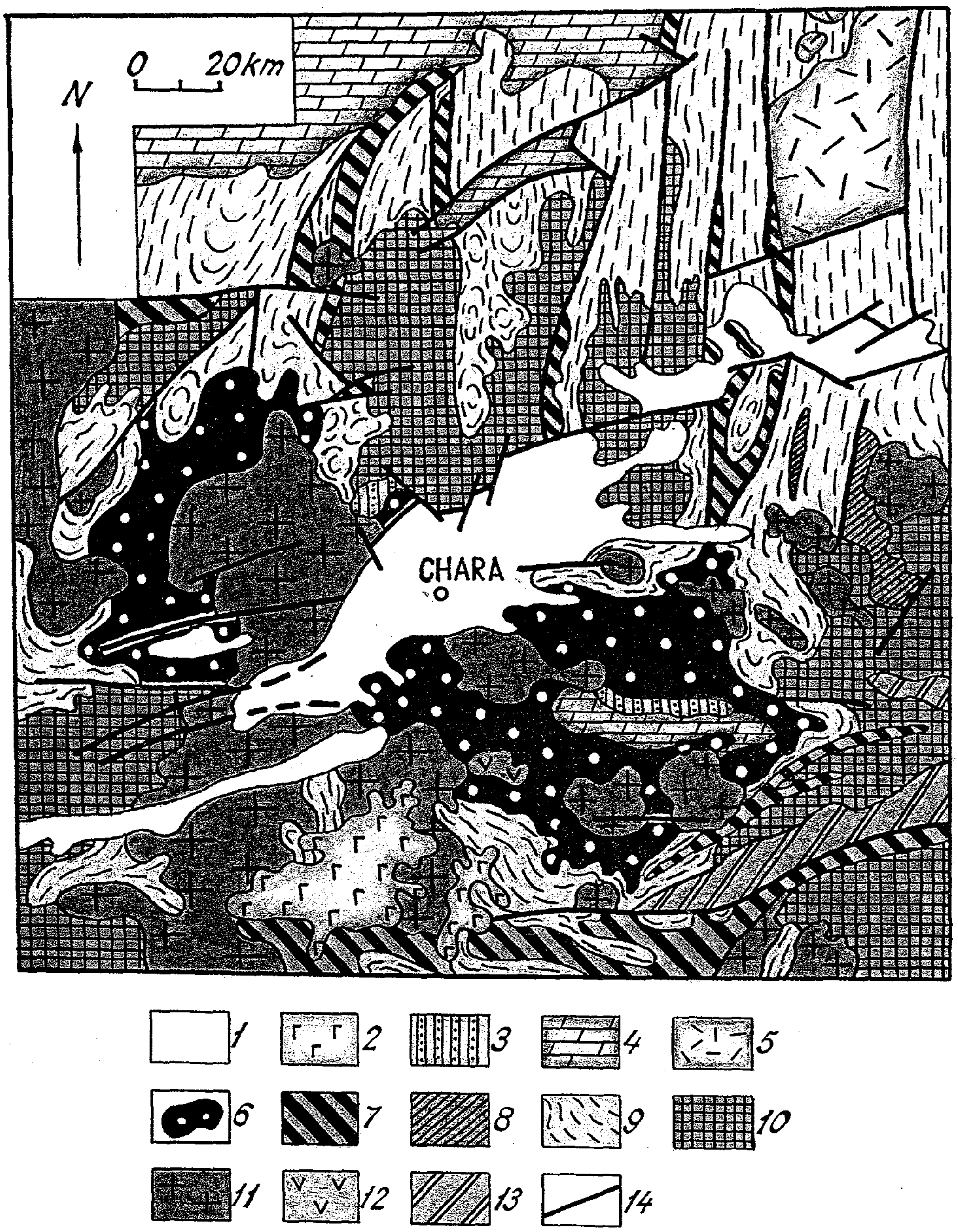

FIGURE 4
Geological map of the central part of the Chara-Olyekma granite-greenstone system (for location map, see Fig 2A) (including data from FEDEROVSKY, 1985).
1 : Cenozoic sediments of rift basins; 2 : Cenozoic basalts; 3 : Mesozoic coal-bearing sediments; 4 : Paleozoic platform cover; 5 : Late Proterozoic sediments of near-fault graben; 6 : Early Proterozoic Udokan complex; 7 : Late Archean Olondo complex; 8 : Middle Archean Borsalinsky complex; 9 : Early Archean granulite-grey gneiss Olyekma complex; 10 : Early Archean granulite-grey gneiss Kurulta complex; 11 : Paleozoic-Proterozoic granitoids; 12 : Early Proterozoic basites and ultrabasites; 13 : Archean anorthosites; 14 : faults.

eastern near-rift part of the wedge. To the north-west they are rarely found and, when exposed, occur as relicts (in gneisses, amphibolites and migmatites), all of which are in amphibolite facies. The intensity of the internal linearization by lateral shear processes also increases from south-east to north-west. There is a concomitant partial to complete disappearance of fold forms (KRYLOV & SHAFEEV, 1969; GRABKIN & MELNIKOV, 1980).

Detailed structural and petrological studies show that the granulites are the most ancient of the complex. They contain no relicts and were the substrate for later transformation (KRYLOV & SHAFEEV, 1969; GRABKIN & MELNIKOV, 1980; PETROVA & LEVITSKY, 1984). They are composed of basic crystalline schists, various types of gneisses and quartzite, some ferruginous. Marbles and calc-silicate rocks are also common. These rocks form small isolated interbedded layers or lenticular bodies embedded within large masses of migmatites and granitoids. For further details, their petrology, mineralogy and geochemistry is comprehensively discussed in PETROVA & LEVITSKY (1984). Estimations of the P-T conditions suggest that all these rocks originated under a wide range of temperatures from 670 to 800°C, and pressures from 5.5 to 7.5 Kbar (SHAFEEV, 1973; PETROVA & LEVITSKY, 1984; KURDYUKOV, 1987).

Early Proterozoic ultra metamorphism and pervasive anatexis transformed 80 % of the massifs to a complex assemblage of migmatites, granitoids and skarns which show both concordant and cross-cutting contacts with the relict granulites (KRYLOV & SHAFEEV, 1969; GRABKIN & MELNIKOV, 1980). The extreme migmatites or nebulites are in close association with various granitoid rocks : enderbites (*Editor's note : enderbites are granodioritic charnockites (TILLEY, 1936). – Enderbite, a new member of the Charnockite series* : Geol. Mag. **73**, *312-316.*) and charnockites. Leucocratic-biotite granites and alaskite-type granites (*Editor's note : alaskite is an alkali granite with a high feldspar content (K-feldspar 90-100 %, Plagioclase 0-10 %), some quartz and very few mafic minerals.*) as well as occasional pyroxene and amphibole granite-syenites and syenites are also encountered. Estimations of the P-T conditions suggest that all these rocks originated under a wide range of temperatures which decreased gradually from 810 to 615°C, whereas the pressure remained at about 7 Kbar (PETROVA & LEVITSKY, 1984).

Of the intrusive rocks, the most ancient comprise metamorphosed mafic and ultramafic rocks of the **Elovsky complex**, which make up a number of small massifs in the southern part of the block. Based on Rb-Sr dating, they are 2510 ± 100 My old (BRANDT *et al.*, 1987). In addition, the Sharyzhalgay block is intruded by a series of coarse to medium-grained granites forming the **Sayan complex** dated at 1700-2000 My, which, in turn, are cut by tholeite dykes – 530 My, and by alkali basalt dykes – 331 and 296 My (K-Ar method : ESKIN *et al.*, 1988).

Three age-sets can be arbitrarily distinguished, which correspond to three main rock groups and are dated at older than 3000 My, 2900 to 2400 My, and 2000 to 1700 My. The first group, older than 3000 My, includes two-pyroxene-hornblende schists (without paragene zircon) and granulite-facies pyroxene gneisses (Rb-Sr whole rock method : MELNIKOV, 1991; MEKHANOSHIN *et al.*, 1987). The second group, dated at between 2900 and 2400 My, comprises marbles, ferruginous quartzites, peraluminous gneisses, meta-ultrabasites and granitoids – including enderbites and charnockites (Rb-Sr whole rock method : MEKHANOSHIN *et al.*, 1987; U-Pb zircon, Pb-Pb, Rb-Sr, Sm-Nd methods : AFTALION *et al.*, 1991). The third group, 2000 to 1700 My, is composed of granite gneisses, migmatites, granites (some pegmatoid) of the Sayan complex (MEKHANOSHIN *et al.*, 1987; AFTALION *et al.*, 1991).

The ages for the last two groups are relatively well constrained. The Sm-Nd and U-Pb methods do not provide good evidence for rocks older than 3000 My. However, as the samples have model ages greater than 2500 My, and corresponding epsilon values for 2500 My which vary from + 1.6 to + 4.6, there are possible grounds to believe that the age interval of 2.4 – 2.9 Gy corresponds to an important episode of crust growth (MELNIKOV, 1991).

As the result of multiphase folding and faulting, a complicated fold structure developed in the Sharyzhalgay block which consists of granite-gneiss domes, brachyforms (*Editor's note : a brachyform is an antiform whose length is short in comparison with its width; partially synonymous with pericline (International Tectonic Dictionary,* 1967, AAPG, **Mem.** 7)) and linear folds which in turn are cut by numerous faults (Fig. 2) (GRABKIN & MELNIKOV, 1980, MELNIKOV, 1989; HOPGOOD & BOWES, 1990). Small isoclinal folds, associated with intensive metamorphic segregation, are thought to represent the oldest identifiable structures. The domes are slightly elongated in a NW-SE direction and the largest have a half wavelength of 3-5 km. They verge to the north-east with numerous parasitic domes with a half wavelength of up to 500 m. Their limbs and the tight interdome synforms are strongly deformed. Genetically related minor folds show intense vergation, rapid plunge variations and also considerable thickening of the hinge zone. These non-linear folds are locally transformed by intense pure shear to a strong NNW trending linear fabric and shear zones, steeply dipping to the west. The latter are mylonitised and brecciated in association with reverse and thrust faults.

The Aldan shield (Fig. 2 and 4) is the most extensive outcropping area of the Siberian platform basement. It is about 1200 km long and between 270-350 km wide. To the south, it is separated from the Stanovoy Fold Belt by the Stanovoy shear zone system. To the north and east, the basement dips at a low angle beneath the Vendian-Paleozoic sedimentary cover. Recent tectonic maps show the Aldan shield divided into three major blocks bound by deep-seated faults. The central block is the Aldan crystalline massif which is an Early Archean nucleus. To the west and east are the Late Archean Chara-Olyekma and Batomga granite-greenschist fold systems respectively (RUNDKVIST & MITROFANOV, 1988).

