Bull. Soc. géol. France, 2016, t. 187, n° 1-2, pp. 101-118

Late Jurassic - Early Cretaceous paleoenvironmental evolution of the Transbaikal basins (SE Siberia): implications for the Mongol-Okhotsk orogeny

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Keywords. – Palynology, SE Siberia, Mongol-Okhotsk, Mesozoic topography, Extension

Abstract. – The Late Jurassic - Early Cretaceous tectonic evolution of SE Siberia was marked by the closure of the Mongol-Okhotsk ocean. While this geodynamic event led to compressive deformation and denudation in a wide area encompassing the North-Altay, Sayan and Baikal Patom ranges, it was contemporaneous to widespread extension from the Transbaikal region situated immediately north of the suture zone to the Pacific plate, affecting eastern Mongolia and northeastern China. In this study we review the paleontological and sedimentological data available in the Russian literature and provide new macro-floral and palynological data from the Mesozoic sediments of three Transbaikal basins. These data are used to describe the paleoenvironmental and paleoclimatic evolution of the Transbaikal area in order to assess the topographic evolution of the region in relation with the closure of the Mongol-Okhotsk ocean. We establish that the Transbaikal basins evolved in a continuously extensional tectonic setting from at least the Early-Middle Jurassic to the Early Cretaceous. The associated sedimentary environments are characterized by retrogradation from alluvial fan –braided river dominated systems prevailing during the Early to Middle Jurassic initial opening of the basins to meandering river– lacustrine systems that developed during the Late Jurassic - Early Cretaceous interval. No evidence of high relief topography was found and we conclude that, while compression and denudation occurred in the North Altai, Sayan and Patom ranges, in the Transbaikal region, the docking of the Mongolia-North China continent to Siberia was a "soft collision" event, possibly involving a major strike-slip displacement that did not lead to an orogenic event implying strong compressive deformation, crustal thickening and topography building.

Evolution paléoenvironnementale des bassins du Transbaïkal (SE Sibérie) au Jurassique supérieur - Crétacé inférieur : implications pour l'orogenèse Mongol-Okhotsk

Mots-clés. – Palynologie, SE Sibérie, Mongol-Okhotsk, Topographie mésozoïque, Extension.

Résumé. – L'évolution tectonique du SE de la Sibérie au Jurassique supérieur - Crétacé inférieur a été marquée par la fermeture de l'océan Mongol-Okhotsk. Si cet événement géodynamique a généré une déformation compressive et de la dénudation dans une vaste zone comprenant le nord de l'Altaï, et les chaînes des Sayan et de Baïkal Patom, il est contemporain d'une phase d'extension généralisée depuis la région du Transbaïkal située immédiatement au nord de la zone de suture jusqu'à la plaque Pacifique, affectant l'est de la Mongolie et le nord-est de la Chine. Dans cette étude nous présentons une synthèse des données de paléontologie, palynologie et sédimentologie disponibles dans la littérature russe auxquelles nous ajoutons de nouvelles données de macro-flore et de palynologie dans les sédiments mésozoïques de trois bassins du Transbaïkal. Ces données sont utilisées pour décrire l'évolution des paléo-environnements et du paléo-climat dans la région du Transbaïkal afin d'établir l'évolution topographique de la zone à l'époque de la fermeture de l'océan Mongol-Okhotsk. Nous montrons que la région du Transbaïkal a évolué de manière permanente dans un contexte extensif depuis au moins le Jurassique inférieur à moyen jusqu'au Crétacé inférieur. Les paléo-environnements sédimentaires associés aux bassins montrent une tendance générale rétrogradante depuis des systèmes de cônes alluviaux –rivières en tresses majoritaires au cours de la phase initiale d'ouverture des bassins au Jurassique inférieur et moyen– jusqu'à des systèmes à méandres et lacustres au Crétacé inférieur. Aucune topographie à relief élevé n'a été mise en évidence et nous concluons que, alors que les chaînes du Nord Altaï, Sayan et Baïkal Patom étaient soumises à de la compression et de la dénudation, l'accrétion des blocs Mongolie-Chine du Nord dans la région du Transbaïkal s'est faite par l'intermédiaire d'une « collision douce » potentiellement accommodée par une forte composante en décrochement n'ayant pas entraîné la formation d'un orogène impliquant compression, épaississement crustal et construction de relief.

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Manuscript received on October 27, 2015; accepted on March 19, 2016.

INTRODUCTION

The Mesozoic geodynamic evolution of the Amuria region (SE Siberia - NE Mongolia) was largely controlled by the scissors-like closure of the Mongol-Okhotsk ocean that separated Mongolia from Siberia [e.g. Enkin *et al.*, 1992; Zorin, 1999; Metelkin *et al.*, 2007, 2010; Jolivet *et al.*, 2009; Jolivet 2015]. During the late Paleozoic, the North China craton collided with Mongolia, closing the Solonker ocean [e.g. Zonenshain *et al.*, 1990a,b; Zorin 1999; Chen *et al.*, 2000; Xiao *et al.*, 2003; Lin *et al.*, 2008] and triggering the closure of the Mongol-Okhotsk ocean to the north. Mesozoic continuous subduction of the Mongol-Okhotsk oceanic lithosphere beneath Siberia is evidenced by a widespread Triassic to Early Jurassic volcanoplutonic activity within SE Siberia [e.g. Filippova, 1969; Zorin *et al.*, 1990; Donskaya *et al.*, 2012, 2013]. Several authors suggested that the early Middle Jurassic switch from marine to continental sedimentation within the Transbaikal region marked the final closure of the ocean [Mushnikov *et al.*, 1966; Ermikov, 1994; Cogné *et al.*, 2005]. However, paleomagnetic data indicate that, by late Middle to early Late Jurassic, the oceanic domain might have still been up to 1000 km wide and that full concordance between the paleomagnetic poles was not reached before the Early Cretaceous [Enkin, 1992; Kravchinsky *et al.*, 2002; Metelkin *et al.*, 2004, 2007]. Low temperature thermochronology and sediment analysis data indicate Jurassic to Early Cretaceous cooling within a wide region encompassing the NE Altai [De Grave and Van den haute, 2002; De Grave *et al.*, 2008], the West Sayan ranges [Le Heron *et al.*, 2008], and the Baikal - Patom region [Van der Beek *et al.*, 1996; Jolivet *et al.*, 2009] (fig. 1). This denudation phase is generally interpreted as renewed relief building and erosion associated to the onset of the Mongol-Okhotsk orogeny that followed the docking of the Mongolia-North China block to Siberia. In the Irkutsk basin, along the Sayan fault (fig. 1), Lower to Middle Jurassic conglomerates derived from the East Sayan ranges, associated to folding of the Jurassic series also suggest some relief building and erosion [Florensov, 1960]. Furthermore, detrital zircon U-Pb dating on Jurassic deposits revealed that the sediment sources included Upper Paleozoic to Lower Jurassic volcanics from the Transbaikal area implying some erosion in that region [Demonterova *et al.*, 2015]. However, low temperature thermochronological studies inside the East Sayan ranges show only slow, continuous erosion during that period, without any obvious tectonic pulse [Jolivet *et al.*, 2013a]. Similarly, in the Transbaikal region, i.e. very close to the suspected location of the Mongol-Okhotsk suture zone (fig. 1), there is no evidence of shortening, metamorphism, topography building or renewed exhumation associated to the Mongol-Okhotsk orogeny [Jolivet *et al.*, 2009]. In the Transbaikal area, the late Mesozoic tectonic pattern was marked by extension and low to moderate sedimentation apparently restricted to small-scale grabens or semi-grabens [e.g. Jolivet *et al.*,

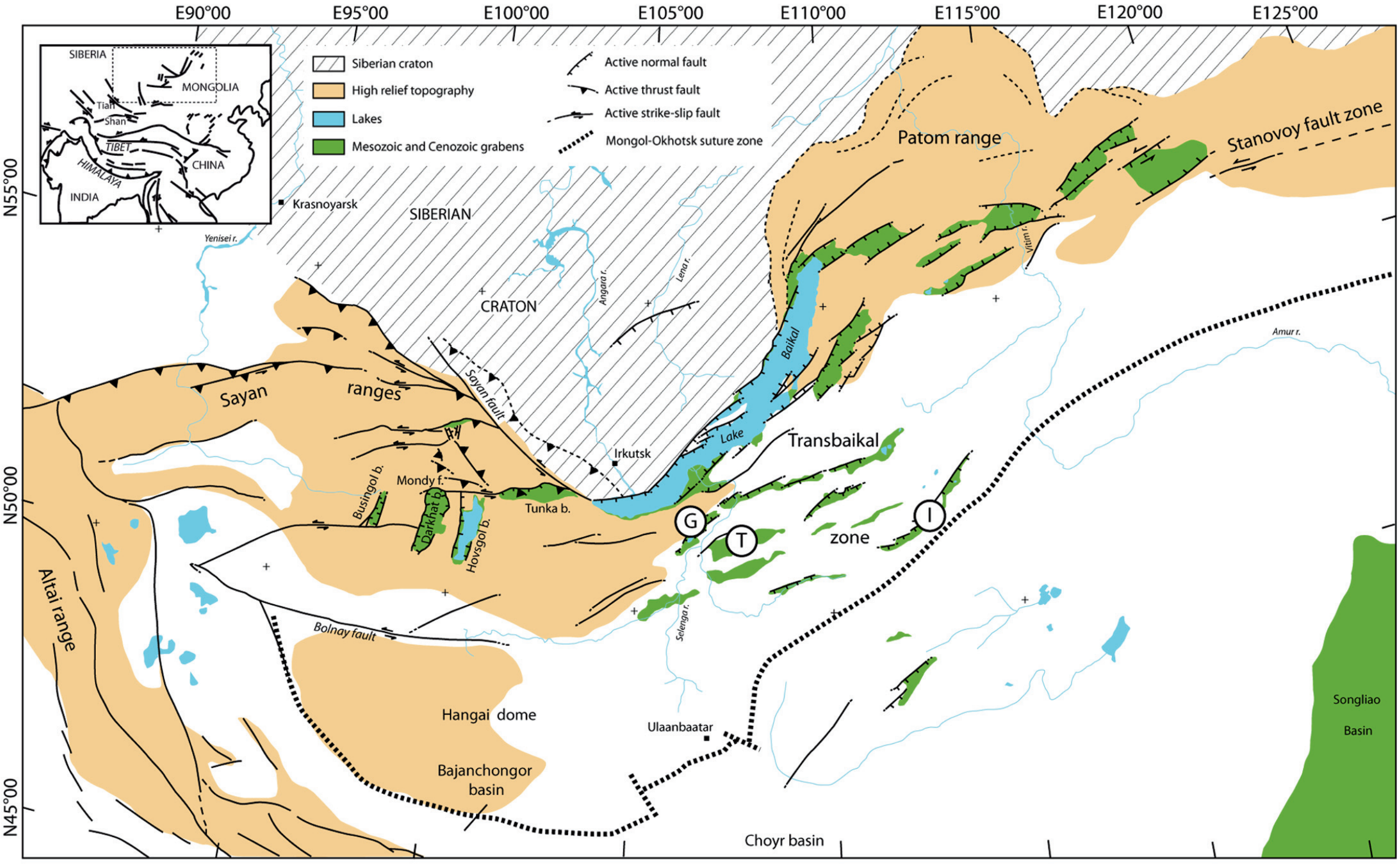

FIG. 1. – General tectonic and physiographic map of the study area. G: Gussinoozerskaya basin; T: Tugnuyskaya basin; I: Ingodinskaya basin.

