# MAGMATISM RELATED TO THE EASTERN SIBERIA RIFT SYSTEM AND THE GEODYNAMICS

# *MAGMATISME ASSOCIÉ AU RIFT DE SIBÉRIE ORIENTALE : IMPLICATIONS GÉODYNAMIQUES*

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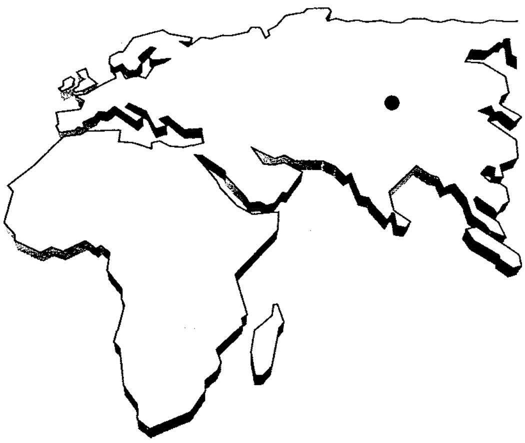

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En se référant aux variations spatiale et temporelle de composition des roches volcaniques associées au rifting de la région Trans-Baïkal, l'auteur montre que les phénomènes cénozoïques profonds sont hérités des activités tectoniques et magmatiques pendant la période du Paléozoïque moyen au Mésozoïque. Le système de rift est-sibérien est divisé en trois groupes de bassins : l'ensemble Tunka-Eravna avec un volcanisme associé, actif du Crétacé supérieur au Cénozoïque moyen, et les groupes essentiellement non volcaniques du Baïkal-Chara et du Khubsugul-Darkhat formés au Cénozoïque supérieur. Quoique le développement du rift est-sibérien soit contemporain de la collision Inde-Asie, la rotation relative des blocs séparés par le groupe Baïkal-Chara autour de sa terminaison nord-est indique que les forces d'extension étaient locales.

Le modèle de « hot spot » proposé pour expliquer les phénomènes géodynamiques dans le système de rift est-sibérien implique l'existence d'un flux thermique puissant le long de la bordure méridionale du craton sibérien, entre –29 et –12 Ma (Oligocène supérieur à Miocène). Il s'est manifesté par un « doming » un rifting et un volcanisme peu alcalin vigoureux. La migration des épisodes volcaniques dans la partie occidentale du groupe Khubsugul-Darkhat pourrait indiquer un déplacement lent (0,8 à 0,9 cm/an), vers l'est, de la plaque eurasienne chevauchant un panache mantellique fixe.

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**Mots-clefs** : Roche volcanique, Crétacé supérieur, Cénozoïque, Formation rift, Point chaud, Rift Baïkal.

ABSTRACT

Based on the variation in space and time of the composition of rift-related volcanic rocks in the Trans-Baikal region, the Cenozoic deep-seated processes are shown to be inherited from the tectonic and magmatic activity during the Mid-Paleozoic to Mesozoic. The Eastern Siberia rift system is divided into three groups of rift basins : the Tunka-Eravna group with associated volcanics formed in the Late Cretaceous to Mid-Cenozoic, and the essentially non-volcanic Baikal-Chara and Khubsugul-Darkhat groups which formed during the Late Cenozoic. Although development of the Eastern Siberia rift system was contemporaneous with the Indian-Asian collision, the relative rotation of terranes separated by the Baikal-Chara group of rift basins around the pole at its northeastern termination, indicates that extensional forces were local.

A hot spot model which proposed to explain the geodynamics within the Eastern Siberia rift system, implies a powerful heat impulse along the southern edge of the Siberian craton from –29 to –12 My (Late Oligocene to Miocene). This was expressed by doming, rifting and vigorous mildly alkaline basaltic volcanism. A migrating sequence of volcanism within the western area of the Khubsugul-Darkhat group might indicate a slow (0.8-0.9 cm/yr) eastward motion of the Eurasian plate overriding a fixed mantle hot plume.

**Key words** : Volcanic rocks, Upper Cretaceous, Cenozoic, Rifting, Rift zones, Hot spots, Baikal rift zone.

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## CONTENTS



## INTRODUCTION

The role of the Indian-Asian collision in the tectonic and magmatic reactivation of Inner Asia has been discussed since the hypothesis of Molnar & Tapponier (1975) was published (Zonenshain & Savostin, 1981; Zonenshain *et al.*, 1990; Kiselev, 1982; Samoylov & Yarmolyuk, 1992; Logatchev *et al.*, 1983; Logatchev & Zorin, 1992; Logatchev, 1993, and others). Volcanism within the Eastern Siberia rift system (ESRS) has also been considered to be due to the collision-related syntectonic decompressive melting of the lithosphere (Kiselev, 1982; Samoylov & Yarmolyuk, 1992). Logatchev *et al.* (1983) suggested that the evolution of the Eastern Siberia rift system was driven mainly by the heating and upwelling of the asthenosphere, rather than being directly caused by a collisional deformation of the lithosphere.

To evaluate the role of various deep-seated processes in the reactivation of the lithosphere, this paper presents a general space-time analysis of rift-related magmatism during the Mid-Paleozoic to Mesozoic, the Late Mesozoic to Mid-Cenozoic, and the Late Cenozoic episodes in the folded terranes, south of the Siberian craton.

Based on available data, an inherited local thermal evolution of the Eastern Siberia rift system is inferred. These data contradict the suggestion that syntectonic magmatic processes were dominant but they support the hypothesis of a plume-derived heating of the asthenosphere which has been active near the southern margin of the Siberian craton at least since the Mid-Paleozoic.

The interpretation of the evolution of volcanism in space and time is based on more than 150 new K-Ar ages recently obtained from all the volcanics of South Siberia. A detailed list will be subsequently published in the Bulletin des Centres de Recherches Exploration-Production Elf Aquitaine (Bagdasaryan *et al.*, 1983; Baturina & Ripp, 1984; Endrichinsky, 1991; Kononova *et al.*, 1988; Rasskazov, 1993; Rasskazov *et al.*, 1992; Rezanov, 1991, and others).

## 1. — MID-PALEOZOIC TO MESOZOIC RIFT-RELATED MAGMATISM AS A PRECURSOR TO THE CENOZOIC RIFTING

Voluminous basaltic volcanism was widespread in the Devonian rifted areas which stretched for more than 2000 km along the southwestern and southeastern edges of the Siberian craton (Luchitsky, 1960; Gordienko, 1987). During the Carboniferous and Permian, the volcanics to the southwest of the craton differed from those to the southeast in terms of both their volume and composition. To the southwest, only sparse dikes of basalt, trachyte, rhyolite and lamprophyre and a few intrusions of granite have been mapped (Rasskazov, 1993). To the southeast, a more voluminous magmatism of a variable composition was active during the Late Paleozoic as well as the Mesozoic (Litvinovsky *et al.*, 1989; Zonenshain *et al.*, 1990).

In the vast southeastern Trans-Baikal area, Mesozoic volcanism was related to rifting (Florensov, 1960) similar to that of the Basin and Range Province, western USA (Zonenshain *et al.*, 1990). Some authors (Komarov *et al.*, 1984; Ermikov, 1994) have emphasized that the uplift had a leading role and they argue that an orogeny took place during the Mesozoic. Recent K-Ar dating (Bagdasaryan *et al.*, 1983; Baturina & Ripp, 1984; Kazimirovsky & Goreglyad, 1989; Rasskazov *et al.*, 1992) show that the change in composition of the lavas through time was confined to four major episodes :

- Triassic (about 240 My) : differentiated mugearite to trachyte lavas,
- Early to Mid-Jurassic (200-159 My) : voluminous trachybasalt lavas,
- Late Jurassic to Early Cretaceous (162-133 My) : differentiated trachybasalt to trachyte lavas,
- Early Cretaceous (120-100 My) : small granite intrusions with associated trachybasalt lavas.

## 2. — EVOLUTION IN SPACE AND TIME OF CENOZOIC RIFT-RELATED VOLCANIC ACTIVITY

Volcanic activity in the many Cenozoic volcanic fields of the Eastern Siberia rift system started in the Late Cretaceous-Paleocene (Logatchev, 1974; Bagdasaryan *et al.*, 1983; Rasskazov *et al.*, 1992) and most of the volcanic activity in