The Baikal rift zone in East Siberia terminates to the east in the **Chara-Olyekma system** (Fig. 4).

Five Early Archean and Proterozoic complexes are distinguished based on differences in lithology, structural development, metamorphic processes and isotopic ages.

The **Olyekma complex** which makes up the largest part of the western Aldan shield, consists essentially of amphibolite, amphibole plagiogneiss with subordinate quartz-rich gneiss, and garnet-bearing gneiss with occasional lenses of ferruginous quartzites in association with biotite gneisses. With P-T conditions estimated at T = 650 – 700°C and P = 5 - 6 Kbar, the metamorphic grade corresponds to the high temperature sub-facies of the cummingtonite-amphibolite facies (MITROFANOV, 1987). The age for mafic relicts is fixed at around 3490 ± 70 My (Sm-Nd isochrone method : ZHURAVLEV *et al.*, 1987).

The Olyekma complex includes blocks of granulite-facies rocks which are ascribed to the **Kurulta complex** (MIRONYUK *et al.*, 1971; MITROFANOV, 1987). These are only exposed along the large fault zones which cut the granite-schists. The contacts with the Olyekma complex are either clearly tectonic or are hidden by superimposed metamorphism. The Kurulta rocks are predominantly pyroxene schists and gneisses (meta-gabbroids and meta-ultrabasites) intercalated with garnet gneisses, lenses of quartzites and calc-silicate rocks and igneous rocks. These are syn-kinematic granitoids such as charnockites, enderbites and garnet-bearing granites. The initial sedimentary and igneous rocks have been subjected to regional metamorphism and ultra-metamorphism under granulite facies. The average temperature was about 800°C, and the pressure was 7 Kbar. The isotopic age of the Kurulta complex is 3 540 ± 370 My (Sm-Nd : SHURKIN *et al.*, 1990). The fold structure of the Kurulta and Olyekma complexes is generally the same as that of the Sharyzhalgay complex. There are several generations of ancient, mainly isoclinal, flow folds and numerous isometric granite-gneiss and migmatite domes which have been modified by subsequent shearing (PETROV, 1976; ZAMAREV *et al.*, 1983).

The complexes described above are coeval with the granulites of the Aldan massif dated at 3 570 ± 60 My (U-Pb zircon method : MOROZOVA *et al.*, 1989). They appear to be relicts of the Aldan granulite-grey gneiss which was once widely developed and formed the Early Archean basement of the Chara-Olyekma granite-greenstone belt.

The Early Archean structures in the granulite-grey gneiss basement are traversed by sub-north-south linear granite-greenstone belts which mark an abrupt change in the tectonic evolution of the Aldan region (ZAMAREV *et al.*, 1983; FEDOROVSKY, 1985; GLUKHOVSKY, 1990).

The oldest unit is the terrigeno-volcanogenic **Borsalinsky greenstone complex.** It consists of highly ferruginous amphibolites, quartz-rich gneisses, aluminous schists, ferruginous quartzites, plagiogneisses and blastomylonites. Some sequences contain carbonate rocks.

The regional metamorphic grade is not uniform and ranges from epidote-chlorite to high-temperature amphibolite facies. The average temperature is 675°C, whilst the pressure is 4-5 kbar. (MITROFANOV, 1987). The Sm-Nd date of komatiites (*Editor's note : komatiites are ultrabasic rocks with MgO content of between 18 % and 31 %. Most were emplaced in the Archean. They display pillow-like structures, brecciated flow top spherulites, vesicles and variolites. They have a very high melting temperature which is difficult to generate in normal magmatic processes. GREEN (1977) suggests that such high temperatures could be generated by meteor impact (GREEN, 1977). – Archean greenstone belts may include terrestrial equivalents of lunar maria. –* In : *MCCALL, G.J.H. (ed.) : The Archean. Dowden, Hutchinson & Ross, Stroudsburg, 47-54.*), which occur structurally low in the section is 3 507 ± 123 My. Granitoids which intruded the complex and are now granito gneiss domes, are dated at about 3 150 My (RUDNIK, 1989).

The structure of the Borsalinsky greenstone complex is typified by narrow, tight synforms the flanks of which either show refolding in minor folds or one of the limbs may be sheared out leaving a steeply-dipping monocline in a series of cataclized tectonic lenses.

The Late Archean **Olondo greenstone complex** comprises younger granite-greenstone units which inherited the structure of the ancient belts. A key cross-section of the complex is exposed south of the Tokko rift basin (Fig. 2 and 4). Two metasedimentary-volcanogenic sequences are separated by a stratigraphic discontinuity (GOLOVKOV & KRIVENKO, 1990). The base of each sequence is made up of a thick unit of metasedimentary rocks followed by metavolcanic rocks – komatiitic and tholeitic at the base followed by a calc-alkaline, shoshonitic and tholeiitic series. All are under greenschist to amphibolite metamorphic facies (representing an average temperature of 500-600°C and a pressure range of 3.5-5.4 Kbar). The volcanogenic greenschists have been dated at 2 970 ± 20My (Sm-Nd method : ZHURAVLEV *et al.*, 1989) and granitoids from the granite-gneiss domes in the Olondo complex at 2 820 ± 20 My (U-Pb method : BIBIKOVA, 1989). The structure of the Olondo complex is a tight strongly deformed north-south trending syncline with steeply dipping limbs which, to the north, splits into two branches. These northern branches are complicated by minor folding and faulting.

The Early Proterozoic **Udokan complex** comprises the large Kodaro-Udokan foredeep in the south-western Chara-Olyekma system in a series of graben – synclinales (Fig. 2 and 4). The lower units are mainly greywacke sandstones, reworked by contemporaneous volcanics, interbedded with meta-argillites, siltstones and schists. The upper units are mainly arkose grading up to impure carbonates and copper-bearing meta-sediments. These are rich in copper and form the ore of the largest Udokan copper deposit. Most of the complex is metamorphosed to greenschist/amphibolite facies whereas most of the central part is in chlorite-sericite sub-facies. The metamorphic grade is highest close to the contact with the remobilized basement (MITROFANOV, 1987). The structural style varies with level. The structurally lower units display isometric brachy-folds of variable size with multi-phase minor linear folds, whereas the upper units are typified by brachy synclines.

After the Udokan complex was formed, wide areas experienced intense magmatism, with various granitoids and granites (both anatectic and metasomatic) predominating. These bodies are associated with reactivation of the basement and the emplacement of granite-gneiss domes (ZAMARAEV *et al.*, 1983; FEDOROVSKY, 1985; GLUKHOVSKY, 1990). The largest granite massif is the lopolith-shaped Kodar-Kemen massif which occupies the central part of the foredeep.

In western Pribaikalye, Early Proterozoic rocks of a terrigeno-volcanic association (known as the **Sarma complex**) occur in small and often isolated bodies along the edge of the Siberian platform from the Olkhon region in Central Baikal to the northern end of Lake Baikal. They make up a deep and narrow near-suture foredeep (ZAMARAEV *et al.*, 1975). The lower part of the Sarma complex is composed of schists, quartzites and metavolcanics of acidic and basic composition. The upper part is mainly various meta-volcanics, tuffs and schists. All are regionally metamorphosed to greenschist facies. The complex has locally suffered dynamo metamorphism in linear zones sub-parallel to the Primorsky shear zone and to the marginal suture of the Siberian platform (ZAMARAEV *et al.*, 1983).

At the northern end of the Lake Baikal basin lies the highly metamorphosed and migmatized **Ukuchikta complex** of biotite and amphibolite-biotite plagiogneisses and gneisses and rare amphibolites and biotite-cordierite-sillimanite schists. Relict granulites and gneisses are preserved in the migmatites. The early granulites show retrogressive metamorphism at medium pressures down to amphibolite facies with andalusite-sillimanite assemblage (MAZUKABZOV & SIZYKH, 1988). This later metamorphism has almost completely obliterated the earlier structures, with isoclinal 'flow' folds being rarely found. It is associated with the development of granite-gneiss domes and swells and with several phases of minor folds. No reliable isotopic ages have so far been obtained for this complex. However, analogy with similar assemblages elsewhere in the Siberian platform basement suggests a Late Archean age (MAZUKABZOV & SIZYKH, 1988).

2.1.2. Middle Proterozoic Pribaikalian volcano-plutonic belt

The Middle Proterozoic of the wide Pribaikalian (Akitkan ridge) belt is volcanic molasse and associated intrusive complexes (Fig. 2). It overlies the older rocks with manifest structural and metamorphic unconformity (SALOP, 1964; BUKHAROV, 1987; FEDOROVSKY, 1985) and is itself discordantly overlain by a Riphean complex. In the Akitkan and Baikal ridges, they constitute the sedimentary-volcanic Akitkan series and granitoids of the **Irel complex** and in the Primorsky ridge, they are represented by rapakivi-like granites of the **Primorsky complex.**

The structure of the Pribaikalian volcano-plutonic belt changes along the strike. In the Akitkan ridge, the **Akitkan series** is a 4 km thick sequence of trachyandesite and trachi-liparite volcanic rocks with tuffs, arkose sandstones and siltstones. This series is intruded by granite-syenites and granodiorite porphyries of the Irel complex. Both are overlain by a 3.5 km thick sequence of variable polymictic and arkose sandstones with occasional conglomerates, shales and acidic volcanics. In the Baikalsky ridge, the lower unit (equivalent to the Akitkan series) is up to 3 km of variable polymictic sandstones, conglomerates, quartz-porphyries and associated tuffs. These are overlain by 2 km of acidic volcanic rocks and associated tuffs with rare sandstones. The isochrone ages of Akitkan volcanic rocks range from 1 700 ± 35 My to 1 620 ± 40 My (Rb-Sr method : SHURKIN, 1980). Similarly, the granitoids of the Irel complex could be co-magmatic being dated at 1 700 ± 100 My (BRANDT *et al.*, 1978), whereas their U-Pb isochrone age is inferred to be 1 860 ± 30 My (NEIMARK *et al.*, 1990). The rapakivi-like granites of the Primorsky complex give a Rb-Sr date of 1 690 ± 40 My (BRANDT *et al.*, 1987).

In the Baikalsky ridge, the Pribaikalian volcano-plutonic belt rocks are almost unmetamorphosed, as are those on the western slope of the Akitkan ridge. However, close to the axis of the Baikalsky ridge and further eastwards, the metamorphic grade reaches epidote-amphibolite facies. Similarly, the granitoids of the Primorsky complex close to the Primorsky fault zone have a well-developed schistosity.