2009, 2013b]. Similarly, from NE Mongolia to NE China, the Late Jurassic - Early Cretaceous period was marked by widely distributed extension leading to the emplacement of metamorphic core-complexes [e.g. Zheng *et al.*, 1991; Davis *et al.*, 1996; Webb *et al.*, 1999; Donskaya *et al.*, 2008; Daoudene *et al.*, 2009, 2013, 2017; Charles *et al.*, 2011a,b, 2012, 2013]. The question thus remains to reconcile the suspected Late Jurassic - Early Cretaceous continental collision between Mongolia-North China and Siberia with an apparent absence of orogeny.

This work aims to bring more constraints on the late Mesozoic evolution of the Transbaikal area. Based on a synthesis of sedimentological and paleontological data (mainly palynology and mega-flora) both already available in the Russian literature and newly acquired, we document the tectonic, topographic and paleoenvironmental evolution of three of the main Transbaikal basins (the Gussinoozerskaya, Tugnuyskaya and Ingodinskaya basins, fig. 1) during the key Late Jurassic - Early Cretaceous period. The data are then used to discuss the geodynamic evolution of that region in relation with the Mongol-Okhotsk orogeny.

GENERAL TECTONIC SETTING OF THE GUSSINOOZERSKAYA, TUGNUYSKAYA AND INGODINSKAYA BASINS

As mentioned above, the Upper Jurassic - Lower Cretaceous Transbaikal basins belong to a huge province –extending from the Pacific coast to the Transbaikal and Baikal-Vitim regions– affected by broadly distributed Late Mesozoic extension (fig. 1) [e.g. Zheng *et al.*, 1991; Webb *et al.*, 1999; Davis *et al.*, 1996; 2002; Meng, 2003; Charles *et al.*, 2011a,b, 2013; Jolivet, 2016]. The emplacement of major metamorphic core-complexes throughout the whole area during the Early Cretaceous between 140 Ma and 120 Ma marked the peak of extension [Charles *et al.*, 2012, 2013; Daoudene *et al.*, 2013]. Several models have been put forward to explain this tectonic phase. One largely accepted model suggests that the Early Jurassic to Cretaceous scissors-like collision between Siberia and Mongolia - North China induced a major thickening of the Mongolian crust (up to 60-70 km) [e.g. Zheng *et al.*, 1996; Darby *et al.*, 2001; Litvinovsky *et al.*, 2002; Donskaya *et al.*, 2008]. Orogenic collapse of this over-thickened crust was then facilitated by the free border formed by the Pacific trench leading to distributed extension in the East Asian crust [e.g. Graham *et al.*, 2001; Kusky *et al.*, 2007; Donskaya *et al.*, 2008]. More recently, Daoudene [2011] rejected the idea of an over-thickened crust (and thus of a major collision event along the Mongol-Okhotsk suture zone) and related the Cretaceous extension to a conjunction between an abnormally hot eastern Asia lithosphere and stress due to the roll-back of the subducting Izanagi (Paleo-Pacific) plate. The hypothesis of a driving mechanism linked to the Izanagi plate subduction is also supported by the results of Charles *et al.* [2013] on the North China metamorphic core complexes.

The NNE-SSW-elongated Gussinoozerskaya basin, situated immediately southeast of Lake Baikal (fig. 2) is either a strongly asymmetric graben or a semi-graben filled by Jurassic - Cretaceous clastic sediments (see below) [e.g. Bulnaev, 2006; Tsekhovsky and Leonov, 2007]. To the east the basin is separated from the Monostoy ridge by the Monostoy normal fault that was the most active fault during the Mesozoic evolution of the basin (the sedimentary sequence is much thicker on that side of the structure) (fig. 2). The Monostoy normal fault is largely super-imposed upon a probably Paleozoic ductile shear zone. To the west, the basin is separated from the Khambinsky ridge by the Khambinsky normal fault [Bulnaev, 2006]. However, the latest is not associated to any obvious inherited fault such as to the east of the basin. The much thinner Mesozoic series that were deposited on the western side of the basin associated to the highly segmented, poorly connected geometry of the Khambinsky fault suggest that this fault is a neo-formed Cenozoic structure [Jolivet *et al.*, 2013b]. In both the Monostoy and Khambinsky ridges, the geological map indicates that the basement was intruded by numerous Permian to Lower Triassic granitoids and by some more restricted Upper Triassic alkaline granites [e.g. Sklyarov *et al.*, 1997; Donskaya *et al.*, 2013 and references therein]. However, only a limited amount of radiometric ages exist for those rocks and some differences occur between newly acquired ages and the ages attributed on the map [e.g. Donskaya *et al.*, 2008].

The Tugnuyskaya basin is a ENE-WSW 150 km long and 4 to 12 km wide depression, situated some 60 km east of the Gussinoozerskaya basin (fig. 1). The Tugnuyskaya basin is asymmetric as well and controlled by a major normal fault (the Tugnuy-Kondinskiy mylonitic shear zone) along its southern edge [e.g. Kolesnikov, 1964]. The brittle Mesozoic reactivation of that fault is clearly evidenced by the much larger sediment thickness along the southern margin of the basin. The present morphology of the basin is marked by a steep topography to the south and a central ridge separating the depression in two sub-valleys, the Tugnuy river valley to the north and the Sukhara river valley to the south (fig. 3). Like in most of the Transbaikal basins (except for the Gussinoozerskaya basin), the Mesozoic sedimentary series were deposited on a volcano-sedimentary sequence emplaced during the initial phase of extension (the Ichetuyskaya Formation) [e.g. Komarov *et al.*, 1965; Donskaya *et al.*, 2013]. No evidence has been found for Cenozoic reactivation of the basin.

The 180 km long E-W oriented Ingodinskaya basin is one of the largest basin of the Transbaikal area. Situated some 400 km east of the Gussinoozerskaya basin, near the city of Chita (fig. 4), the basin is enclosed between the Yablonoviy ridge to the north and the Cherskogo ridge to the south [e.g. Jolivet *et al.*, 2013b and references therein]. Like in the previous basins, the Mesozoic detrital series are deposited on volcanics. Although these volcanics are not dated, they are probably of Early Jurassic age. The overall volcanic series is 1500 m thick and composed of plagioclase-rich porphyry, volcano-sedimentary breccia and tuffs [Kolesnikov, 1964]. Similarly to the Gussinoozerskaya basin, the Ingodinskaya basin is affected by the Cenozoic extension associated to the opening of the Baikal rift system. However, this deformation is accommodated along the reactivated Chikoy-Ingoda normal fault bordering the Yablonoviy rigde along the northern edge of the basin and not along a newly formed fault [Jolivet *et al.*, 2013b].

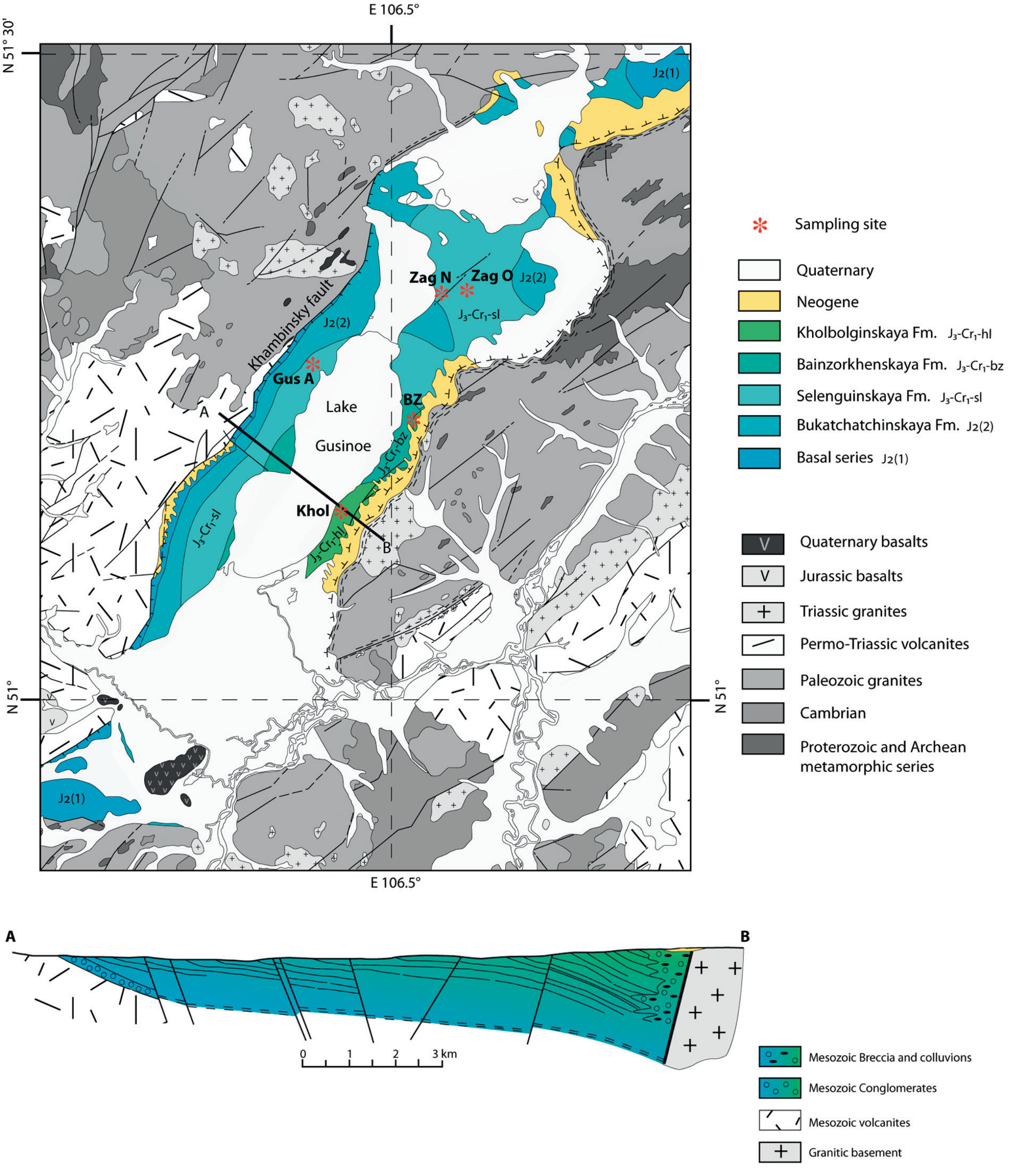

FIG. 2. – Simplified geological map of the Gussinoozerskaya basin and surrounding area showing the outcrops of Mesozoic formations. The indicated formation names and stratigraphic ages follow the Russian geological map [VSEGEI, 1961]. Sampling sites are indicated by red stars: GUS A: 90 m road cut; Zag N: new Zagustai quarry; Zag O: old Zagustai quarry; Khol: Kholbol quarry; BZ: Bain-Zurkhe quarry. The simplified geological section displays the dissymmetry of Mesozoic deposits across the basin (modified after Bulnaev [2006]). See text for discussion.