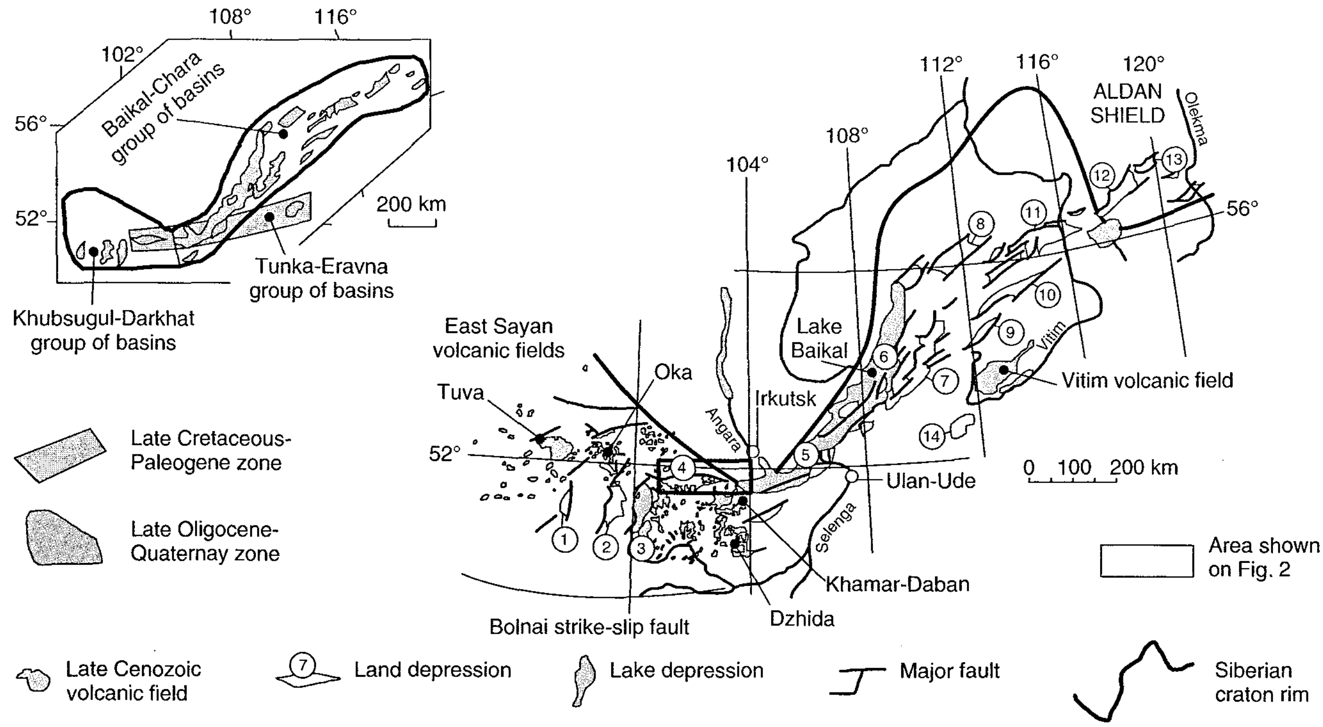


Figure 1

General structural setting of the Eastern Siberia rift system (from Logatchev, 1993, modified).
Numbered circles – rift basins : ① Busingol; ② Darkhat; ③ Khubsugul; ④ Tunka; ⑤ South Baikal; ⑥ North Baikal; ⑦ Barguzin; ⑧ Upper Angara; ⑨ Tsipa; ⑩ Baunt; ⑪ Muya; ⑫ Chara; ⑬ Tokko; ⑭ Eravna.

*Schéma structural général du système du rift est-sibérien (d'après Logatchev, 1993, modifié).*
*Les numéros cerclés correspondent aux bassins de rift : ① Busingol; ② Darkhat; ③ Khubsugul; ④ Tunka; ⑤ Sud Baïkal; ⑥ Nord Baïkal; ⑦ Bargazin; ⑧ Haute Angara; ⑨ Tsipa; ⑩ Baunt; ⑪ Muya; ⑫ Chara; ⑬ Tokko; ⑭ Eravna.*

those times occurred in the Tunka-Eravna group of basins (TEGB), comprising the large Tunka, South Baikal and Eravna basins.

The essentially non-volcanic Late Oligocene-Quaternary basins of the Eastern Siberia rift system as described by Logatchev (1993), are divided into two groups :

— the Baikal-Chara group of basins (BCGB), comprising the North Baikal, Barguzin, Upper Angara, Tsipa, Baunt, Muya, Chara and Tokko basins,

— the Khubsugul-Darkhat group of basins (KDGB), comprising the N-S trending Busingol, Darkhat and Khubsugul basins, the W-E trending Tunka rift valley and smaller basins in East Sayan (Fig. 1).

## 2.1. LATE CRETACEOUS TO PALEOGENE VOLCANISM

Volcanic activity in the Trans-Baikal region was related to the Late Cretaceous-Paleogene elements of the Eastern Siberia rift system, namely the Tunka, South Baikal and Eravna basins. In the Tunka basin, the 60 m of basaltic lava interbedded with sediments were formed (Logatchev, 1974; Kashik & Masilov, 1994).

Volcanic eruptions at the beginning of the Oligocene (about 35 My) produced lavas outcropping on the Elovsky spur - on the heights between the Tunka and Tory basins (Fig. 2). South of the Tunka valley, Paleogene basalts (61-29 My) occur in the Dzhida river area and as outliers on the Khamar-Daban ridge.

In the South Baikal basin, no lavas were encountered in the 3 000 m-deep well in the Selenga delta, which bottomed in Eocene sediments. Volcanics could be present in the undrilled Paleocene-Upper Cretaceous section which is estimated to be almost 3 km thick (Logatchev, 1974). The Late Cretaceous and Paleogene volcanics have been mapped 100-200 km south of Lake Baikal. Their K-Ar ages are from 72 to 25 My (Bagdasayan *et al.*, 1983; Kononova *et al.*, 1988; Endrichinsky, 1991; Rezanov, 1991).

In the Eravna basin, almost 250 m of Late Cretaceous and Paleocene-Eocene sediments and volcanics have accumulated. The volcanics are located in the upper part of the sequence. Late Cretaceous and Paleogene volcanics also outcrop on the Vitim plateau to the northeast of the Eravna basin (Fig. 3).

## 2.2. LATE OLIGOCENE - QUATERNARY VOLCANISM

Late Cenozoic rifting in the BCGB and KDGB and the related magmatism was partially superimposed on the Tunka-Eravna rift zone.

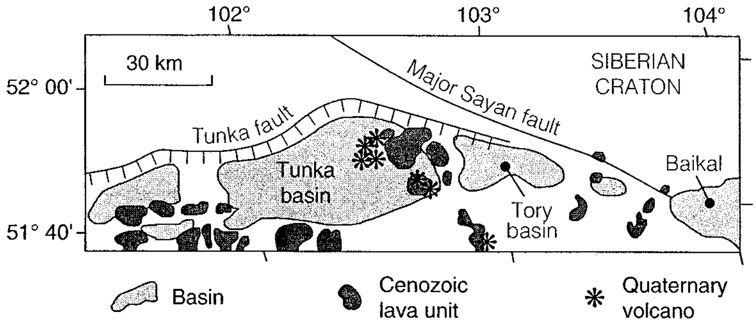


FIGURE 2

Distribution of volcanics in the Tunka rift valley (for location, see Fig. 1).

*Répartition du volcanisme dans la rift-vallée de Tunka (pour la localisation, voir Fig. 1).*

2.2.1. 29-24 My (Late Oligocene)

Late Cenozoic rifting initiated towards the end of the Oligocene (LOGATCHEV *et al.*, 1983; LOGATCHEV & ZORIN, 1992). This started with doming at both ends of the future Baikal basin. Simultaneously, large basins began to subside and fine-grained sediments to accumulate.

In the Eravna basin, volcanism was quiescent but continued in the Vitim volcanic field, on the southern part of the Barguzin-Ikat domal uplift. Similarly, volcanism terminated in the south of the Baikal basin but resumed on and to the west of the Khamar-Daban dome. (Fig. 4).

2.2.2. 23-17 My (Early Miocene)

In the Early Miocene the western and northeastern ends of the Eastern Siberia rift system developed differently. The uplift of the northeastern termination migrated northeastwards from the Barguzin-Ikat dome as the Vitim river dissected the area. The southwestern termination migrated to the northwest along the southwestern edge to the Siberian craton, thus significantly widening the rift system. The Belsky domal uplift was formed near the craton edge, and was dissected by the Oka river. Basins with infills of up to 100 m of lacustrine sediments were formed on these terminal domes.

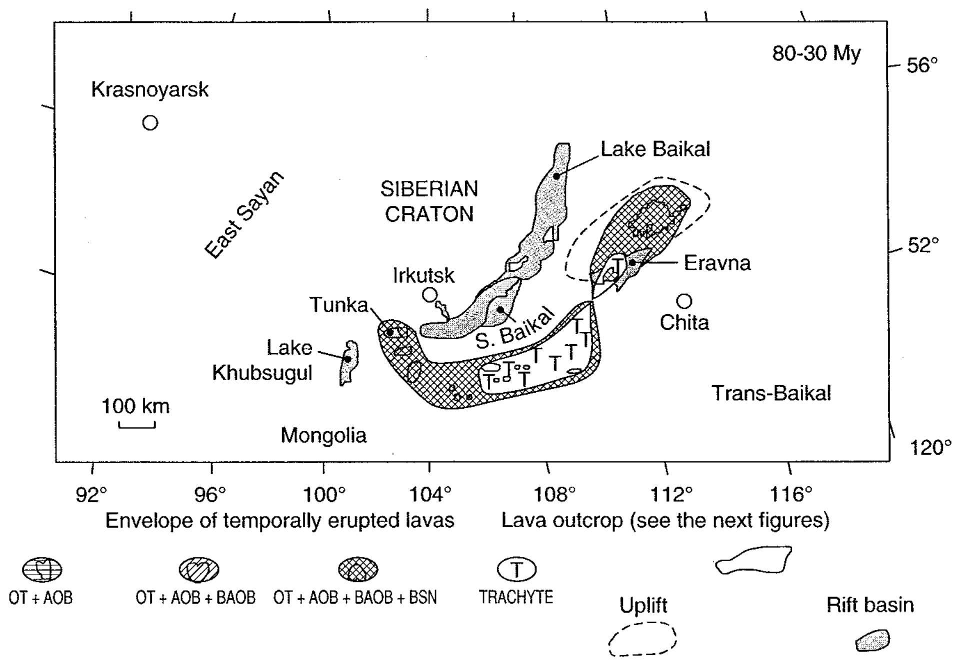


FIGURE 3

Late Cretaceous to Paleogene rift basins in South Siberia (from LOGATCHEV, 1974) and volcanic fields.
Rock types : OT : olivine tholeiite; AOB : alkali olivine basalts; BAOB : basanitic alkali olivine basalt (nepheline 5-8 %); BSN : basanite (nepheline 8-20 %); T : trachyte.