The Pribaikalian belt, and particularly the volcano-sedimentary Akitkan series, display the structure of a typical fold and thrust belt (ALEXANDROV, 1990). It developed along the south east margin of the Siberian craton with a NE-SW trend. Several imbricated thrust sheets were emplaced with 10-12 km throw to the north west. Locally, the thrust sheets are folded with NW vergence. They are also affected by high-angle reverse faults parallel to the general trend, and by cross-cutting strike-slip faults (DELVAUX *et al.*, 1993).

In the north-eastern area, in the Vitim river and Patom river basins, the porphyrito-granitoids of the Chuya complex are probably the continuation of the Pribaikalian volcano-plutonic belt. They are similar to the granitoids of the Irel complex (see above), both in their petrological characteristics and their structural position (BUKHAROV, 1987). These granitoid massifs are considerably elongated parallel to the structural trend of the host rocks; oval shaped massifs are rare. In the northern Pribaikalye, metavolcanics and cross-cutting granitoids of 1 560 ± 80 My are common (OVCHINNIKOV, 1968). According to petrological characteristics, metavolcanics are regarded as metamorphosed equivalents of the Pribaikalian volcano-plutonic complex.

2.2. LATE PROTEROZOIC (RIPHEAN) MARGINAL COMPLEXES

2.2.1. Western Pribaikalian Baikal series

In the western part of the Pribaikalian Fold Belt, the Late Proterozoic is represented by the **Baikalian series** of mainly Riphean age, which occurs in marginal depressions of the Siberian platform, all along the Pribaikalian Fold Belt, from the Angara river to the Okunayka river (Fig. 2).

The series consists of terrigene-carbonate rocks with successively : quartz sandstones and carbonates followed by carbonate schists and flysch-type rocks. In places, for example in the Goloustny river valley, the sequence is completed by molasse. In the north-western Pribaikalye the maximum thickness is 3 500 m (SALOP, 1964; ZAMARAEV *et al.*, 1979). The Riphean complex is deformed in linear, NE-SW trending asymmetric folds with vergence to the NW (axial planes dip to the SE at 50-70° and the steeper limbs at 80° to the NW). Mostly, the amplitudes of folds vary from metres to hundreds of metres and are associated with longitudinal reverse and thrust faults and with imbricate structures. Seismic and drilling data have shown the presence of a major horizontal décollement in the lower parts of the Riphean complexes (ALEXANDROV, 1990) (Fig. 2 A and 5). The Upper Riphean is thus partly allochthonous and forms a nappe structure.

2.2.2. Baikal-Patom and Mama-Bodajbo foredeeps

Late Proterozoic formations are best developed in the outer part of the Baikal mountain area. They comprise the marginal Baikal-Patom and internal Mama-Bodajbo fordeeps which are separated by the Chuya-Nechera anticlinorium (Fig. 2). These structures developed on the heterogeneous and fractured basement of the Siberian craton.

Early Riphean sequences are only exposed in the core of the Chuya-Nechera anticlinorium. The lowest units are quartzites, metaconglomerates and aluminous schists – the metamorphosed erosion products of mature weathering. The upper units are mainly comprised of sandstones and conglomerates with only rare argillaceous rocks and intermediate and basic volcanics. The total thickness of these units varies from 900 to 3 000 m. Middle Riphean rocks are well exposed in the anticlinorium and they rest unconformably on the Early Riphean sequences. They are typically carbonate-terrigenous flysch-like sediments with occasional pyroclastic rocks. The sediments of the Mama-Bodajbo foredeep show a maximum thickness of 8 000 m, whilst the Baikal-Patom foredeep sediments are up to 4 000 m thick. Upper Riphean rocks in the Patom area are mainly terrigene-carbonates and in the Bodajbo zone they consist of terrigenous meta-sandstones and argillaceous rocks. Thickness varies from 900 to 3 000 m.

The Riphean rocks of the Baikal – Patom foredeep were intensively deformed during Early to Middle Paleozoic. The degree of deformation gradually decreases towards the platform edge. Folds up to several hundred kilometres long and 40 km wide and with an amplitude of up to 2.5 km form an acuate pattern. High grade metamorphism (it is thought during Early to Middle Paleozoic) occurs locally in some

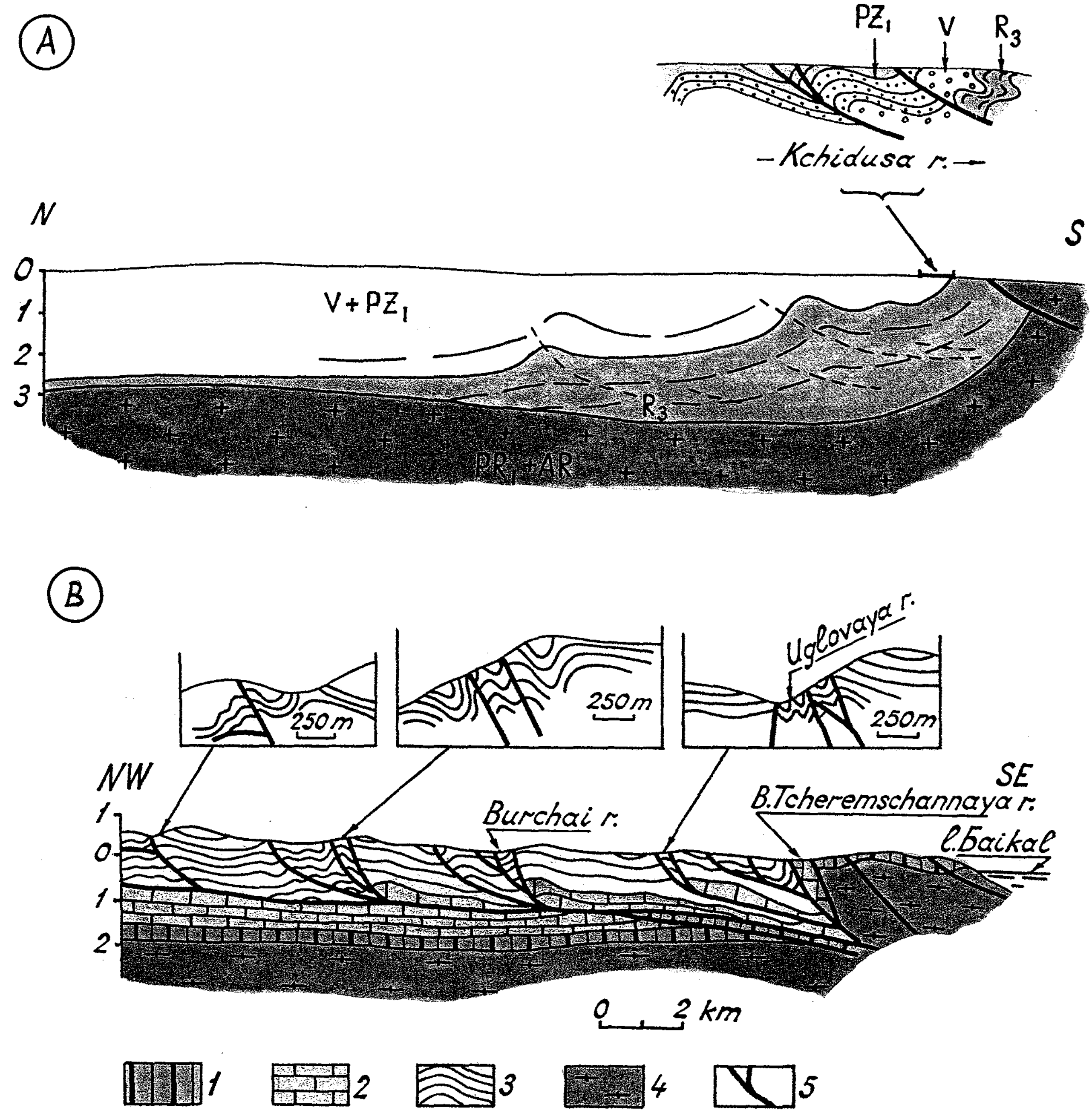

FIGURE 5

Geological cross sections across the Pribaikalian foredeep (for location map, see Fig. 2A).
A : Interpreted geological and seismic data showing the north-component verging folded Late Riphean and Vendian with thrusts replacing lower limbs. Yellow : Vendian and Lower Paleozoic; green : Upper Riphean; pink : Archean and Lower Proterozoic crystalline basement.
B : Nappe of Late Riphean (confirmed by seismic data) with décollement rooted in the Early Riphean and suture thrust.
1 : Late Riphean Baikalian complex; 2 : Middle Riphean; 3 : Early Riphean; 4 : crystalline basement; 5 : faults.

zones of the Mama-Bodajbo foredeep with polyphase deformation resulting in complicated superposed folding including the development of granite-gneiss domes. Reverse and thrust faulting, with a strike slip component are synchronous. The Mama-Bodajbo foredeep series is thrust onto the Chuya-Nechera anticlinorium, which is in turn thrust onto the complexes of the Riphean of the Baikal-Patom foredeep (IVANOV & RYAZANOV, 1992).

Several granite bodies intruded the Riphean series in the Baikal-Patom and Mama-Bodajbo foredeeps. They provide an age of 339 My (Rb-Sr isochrone). The Pb-Pb dating for the regional metamorphism of the Riphean rocks in the Mama zone is 473 ± 23 My (BUKHAROV *et al.*, 1992). Thus the deformation and synchronous metamorphism of the Riphean complexes occurred between Early Ordovician and the Silurian.

2.3. VENDIAN-PALEOZOIC PLATFORM COVER

The Vendian-Paleozoic sediments are located in the Angara-Lena foredeep (Fig. 2) and comprise molasse, carbonates, evaporates and red beds (*Editor's note : Vendian = Eo- or infra-Cambrian.*).

In the Pribaikalye, the Vendian – Cambrian basal molasse comprises polymict sandstones, grit stones and conglomerates with minor siltstones and argillaceous rocks. The carbonate series consists of dolomites and limestones and interbedded anhydrites bearing dolomites, marls and carbonate breccias. The total thickness is almost 1 500 m. To the west, carbonates are replaced by evaporites, comprising thick salt units interbedded with anhydrites, anhydrite/carbonate rocks and dolomites, with a maximum thickness of 2 000 m. Both the carbonates and evaporates are covered by red beds which comprise sandstones, siltstones, marls, limestones and dolomites, grit stones and conglomerates with gypsum and anhydrite. The red beds range from Middle Cambrian and Middle Ordovician (ZAMARAEV, 1967; ZAMARAEV *et al.*, 1979).

The Vendian-Paleozoic sequence is, like the Late Proterozoic complexes, folded with structures trending subparallel to the platform edge. Along the Pribaikalye and along the trend, the fold-type remains constant, whereas radially, *i.e.* from the platform edge towards the intraplatform area, the style changes considerably. Close to the platform edge there is a narrow (30km wide) zone with complete folds which are analogous to those affecting the Late Proterozoic series. In the intra-platform area the style changes to one of periclinal folds often of box-fold type. The style of faulting is similar to that affecting the Late Precambrian, with longitudinal and transverse reverse faults and thrusts. All fault types have a strike-slip component (ZAMARAEV *et al.*, 1979).