SYNTHESIS OF AVAILABLE SEDIMENTOLOGICAL AND PALEONTOLOGICAL DATA IN THE LITERATURE

Sedimentology of the Gussinoozerskaya basin

The data available in the Russian literature on the facies, depositional environment and age of the detrital series in the Gussinoozerskaya basin continue to be debated. An early lithological description by Florensov and Larina [1937] was followed in the mid sixties by several, more complete studies based on lithologies, fauna and flora [e.g. Martinson, 1955, 1961; Kolesnikov, 1961, 1964; Otchirov, 1964; Skoblo, 1967]. Despite differences in lithological description and formation names, those studies dated the series from Middle Jurassic to Lower Cretaceous. However,

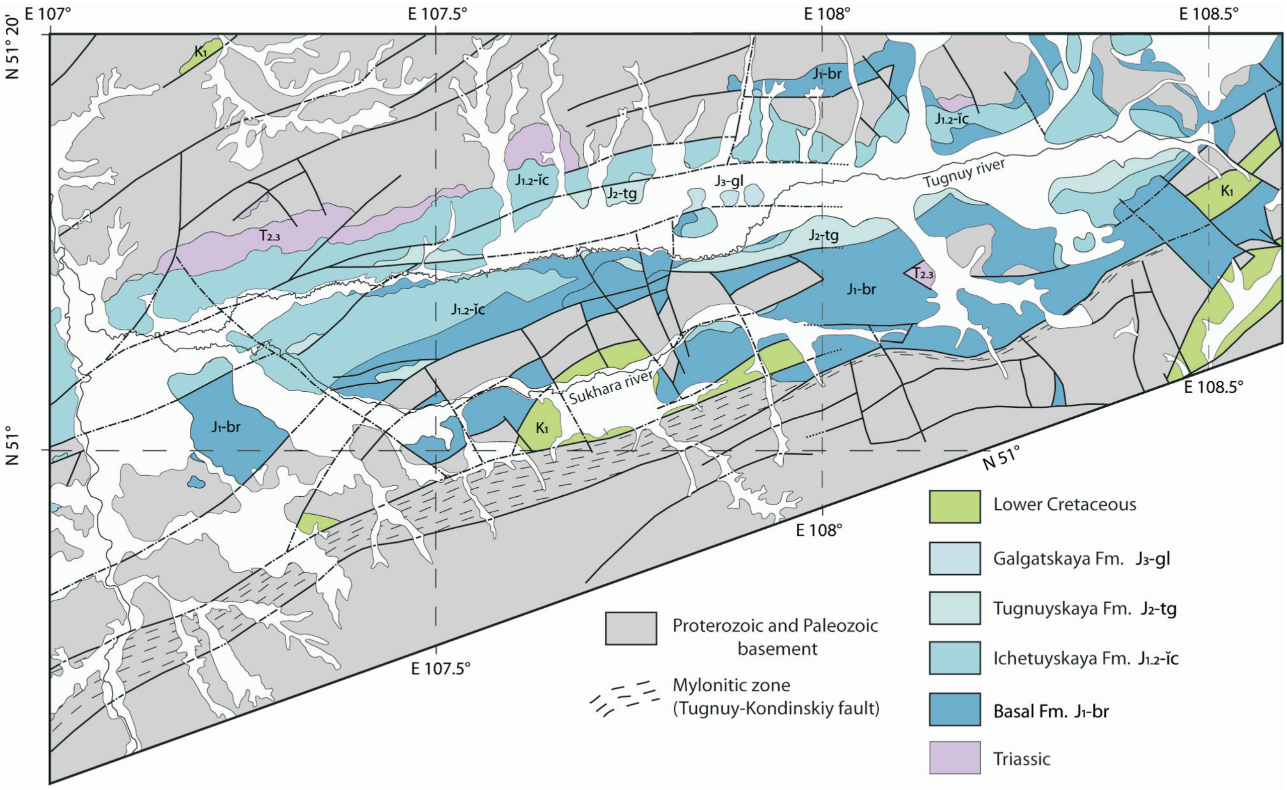

FIG. 3. – Simplified geological map of the Tugnuyskaya basin and surrounding area showing Mesozoic outcrops. Formation names and stratigraphic ages follow the Russian geological map [VSEGEI, 1957]. See text for discussion.

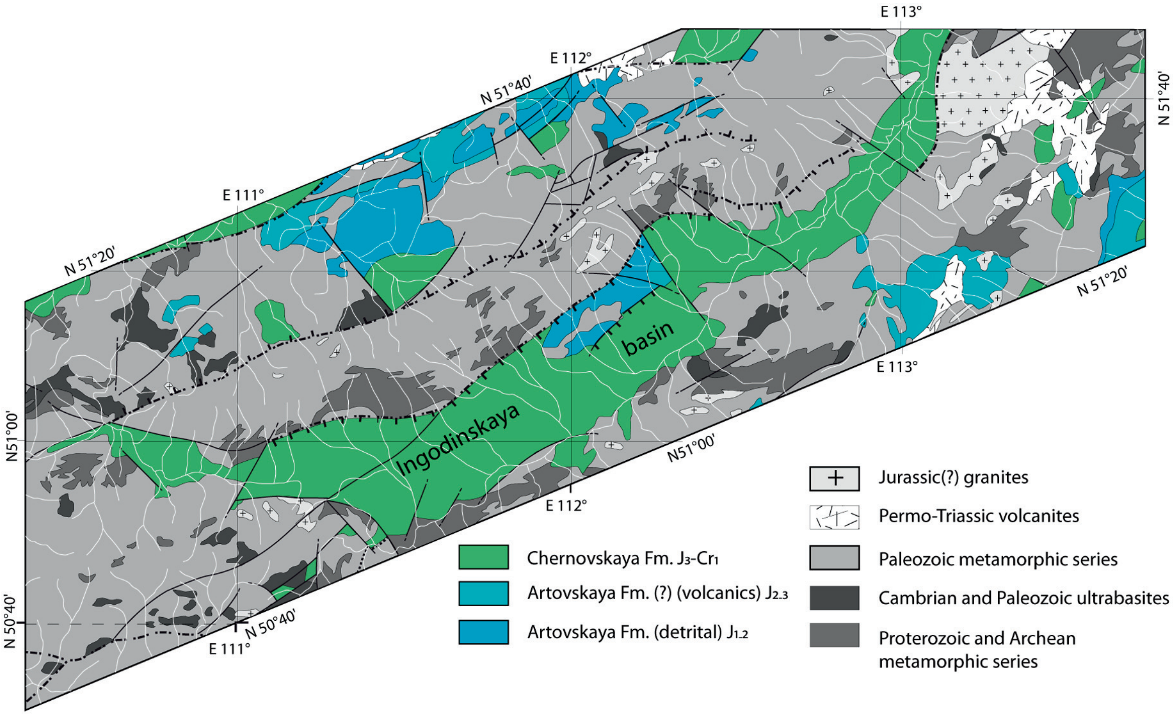

FIG. 4. – Simplified geological map of the Ingodinskaya basin and surrounding area showing the outcropping Mesozoic formations. Formation names and stratigraphic ages indicated are from the Russian geological map [VSEGEI, 1960]. See text for discussion.

more recently, Skoblo *et al*. [2001], based on new flora and fauna restricted the age of the series to the Early Cretaceous.

Figure 5 summarizes the formation names, thicknesses and ages as suggested by the various authors. In order to be comprehensive the synthesis presented below will mainly refer to formations of Martinson [1961] for the Gussinoozerskaya basin with references to other formation names for details.

The entire Mesozoic sedimentary sequence of the Gussinoozerskaya basin is uncomformable either on the Proterozoic and Paleozoic metamorphic basement or on lower Mesozoic volcanic flows (the 300 to 400 m thick Khambinskaya Fm. [Otchirov, 1964]) associated with the initiation of the basin [e.g. Tauson *et al.*, 1984; Rutshtein, 1992; Gusev and Khain, 1996; Graham *et al.*, 2001; Daoudene, 2011]. Martinson [1961] distinguishes a 50 to 70 m thick basal unit composed of conglomerates and coarse to medium grained sandstones from the overlying Bukatchatchinskaya Fm. (fig. 5). The 150 to 200 m thick Bukatchatchinskaya Fm. is concordant on the basal unit. It is composed of shale, coal, carbon-rich siltstone, siltstone and medium to fine grained sandstone; it provided a very rich fauna and flora considered by Martinson [1961] as Middle Jurassic in age and representing a potential standard reference for the Transbaikal area (table Ia, electronic supplementary material). The author also provides palynological data. Unfortunately, the indicated percentages and grain numbers for each species are not consistent and the sum of all percentages is over 100%. For that reason only the names of the various recognised taxa are given here: *Lycopodium, Selaginella,* Filicales, *Cibotium,* Polypodiaceae, *Gleichenia, Lygodium,* Osmundaceae, *Leiotriletes,* Bennettitales, Cycadales, Ginkgoales, Coniferae, Podocarpaceae, *Podocarpus, Podozomites,* Pinaceae, *Abies, Picea, Picea sec. Omorica, Pinus, Pinus s/g. Haploxylon, Lygodium, Leptopterus* and Taxaceae. The Bukatchatchinskaya Fm. is equivalent to the Tachirskaya Fm described by Kolesnikov [1961, 1964] or the Naringol-Murtoiskaya Fm. of Otchirov [1964]. However, the thickness of the basal conglomerates described by these authors is much more important, varying between 160 m and 540 m (fig. 5) possibly depending on the geographic location of the section within the basin.

The Ulanganguinskaya Fm. rests unconformably on the Bukatchatchinskaya Fm. and is divided into two units: the Severoozerniy Unit and the Khaiano-Tarchirskiy Unit (fig. 5). The 120 to 200 m thick Severoozerniy Unit is composed of fine to medium grain sandstone and gravelly