*Bassins de rift du Crétacé supérieur au Paléocène dans le sud de la Sibérie (d'après LOGATCHEV, 1974) et terrains volcaniques. Types pétrographiques : OT : tholéiite à olivine; AOB : basalte alcalin à olivine; BAOB : basalte basanitique alcalin à olivine (5-8 % de néphéline); BSN : basanite (8-20 % de néphéline); T : trachyte.*

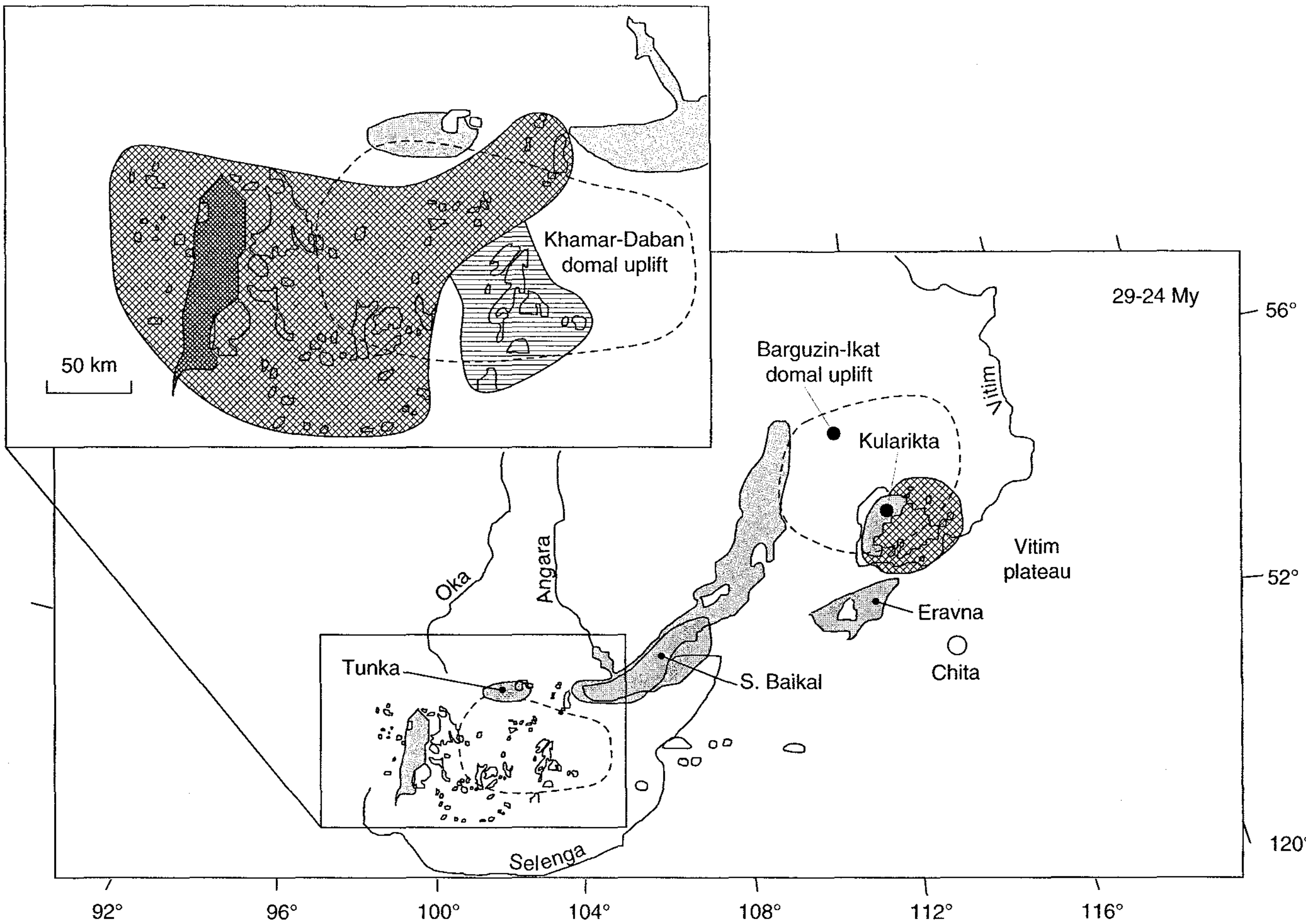


FIGURE 4

Variations in composition of the lavas and location of the basins and uplifts during the Late Oligocene (for legend, see Fig. 3).
*Variation de composition des laves et positions des horsts et des bassins à l'Oligocène supérieur (pour la légende, voir Fig. 3).*

At the northeastern end of the Eastern Siberia rift system, Early Miocene lavas are rare, and have only been dated in the northwestern part of the Vitim volcanic field. In the southwest, volcanism not only continued on the Khamar-Daban dome but was initiated on the Belsky dome (Fig. 5).

### 2.2.3. 16-12 My (Mid-Miocene)

As the rift system grew into the west and northeast during the Mid-Miocene, the uplifts were deeply dissected by river systems. To the northeast, after uplift and dissection, volcanism restarted on the Vitim plateau. At the same time, volcanic eruptions began on the Udokan range (Fig. 6).

To the west, the volcanic areas increased both by the continued expansion of the active volcanic fields in the Eastern Sayan and by the initiation of eruptions in Tuva (Fig. 6). The Mid-Miocene lavas all buried a deeply-dissected relief (Fig. 7), resulting in a general levelling-out of the relief in the volcanic areas.

### 2.2.4. 11-8 My (Late Miocene)

During the first half of the Late Miocene, lacustrine sediments were widespread and intercalated with basalt lavas (Fig. 7) (perhaps due to the local damming of watercourses by lava-flows). On the Vitim plateau and Udokan range, eruptions took place within the limits of former volcanic fields. In the KDGB, the area of volcanics was reduced. Eruptions continued in the Tunka basin and to the south of it, on the Khamar-Daban ridge. Volcanism also occurred in the Oka river basin (Fig. 8).

### 2.2.5. 7-0 My (Pliocene-Recent)

The progressive uplift of the terminations of the Eastern Siberia rift system was complicated by the formation of a number of intramontane saddles and basins. As previously, to the northeast, volcanic activity was concentrated on the Vitim and Udokan volcanic fields. It is noteworthy that volcanics are absent from the BCGB. The volcanic area increased to the west.

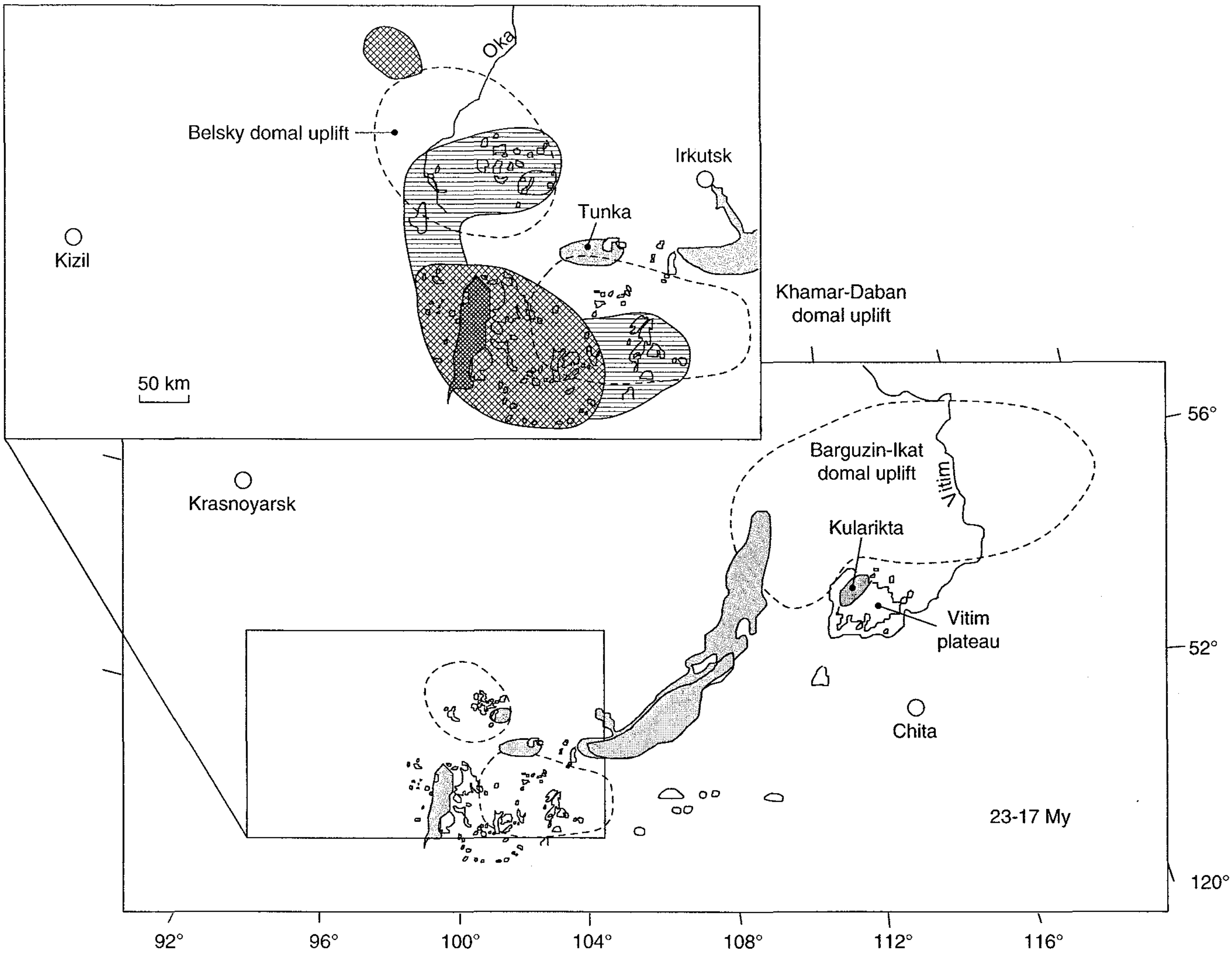


FIGURE 5

Variations in composition of the lavas and location of the basins and uplifts during the Early Miocene (for legend, see Fig. 3).
*Variation de composition des laves et positions des bassins et des horsts au Miocène inférieur (pour la légende, voir Fig. 3).*

## 3. — COMPOSITIONAL VARIATIONS OF CENOZOIC VOLCANICS IN SPACE AND TIME

The Cenozoic volcanics of South Siberia differ from the Mid-Paleozoic to Mesozoic rift-related lavas and dikes, in terms of both major and trace elements (RASSKAZOV, 1993). In the following, the nomenclature used is based on modal mineralogy; total alkali-silica diagrams and CIPW normative compositions are used (GONSHAKOVA, 1985; LE BAS, 1989; LE BAS & STRECKEISEN, 1991).