Close to the Angara river outlet at the southern end of Lake Baikal, Jurassic coal-bearing molasse composes the basin of the Prisayan piedmont foredeep (Fig. 2). The gentle dips and absence of big amplitude folding are typical. Only in the outlet of the Angara river are cross-cutting faults observed and interpreted as thrusts (DANILOVICH, 1963).

The Pristanovoy piedmont foredeep (analogous in terms of rock type and tectonic position to those of the Prisayan foredeep) is situated to the south of the Aldan shield. However, it is more highly folded and faulted.

3. — SAYAN-BAIKAL FOLD BELT

The Sayan-Baikal fold belt is made up of heterochronous blocks which differ in composition and structure. These blocks are termed the Dzhida terrane and the Barguzin and Tuva-Mongolian super-terranes (Fig. 2). The super-terranes differ from the Dzhida terrane in having a more complex structure and by the presence of Precambrian metamorphic massifs such as the Muya, Baikalian, Khamar Daban, Gargan and other massifs.

3.1. BARGUZIN SUPER-TERRANE

The Barguzin super-terrane, located in the central part of the Baikal mountain region, is adjacent to the edge of the Siberian platform. Traditionally, the structure of this area was regarded as the Baikalide tectonotype. However, in the last two decades this view has been criticised (BELICHENKO,1977; FEDEROVSKY, 1985) after dating some of the principal complexes and reinterpreting their relationships.

3.1.1. Angara-Vitim batholith

The centre of this super-terrane is occupied by large areas of poorly exposed Riphean-Paleozoic granitoids which make up the huge **Angara-Vitim batholith.** Towards the margins of the granitoids, in the Khamar Daban, Baikalian and Muya massifs, relicts of older complexes are observed which comprise :

— Early Precambrian (*Editor's note : poorly dated and thus age is inferred.*) gneisses, crystalline schists, migmatites, marbles and calc-silicate rocks;

— ophiolites with associated island arc-type metasediments which are inferred to be of Early Riphean age;

— Riphean sedimentary and volcano-sedimentary complexes;

— Vendian-Cambrian shelf carbonates.

3.1.2. Baikal-Vitim ophiolite belt

The ophiolites and associated island-arc formations make up the arcuate Baikal-Vitim belt in the northern part of the super-terrane, adjacent to the platform (Fig. 6 and 11) (DOBRETSOV *et al.*, 1985). They consist of amphibolites, quartzites, garnet amphibolites, gabbroids and ultrabasites. The latter occur as highly deformed slabs of serpentinized harzbergiites, dunites and pyroxenites in olistostromes which have been subjected to Early Riphean metamorphism (ZONENSHAIN *et al.*, 1990).

The Riphean sediments in the eastern Muya massif are of turbiditic-flysch type, often of pyroclastic material which is closely related to gabbro-tonalite-plagiogranite intrusions. Thus, they probably formed in an island arc environment. The most complete reconstruction of the geodynamic evolution of the Baikal-Vitim belt has been carried out in the Muya area (Fig. 6) (GUSEV *et al.*, 1992).

On the flanks of the Barguzin super-terrane, Riphean carbonate-terrigenous and volcano-sedimentary complexes are not associated with ophiolites. Volcanics occur at the base of the sequence in the Synnyr and upper Angara ridges of the Pribaikalian and in the upper part of the sequence in the Khamar Daban ridge. These Riphean non-ophiolitic sediments are thought to have accumulated in a forearc-basin environment.

After the Archean and Proterozoic Barguzin super-terrane had been consolidated and deeply eroded, sediments were unconformably laid down during the Vendian to Lower Cambrian. Locally terrigeno-volcanics occur at the base followed by extensive shelf-carbonates. The sequence terminates, again locally, with molasse detritics (ZONENSHAIN *et al.*, 1990).

A collision between the Barguzin super-terrane and the Siberian craton took place in the Early Paleozoic (Middle Cambrian – Ordovician). It was accompanied by the intrusion of the huge volumes of granitoids of the Angara-Vitim Batholith which, except on the south western flank of the super-terrane in the area of the Khamar Daban ridge, obliterated many of the previous units.

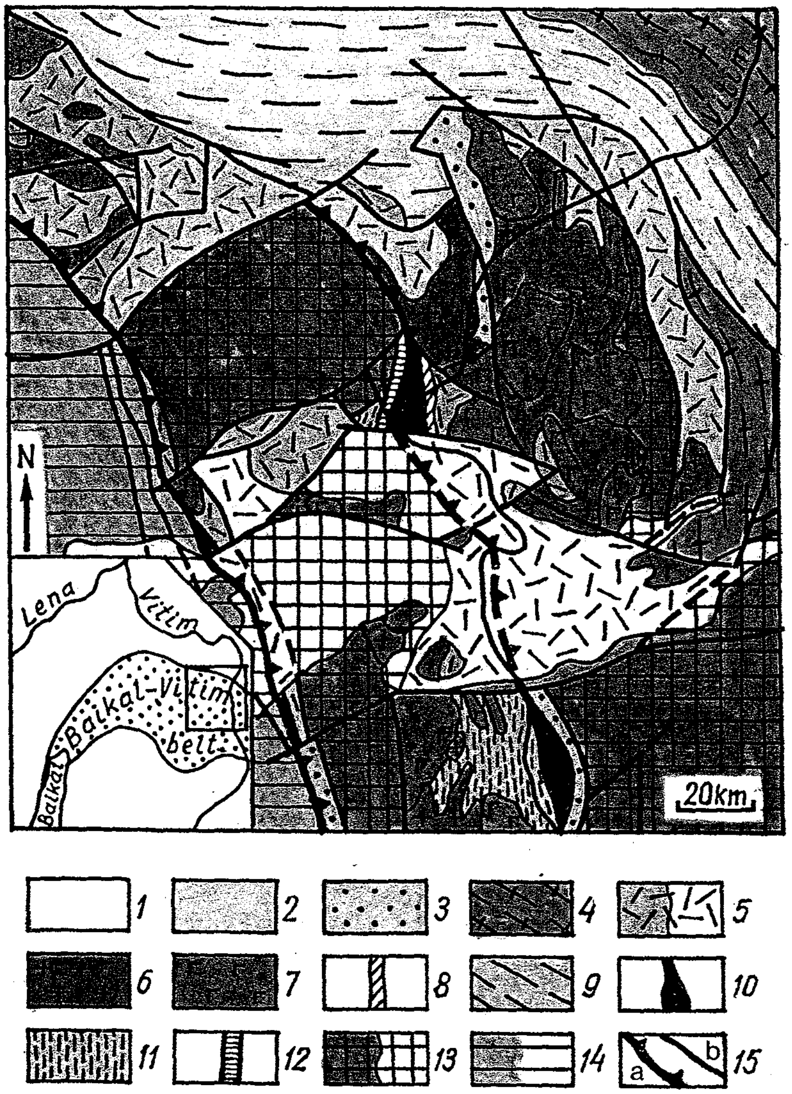

FIGURE 6

Geological map of the Muya segment of the Baikal-Vitim belt modified from GUSEV *et al.* (1992) with geodynamic interpretation. (for location map, see Fig 2 A)

1 : Cenozoic sediments of the Muya rift basin;
2 : Vendian-Cambrian shelf sediments. Proterozoic complexes; 3 : post-collisional terrigeno-volcanic sediments; 4 : collisional granito-gneisses;
5 : island arc volcano sedimentary rocks;
6 : tonalites and plagiogranites; 7 : gabbroids;
8 : volcano-clay carbonate turbidites of fore-arc fore-deep; 9 : flysch sediments of back-arc basin;
10 : rocks of ophiolite association;
11 : terrigeno-carbonate sediments of passive margin shelf and continental margin;
12 : sedimentary-volcanic rocks of continental rift;
13 : Early Archean complexes of the Muya block;
14 : Riphean volcano-plutonic complexes of active continental margin;
15 : thrust (a) and other faults (b).

3.1.3. Khamar Daban ridge

The Khamar Daban ridge is composed of complexes of varying age (Fig. 7).

The following stratigraphic succession is recognised (Tab. I).

Generally, the metamorphic grade increases with the age of the complex, though, in detail, isograds cut across stratigraphic boundaries and unconformities. There is some lateral inhomogeneity in the inferred P-T gradients. The metamorphic facies varies from Ky-Sill in the south and west of the ridge, And-Sill in the central part to granulite facies

TABLE I

Stratigraphic succession in the Khamar Daban ridge

	Series	Age	Composition
1	Slyudyanka	AR2 (*Upper Archean*)	Alternating quartz-carbonates, tholeitic schists and various gneisses (granulite facies)
2	Khangarul	PR1 (*Lower Proterozoic*)	Unconformable on Slyudyanka : Lower unit of metapyroxenites (of andesitic composition) Upper unit of gneisses with thin marble layers
3	Khamar Daban	R (*Riphean*)	Unconformable on Khangarulsk : Lower unit of meta-terrigenous rocks Upper unit of a carbonate/volcano-terrigenous association.
4	Zunmurin	V-Cml (*Vendian – Lower Cambrian*)	Oversteps onto various Proterozoic units Dominantly carbonate