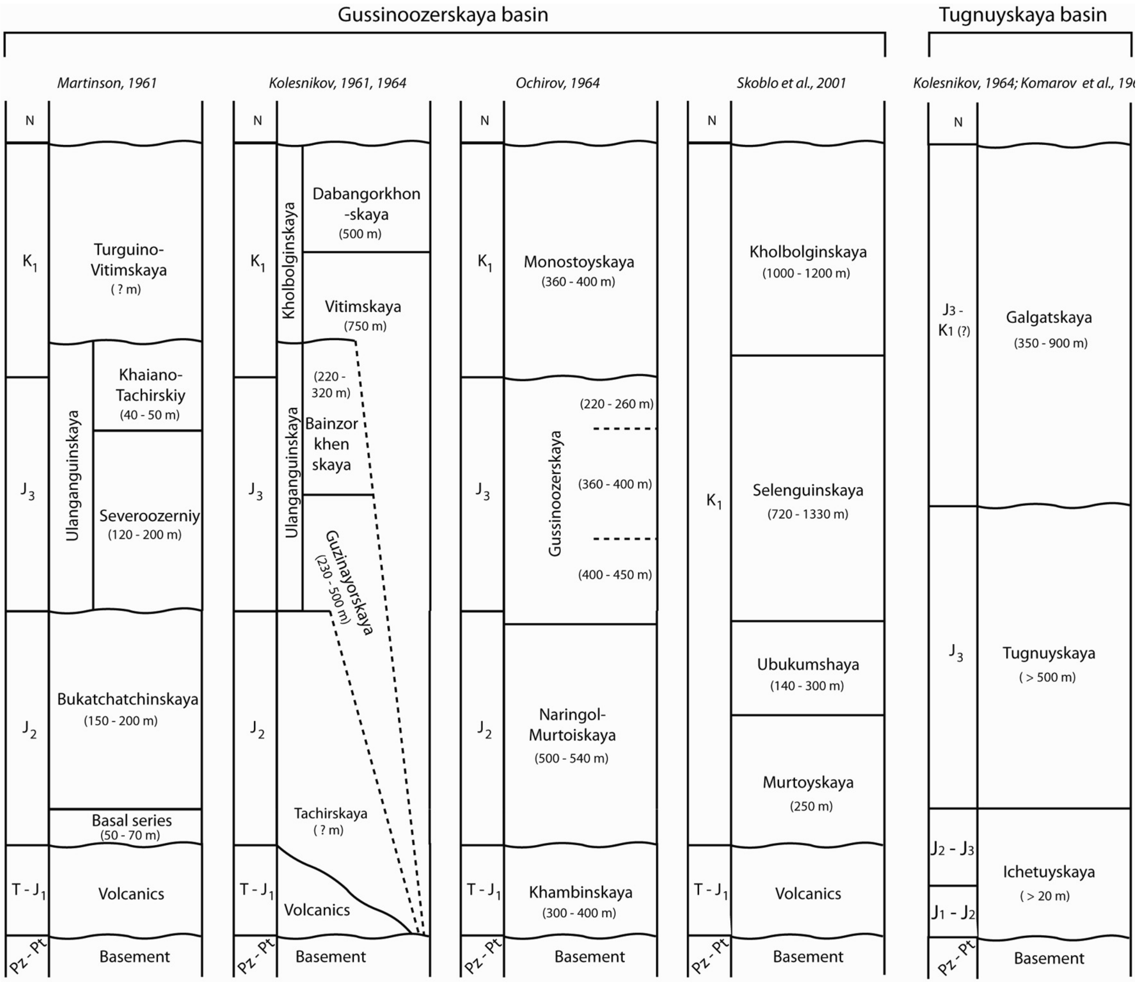

FIG. 5. – Synthesis of the various stratigraphic columns available for the Gussinoozerskaya and Tugnuyskaya basins.

conglomerate alternating with shale, coal and siltstone. The fauna recovered from this unit, especially the fresh water shells, indicate a Late Jurassic age [Martinson, 1961] (table Ia). The stratigraphically concordant, 40 to 50 m thick Khaiano-Tarchirskiy Unit is mainly composed of medium to coarse grain sandstone and gravel to pebble size conglomerate alternating with minor siltstone and carbon-rich shale. The fauna and flora recovered from that unit pointed to an Early Cretaceous age [Martinson, 1961] (table Ia). This is confirmed by palynological data [Martinson, 1961] in two different outcrops: outcrop 1: *Lycopodium* (2.7%), *Selaginella* (0.7%), Filicales (4.6%), *Cibotium* (2.7%), *Ginkgo* (12.0%), *Podocarpus* (1.3%), Pinaceae (4.6%), *Picea* (27.4%), *Lygodium* (1.3%), *Mohria* (0.7%), *Osmunda* (12.0%), *Leptopteris* (6.7%), *Leiotriletes* (19.1%), *Pinus* (0.7%), *Pinus s/g. Haploxylon* (3.3%); outcrop 2: *Cibotium* (3.3%), *Cyathea* (2.5%), *Coniopteris* 3.3%), *Onychium* (0.8%), *Gleichenia* (18.0%), *Osmunda* (2.5%), *Danaea* (1.6%), *Leiotriletes* (1.6%), Cycadales (0.8%), *Ginkgo* (8.3%), *Podozamites* (2.5%), *Podocarpus* (1.6%), Pinaceae (10.0%), *Picea* (21.0%), *Cedrus* (0.8%), *Pinus s/g. Diploxylon* (0.8%), *Brachyphyllum* (4.1%), Juglandaceae (2.5%), undetermined grains (12.4%). The author indicates that towards the south and north of the basin, the Ulanganguinskaya Fm. deposits are finer-grained than in the central part of the basin, suggesting two depressions separated by a central delta. Kolesnikov [1961, 1964] also described the Ulanganginskaya Fm. but divided it in two different units: the 230 to 500 m thick Gussinoozerskaya Unit at the base and the 220 to 320 m thick Bainzorkhenskaya Unit to the top. Once again, the total thickness of the formation is much larger than for Martinson [1961] probably due to a different location within the basin. Nonetheless, the distribution of units and the lithological description of the Ulanganginskaya Fm. provided by both authors are very similar. Kolesnikov [1961, 1964] reports that the formation is either concordant on the underlying Tachirskaya Fm. or lies directly on the metamorphic basement. This suggests that either the Ulanganginskaya Fm. depositional system was locally eroding the underlying sediments and basement (as suggested by Martinson [1961]) or that sediments were locally deposited on a relatively important paleo-topography. Finally, the Gussinoozerskaya Fm. of Otchirov [1964] corresponds again to the Ulanganguinskaya Fm. and is divided in three units: a basal, 400 to 450 m thick unit composed of shale, siltstone, and fine to medium grain sandstone with thin coal layers which might partially belong to the late Middle Jurassic; a middle unit, 360 to 400 m thick, characterised by a thickening of the coal and sandstone layers and a relative decrease in the amount of shale and siltstone; the upper unit is 220 to 260 m thick and shows a large decrease in the amount of sandstone and a thickening of the coal layers. According to Otchirov [1964], the Gussinoozerskaya Fm. is conformable with the underlying Naringol-Murtoiskaya Fm.

The Turguino-Vitimskaya Fm. rests again uncomformably on the Ulanganguinskaya Fm. (fig. 5). The series are composed of coarse to fine grain sandstone, siltstone and shale with a few conglomerate layers. Some carbon-rich shale, bituminous schist and coal layers are also present. The formation is characterised by sharp lateral variations of sediment facies. The amount of shale, siltstone and coal increases towards the center of the basin while sandstone and conglomerate dominate to the north and south suggesting the occurrence of a lake within the central part of the basin similarly to the present geography. The Turguino-Vitimskaya Fm. can be compared with the 1250 m thick Kholbolginskaya Fm. of Kolesnikov [1961, 1964]. This formation is described as uncomformable on the underlying Ulanganguinskaya Fm. and in some places rests directly on the Mesozoic volcanics suggesting again either a strong erosion or some paleo-topography. The Kholbolginskaya Fm. is divided in two units: the 750 m thick Vitimskaya Unit composed of a basal coarse conglomerate with argillaceous to carbonated cement followed by alternating fine-grain sandstone, shale and thin coal layers; the 500 m thick Dabangorkhonskaya Unit composed of shale, siltstone, thick coal layers and few fine grained sandstone. The 360 to 400 m thick Monostoyskaya Fm. described by Otchirov [1964], resting uncomformably upon the Gussinoozerskaya Fm. seems restricted to the eastern edge of the basin, along the Monostoy ridge (fig. 5 and see Kholbolginskaya Fm. on fig. 2). The series, which include some thin coal and shale layers are largely dominated by conglomerate and sandstone suggesting that this formation corresponds to piedmont deposits such as alluvial fans [Skoblo, 1967]. The fauna and flora recovered from the Turguino-Vitimskaya Fm. or its equivalents suggest a Lower Cretaceous age (table Ia).

Along the margins of the basin, and especially to the east along the Monostoy ridge, the Mesozoic series are cut by coarse-grained conglomerates alternating with sandstone and siltstone. These poorly consolidated deposits have been described as Tertiary (Neogene ?) however no fauna or flora is provided [VSEGEI, 1960, 1961]. They correspond to piedmont deposits along the active normal fault that bounds the basin. Similar Quaternary deposits are observed to the west along the Khambinskiy ridge [VSEGEI, 1960, 1961].

Recently, Skoblo *et al.* [2001] re-evaluated the age of the Mesozoic series and considered them as entirely of Early Cretaceous age (fig. 5) based on new fauna and flora (table Ia). The up to 250 m thick Murtoyskaya Fm. is exposed along the Khambinskiy ridge. Resting uncomformably on the Mesozoic volcanics it is composed of a basal, fining upward conglomerate and sandstone unit followed by a fine-to-medium grained sandstone, siltstone and shale unit. Strong lateral variations of facies are observed. The overlying (conformable) 140 to 300 m thick Ubukunskaya Fm. is composed of shale and siltstone in its lower part and sandstone with grey shale and small coal layers in its upper part. The 720 to 1330 m thick Selenguinskaya Fm. is again conformable. The lower part of the formation is characterized by transgressive-regressive cycles and the deposition of sandstone to gravelly conglomerates and siltstone. The upper part is formed by alternating shale, siltstone, fine-grain cross-bedded sandstone, conglomerates and coal layers. Some iron nodules and several tuff fragments have been observed. The composition and thickness of the Kholbolginskaya Fm. is largely variable across the basin. To the SE of the basin, it is composed of cross-bedded fine to coarse grain sandstone alternating with thinner shale and siltstone. Thick coal layers (2 to 53 m) forming the main coal deposits in the basin are intercalated within either sandstone or conglomerate deposits. Towards the Monostoy ridge, the formation is mainly composed of conglomerate, breccia and sandstone.

Paleo-environmental evolution of the Gussinoozerskaya basin

Models of the basin's paleo-environmental evolution are based on sedimentological and paleontological data. While the age of the sedimentary sequence is still under discussion, the general evolution of the basin appears to be well constrained. The main differences between models are due to the strong lateral variations in contemporaneous sedimentological facies within the basin. It is obvious that most of the differences observed in the sections described above are linked to the geographic position of the studied sections.

The Gussinoozerskaya basin was initiated before or during the early Middle Jurassic [Martinson, 1961; Otchirov, 1964] or in the Early Cretaceous [Skoblo *et al*., 2001] with the deposition of coarse alluvial fan conglomerates and breccia. These deposits indicate a strong relief, most probably generated by movement on the normal faults controlling the basin. The Bukatshatchinskaya Fm. and the equivalent Tachirskaya, Naringol-Murtoiskaya and Ubukunskaya formations (figs 2 and 5), were deposited in a lacustrine (sometimes deep lacustrine) to alluvial plain environment surrounded by thick forest and marsh type vegetation. The lacustrine and wet alluvial plain systems were probably covering most of the basin's surface and no large river systems are observed. Active subsidence of the basin allowed the accumulation of sedimentary deposits several hundreds of metres in thickness [Martinson, 1961]. Martinson [1961] indicates that the Middle/Late Jurassic boundary is marked by an erosional event. However, most of the authors describe the transition between the corresponding formations as conformable [Kolesnikov, 1961, 1964; Otchirov, 1964; Skoblo *et al*., 2001]. Only Kolesnikov [1961, 1964] describes the Gussinoozerskaya Fm. as locally resting on the metamorphic basement, suggesting either erosion of the underlying Tachirskaya Fm. or the occurrence of a paleotopography. During the Late Jurassic - Early Cretaceous (Ulanganguinskaya Fm.), two sub-basins developed in the north and south of the main depression with the emplacement of forested marshes corresponding to an inundated alluvial plain system. These two depressions were separated by a delta to alluvial plain system fed by paleorivers issued from the Monostoy ridge to the east [Martinson, 1961]. The topography along the western edge of the basin (Khambinskiy ridge) was less elevated indicating that the western normal fault was not at all or much less active [Bulnaev, 2006]. The transition between the Upper Jurassic - Lower Cretaceous and Lower Cretaceous formations is marked by an erosional event indicated by most authors except Skoblo *et al.* [2001]. The Turkino-Vitimskaya Fm. corresponds to a wide lacustrine environment with a decreasing influence of the river systems. Marshes developed in the alluvial plain system bordering the lakes but decreased upward due to the expansion of the lacustrine environment [Martinson, 1961]. However, the large amount of conglomerate described by Otchirov [1964] in the Monostoyskaya Fm. suggests that the Monostoy normal fault was active creating some topography and leading to the emplacement of alluvial fans along the eastern edge of the basin [Skoblo *et al*., 2001].