The predominant varieties of the Cenozoic volcanics are ol-hy- normative basalts (olivine tholeiites) and basalts with 0-5 % of normative ne (alkali olivine basalts and hawaiites). The latter are related to basanites (8-20 % ne), olivine melaleucites and melanephelinites (ne + lc > 20 %). Silicic alkali olivine basalts (ol-hy- normative, $SiO_2$ 50-54 wt %) and qz- normative tholeiites ($SiO_2$ 47-49 wt %) are of relatively minor importance in the studied volcanic fields. Moderately and highly alkaline differentiated series evolve respectively from alkali olivine basalt and hawaiite through mugearite and benmoreite to trachyte and from basanite to melaphonolite.

### 3.1. LATE CRETACEOUS - PALEOGENE VOLCANISM

Development of the Tunka and Eravna rifts, during the Late Cretaceous to Paleogene was accompanied by eruptions of lava which show a wide range of compositions similar to those shown by the younger volcanic rocks of the Eastern Siberia rift system. A moderately alkaline differentiated series, comprising alkali olivine basalt to trachyte, is a characteristic of the central-eastern part of the TEGB – the oldest part of the Eastern Siberia rift system. Olivine tholeiites, alkali olivine basalts, and basanites have been found along its entire length. The basanites contain inclusions of mantle material.

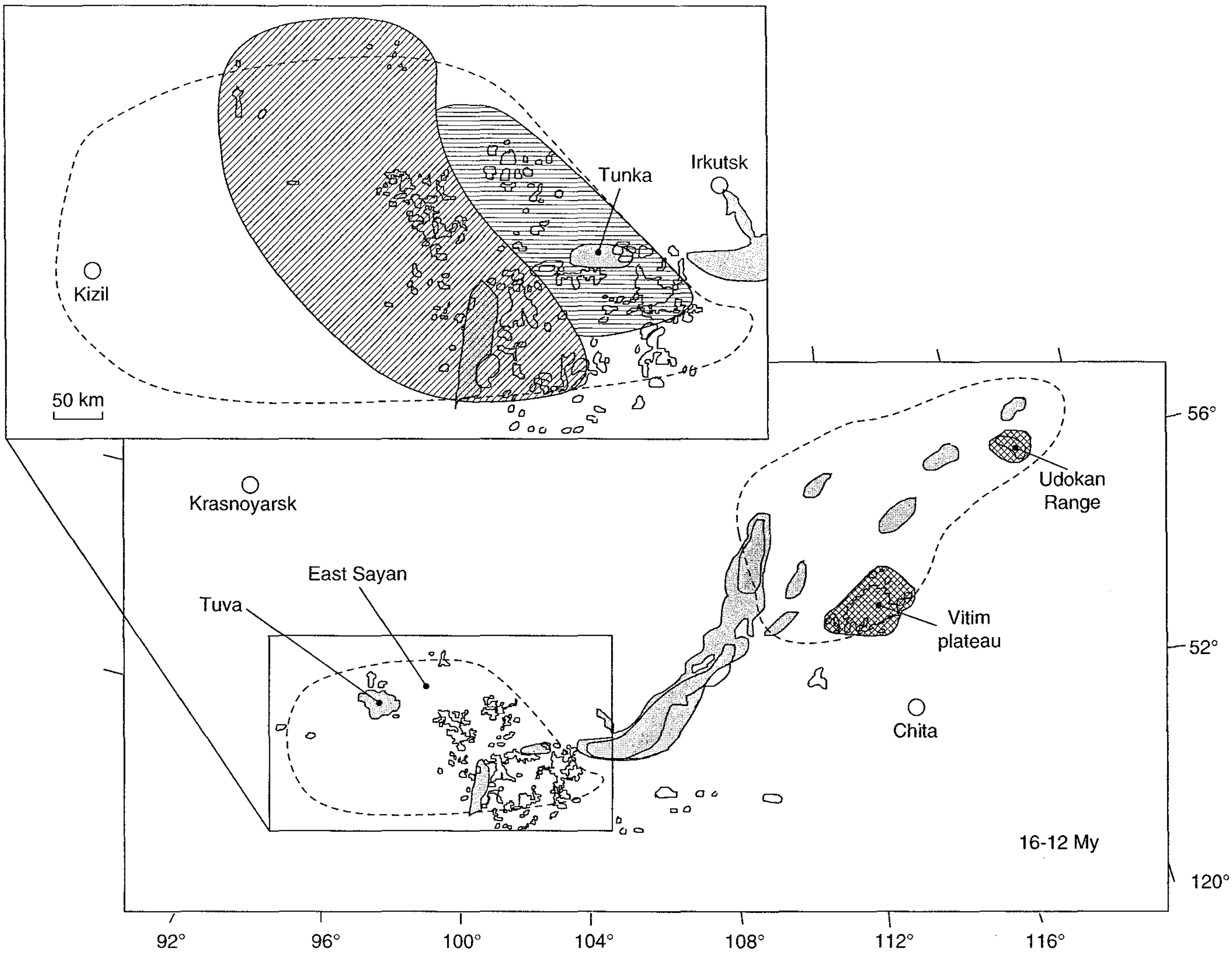


FIGURE 6

Variations in composition of the lavas and location of the basins and uplifts during the Mid-Miocene (for legend, see Fig. 3).
*Variation de composition des laves et positions des bassins et horsts au Miocène moyen (pour la légende, voir Fig. 3).*

## 3.2. LATE OLIGOCENE – QUATERNARY VOLCANISM

From the beginning of the formation of the Eastern Siberia rift system, variations in lava composition through space and time apparently reflect features of the precursor Mesozoic tectonic and thermal regime and also reflect the changes in the structural evolution of the rift system terminations.

### 3.2.1. Western part of the Eastern Siberia rift system (ESRS)

During the Late Oligocene – Early Miocene uplift of the Khamar-Daban dome, magmatism showed the inherited characteristics of the previous stage. Olivine tholeiites and alkali olivine basalts erupted in the area of Early-Mid-Cenozoic volcanics, in the Dzida river basin and the Khamar-Daban range. In contrast, new volcanic fields developed between Lake Baikal and Lake Khubsugul. These are characterized by more undersaturated basanitic alkali olivine basalts.

The uplift of the Belsky dome (Fig. 5) was accompanied by the eruption of olivine tholeiites and alkali olivine basalts. Rare qz-normative tholeiites also erupted. Basanites dated 20 My occur in the northwestern part of the dome.

During the Mid-Miocene, a zone of olivine tholeiite and alkali olivine basalt lavas stretched along the southwestern edge of the Siberian craton, with widespread basanitic alkali olivine basalts to the west.

Besides a marked reduction in the volume of lavas (reflected by a reduction in area), the Late Miocene was most remarkable for the change in the composition of the lavas, in that the alkali content drastically increased. Many of the alkaline lavas erupted after 11 My (Late Mid-Miocene) also contain mantle inclusions.

In terms of the distribution of the moderately and highly alkaline magmatism from the Late Miocene to Quaternary, a zonation which is generally concentric to the margin of the Siberian craton can be distinguished (Fig. 9). In the central part, lava composition varies from olivine tholeiites and

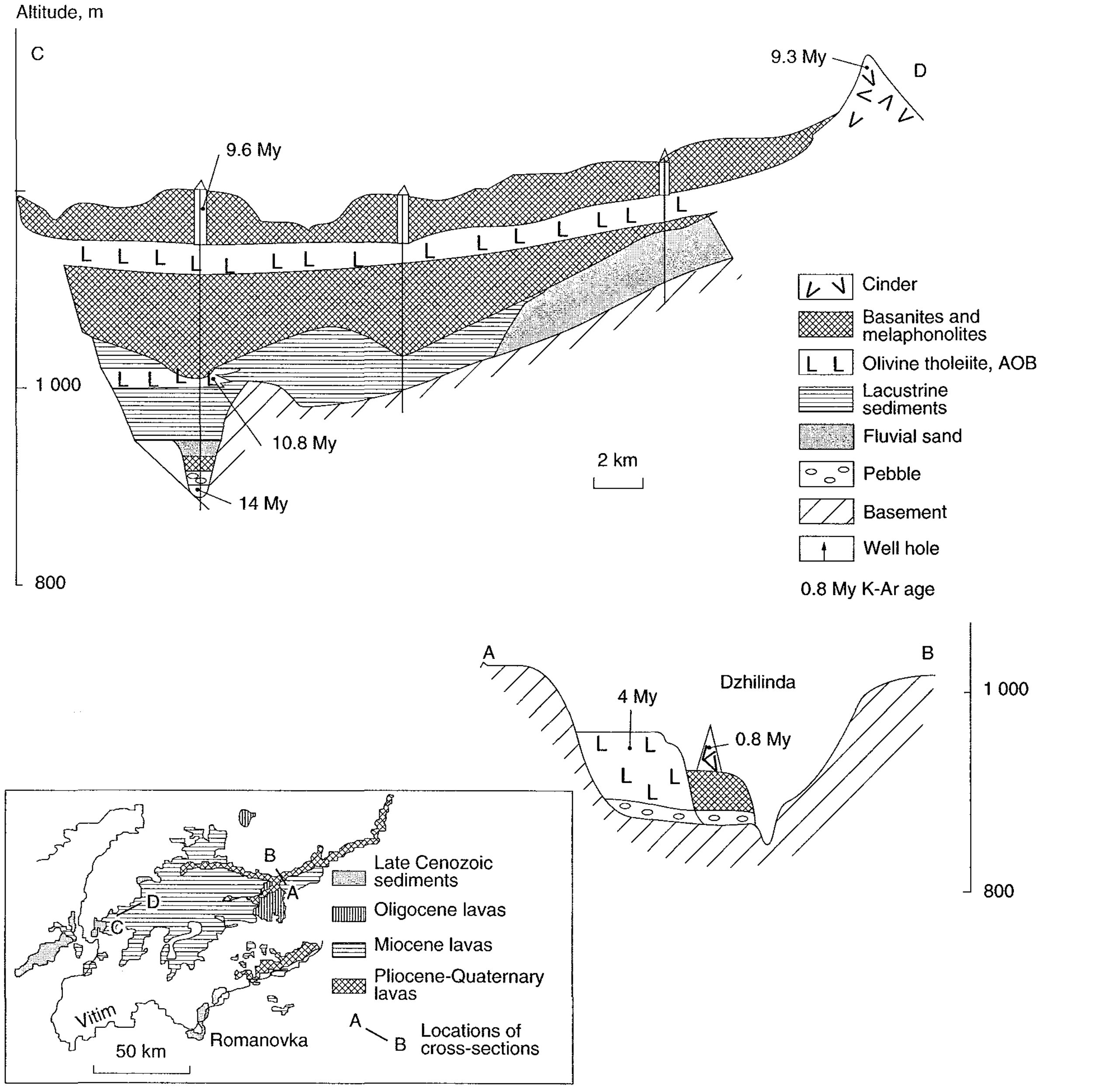


FIGURE 7

Cross-sections of Pliocene-Quaternary (A-B) and Mid-Upper Miocene volcanics (C-D) of the Vitim plateau (for location, see Fig. 6).