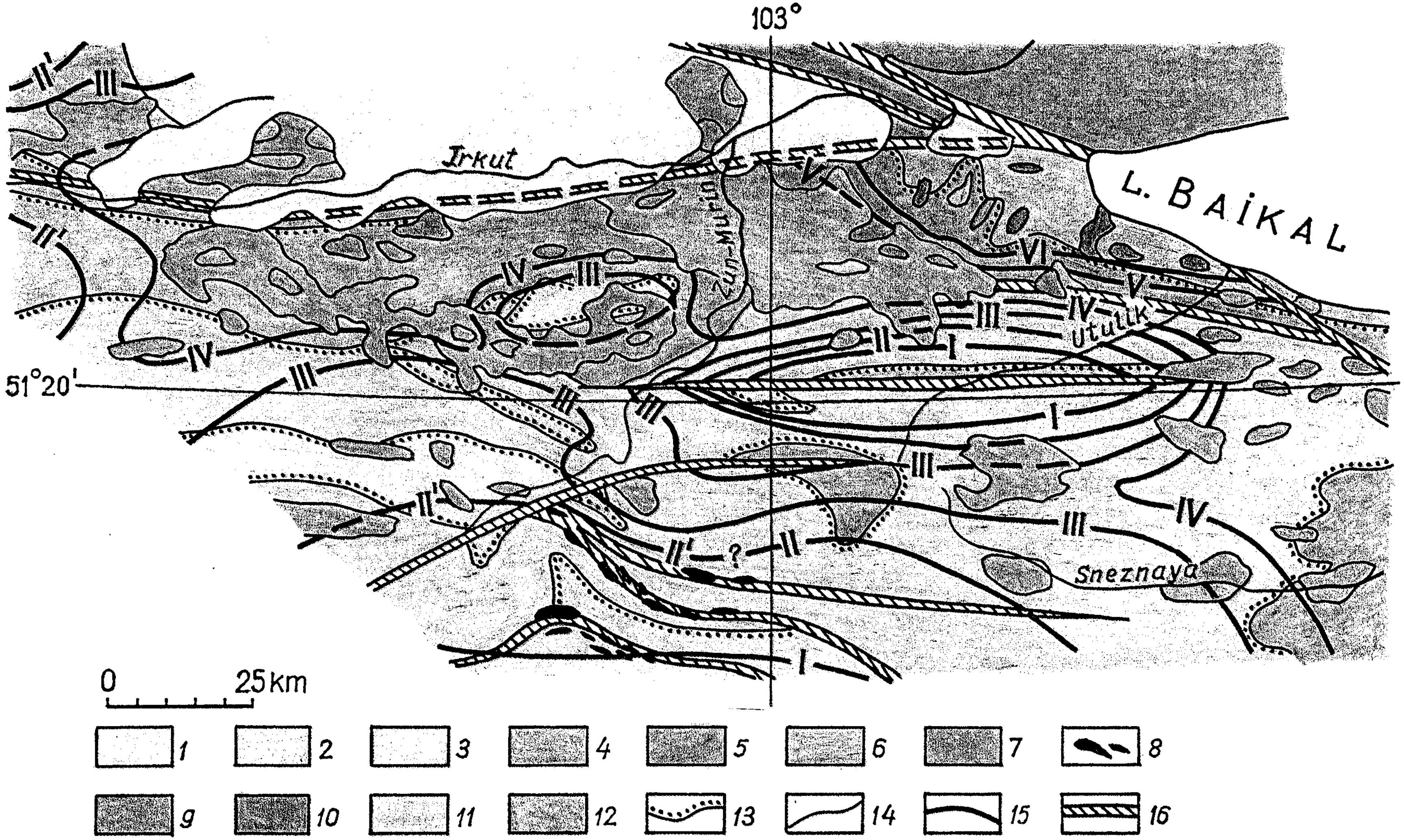

FIGURE 7
Geology and metamorphism of the Khamar-Daban ridge. (For location map, see Fig 2 A)
1 : Cenozoic sediments; 2 : Cambrian island arc sediments of the Dzhida ridge; 3 : Zunmarin series (Vendian-Lower Cambrian); 4 : Khamar Daban series (Riphean); 5 : Khangarul (Lower Proterozoic); 6 : Slyudyanka series (Upper Archean); 7 : Sharyzhalgay complex (Lower Archean); 8 : ultrabasites (Vendian-Lower Cambrian); 9 : granites (Riphean-Paleozoic). Early Proterozoic : 10 : alaskite granite-pegmatites (see editor's note in the Conclusion); 11 : syenites; 12 : gabbroids; 13 : stratigraphic and structural unconformities; 14 : other geological boundaries; 15 : metamorphic isograds (I : garnet, II : staurolite and andalusite, III : sillimanite, IV : K - feldspar, V : garnet-cordierite paragenesis, VI : hypersthene-cordierite-orthoclase paragenesis); 16 : mean shear zones.

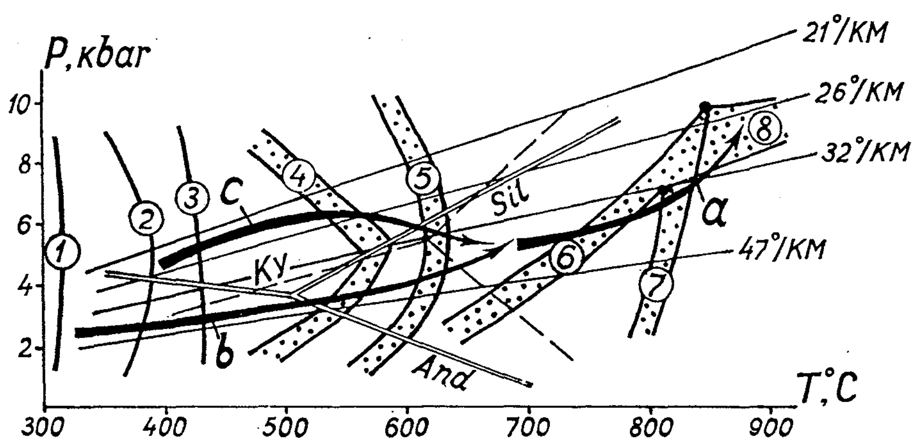

FIGURE 8

P-T field with geothermal gradients : position of metamorphic zones for various complexes.

a : Slyudyanka granulite complex, b : Central Khamar Daban : andalusite-sillimanite zones, c : Western Khamar Daban : kyanite-sillimanite zones. Boundaries of mono-variant equilibrium and the occurrence of index minerals :
1 : biotite, 2 : garnet, 3 : staurolite, 4 : fibrolite (*Editor's note : Felted mats of fine grained sillimanite.*), 5 : sillimanite + orthoclase, 6 : cordierite + orthoclase, 7 : cordierite + hypersthene, 8 : hypersthene + sillimanite.
Lines of Al_2SiO_5 polymorphic transitions (Double lines : after HOLDAWAY, 1971; Hatched lines : RICHARDSON *et al.*, 1969).

in the Slyudyanka granulite complex at the southern end of Lake Baikal. The local P-T trends are shown in Figure 8.

There has been considerable controversy over the origin of the metamorphic zoning. Some researchers consider it to be a single-act phenomenon related to the Middle Paleozoic collision (BELICHENKO & BOOS, 1990). However, some isotopic data suggest that the Slyudyanka granulite facies was imposed during the Early Proterozoic (VOLOBYEV *et al.*, 1980; BRANDT *et al.*, 1987). Other authors believe that the zoning may be regarded as a result of consequent accretion of heterogeneous metamorphic complexes (Lower Proterozoic – Upper Paleozoic) (VASILJEV *et al.*, 1985). In any case, metamorphic activity together with the subsequent collision of the Barguzin super-terrane and the Siberian craton is evident whereas previous metamorphic history is still under debate.

3.2. TUVA-MONGOLIAN SUPER-TERRANE

The Tuva-Mongolian super-terrane is located in the south-eastern Sayan and adjacent regions and neighbouring northern Mongolia (Fig. 9). This area was previously regarded as a microcontinent from the presence of blocks of metamorphic basement with Paleozoic carbonate shelf cover (BELICHENKO & BOOS, 1990). However, the super-terrane has a more complicated make-up with the following major elements now being recognized (Tab. II).

3.2.1. Gargan and Shutkhulay metamorphic core complexes

Recent studies have shown that the **Gargan and Shutkhulay massifs** (Fig. 9 and 10) reveal the features of metamorphic core complexes of Cordillierian and Himalayan types respectively (SKLYAROV, 1993).

The Gargan massif is dome-shaped (Fig. 10) and is composed of tonalitic granite– (often augen) gneiss with rare thin amphibolite layers. Most of the gneisses have been retrogressively metamorphosed to low amphibolite facies. The massif is separated from the younger formations (see Tab. II, 2-6) by mylonitic and blasto-mylonitic zones with occasional lenses of carbonate and chlorite breccias. The dip of the contacts are 25-45° at the northern flank and 60-85° in the southern flank. Preliminary isotopic dating of the tonalitic gneiss at 3 240 ± 57 My (Rb-Sr isochrone method) supports the inferred Archean age of the protolith (AKTANOV *et al.*, 1992).

TABLE II

Major elements of the Tuva-Mongolian super-terrane

	Age	Composition	Massifs, Belts and Series
1	Early Precambrian	metamorphic core complexes	Gargan and Shutkhulay massifs
2	Riphean	ophiolites	Shishkhid belt and massif North and South Ilchir belts
3	Riphean	accretionary wedges, mostly terrigenous with slices of ophiolites and glaucophane schists	Oka and Khugein zones
4	Upper Precambrian	volcano-terrigenous sub-aerial formation	Sarkhoy and Darkhat series
5	Vendian – Cambrian	thick carbonates, resting unconformably and thrust over 1 - 4	Bokson and Khubsugul series
6	Lower-Middle Paleozoic	active margin volcano-terrigenous formations	
7	Mainly Lower-Middle Paleozoic	Granitoids of varying types	

All the contacts are tectonic rather than stratigraphic due to the intense deformation. As a result and with the lack of Fauna, few radiometric data and their ambiguous interpretation, debate on the tectonics of the area continues.