No Upper Cretaceous and Paleogene sediments have been reported in the basin or in most of the Transbaikal basins and have either been eroded or not deposited.

Sedimentology and paleoenvironments of the Tugnuyskaya basin

Within the Tugnuyskaya basin, the Ichetuyskaya Fm. is composed of basal sedimentary deposits covered by volcanics (figs. 3 and 5). The 20 m thick basal sediments coarsen upwards and are composed of siltstone, fine-grained sandstone and conglomerate. Fossil insects have been described (table Ib, electronic supplementary material) and some few volcanic tuffs, usually reworked within sandstone layers have been reported. The insect fauna is similar to the one described from the Lower to Middle Jurassic Tcheremkhovskaya Formation exposed in the Irkutsk basin. Within nearby basins, the Ichetuyskaya Fm. also yield fossil shells and plants (especially ferns) of early Jurassic affinity [Komarov *et al*., 1965 and references therein] (table Ib). However, Serdobolskaya and Kosubova [1976], based on further discoveries of flora within the formation corrected this age to Late Jurassic - Early Cretaceous (table Ib). The overlying alkaline to calc-alkaline volcanics are typically composed of a trachy-basalts sequence followed by trachytes. However, the upper trachyte sequence is not represented in the Tugnuyskaya basin. The volcanics have been dated between 145 and 166 Ma using K-Ar on whole rock [Shadaev *et al*., 1992; Ivanov *et al*., 1995] and at 158 ± 8 Ma using Rb-Sr on whole rock [Shadaev *et al*., 1992; Gordienko *et al*., 1998]. These ages are consistent with the Early to Middle Jurassic age estimated from the underlying fauna and flora by Komarov *et al.* [1965] although the Late Jurassic to Early Cretaceous age of Serdobolskaya and Kosubova [1976] cannot be rejected.

The Tugnuyskaya Fm. varies in thickness from about 50 m along the northern margin of the basin to over 500 m thick along the southern margin (figs 3 and 5) [Kolesnikov, 1964]. The sequence is composed of sandstone, silty-sandstone, siltstone, shale, coal and conglomerates. Its base is formed by conglomerate and sandstone, followed by alternating sandstone, siltstone, conglomerate and coal. Towards the top of the formation, the coal layers disappear. The middle part of the sequence, containing at least four thick layers of low-grade coal is up to 500 m thick and provided a large diversity of presumably Middle Jurassic flora and fauna (table Ib, electronic supplementary material) [Martinson, 1961; Kolesnikov, 1964]. However, considering the Late Jurassic to Early Cretaceous radiometric ages obtained on the underlying Ichetuyskaya Fm. the Tugnuyskaya Fm. is at least of Late Jurassic - Early Cretaceous age. This result questions the typical Middle Jurassic fauna and flora proposed by Martinson [1961].

The 350 to 900 m thick Galgatskaya Fm. lies uncomformably on the Tugnuyskaya Fm. (fig. 5). The series is composed of retrograding sequences starting with siltstone and ending with conglomerate. The basal deposits are predominantly red-coloured near the edges of the basin and grey-coloured in the centre [Kolesnikov, 1964]. Skoblo and Lyamina [1972] suggested that those sediments were deposited in an alluvial plain to lacustrine environment under arid to sub-arid climate. Fresh water fauna and some flora suggest an upper Jurassic age for the Galgatskaya Fm. [Kolesnikov, 1964]. While this age can be consistent with the radiometric ages obtained on the Mesozoic volcanics, it remains questionable.

The Galgatskaya Fm. is uncomformably covered by Cenozoic alluvial deposits suggesting that, similarly to the Gussinoozerskaya basin, at least the Upper Cretaceous series are missing.

Sedimentology and paleoenvironments of the Ingodinskaya basin

In the Ingodinskaya basin, the Artovskaya Fm., overlying the basal volcanics (fig. 4), is up to 500 m thick and composed of alluvial fan conglomerate, silicified gravelly conglomerate, sandstone and siltstone as well as “acidic” volcanics and tuffs [Kolesnikov, 1964]. The flora recovered from this formation suggests a Lower to Middle Jurassic age (table Ic, electronic supplementary material). The Artovskaya Fm. is exposed both within the basin and on the surrounding ridges indicating that sediments were deposited prior or during the initial opening of the basin.

The c.a. 1300 m thick Chernovskaya Fm. rests unconformably on the Artovskaya Fm. but also on the Proterozoic to Paleozoic metamorphic basement and on the Mesozoic volcanics. The formation is divided into three sub units: the base of the series is composed of alluvial fan conglomerate, breccia and sandstone up to 550 m thick, fining upward to sandstone, siltstone and shale. Pebbles and blocks within the conglomerate are clearly derived from the metamorphic basement and contain granitoids, gneisses, schists and porphyry; the intermediate unit is over 650 m thick and rests conformably on the lower unit. It is composed of siltstone, shale, some gravel-size conglomerate and few lenses of brown coal. Fresh water gastropod and ostracod assemblages (table Ic) suggest a Late Jurassic - Lower Cretaceous age [Kolesnikov, 1964]; the upper unit is up to 190 m thick and conformable with the intermediate unit. The sediment is composed of alternating sandstone, siltstone, shale and numerous, thick (up to 11 m) low-grade coal layers. Flora and pollen assemblages (table Ic, electronic supplementary material) suggest a Late Jurassic - Early Cretaceous age, consistent with the similar Late Jurassic - Early Cretaceous age obtained from the fresh water shells in the intermediate unit [Martinson, 1961; Kolesnikov, 1964].

SEDIMENTOLOGICAL, PALYNOLOGICAL AND PALEOBOTANICAL RESULTS

In order to fully assess the age of the Mesozoic deposits exposed in the Gussinoozerkaya basin and to complete the description of the Mesozoic paleoenvironments in that basin, we collected a number of palynological and paleobotanical samples along sections exposed in quarries. The samples are distributed within the Selenguinskaya Fm., the Bainzorkhenskaya Fm. and the Kolboldzhinskaya Fm. (formations names are taken from the geological map (fig. 2)).

Selenguinskaya Formation

The Selenguinskaya Fm. was studied in two quarries (Old Zagustay and New Zagustay), close to the northern shore of Lake Gusinoe as well as on a section exposed along a road-cut west of the lake (section GUS A) (fig. 2). In the Old Zagustay quarry, only about 15 m of Mesozoic sediments are accessible, composed of two layers of coal alternating with fine- to medium grain brown-coloured sandstone and some minor siltstone (fig. 6). In the New Zagustay quarry, about 25 m of Mesozoic sediments are exposed. The series are composed of light-gray, fine-grained sandstone alternating with dark-gray argillaceous, organic rich siltstone and coal. The upper part of the section is formed by brown-yellow conglomerate associated to some decimetre thick coal layers (fig. 6). Along the road-cut, 90 m of Mesozoic series are exposed. The lower part of the measured section is mainly composed of medium- to fine-grained light grey sandstone alternating with siltstone and some rare decimetre thick coal layers. In the upper part of the section coal becomes more abundant with decimetre to meter thick layers alternating with siltstone and few decimetre thick fine-grained sandstone. This second part of the section is very similar to the series observed in the New Zagustay quarry (fig. 6). In agreement with Martinson [1961], we interpret these sediments as deposited in an actively subsiding, wet, well vegetated alluvial plain environment. The change from sand-dominated to coal and siltstone-dominated environment in the road-cut section might indicate a retrogradation trend towards lacustrine environment. Finally, the occurrence of coal and generally fine-grained sediments indicates a relatively low sediment supply and thus a probably flat topography surrounding the basin. The conglomerate layers exposed on the upper part of the New Zagustay section are interpreted as river deposits indicating the occurrence of higher energy river systems within the basin [Martinson, 1961].

In the Old Zagustay section, 18 samples were collected and analysed individually before being grouped into 5 representative samples (figs 6 and 7a, and table IIa, electronic supplementary material). Among the 5 samples, the spore-pollen spectra correspond to a single Jurassic floristic composition. However a few Cretaceous spores have been identified (<1% of the total dataset). They are dominated by gymnosperm pollen (86 to 98%): Coniferae (25 to 43%), fir tree pollen (4 to 13%), pine tree pollen (5 to 25%), *Dipterella oblatinoides* (3 to 5%) and Podocarpaceae (1 to 8%). Some of the spectra is also composed of gymnosperm monocolpate pollen such as *Bennettites* (up to 13%), *Cycadophytus* sp. (up to 11%) and *Ginkgocycadophytus* sp. (up to 11%). Spores (2 to 14% of the spectra; fig. 7a) are mainly composed of *Cyathidites* sp. (up to 9%). Plant macro-remains from the same section are dominated by coniopteroid ferns with a large occurrence of *Birisia alata* (PRYN.) SAMYL. and *Coniopteris obrutchewii* (KRASS.) PRYN., typical of the early to middle Early Cretaceous [e.g. Samylina, 1972; Yadrishenkaya, 2002]. Among the gymnosperms, *Ginkgoites* ex gr. *adiantoides* (UNGER) HEER are widely represented with few occurrences of *Phoenicopsis* (?) ex gr. *angustifolia* HEER.