*Coupes transversales des appareils volcaniques du Vitim plateau au Plio-Quaternaire (A-B) et au Miocène moyen-supérieur (pour la localisation, voir Fig. 6).*

silicic alkali to basanitic alkali olivine basalts. The only locality of more undersaturated basanites in this inner zone is in the Eastern Tuva volcanic field. In the outer parts of the western ESRS, basanites and their derivatives are widespread.

### 3.2.2. Northeastern part of ESRS

In the northeastern area, a characteristic feature of the Late Miocene and post-Late Miocene magmatic episodes is that a wide variety of differentiated lavas with a highly alkaline magmatism played a more significant role (in contrast to the western area, where moderately alkaline magmatism predominated). On the other hand, many alkaline lavas of the Udokan and Vitim volcanic fields which erupted after 11 My, contain deep-seated inclusions as do those in the western area.

Like the Lower-Mid-Cenozoic volcanics, those which erupted during the Late Cenozoic vary in composition from olivine tholeiites to basanite. At the end of the activity of the western Vitim volcanic field, at about 9-8 My (Late Miocene), melaphonolitic lavas erupted. An increase in

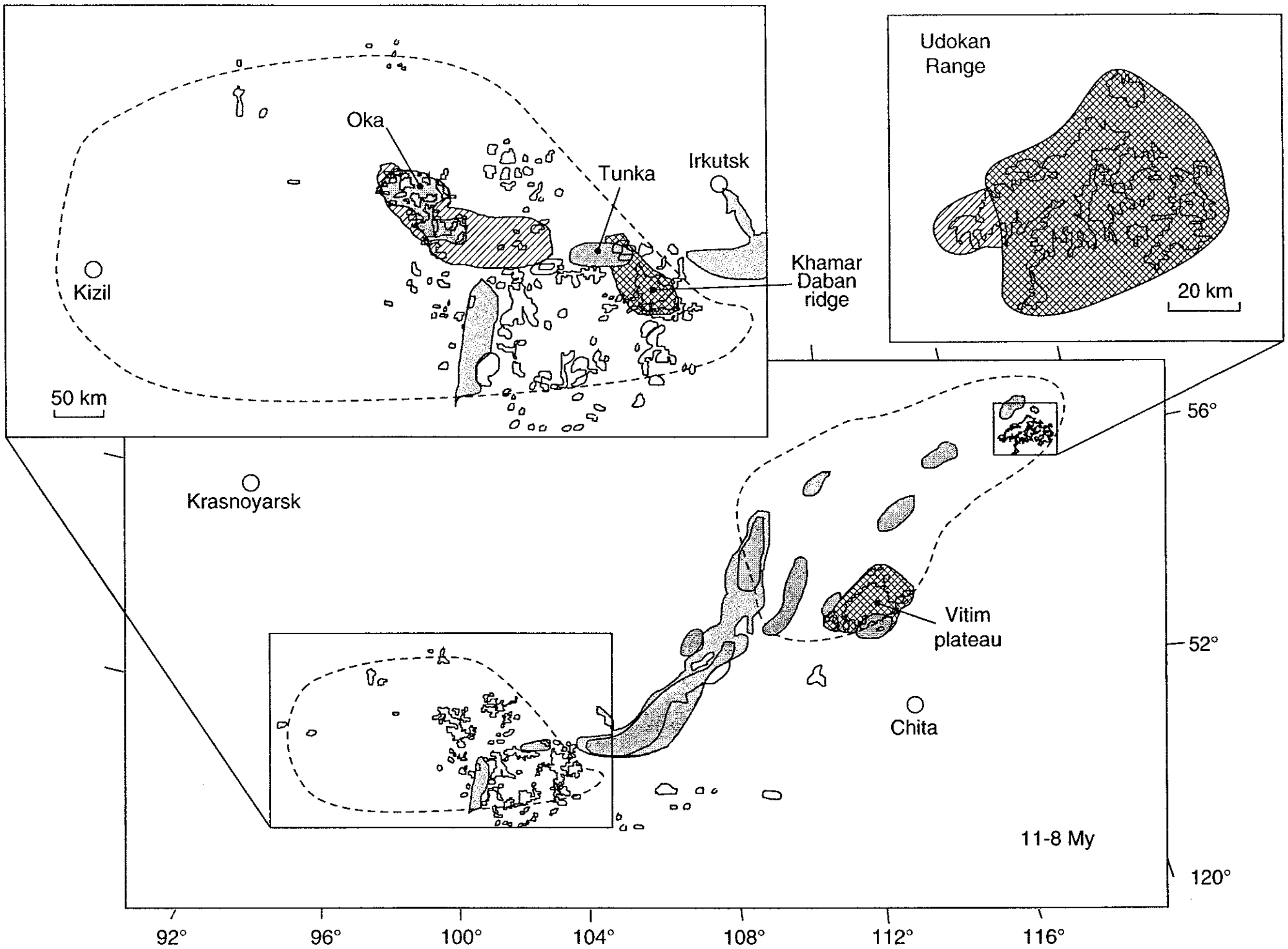


FIGURE 8

Variation in composition of the lavas and location of the basins and uplifts during the early part of the Upper Miocene (for legend, see Fig. 3).

*Variation de composition des laves et position des bassins et horsts au Miocène supérieur (pour la légende, voir Fig. 3).*

explosive volcanism resulted in the formation of a large number (about 70) of cinder cones. During the Pliocene and Quaternary rejuvenation of volcanism in the northeastern volcanic field, alkali olivine basalts were followed by basanitic and melaphonolite lavas (Fig. 7).

Differentiated lavas in the Udokan volcanic field show a greater variation than in the western zone, with both highly and moderately alkaline series, basanite-melaphonolite and alkali olivine basalt – trachyte respectively (KISELEV *et al.*, 1978; RASSKAZOV, 1985; STUPAK, 1987). Trachytic volcanic centres are concentrated in lineaments which trend SW-NE in the southeastern part, but in the centre and to the west, they trend E-W (Fig. 9).

The major cause of these drastic lateral changes in lava compositon of the Udokan ridge is probably due to a magmatic evolution taking place under an active complex strike-slip and a normal faulting regime. Olivine tholeiites are rare in this volcanic field and are only found in the northeastern part of the area. In the northern part, eruptions began with outpourings of hawaiites, followed by Na-rich basanites and olivine mela-nephelinites. In the final stages, K-rich olivine mela-leucitites erupted (STUPAK, 1987). In the central part, Na-rich highly alkaline lavas predominated but, in the western part, no basanite with ne > 8 % was found. In the latter area, lavas are represented by a moderately alkaline series (alkali olivine basalt and basanitic alkali olivine basalt to trachyte).

## 4. — DISCUSSION

### 4.1. THE ROLE OF INHERITANCE IN THE EVOLUTION OF RIFTING AND MAGMATISM

In the Trans-Baikal region, a magmatic lull between 100 and 70 My was contemporaneous with the transition from the Mesozoic to Cenozoic stage of rifting (for a discussion of the Mesozoic phase, refer to ERMIKOV, 1994). During this episode, the crust was probably affected by compression