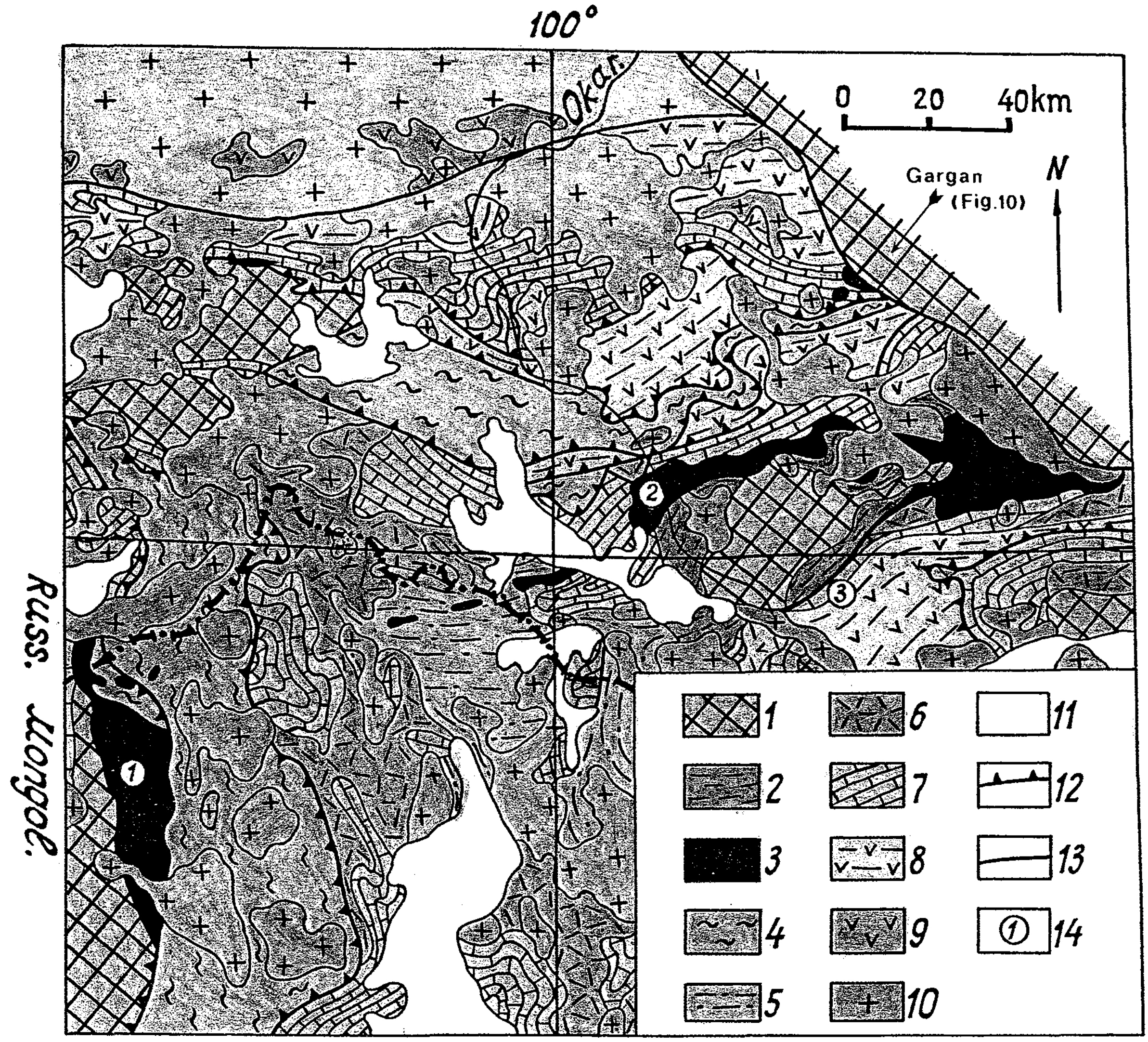

FIGURE 9

Geological map of south-eastern Sayan and northern Mongolia (for location map, see Fig 2 A).

1 : Precambrian metamorphic massifs (Gargan, see Fig. 10); 2 : Late Precambrian and Early Paleozoic volcano-terrigenous and carbonate-terrigenous series; 3 : ophiolites (Riphean); 4 : volcanic-terrigenous series with blueschists (Riphean); 5 : flysch-type sediments (Riphean accretionary wedges); 6 : sub-aerial volcano-sedimentary series (Upper Riphean – Sarkhoy series in Siberia, Darkhat series in Mongolia); 7 : shelf carbonate series (Vendian-Cambrian); 8 : Early Paleozoic volcano-sedimentary series; 9 : Middle Paleozoic volcanic series; 10 : undivided granites; 11 : Cenozoic sediments; 12 : thrusts; 13 : other faults and boundaries; 14 : ophiolite belts : ① Shishkhid belt and massif, ② North Ilchir belt, ③ South Ilchir belt.

The Shutkhulay massif (Fig. 9) is composed mainly of biotite gneiss intruded by aplites both parallel and cross-cutting the foliation and rare lenses and layers of amphibolites and marbles. To the north and south the massif is bordered by faults and to the east shows a gradual metamorphic contact with the Late Precambrian essentially terrigenous series. Based on few K-Ar ages, a Mid-Paleozoic age can be inferred for the tectonic exposure of the block. By a number of criteria the Shutkhulay massif resembles the Mesozoic metamorphic core complexes of the Cyclades (LISTER *et al.*, 1984) and Alaska (MILLER *et al.*, 1991).

3.2.2. Ophiolite belts

Ophiolites are widespread in southern Siberia and northern Mongolia (Fig. 11). In the area under consideration, three ophiolite belts are distinguished :

- the **Shishkhid** belt (① in Fig. 9 and 11) includes the large massif of the same name composed of mainly serpentinized dunites and harzburgites with rare lerzolites and a number of small lenses of serpentinite;

- the **North Ilchir** belt (② in Fig. 9) comprises a number of slices of ophiolites including complete ophiolite sequence with a basal restite dunite-harzburgite complex, followed by a zone of pyroxenite-peridotite, cumulate gabbro, massive gabbro, a sheeted dyke complexes and finally pillow and massive lava overlain by turbidites (SKLYAROV, 1990; SKLYAROV *et al.*, 1993). The dykes and laves are of very low -Ti type according to Beccaluva's classification (BECCALUVA *et al.*, 1983). Boninites (*Editor's note : Boninites are high-Mg, andesitic lavas resulting from direct melting of the upper mantle. Original mineralogy comprises olivine and bronzite (Mg-pyroxene) phenocrysts in andesitic glass, but no felds-*

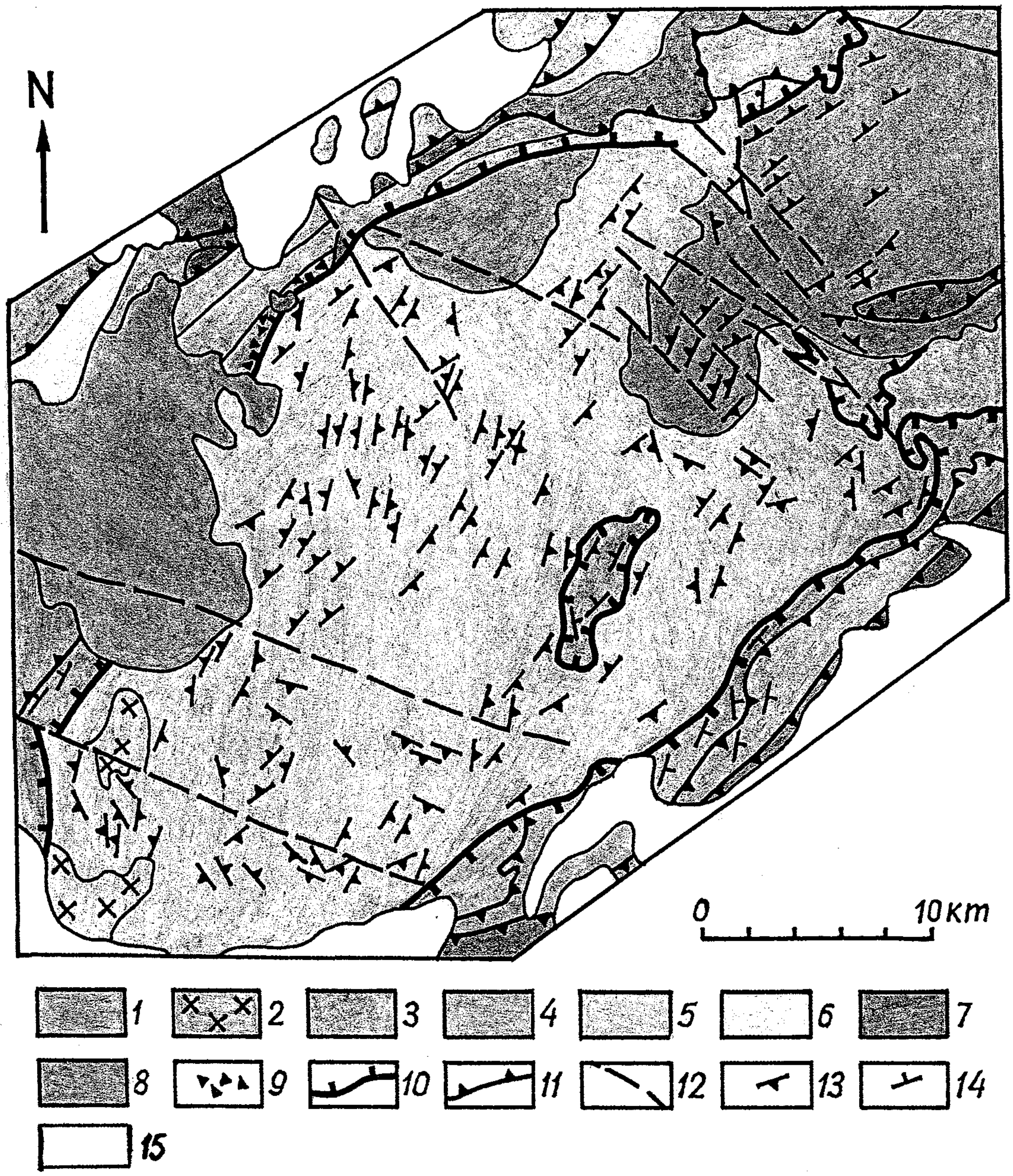

FIGURE 10

Geological map of the Gargan metamorphic core complex.

1 : tonalite gneiss (Archean); 2 : granites (Lower Proterozoic); 3 : multiple slices of carbonate and carbonate-terrigenous series (Upper Proterozoic – Lower Paleozoic); 4 : multiple slices of terrigenous and volcano-terrigenous series (Lower Paleozoic) in the Oka synclinorium; 5 : volcanic series (Riphean); 6 : quartzite-carbonate series (Lower Paleozoic); 7 : ophiolites (Riphean); 8 : Early Paleozoic granite-granodiorites; 9 : carbonate and chlorite breccias; 10 : decollement; 11 : thrusts; 12 : undifferentiated faults; 13 : foliation; 14 : layering; 15. Cenozoic sediments.

par.) are also very common. At the base, where the ophiolites are thrust over a complex package of Late Precambrian and Upper Paleozoic volcano-terrigenous and carbonate-terrigenous rock, the serpentinite melange zone of varied thickness and metamorphic sole is present. Preliminary Sm-Nd and U-Pb dating limit the age of the ophiolites to about 1 000 My;

• the **South Ilchir** belt (③ in Fig. 9) consists of serpentinite and meta-basite slices with few pyroxenites and gabbroids. According to geochemical features and peculiarities of associated complexes, these ophiolites are similar to those of the younger Dzhida terrane (DOBRETSOV *et al.*, 1985).