In the New Zagustay section, 11 samples were collected and analysed individually before being grouped into 3 representative samples (figs 6 and 7a, and table IIa). Alike the previous section the spore-pollen spectra correspond to a single Jurassic floristic composition very similar to the previous one. The assemblage is again dominated by gymnosperm miospores (61 to 64%): Coniferae (23 to 28%, crushed and poorly preserved), different species of fir trees

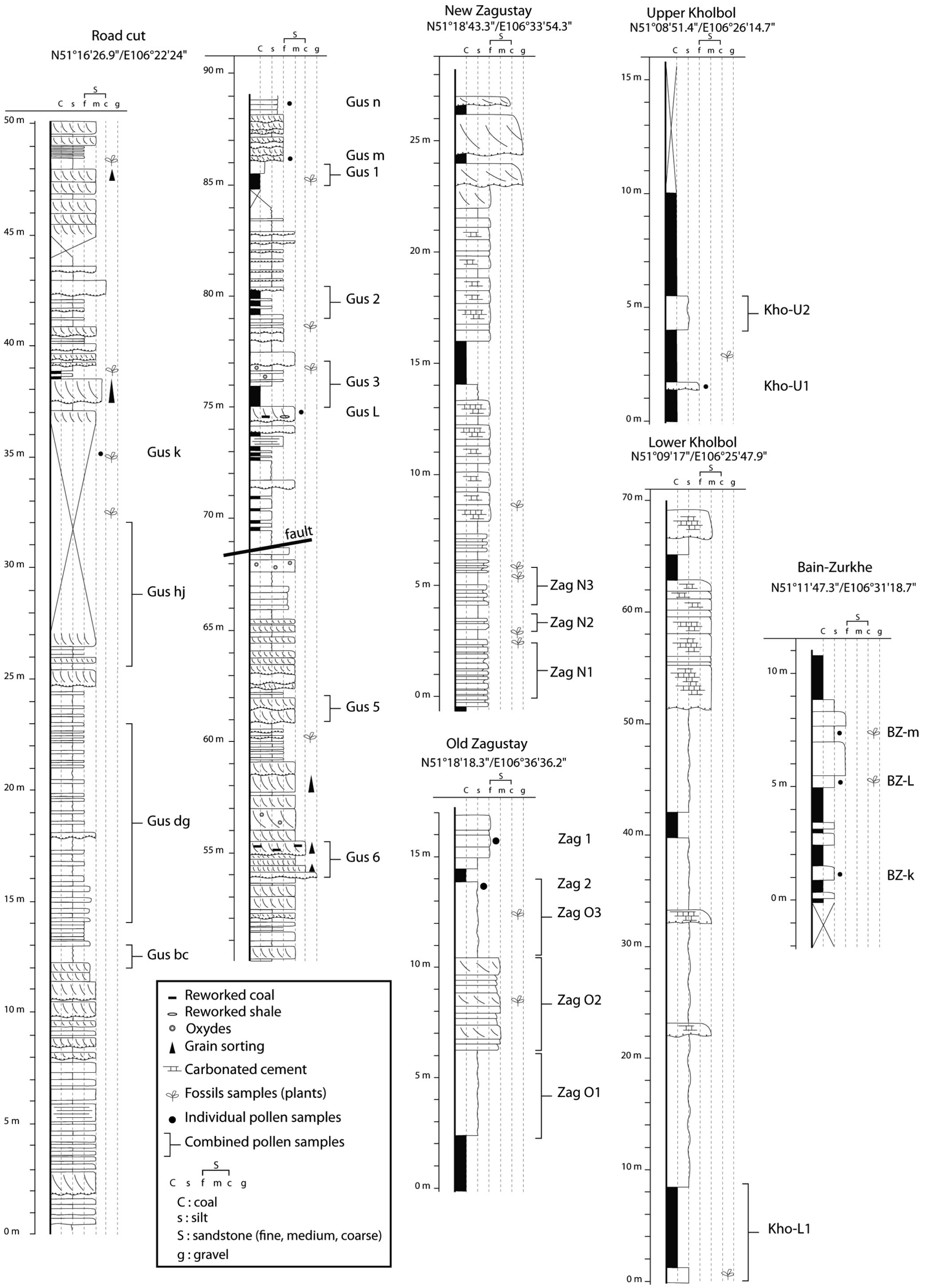

FIG. 6. – Sedimentary sections studied in each sampling site showing the stratigraphic position of the pollen and macro-flora samples. Note that for graphical purpose, the vertical scale for the Lower Kholbol section is different from the other. See text for discussion.

(up to 10%), some ancient pine trees (<12%) and some Podocarpaceae (8%). Other conifers are also present. Similarly to the Old Zagustay section, the samples contain some monocolpate pollen. Spores represent 36 to 39% of the spectra, including amongst others *Cyathidites* sp. (up to 13%), *Stereisporites* sp. (up to 13%) and *Osmundacidites* sp. (up to 8%). Finally one Cretaceous spore of *Lygodium echinaceum* was observed. Macro-remains of plants are again dominated by coniopteroid ferns *Birisia alata* (PRYN.) SAMYL., *Birisia* sp. *Coniopteris obrutchewii* (KRASS.) PRYN., and *Conipteris* sp. Trees are represented by conifers (*Podozamites lanceolatus* (L. et H.) SHIMP., *Podozamites* sp., *Pityophyllum* ex gr. *nordenskioldii* (HEER) NATH., *Pityphyllum* (?) sp., and minor occurrences of *Elatocladus* sp.) and Ginkgoaceae (*Ginkgoites* ex gr. *adiantoides* (UNGER) HEER, *Ginkgoites* ex gr. *huttonii* (STERN.) BLACK, and few impressions of *Sphenobaiera* (?) sp.). Finally, Leptostrobales such as *Czekanowskia* (?) ex gr. *rigida* HEER, *Phoenicopsis* (?) ex gr. *angustifolia* HEER, *Phoenicopsis* ex gr. *speciosa* HEER and *Leptostrobus* (?) sp. were also observed.

In the GUS road-cut section, 21 samples were collected and analysed individually before being grouped in

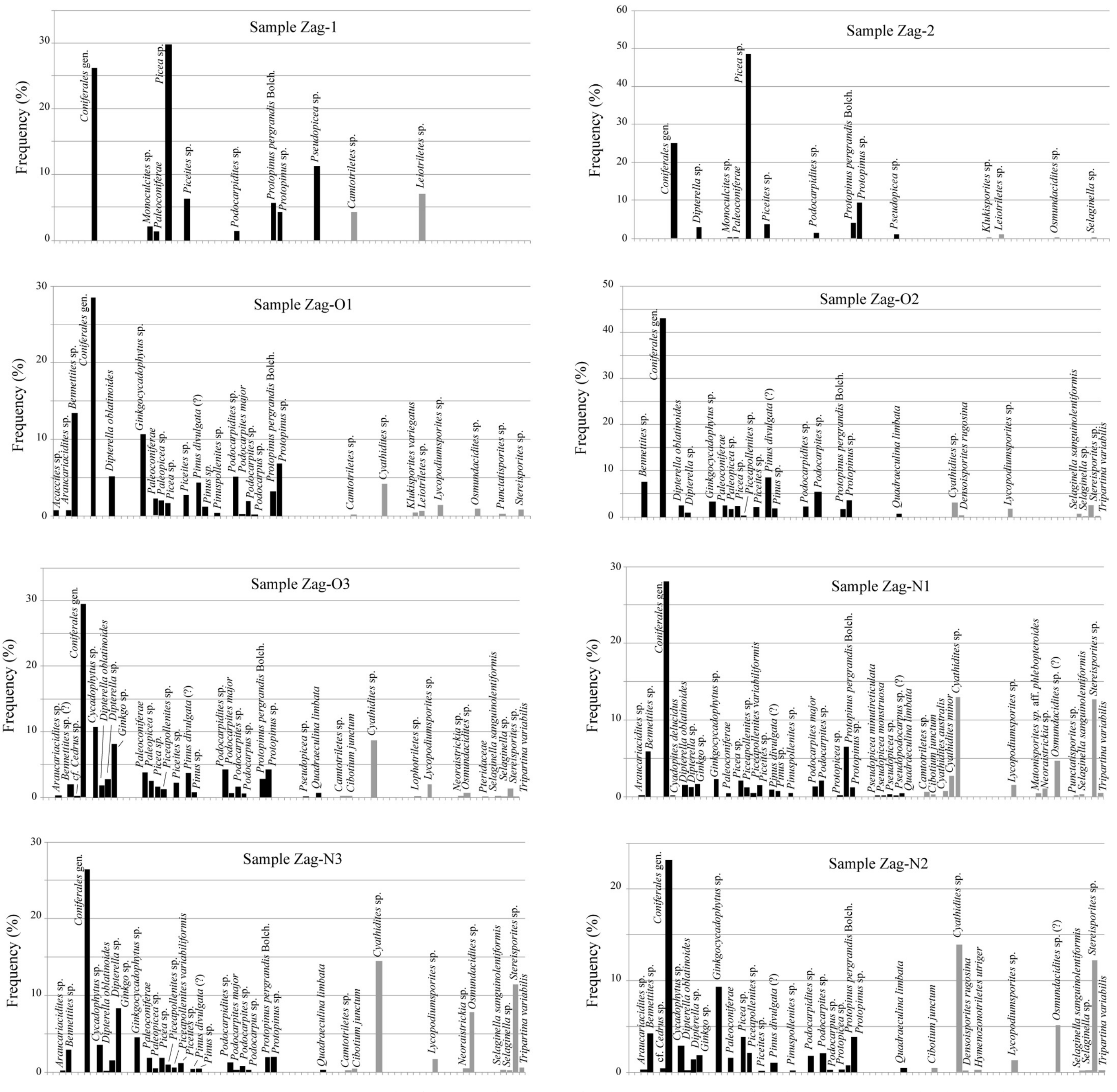

FIG. 7a. – Jurassic pollen (black) and spore (grey) species frequency histograms for the samples analysed in this study that provided more than 100 grains. Data are express in percentage of Jurassic material. Zagustai samples.

10 representative samples (figs 6 and 7b, and table IIa). The Jurassic component largely dominates these samples (72 to 99%) but a significant amount of Cretaceous spores and a few pollens is also observed. In the lower part of the section (sample Gus bc to Gus 5) (figs 6 and 7b), the Jurassic spore-pollen spectra is dominated by gymnosperms (76 to 94%), especially coniferales (35 to 61%) associated to different species of fir trees such as *Picea* sp. (up to 30%), some ancient pine trees and some Podocarpaceae. Finally, the samples contain monocolpate pollen such as *Ginkgo* sp. (up to 11%), *Ginkgocycadophytus* sp. (up to 7%) or *Bennettites* sp. (up to 10%). The Jurassic spores are dominated by *Baculatisporites* sp. (up to 6% of the total Jurassic material), *Klukisporites* sp. (up to 7%) and *Leiotriletes* sp. (up to 5%). The Cretaceous pollen is represented by *Ephedra* sp., *Abietites* sp., *Cedripites* sp., *Dacrydiumites* sp., *Glyptostrobus* sp., Taxodiaceae *Fraxinoipollenites* sp. while Cretaceous spores are *Cicatricosisporites* sp., *Pilosisporites* sp., and *Schizoporites* sp. In the more fine-grained, organic rich upper part of the section (samples Gus L to Gus n) (figs 6 and 7b), the Jurassic spectra is again dominated by gymnosperms (63 to 90%), among which Coniferales still dominate (10 to 54%). Fir trees are represented, amongst others, by *Picea* sp. (up to 29%), *Piceapollenites* sp. or *Pinaceae* sp. (up to 40%), associated to pine trees and Podocarpaceae. Monocolpate species are