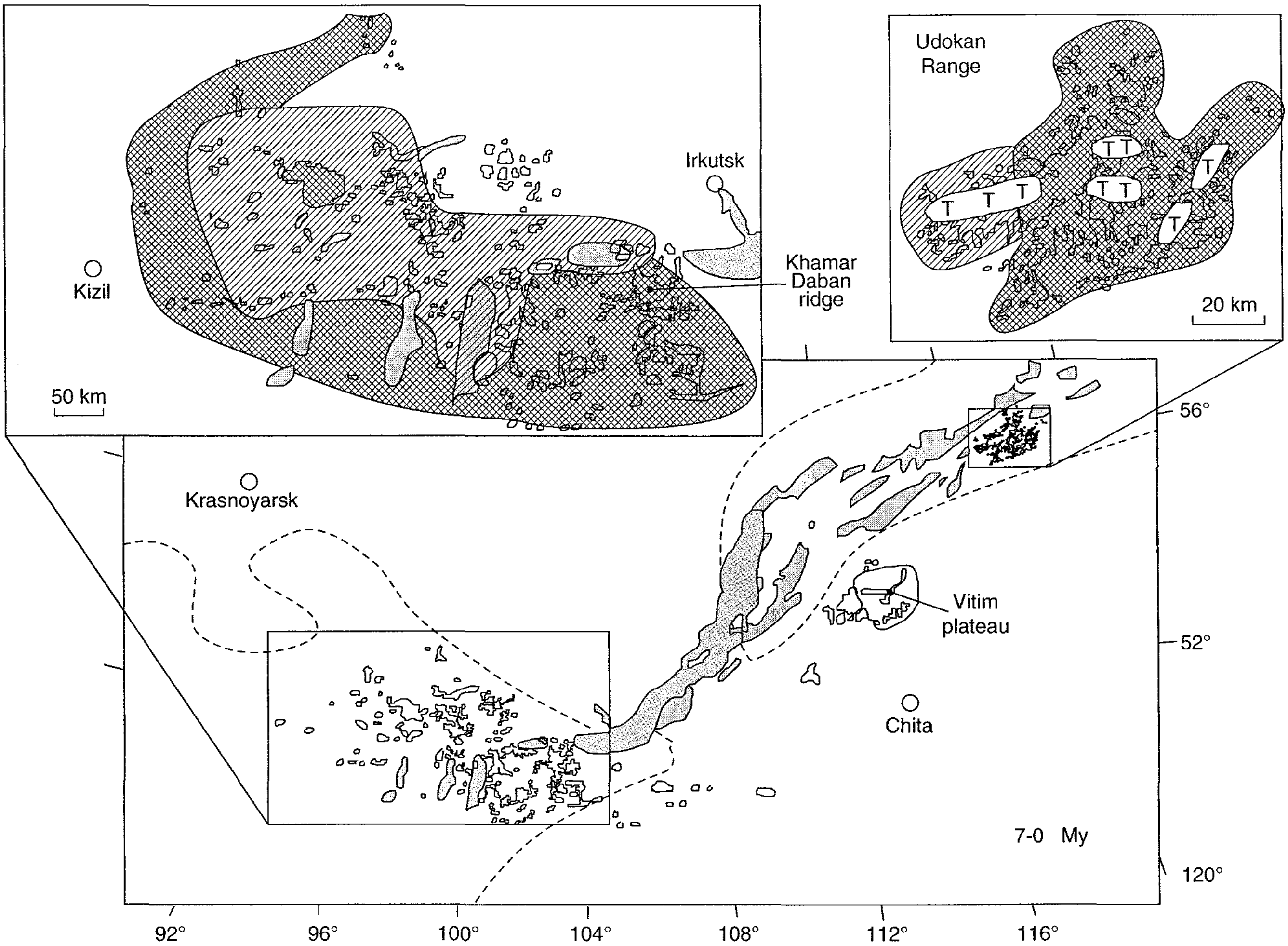


FIGURE 9

Variation in composition of the lavas and location of the basins and uplifts during the last part of the Upper Miocene (for legend, see Fig. 3).

*Variation de composition des laves et position des bassins et horsts au Miocène terminal (pour la légende, voir Fig. 3).*

and thrust faulting (FLORENSOV, 1960). During the Cenozoic, the crust underwent extension, having as its ultimate expression the formation of the deepest basins of the central Eastern Siberia rift system.

The lack of sedimentation during the Late Cretaceous – Mid-Cenozoic, throughout the Eastern Siberia rift zone suggests a pre-orogenic phase in this area (LOGATCHEV, 1974; KASHIK & MAZILOV, 1994). The evolution of Cenozoic basaltic magmatism in space and time is also consistent with the Late Cretaceous—Mid-Cenozoic and Late Cenozoic stages of rifting. The former is represented by the Tunka-Eravna rifts which trend roughly E-W, and the latter by the NE-SW trend of the rifting of the BSGB which is partially restricted to the edge of the Siberian craton. The South Baikal basin which overlaps the axial basin of the Tunka-Eravna rift zone is, in fact, the oldest Cenozoic rift basin (LOGATCHEV, 1993).

Unlike in the Baikal and Trans-Baikal areas, Cenozoic magmatism and rifting in the East Sayan followed a period of relative tectonic stagnation and a lack of any mantle-derived magmatism. In the southwestern part of the area, the magmatic lull lasted as long as 300-360 My. During the Late Cretaceous to Mid-Cenozoic, tectonic and magmatic activity were not significant and the Late Cenozoic rifting only affected the extreme southeasterly part of East Sayan with a propagation of the Eastern Siberia rift system from its central part towards the west.

## 4.2. STRUCTURAL CONTROL OF VOLCANISM

One of the most striking features of the Late Cenozoic volcanism is its southwards shift relative to the BSGB – towards Vitim and Udokan (Fig. 8 and 9). This shift of volcanism with respect to the axial basins is explained either by a directed, under-lithospheric flow of heated mantle material (ZORIN, 1971), or by a tectonic control of magma ascent by low-angle detachment zones in the crust (BOSWORTH, 1987; KAZMIN, 1991). In the KDGB – the southwestern zone of the Eastern Siberia rift system, the width of the volcanic area increases to the north and south. The basins of the KDGB display complex structures with changes of polarity accommodation zones. Some of the latter are thought to control the location of volcanic fields (RASSKAZOV, 1993). Thus, the Eastern Siberia rift system is characterized by a fundamental structural change along its strike.

The basins of the BSGB have uniform asymmetry with steep northwestern and more gentle southeastern shoulders showing a tendency to half grabens with major faults down to the southeast. The only exception is an area of the Baunt, Tsipa and small Amalat basins buried beneath basalts of the Vitim volcanic field. These basins show reverse structural polarity (RASSKAZOV & IVANOV, 1994) (Fig. 1).

Towards the end of the Late Cretaceous-Paleogene Tunka-Eravna group of rifting, the volcanism shifts in opposite directions – to the south of the Tunka and South Baikal basins and to the north of the Eravna basin (Fig. 3). The latter is adjascent to the Baunt-Tsipa-Vitim group of basins with reverse structural polarity and is considered to be an element with the same structural features. Since the different structural polarity of the South Baikal and Eravna basins is consistent with the shift of the volcanism, it is possible that, during the Late Cretaceous-Paleogene, the Eravna termination of the rift zone was connected with the South Baikal basin through the intervening accommodation zone.

## 4.3. GEODYNAMICS

### 4.3.1. Role of Indian-Asian collision

The major episode of collision between the Indian and Asian lithospheric plates was demonstrated by the compression and metamorphism of the Himalayan rocks at about 55-50 My – Lower Eocene (TRELOAR & COWARD, 1991). The compressional phase was followed by an extension which initiated in Inner Asia between 40 and 25 My – Upper Eocene to Lower Miocene (CHAMBERLAIN *et al.*, 1991). This period corresponds to the beginning of the shift of volcanic activity from the central Eastern Siberia rift system to the west and northeast and the initiation of the lateral extension of the rifting.

Focal-mechanism solutions of a large number of recent small earthquakes show that the present-day maximum horizontal stress has an overall radial orientation which extends from the Indian-Asian collision zone through China, Tibet and Mongolia up to the Baikal area (ZOBACK, 1992; ZHONGHUAI *et al.*, 1992). The collision evidently affected the local stress field in Inner Asia. This influence was probably manifested by strike-slip faulting being superimposed on a normal-faulting regime in the Eastern Siberia rift system (MOLNAR & TAPPONIER, 1975; SHERMAN, 1992; RASSKAZOV, 1985, 1993).

However, all aspects of the evolution of the rift system can not be explained by a "passive rifting" hypothesis. For example, it is difficult to explain the migration of volcanic activity and the zonation of lava composition in the southwestern Eastern Siberia rift system by the suggested syntectonic origin of magmatism in the lithosphere (KISELEV, 1982). It is obvious that magmatism evolution in this area was dominated by the sub-lithospheric processes. A more satisfactory model which takes these observations into account is that of an active upwelling of hot mantle material (LOGATCHEV *et al.*, 1983; LOGATCHEV & ZORIN, 1992; RASSKAZOV, 1993; LOGATCHEV, 1993).

### 4.3.2. The hot spot hypothesis

Hot spots are thought to be initiated with large blobs or "heads" (up to 2 000 km in diameter) of over-heated lower mantle material which ascend from near the core/mantle boundary and which are capable of melting the upper mantle and cause doming, rifting and flood basalts (RICHARDS *et al.*, 1989; WHITE & MCKENZIE, 1989). The path of the blob is followed by a much narrower chimney (hotplume) which supplies hot mantle material into the head. After the head flattens against the base of the lithosphere, which partially melts, the hot plume eventually intercepts the lithosphere. This produces an uplift and a migrating sequence of volcanism in the over-riding plate – a hot spot track (RICHARDS *et al.*, 1989).

According to KRILOV *et al.* (1981) the earthquake data beneath the South Baikal basin can be interpreted as showing the presence of a narrow conduit which joins the Gutenberg wave guide and a low-velocity sub-crustal lense. The continuing subsidence of the basin implies that, during the Cenozoic, hot mantle material might have ascended through this conduit from beneath the asthenospheric mantle. A stable position of a feeding conduit beneath the South Baikal suggests either a lack of absolute motion of the Eurasian plate (SIMKIN *et al.*, 1989) or a very slow absolute motion (RICARD & VIGNY, 1989; GRIPP & GORDON, 1990; WUMING *et al.*, 1992; RICHARDSON, 1992).

On the other hand, the stepwise westward shift of volcanic activity in East Sayan has been interpreted as a hot plume track (RASSKAZOV, 1990, 1993, 1994). This shift may indicate an absolute motion of the Eurasian plate with a slow velocity of 0.8-0.9 cm/yr towards the east which would be in agreement with the direction inferred by RICARD & VIGNY (1989) and WUMING *et al.* (1992).

A plume rose from the lower mantle and, with decompression, melting occurred in its upper levels, probably throughout the Cenozoic. Until the end of the Oligocene, the plume was located beneath the southern edge of the Siberian craton. The thick lithosphere of the craton (estimated at up to 200 km by ZORIN *et al.*, 1989) prevented the plume from rising and thus limited large-scale decompressional melting. Nevertheless, it seems probable that, due to the anisotropic structure of the lithosphere (MELNIKOV *et al.*, 1994), the hot mantle material shifted laterally towards the Baikal and Trans-Baikal area. This resulted in magmatism along the Tunka-Eravna rift zone.

Since an area of active volcanism is considered to be a temporal projection of the deep magmatic source at the Earth's surface, the expansion of an area of volcanism is interpreted as reflecting a relative widening of the deep magmatic region. On the other hand, during the Late Cretaceous to Mid-Cenozoic, the volcanism was reactivated in the limits of older volcanic fields, and can be explained as being due to the deep magmatic region not receiving significant additional heating.