3.2.3. Volcano-terrigenous complexes

The **Riphean accretionary wedges** (Fig. 9 and 11) which consist mostly of greywacke with minor basic-ultrabasic

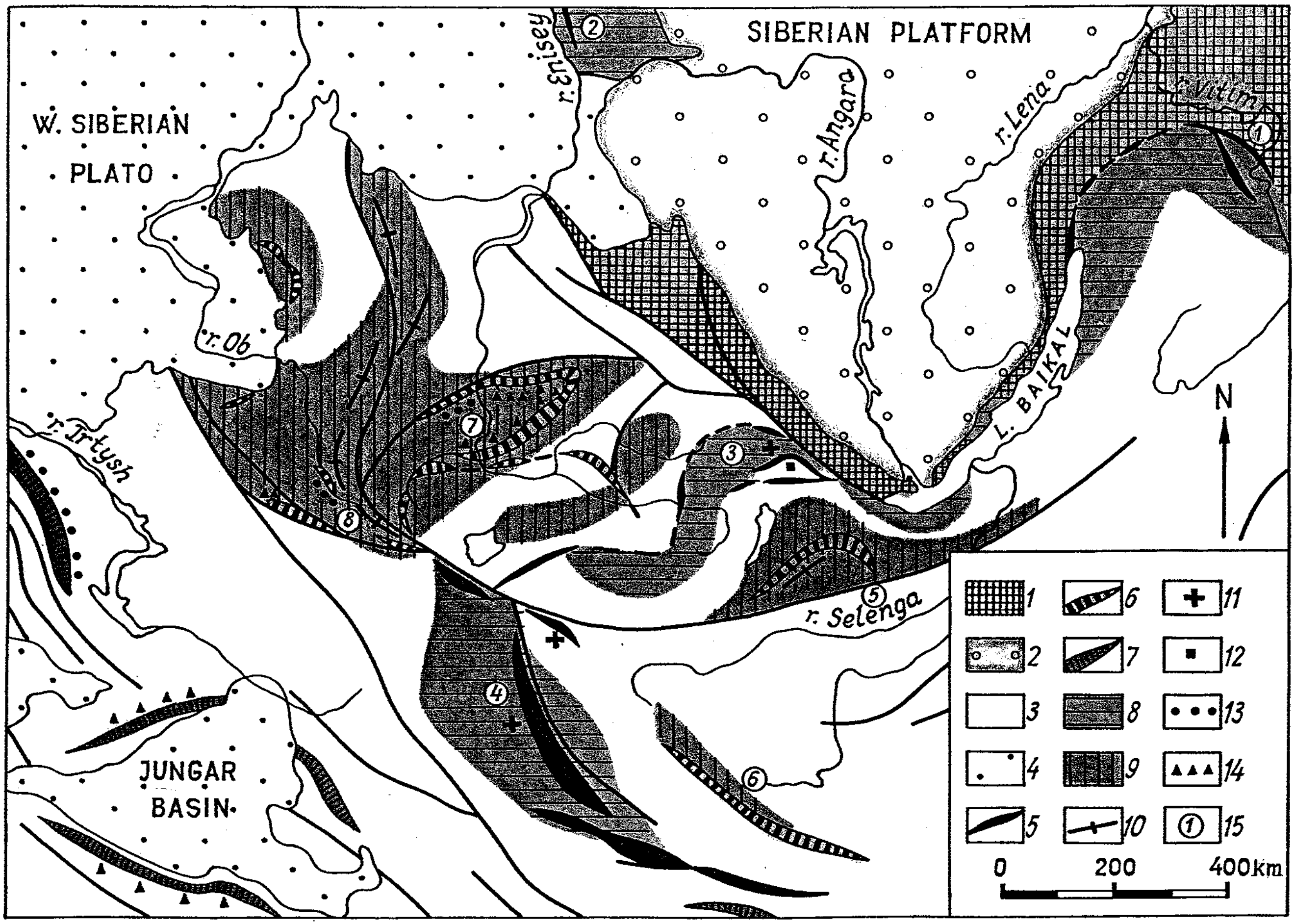

FIGURE 11

Ophiolite belts of South Siberia and northern Mongolia.

1 : Early Precambrian basement of the Siberian craton; 2 : craton cover; 3 : Late Precambrian – Paleozoic fold belts; 4 : Cenozoic – Mesozoic cover. Ophiolite Belts : 5 : Late Precambrian, 6 : Vendian – Cambrian, 7 : Early to Middle Paleozoic. Island arc and back-arc complexes : 8 : Late Precambrian, 9 : Vendian – Cambrian; 10 : intra-oceanic island arc complexes with boninites; 11 : presence of boninites in ophiolites; 12 : presence of metamorphic sole; 13 : eclogites and jadeite rocks; 14 : blueschists; 15 : names of ophiolite belts and systems of belts : ① Baikal – Muya belt, ② Enisey belt, ③ East Sayan system, ④ Lake system, ⑤ Dzhida belt, ⑥ Bayan Hongor belt, ⑦ West Sayan system, ⑧ Gornay Altai system.

rocks regarded as dismembered ophiolites, make up the E-W trending Oka zone in south east Sayan and the N-S trending Khugein zone in northern Mongolia. Based on the type of sediments and their composition, these complexes correspond to the infill of a Riphean back-arc basin (SKLYAROV, 1990). They show thrust contact with the adjacent complexes marked by blueschists at the south eastern boundary (DOBRETSOV, 1985).

The **Upper Riphean complex** of volcano-terrigenous rocks of the Sarkhoy series in Siberia and the Darkhat series in Mongolia, consist of coarse grained sub-aerial, often red or variegated sediments and tuffs and lavas of rhyolites, dacites, andesites and basalts. Abrupt facies changes indicate that during sedimentation and the volcanism, the topography was considerably dissected. Geochemically the volcanic rocks belong to a differentiated calc-alkaline series, typical for active margin or mature island arc settings. Traditionally this series was considered to be the final molasse related to the orogenesis of the Baikalides followed by the Late Proterozoic Sarkhoy-Khubsugul rifting (ILJIN, 1982). However, based on the geochemistry of the volcanic rocks, the complex was formed under mature volcanic-arc conditions.

3.2.4. **Vendian-Lower Cambrian shelf carbonates**

The Vendian-Lower Cambrian shelf carbonates are, in the lower part, mainly dolomites often stromatolitic and the upper part is limestone. Within the dolomites are thin layers of bauxite and phosphorites indicating a subequatorial climate. The presence of a chromite-bearing basal quartz sandstone suggests deposition after the amalgamation of the underlying complexes into a single terrane and erosion of the associated ophiolites.

Even where they have been thrust as nappes onto the underlying complexes, the carbonates are only slightly deformed.

3.2.5. Early Paleozoic flysch

Early Paleozoic flysch-like volcano-terrigenous and carbonate-terrigenous formations occur at the boundary of the Gargan massif (Fig. 9 and 10). The boundaries of these structures are composed of complex tectonized packages of the above described Late Precambrian formations. The boundary of the Gargan massif is a megabreccia with elements from almost all the Upper Precambrian and Paleozoic complexes. Such deposition is typical at the boundaries of metamorphic cores (CRITTENDEN *et al.*, 1980) where, during post-collisional extension, there is syn-tectonic sedimentation in the linear depressions separating the tectonically exposed massifs.

3.3. DZHIDA TERRANE

This terrane is located in the south-west of the area under consideration (Fig. 2). Even though the rocks are very varied, only two major pre-collisional complexes are distinguished.

The first comprises considerably dislocated ophiolites which form numerous tectonic slices from different parts of the ophiolite suite. Normal relationships are rarely seen. The lower units comprise highly serpentinized dunites, harzburgites or peridotites. Lenses of these occur in arcuate belts which demarcate thrust planes. Gabbro-pyroxenite complexes are only occasionally found and dyke complexes are rare. The upper parts of the ophiolite suite are composed of high-Ti undifferentiated alkali basalts which occur as pillow lavas associated with lenses and thin slices of grey and dark limestone and chert. Based on paleontological evidence, the undifferentiated series is dated at Vendian-Early Cambrian (BELICHENKO, 1977).

The second complex comprises sedimentary volcanogenic rocks of Cambrian to Silurian age. The Cambrian rocks are either volcanics of the calc-alkaline suite with abundant agglomerates or limestone olistoliths and volcanic rocks incorporated in debris flows. The Ordovician-Silurian rocks are flysch-type sandstones, schists and carbonates which were deposited in an oceanic island-arc environment (BELICHENKO & BOOS, 1990; ZONENSHAIN *et al.*, 1990).

The entire Dzhida terrane has been folded into complex nappes which probably resulted from interaction between the Dzhida and Barguzin terranes at the beginning of the Devonian.

Three major intrusive complexes are distinguished :

• Cambrian gabbro-diorite-plagiogranites, associated with the volcano-terrigenous island-arc deposits,

• Ordovician-Silurian granite-granodiorites which, being analogous to the Angara-Vitim batholith, are related to a collision phase,

• Late Paleozoic rhyolitic to basaltic volcanic rocks and tuffs, and their intrusive equivalents are widespread in the Dzhida terrane. They are of the sub-alkaline or alkaline suite and thus are regarded as the product of Late Paleozoic continental rifting.

4. — TECTONIC EVOLUTION OF THE PRE-MESOZOIC BASEMENT

The tectonic evolution of the basement of the East Siberian rift system spans the greater part of Earth's entire geological history. Two major stages which affect the Precambrian and the Riphean-Paleozoic can be distinguished. The first pre-collision stage corresponds to the formation of the Siberian craton throughout the Early Precambrian and the second spans the collision and subsequent tectonic development of the area after the opening of the paleo-Asian ocean from the Mid-Proterozoic onwards.

4.1. PRECAMBRIAN EVOLUTION

Opinions on the Early Precambrian geological history of South East Siberia vary widely.

According to one of the most recent paleogeodynamic interpretations, the Siberian craton, prior to the formation of the Udokan complex (2200 My), was composed of several independent continental slabs – the Angara-Anabar, Tunguska, Olenyek and Stanovoy shields, which were separated by oceanic basins of unknown size (ZONENSHAIN *et al.*, 1990).

The Udokan complex is indirect proof of the existence of such an ocean. It was, in our opinion, formed in a passive continental margin setting. Also, the ophiolites of the Baikal-Vitim belt seem to correspond to relicts of an Early Proterozoic oceanic crust (DOBRETSOV *et al.*, 1985; ZONENSHAIN *et al.*, 1990). However, doubts can be cast on this concept. No variation can be observed in the tectonic evolution of the ancient complexes up to the end of the Early Proterozoic (ZAMARAEV *et al.*, 1983; MORALEV, 1986; RUNDKVIST & MITROFANOV, 1988). All the exposed Early Archean granulite-grey gneiss basement includes infra- and supra-crustal highly metamorphosed complexes (the Kurulta and Olyekma in the area under discussion). In the Middle-Late Archean, the basement was dissected either by a single system of granite-greenstone belts (*e.g.* the Sharyzhalgay block) or by several systems as is the case in the Aldan shield.

Thus, from geological data, it is evident that prior to the formation of the Udokan complex, the Siberian craton had been a single body and its subdivision into several units started with the formation of greenstone belts or paleorifts (WINDLEY, 1973; GRACHEV & FEDEROVSKY, 1980; MORALEV, 1986). Horizontal separation of the Siberian, China-Korean and Tarim cratons was probably synchronous and corresponded to the opening of a Late Archean ocean. Spreading was dissipated as newly-formed oceanic structures were separated by crustal blocks or micro continents which had already been consolidated.