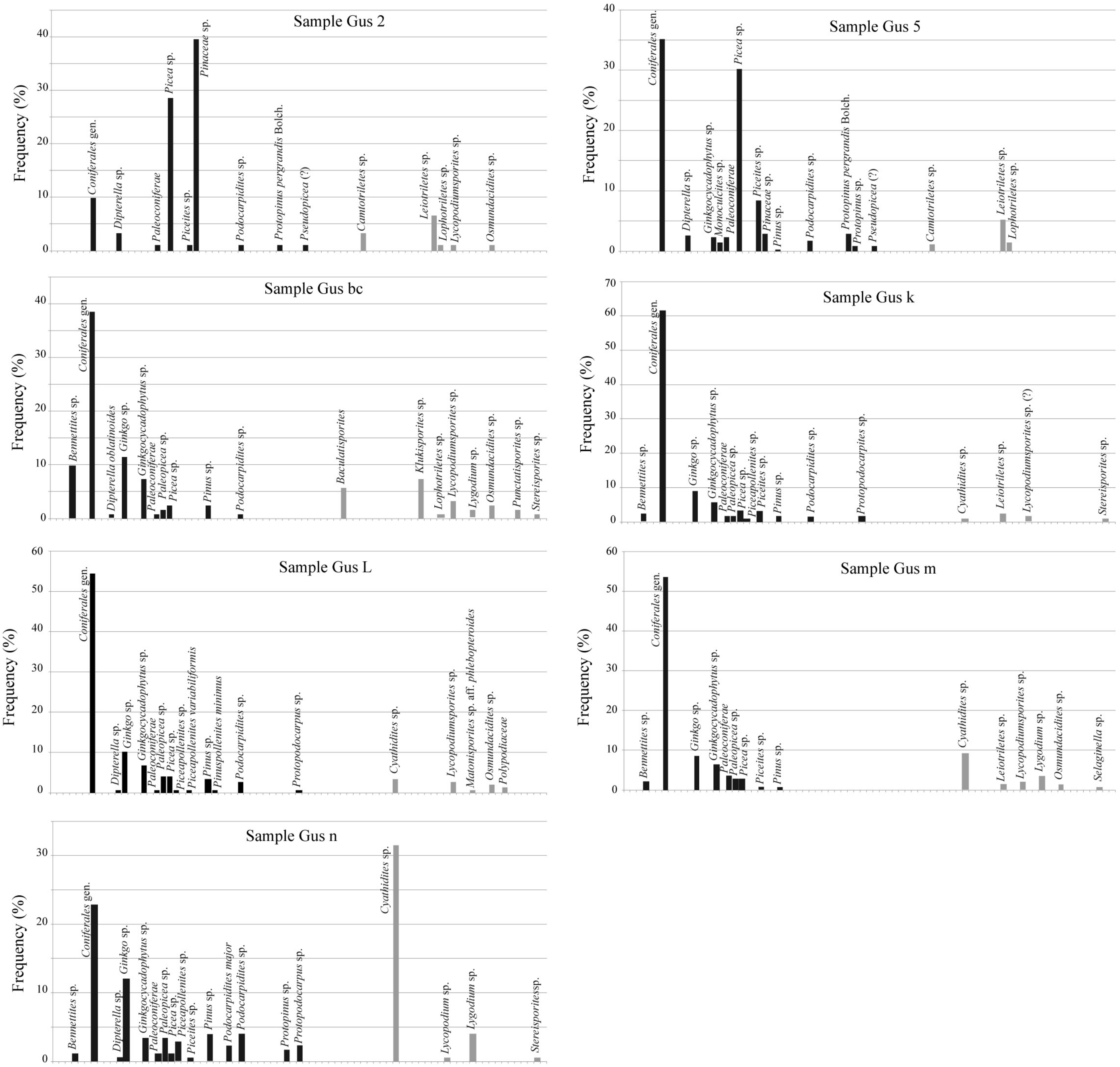

FIG. 7b. – Jurassic pollen (black) and spore (grey) species frequency histograms for the samples analysed in this study that provided more than 100 grains. Data are express in percentage of Jurassic material. Gus A samples.

Ginkgo sp. (up to 12%), *Ginkgocycadophytus* sp., and *Bennettites* sp. The Jurassic spores are largely dominated by *Cyathidites* sp. (up to 31% in sample Gus n). Cretaceous gymnosperms are represented by *Ephedra* sp., *Abietites sp.*, *Cedripites sp.*, *Dacrydiumites sp.* and Taxodiaceae together with the occurrence of the angiosperm *Fraxinoipollenites* sp. Cretaceous spores are *Aequitriradites verrucosus*, *Cicatricosisporites* sp., *Gleicheniidites* sp., *Pilosisporites* sp., Polypodiaceae. Macroremains correspond to sphenopsides *Equisetites* sp., the Lower Cretaceous fern *Birisia alata* (PRYN.) SAMYL. [Samylina, 1972], and *Scleropteris* sp.

Bainzorkhenskaya Formation

The Bainzorkhenskaya Fm. was studied along a ca. 15 m thick outcrop in the Bain-Zurkhe coal quarry, on the eastern shore of Lake Gusinoe (figs 2 and 6).

The section is mainly composed of coal alternating with fine-grained gray sandstone and brown to gray siltstone. Although the outcrop is very restricted and reliable correlation is not possible, the series are similar to the Selenguinskaya Fm. deposits observed in the New Zagustay quarry and in the upper part of the GUS road-cut section. Again, they probably represent a marshy alluvial plain.

Three samples were collected for palynology (figs 6 and 7c, table IIb, electronic supplementary material). Once again, the spore-pollen spectra are dominated by Jurassic species (78 to 88%). However a significant amount of Cretaceous gymnosperms and few spores have been obtained. The Jurassic spectra are mainly composed of gymnosperm pollen (86 to 95%) dominated by coniferales (39 to 42%) and monocolpate species such as *Ginkgo* sp. (up to 13%), Ginkgoaceae-Cycadaceae *Gynkgocycadophytus* sp. (up to 19%) and *Bennettites* sp. Fir trees are also present, especially with *Piceapollenites* sp. (up to 10%), Pine trees are mainly represented by *Paleoconiferus* sp. (up to 9%), Podocarpaceae are dominated by *Podocarpus* sp. (up to 10%); various conifers are also present. Jurassic spores are very few and represented mainly by *Cyathidites* sp., but also by the occurrence of *Callialasporites* cf. *dampiere*, *Callialasporites* sp., *Leiotrilites* sp., *Lophotriletes* sp.,

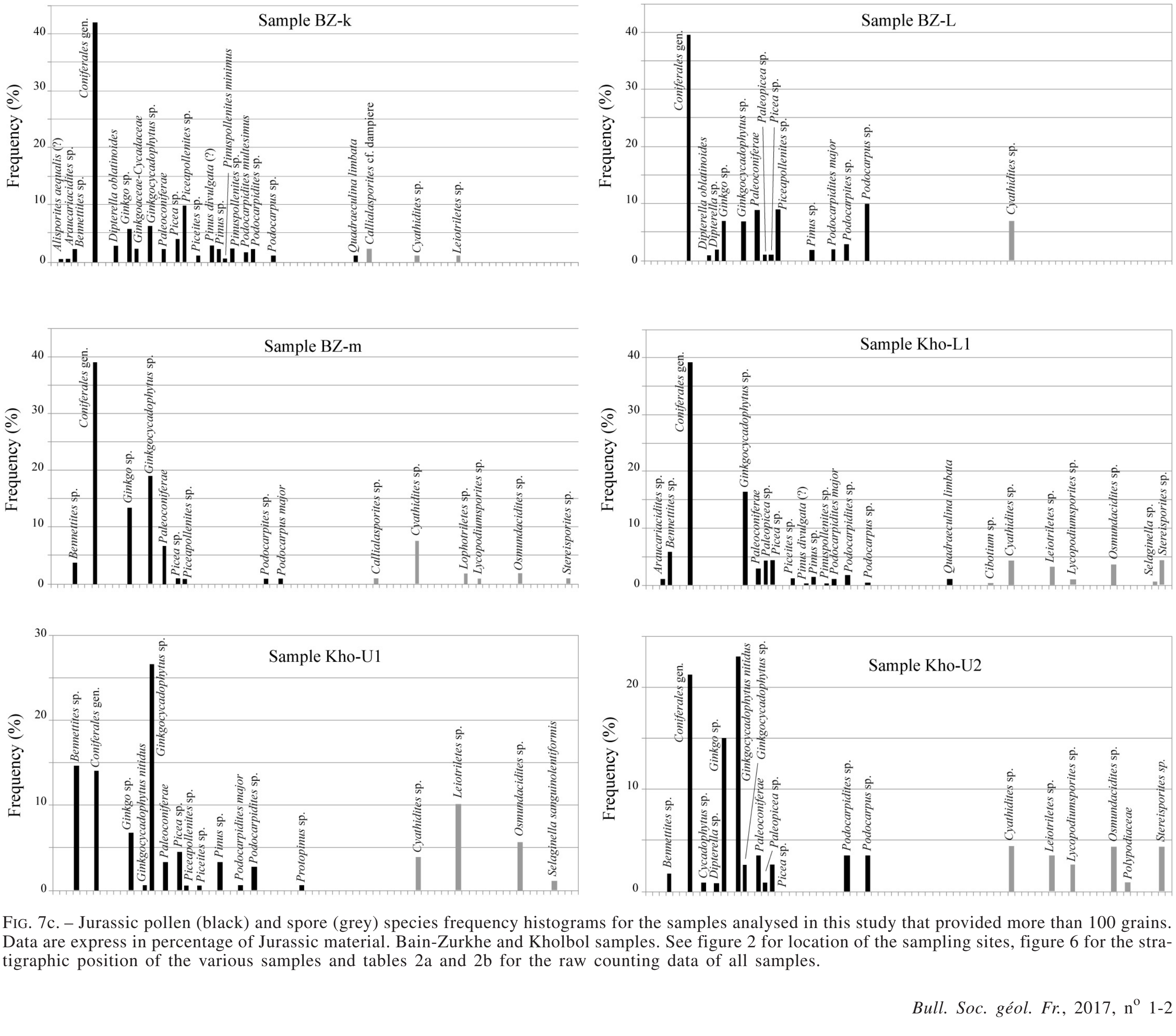

FIG. 7c. – Jurassic pollen (black) and spore (grey) species frequency histograms for the samples analysed in this study that provided more than 100 grains. Data are express in percentage of Jurassic material. Bain-Zurkhe and Kholbol samples. See figure 2 for location of the sampling sites, figure 6 for the stratigraphic position of the various samples and tables 2a and 2b for the raw counting data of all samples.

Lycopodiumsporites sp., *Osmudacidites* sp. and *Stereisporites* sp. (fig. 7c and table IIb).

Gymnosperm pollens dominate the spore-pollen spectra recovered from the Bain-Zurkhe samples with a relatively large occurrence of Taxodiaceae associated to *Abietites* sp., *Cedripites* sp. (?), *Cedrus* sp. (?), *Fraxinoipollenites* sp., *Fraxinoipollenites conistrictus*, *Phyllocladitites* sp. and *Sequoiapollenites* sp. (?) (fig. 7c and table IIb). Spores are very few, mainly *Fovealatisporites* sp., *Gleicheniidites* sp. (?) and *Laevigatosporites* sp. (fig. 7c and table IIb).

Plant macro-remains of coniopteroid ferns are again well represented by *Birisia* cf. *onychioides* (VASSILEVSK. and KARA-MURSA) SAMYL., *Coniopteris depensis* E. LEB., *Coniopteris* sp., *Cladophlebis wiliamsonii* BRONGN., as well as sphenopsides (*Equisetites* sp., leptostrobales (*Phoenicopsis* (?) ex gr. *angustifolia* HEER) and conifers (*Pityophyllum* ex gr. *nordenskioldii* (HEER) NATH.). This macro-flora, and especially the presence of *Birisia* cf. *onychioides* (VASSILEVSK. and KARA-MURSA) SAMYL. indicates an Early Cretaceous age.