Stepwise expansion of the East Sayan hot spot was apparently initiated due to a drastic increase in heat supply. Between 29 and 17 My (Late Oligocene to Early Miocene), the volcanic area in the southwestern Eastern Siberia rift system was about 30-40 000 km$^2$. Between 16 and 12 My

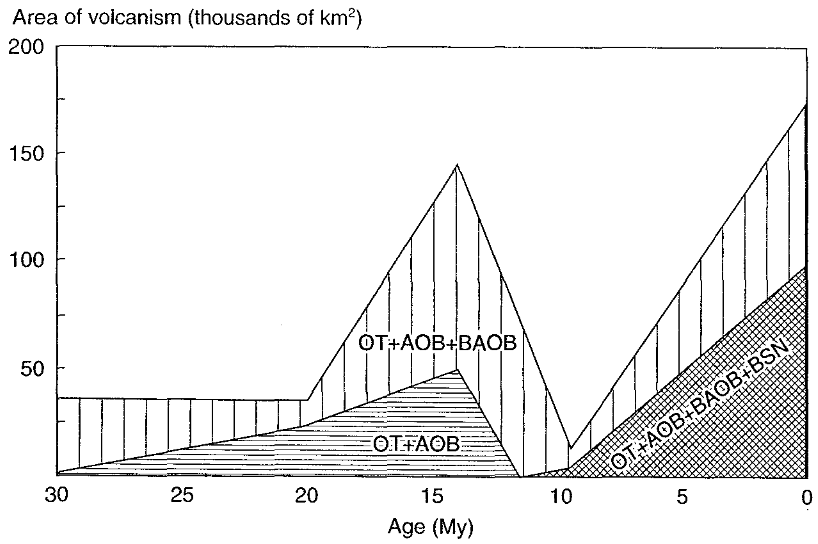


FIGURE 10

Variation in the area of lava flows through time in the southwestern zone of the Eastern Siberia rift system (for legend, see Fig. 3).

*Variation dans le temps des zones d'épanchements des laves dans le sud-ouest du système de rift est-sibérien (pour la légende, voir Fig. 3).*

(Early to Mid-Miocene), it increased by a factor of 4. Between 11 and 8 My (Late Miocene), it decreased by up to 13 000 $km^2$, but during the last 7 My it exceeded 170 000 $km^2$. The most prolific Mid-Miocene outpouring was of moderately alkaline lavas (olivine tholeiite and alkali olivine basalt). During the latest peak of volcanic activity, the role of highly alkaline (basanitic) magmatism increased significantly. Intermediate associations of olivine tholeiite, alkali olivine basalt and basanitic alkali olivine basalt are equally represented during both volcanic peaks (Fig. 10).

The Early-Mid-Miocene peak of moderately alkaline magmatism was apparently related to the period of doming in the early-orogenic stage of the evolution of the Eastern Siberia rift system (LOGATCHEV, 1974, 1993; KASHIK & MAZILOV, 1994). The Late Miocene phase of less voluminous and more alkaline lavas containing mantle inclusions corresponded to the transition from the uplift to the subsidence of the volcanic areas. The Pliocene-Quaternary peak of highly alkaline magmatism was a characteristic of the late-orogenic stage with a transition from "slow rifting" to "fast rifting" in the Eastern Siberia rift system (LOGATCHEV *et al.*, 1983; LOGATCHEV & ZORIN, 1992; LOGATCHEV, 1993)

The inferred eastward shift of the Eurasian plate allowed the plume to migrate across the southwestern suture of the craton; so doming, with concomitant volcanism, began in East Sayan. The track of volcanic migration passes westwards through the Oka plateau which is surrounded by higher ridges. These have a parabolic geometry centred on the Pliocene-Quaternary East Tuva volcanic field, which is interpreted as being the present-day position of the hot plume (Fig. 8). The rift basins occur along the branches of a parabola (Tunka valley, small basins in East Sayan) and stretch radially in its frontal outer part (Khubsugul, Darkhat, Busingol basins). The volcanic fields are located within and outside the parabola, spatially emphasizing its configuration (Fig. 11). The Pliocene-Quaternary basalts are not widespread in the inner part of this structure but occur outside it.

The shape of the high terrain is supposed to have resulted from the temporal delay of the migratory heating of the lithosphere during motion of the plate, and seems to be typical of a hot spot (ANDERS *et al.*, 1989; RASSKAZOV, 1994). Another well-marked shift of volcanic activity was directed to the southeast. This reflected a radial sub-lithospheric flow of the hot mantle material from the hot plume. The radial flow is an attribute to a hot plume model (SLEEP, 1990; BERCOVICI, 1992). In the East Sayan area, the lateral sub-lithospheric flow was controlled by lithospheric extension favorable to magmatism beneath the Tunka rift valley and adjacent areas.

Basanites and their highly alkaline derivatives do not occur in the inner part of the parabolic 'structure' but are widespread outside it (Fig. 9 and 12). These rocks from the southeastern margin of the hot spot (in the Dzhida river basin) are characterized by an epsilon Nd of + 3.2 to + 4.5 and $^{87}Sr/^{86}Sr$ ratios between 0.70400 and 0.70432. In the alkali olivine basalts and olivine tholeiites, epsilon Nd values are lower and Sr isotope ratios are higher (HOUSH *et al.*, 1992). These data show that the basanites are enriched in depleted components, thus implying the partial melting of the lithosphere, mostly in the area beyond the parabolic 'structure'.

Based on the distribution of volcanic activity in space and time, and isotopic and geochemical data, the magmatic evolution in the southwestern zone of the Eastern Siberia rift system can be modelled in terms of heat supply from the mantle plume and melting of the undepleted plume and depleted lithospheric materials. Undepleted molten plume material similar to the subjacent mantle interacted with depleted upper-mantle wall rocks, and induced a small degree of melting. Melts from the plume were mixed with these incipient melts. In the plume and the subjacent mantle, heat supply was sufficient to produce olivine tholeiites and alkali basalts with a high degree of partial melting. The hot material spread radially from the plume beneath the lithosphere, mainly towards the Tunka rift segment where the lithosphere had been attenuated by previous rifting (Fig. 11 and 12). In the remoter parts of the convectively-heated mantle, the proportion of melt from the undepleted plume to that from the depleted lithosphere gradually decreased with time with a relative increase in the proportion of lithosphere-derived magmas. A similar change in magmatic evolution is suggested by CHEN & FREY, (1985) in their model for plume-drived hawaiian basalts; the relative volumes of available molten lithosphere to plume-material increase as a volcanic zone on the over-riding lithospheric plate moves away from the fixed hot plume.

Long-term concentration of Late Cenozoic volcanic activity in the Vitim and Udokan volcanic fields, along with predominantly highly alkaline lavas, might show a relative

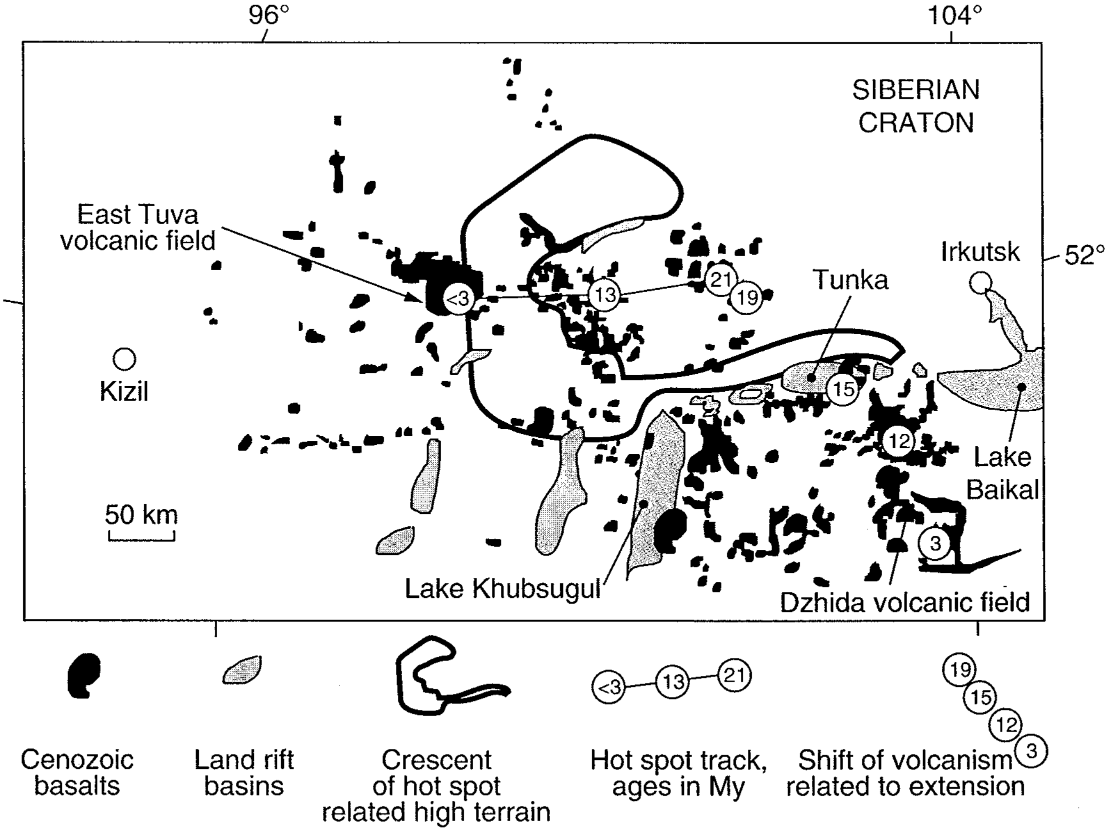


FIGURE 11

Track of hot spot and shift of extension-related volcanism during the Early Miocene to Pliocene in the southwest of the Eastern Siberia rift system.

*Trace du « hot spot » et déplacement du volcanisme d'extension au cours de la période Miocène inférieur-Pliocène au sud-ouest du système de rift est-sibérien.*

increase in the role of lithospheric magmatic processes. Both of these volcanic fields are located on the northeastern margin of the asthenospheric upwelling which is suggested to stretch along the whole length of the Eastern Siberia rift system (ZORIN *et al.*, 1989).

### 4.3.3. Relative rotation of the terranes separated by the Eastern Siberia rift system

It is possible that the actively heated asthenospheric mantle in the southwestern zone has a higher buoyancy than that of the northeastern part. As a result, extension of the lithosphere should increase from the northeast to the southwest, with the concomitant rotation of the separating terranes. As later on shown, the Siberian craton and the adjacent East Sayan area has undergone a clockwise rotation with respect to the Trans-Baikal (Fig. 13). The northeastward decrease in extension, along with a decrease in volcanic activity, reflect an increasing difficulty for magmatic ascent.