In the Early-Middle Proterozoic, the Siberian craton had probably been subdivided into two large plates (those of Angara and Aldan) which were bordered, in part, by subduction zones. An active continental margin developed along the Pribaikalian edge of the Siberian craton, whereas the Aldan shield developed a passive continental margin. The Pribaikalian volcano-plutonic belt probably marks the zone where subduction of the oceanic crust took place.

At the beginning of the Riphean, the southern edge of the Siberian craton developed as a passive continental margin and in the intracratonic area the platform cover accumulated in a broad shallow-sea environment.

4.2. RIPHEAN-PHANEROZOIC EVOLUTION

Reconstructions of the Riphean-Phanerozoic, being highly dependent on the researcher's viewpoint, are far from being unambiguous. Traditionally they were based on the hypothesis that geosynclinal belts had developed on the Early Precambrian basement, and subsequent episodes of reactivation resulted in dislocation and reworking of the Early Precambrian metamorphic rocks and the development of a number of foredeeps, volcano-plutonic belts and various zones of tectono-magmatic activation etc. In terms of the plate tectonics theory, the Riphean-Phanerozoic history is considered to be related to the evolution of the paleo-Asian ocean (ZONENSHAIN *et al.*, 1990). It is suggested that the structural domains during the Early Riphean to Late Paleozoic were mostly produced as a result of interaction of oceanic and continental lithosphere plates. The development of the structures of the Siberian craton suture zone and the Barguzin and Tuva-Mongolian super-terranes, can be explained by the various tectonic processes along the margin of the craton and in marginal areas of the paleo-Asian ocean.

The key change in tectonic evolution, related to the opening of the paleo-Asian ocean, is inferred to have occurred at the end of the Early Proterozoic (about 1 800 My). Though no reliable data are available on the ophiolites of this age, the striking analogy of the volcano-plutonic formations of the Akitkan belt with those of the recent Andean active margin complexes suggests an oceanic-type subduction process was active at the Siberian craton margin at that time. From then up to the end of the Cambrian, the marginal zone of the Siberian craton developed as a passive continental margin with the accumulation of thick, essentially terrigenous sediments of the Bodajbo and Patom series.

Another scenario is envisaged for the reconstruction of the composite terranes (Barguzin and Tuva-Mongolian).

The ophiolites of the Baikal-Vitim belt of the Barguzin terrane are considered to be of Lower Riphean age (1 300 to 1 100 My) (BERZIN & DOBRETZOV, 1993). They are characterized by the presence of komatiites which are typical for ancient ophiolites (SKLYAROV *et al.*, 1993).

The **Baikal-Vitim ophiolite belt** as well as ophiolites of the **Enisey ridge** and **Taimyr Peninsula** (Fig. 6 and 11) are regarded as the most ancient in Siberia. They are located close to the Siberian platform margin and have approximately the same age and the same geochemistry (KUZMICHEV, 1992).

They show characteristics which are similar to those found in recent West Pacific active intra-oceanic island-arc plate margins :

• a close association with penecontemporaneous or younger island arc formations;

• the presence of volcano-terrigenous rocks etc., typical of back-arc and forearc basins (*e.g.* in the **Kotera and Olokit synclinoria**), thus suggesting that such island arc, back arc and forearc basins developed in the Riphean.

A similar interpretation can be made of the Tuva-Mongolian terrane, but with some differences in detail.
Firstly, the system of intra-oceanic island arcs, inter-arc and back-arc basins developed later – between 1 100 and 800 My.

Secondly, ophiolites in the Tuva-Mongolian super-terrane include boninites which are indicators of an intra-oceanic island arc setting.

Amalgamation of the various complexes was probably completed in the Vendian. This inference is supported by :

• the Vendian age of high-pressure metamorphism in the Tuva-Mongolian terrane (SKLYAROV, 1990);

• the presence of erosion products of oceanic crust in the basal formation of unconformably overlying Lower Paleozoic platform facies series.

At the end of the Cambrian the Tuva-Mongolian and Barguzin terranes were probably close to each other and also to the Siberian craton. The whole region was characterized by the accumulation of mainly carbonate sediments (these are abundant in the Tuva-Mongolian terrane).

To the south, another system of intra-oceanic island arcs developed (Dzhida terrane). During the Early Paleozoic this terrane, in turn, moved closer to the Siberian craton and was accreted to it.

The collision of the described terranes with the Siberian craton in Cambrian-Ordovician caused the origin of three principal complexes :

— narrow zones of high-grade zonal metamorphism of Cambrian-Ordovician age between the craton and terranes;
— S-type granites of Ordovician-Silurian age with abundant xenoliths of the substratum rocks;
— metamorphic core complexes of post-collisional stage (Gargan, Shutkhulay), exposed in the south-west (Fig. 12).

At the same time, in the central region, sedimentary and volcano-sedimentary basins developed under continental post-collisional extension. In the eastern part of the region, post-collisional A-type granitoids were emplaced (*Editor's note : anorganic or alkali-granite, often syenitic. It comes from the Lower Crust which may have been melted before. WHITE & CHAPPELL (1983). – Granitoid types and their distribution in the Lachlan Fold Belt southeastern Australia.* – Mem. geol. Soc. Amer., **159**, *21-34.*).

In the Late Paleozoic, plutonic and volcanogenic complexes typical of active continental margins of Andean and Californian type, were widespread not only in the territory under consideration but also thoughout **South Siberia** and **Mongolia.**

5. — CONCLUSION

The above description of the major structural domains and the main stages of their tectonic evolution shows the complexity of the East Siberian rift system's basement. The varied component complexes have been subjected to multi-stage metamorphism and deformation, which created complex nappe-fold systems. This is particularly evident in the collision zone between the Siberian craton and the terranes of the Central Asian Fold Belt. The structure is further

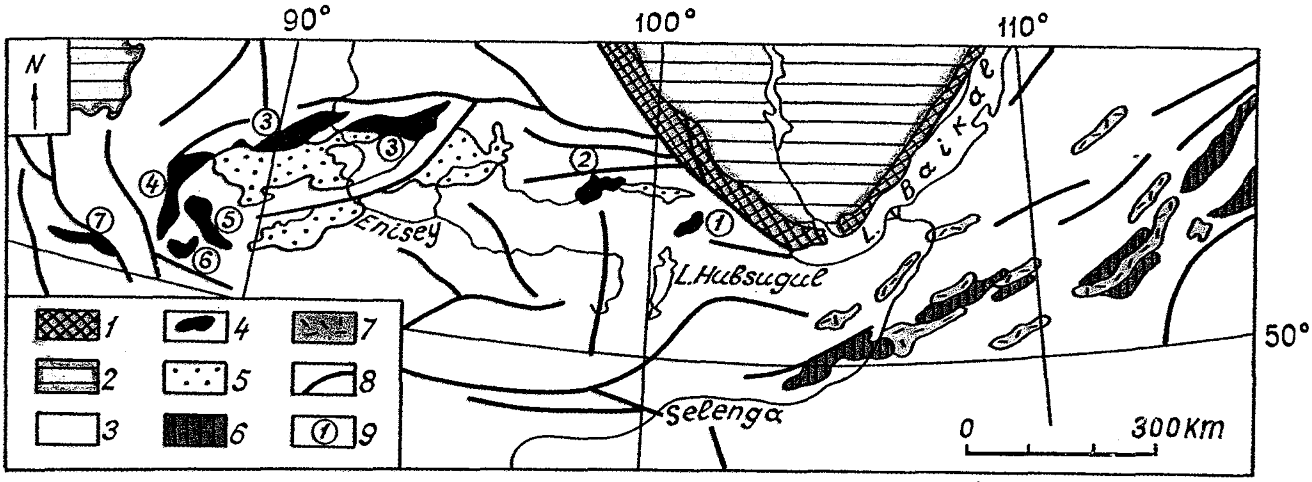

FIGURE 12

Metamorphic complexes of South Siberia.

1 : metamorphic basement of the Siberian craton; 2 : sedimentary cover of the craton; 3 : Upper Precambrian – Paleozoic fold systems; 4 : Paleozoic metamorphic core complexes; 5 : Paleozoic (Ordovician-Silurian) sediments in extension basins; 6 : Mesozoic metamorphic core complexes; 7 : Mesozoic volcanic-sedimentary series in extension basins; 8 : faults; 9 : core complexes within Paleozoic (Caledonide) belt : Paleozoic Metamorphic complexes : ① Gargan, ② Shutkhulay, ③ Dzebash, ④ Teletsk, ⑤ Chulishman, ⑥ Tongulak, ⑦ Katun-Chuya.

complicated by heterogeneous systems of faulting which are of different orders and depth of penetration. Faults have played a significant role in the generation of the overall structural pattern and have often predetermined the location and style of development of later sedimentary basins, and volcano-plutonic and metamorphic belts.

When considering the tectonic setting and the evolution of the basement of the Eastern Siberia rift system, it is reasonable to consider the relationship between the ancient and recent structural elements. The shape of the rift basins (*Editor's note : for the location of the Cenozoic rift basins, see* LOGATCHEV *(1993))* is largely dependent on the structure of the crystalline sub-stratum on which they develop (ZAMARAEV *et al.*, 1979; LOGATCHEV, 1993).

Two main types of basement are distinguished – granite and metamorphic, influencing the orientation and morphology of Cenozoic depression.

The largest and deepest Baikal depression has a complex structure and contour partly because of differences in age and the structure of the basement in its different parts. The development of the former as well as of the south-western and central flanks of the rift zone took place along the main tectonic structures of the ancient basement. These structures (layering, foliation, cleavage, faults) were favourable for reactivation in rift-related stress fields. The Barguzin depression, developed on the large granite batholith, has the simpler structure. The configuration and structure of this depression are dependant on reactivated systems of prototectonic joints and faults of NE (25-30°) and ENE (60-65°) directions. New systems of rifting-related faults were also generated, but their orientation strongly depended on the orientation of the ancient (especially Palaeozoic and Mesozoic) tectonic elements of the basement (ZAMARAEV *et al.*, 1979).

The Muya and Chara depressions of the Baikal rift zone differ in some details from those mentioned above. They are superimposed on highly dismembered Precambrian blocks with complex internal structures and composition. The character of relationship between ancient and Cenozoic structures is one of the reasons in favour of independence of ancient and recent structures for many researchers. However, the problem is more complex. In reality the Muya and Chara rift depressions are ancient fold zones and Cambrian sedimentation basins discordant to the axis of the Muya massif. But there are Cenozoic structures reactivating Palaeozoic and Mesozoic regional faults, fractures, intrusive contacts and dyke swarms.

In the broad sense, it is essential to underline that a study of the relationship between the structural pattern in the basement and superposed taphrogenic structures shows that the details are caused by the non-uniformity of rock masses due to a long geological history, which controlled and still controls their response to tectonic deformation.

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