A pole of rotation has been calculated using two independent techniques :

- by establishing the direction of the present-day extension obtained from focal-mechanism solutions of earthquakes (ZONENSHAIN & SAVOSTIN, 1981), and
- based on gravity data (ZORIN & CORDELL, 1991).

Both techniques indicate that the pole is located at the northeastern termination of the Eastern Siberia rift system near the Tokko basin.

The very fact that the location of the rotation pole is intimately related to the Eastern Siberia rift system can be considered as confirmation of a local origin for lithospheric extension in the area which bears no relation to the Indian-Asian collision.

## 5. — CONCLUSIONS

Along the southeastern edge of the Siberian craton, Cenozoic rifting and rift-related volcanism followed Mesozoic rifting. During the Cenozoic, the Tunka-Eravna and Baikal-Aldan rift systems (which are sub-systems of the Cenozoic Eastern Siberia rift system) evolved separately.

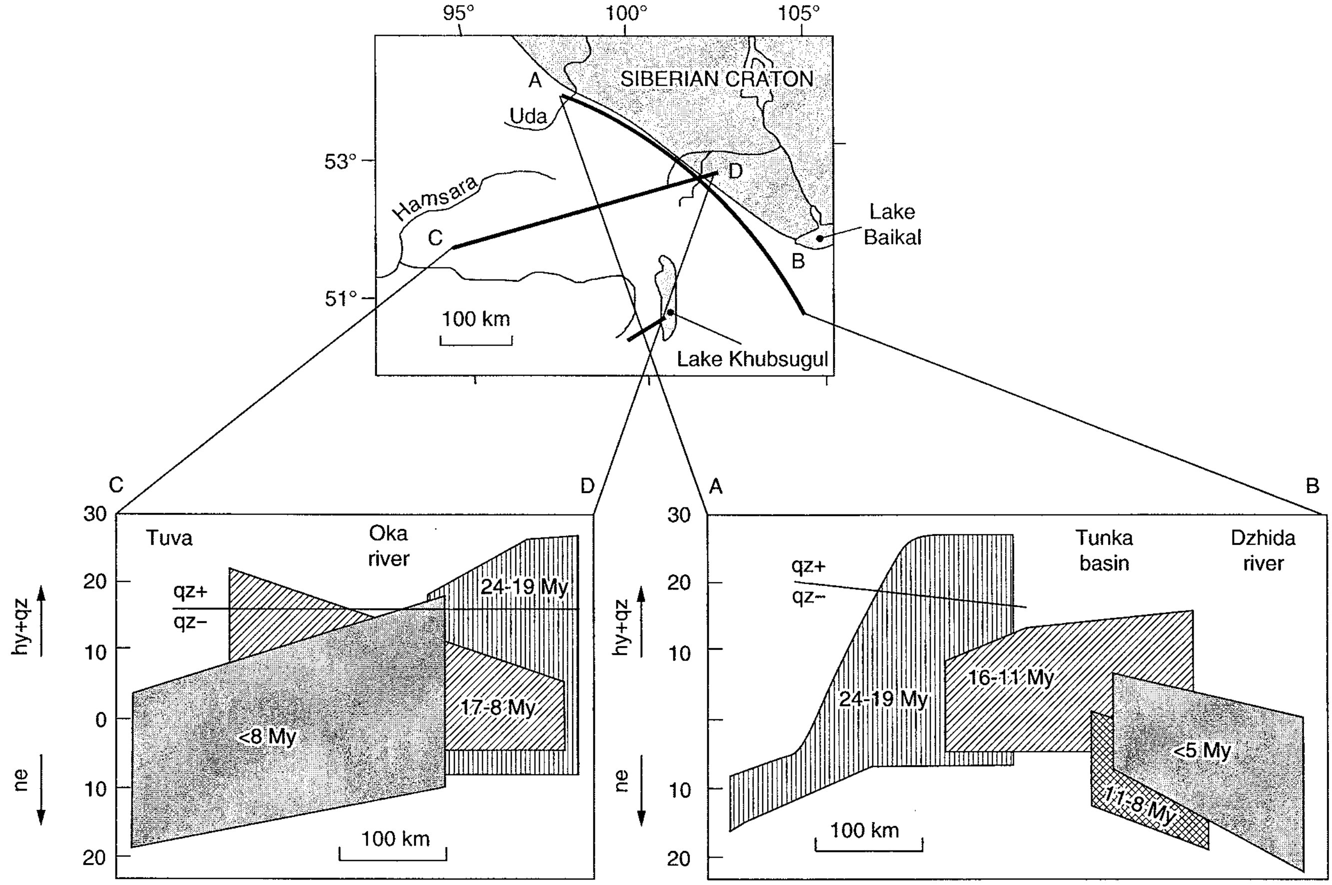


FIGURE 12

Variations in silica saturation-undersaturation in space and time in the southwestern zone of the Eastern Siberia rift system.

*Variation de saturation et sous-saturation en silice dans l'espace et dans le temps, au sud-ouest du système de rift est-sibérien.*

The former system developed in the Late Cretaceous to the Mid-Cenozoic with magmatism limited to that area due to the weak hot plume activity or reflected relict high temperature conditions in the subjascent asthenospheric mantle. The Baikal-Chara rift zone was initiated in the Late Cenozoic when a new impulse of the hot plume reached the southern suture of the Siberian craton in the Late Oligocene to Early Miocene. Due to differences in the thickness of the lithosphere, zonation of the volcanics resulted from the stepwise heating of the sub-Caledonide lithospheric mantle.

From the Late Oligocene to Mid-Miocene, expansion of the hot spot was accompanied by doming and an increase in volcanic activity, which was probably due to the active ascent of material in the hot plume. After the Mid- Miocene, the composition of the volcanics underwent a radical change, with the magmatism of the depleted lithospheric origin playing a greater role.

The greater buoyancy of the more active heated asthenospheric material (manifested by a relative expansion of the volcanic areas) probably resulted in a greater extension of the lithosphere in the western area than in the east and northeast, which in turn resulted in the clockwise rotation of the Siberian craton and the adjacent East Sayan area, relative to the Trans-Baikal region. The rotation pole has been calculated to be at the northeastern termination of the Eastern Siberia rift system (ZONENSHAIN & SAVOSTIN, 1981; ZORIN & CORDELL, 1991) which is thus almost certainly due to local lithospheric movements rather than having any relation to the Indian-Asian collision, 3000 km to the southwest.

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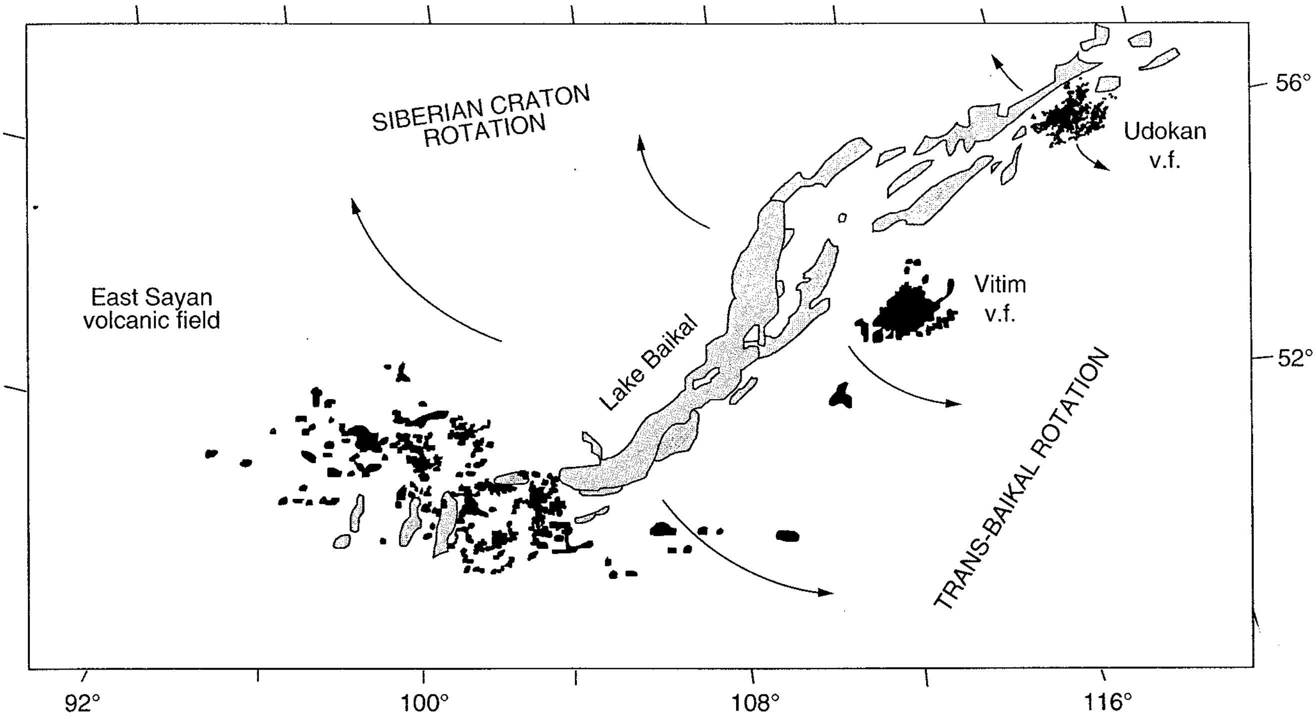


FIGURE 13

Scheme of the relative rotation of the Siberian craton and Trans-Baikal based on focal-mechanism solutions (ZONENSHAIN *et al.*, 1981), gravity data (ZORIN & CORDELL, 1991), and the structural setting of volcanism (this work).

*Schéma de la rotation relative du craton sibérien et du Trans-Baïkal basé sur la solution des mécanismes au foyer (ZONENSHAIN* et al., *1981), les données gravimétriques (ZORIN & CORDELL, 1991) et la position structurale du volcanisme (cette étude).*

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