Kholboldginskaya Formation

The Kholboldginskaya Fm. was studied in two sections of the Kholboldginsky coal quarry, along the eastern shore of Lake Gusinoe (figs 2 and 6). The 70 m long lower section is mainly composed of gray siltstone containing meter to decametre thick coal layers and a few decimetre thick fining-upward medium-grained sandstone with carbonated and/or argillaceous cement. The upper 20 m of the section are characterised by a ca. 10 m thick sandstone layer corresponding to a river deposit. The ca. 10 m thick upper section (Kholbol-U, Fig. X(log)) is mainly formed by coal with minor fine-grained sandstone and silt. In agreement with the description of the equivalent Turguino-Vitimskaya Fm. of Martinson [1961] we consider the Kholboldginskaya Fm. deposits observed in this study as representing a wide alluvial plain with marshes (marked by the coal and sandstone layers) and relatively large lakes (marked by the thick siltstone deposits). However, no evidence of the conglomerate deposits described by Otchirov [1964] and marking the activity of the Monostoy fault has been found, possibly due to the poor preservation of the outcrops within the exploited quarry. The rare conglomerate deposits exposed are situated on the upper part of the quarry and correspond to Neogene series (fig. 2).

Two samples were collected in the lower section and four in the upper one. Samples were analysed individually and grouped into one sample (Kho-L1) for the lower section and two samples (Kho-U1 and Kho-U2) for the upper one (figs 6 and 7c, table IIb). In both sections, the spore-pollen spectra are dominated by Jurassic material (77 to 93% of the total number of grains). Among the Jurassic spectra, gymnosperm pollens again dominate (79 to 82%), mainly represented by Coniferales (14 to 39%), and monocolpate species such as *Bennettites* sp. (up to 15%), *Cycadophytus* sp., *Ginkgo* sp. (up to 15%), *Ginkgocycadophytus* sp. (up to 27%) and *Ginkgocycadophytus nitidus* (up to 23%). Fir trees are represented by and ancient pine trees *Pinus divulgata* (?), *Pinus* sp., *Pinuspollenites* sp. and *Protopinus* sp. Podocarpaceae such as *Podocarpidites major*, *Podocarpidites* sp. and *Podocarpus* sp. Finally the conifer *Quadraeculina limbata* is also present. The Jurassic spores are mostly represented by *Leiotriletes* sp. (up to 10% of the total Jurassic material) and *Osmundacidites* (up to 6%) with some minor occurrences of *Cibotium* sp., *Cyathidites* sp., *Lycopodiumsporites* sp., Polypodiaceae, *Selaginella sanguinolentiformis* sp., *Selaginella* sp., and *Stereisporites* sp. Among the Cretaceous material, gymnosperms pollen dominates represented by *Abiespollenites* sp., *Alisporites* sp., *Fraxinoipollenites conistrictus*, *Glyptostrobus* sp., *Phyllocladitites* sp., *Pinuspollenites minimus*, *Taxodiaceaepollenites hiatus, Sequoiapollenites* sp. (?) and *Taxodiaceaepollenites* sp. The Cretaceous spores include *Aequitriradites verrucosus*, *Balmeisporites* sp., *Callialasporites* sp., *Cicatricosisporites* sp., *Cicatricosisporites stoveri*, *Deltoispora* sp., *Laevigatosporites* sp., *Matonisporites* sp., *Rugubivesisporites rugosus* and *Undulatisporites* sp.

The two sections also provided some macro-remains dominated by ferns, including the ubiquitous Lower Cretaceous *Birisia* cf. *onychioides* (VASSILEVSK. and KARA-MURSA) SAMYL. as well as *Coniopteris* sp. Other species are conifers (*Podozamites lanceolatus* (L. et H.) SHIMP., *Pityophyllum* ex gr. *nordenskioldii* (HEER) NATH.), some Ginkgoaceae (*Pseudotorellia* cf. *pulchella* HEER) and a few Leptostrobales (*Czekanowskia* ex gr. *rigida* HEER, *Phoenicopsis* ex gr. *angustifolis* HEER, *Phoenicopsis* (?) ex gr. *speciosa* HEER).

SYNTHESIS AND IMPLICATIONS FOR THE MONGOL-OKHOTSK OROGENIC CYCLE

The spore-pollen assemblages and flora macro-remains presented above indicate that the vegetation associated with the three studied formations in the Gussinoozerskaya basin was mainly composed of conifers (pine, Podocarpaceae, fir) and monocolpates trees (Ginkgoaceae) associated with numerous ferns and Podocarpaceaes. While the spore-pollen spectra are clearly dominated by Jurassic species, the plant macro-remains are dominated by coniopteroid ferns such as *Birisia alata* (PRYN.) SAMYL., *Birisia* cf. *onychioides* (VASSILEVSK. and KARA-MURSA) SAMYL., typical of the Lower Cretaceous (Hauterivian-Albian) deposits of Siberia [Samylina, 1972; Yadrischhenskaya, 2002]. Similarly, the fern *Coniopteris obrutchewii* (KRASS.) PRYN. is also abundant in the Berriasian to Hauterivian deposits [Markovitch, 2002]. Among the Ginkgoaceae, *Ginkgoites* ex gr. *adiantoides* (UNGER) HEER has a wide stratigraphic distribution covering the Lower Cretaceous to Paleogene period [Vakhrameev, 1991]. Based on the abundance of Jurassic spores and pollen as well as the clearly Cretaceous macro-remains, we estimate, in agreement with previous authors such as Martinson [1961] that the Selenguinskaya, Bainzorkhenskaya and Kholboldinskaya formations are of late Late Jurassic - Early Cretaceous age.

The Late Jurassic climate of most of central and eastern Asia was marked by a general aridification with the disappearance of coal deposits and the appearance of desert-type environments around the Jurassic-Cretaceous transition in the Junggar, Tarim and Fergana basins [Jolivet *et al.*, 2015], the occurrence of drought-resistant *Classopollis* type conifers in the West Siberian basin [Pocok and Jansonius, 1961; Le Heron *et al.*, 2008] and similar appearance of drought-resistant conifers and *Ginkgocycadophytus* in far-east Siberia [Markevich and Bugdaeva, 2009]. The flora described above, that associates numerous conifers suggesting a warm to temperate semi-arid climate, Ginkgoaceaes suggesting a seasonal temperate climate [e.g. Zhou and Wu, 2006] and ferns suggesting a warm and humid climate [e.g. Zhang *et al.*, 2014 and references therein] has also been reported further south in the Choyr and Bajanchongor basins of Mongolia (fig. 1) [Jähnichen and Kahlert, 1972; Krassilov, 1982; Nichols *et al.*, 2006; Saiki and Okubo, 2006] although they lack Bennettitales and Ginkgoaceae. Similarly to the Gussinoozerskaya basin, the Early Cretaceous deposits of the Choyr basin, situated south of the proposed position of the Mongol-Okhotsk suture zone, reflect an overall regressive sedimentary system from an alluvial fan –braided river dominated environment to a meandering river– lacustrine dominated environment [Ito *et al.*, 2006]. The floristic assemblage of the Choyr and Bajanchongor basins are interpreted as characterising an environment formed by lowlands covered by lakes and marshes, where ferns easily grew, surrounded by highlands covered by conifer forest [e.g. Saiki and Okubo, 2006; Zhang *et al.*, 2014]. A similar topography for the Transbaikal basins during the Late Jurassic – Early Cretaceous is perfectly consistent with the data presented above. This topography, and the associated environments, are somehow very similar to the current environment in the area, characterized by forested hills dominated by conifers, surrounding shallow lakes and marshes in the basins dominated where ferns and Ginkgoales are abundant [Bugdaeva and Markevich, 2007]. The near absence of ferns within the basins, mostly replaced by Poaceae, Asteraceae (*Artemisia* sp.) and Chenopodiaceae, is probably due to the present-day strongly seasonal, cold continental climate.

The three formations analysed above are characterised by a wet alluvial plain environment, including lakes and marshes. Although the sections are not complete, a general trend seems to be observed from an actively subsiding basin with a relatively sustained detrital input during the deposition of the lower part of the Selenguinskaya Fm. to a less subsiding, largely lacustrine alluvial plain at the time of deposition of the Kholboldinskaya Fm. Conglomerates in the Selenguinskaya Fm. (fig. 6) indicate the occurrence of braided river systems transporting material from an actively eroding topography. Tectonic activity during the deposition of the Selenguinskaya Fm. is further attested by the unconformity between this formation and the underlying Bukatchatchinskaya Fm. [Skoblo *et al.*, 2001]. These observations indicate that the normal faults controlling the Gussinoozerkaya basin were active, creating some local topography similar to the one actually generated by displacement on the Khambinsky Fault (fig. 2). A similar extensional tectonic setting probably prevailed in the other Transbaikal basins during the Upper Jurassic - Lower Cretaceous as evidenced by the large variations in sediment thickness across the Tugnuyskaya basin and the unconformities between the Galgatskaya and Tugnuyskaya formations (Tugnuyskaya basin) or the Chernosvskaya and Artovskaya formations (Ingodinskaya basin). The Middle Jurassic to Early Cretaceous sedimentation in the studied Transbaikal basins thus appears to be entirely controlled by extensional tectonics. No evidence was found of a strong sediment input derived from the actively eroding high-relief topography that could be expected from the Mongol-Okhotsk orogen [e.g. Zorin, 1999; Jolivet *et al.*, 2009]. Furthermore, extension initiated during Lower to Middle Jurassic in contradiction with the collision-related thickening event proposed by Zorin [1999]. However, evidence for Jurassic shortening and denudation does exist further to the north along the Siberian platform [e.g. Zorin *et al.*, 1993] or in the Baikal-Patom ranges [van der Beek *et al.*, 1996; Jolivet *et al.*, 2009] and remains to be explained with respect to the observed extension along the Mongolia - Siberia collision zone. Daoudene and co-authors [2017] proposed that extension was linked to the thermal and mechanical state of the Transbaikalian lithosphere, the suspected double-verging subduction of the Mongol-Okhotks ocean [Jolivet *et al.*, 2009] and the far field effects of the eastward subduction of the Izanagi plate [e.g. Charles *et al.*, 2013; Daoudene *et al.*, 2013]. As indicated above, the Late Jurassic - Early Cretaceous extension affected the whole east Asian lithosphere from the Pacific coast up to the actual Baikal rift system. Jolivet *et al.* [2009] suggested that the Baikal rift initiated in the early Paleogene as a continuation from this late Mesozoic phase. However, further north and west, the thick and cold lithosphere of the Siberian and Aldan cratons and west Mongolia was affected by compression and denudation as suggested by tectonic, low temperature thermochronology and sedimentological data [Ermikov, 1994; Delvaux *et al.*, 1995, 1997; van der Beek *et al.*, 1996; De Grave and Van den haute, 2002; De Grave *et al.*, 2008; Le Heron *et al.*, 2008; Jolivet *et al.*, 2009].

The tectonic setting associated with the late Mesozoic tectonic pattern combining compression and relief building to the West and North in the Altai - Sayan and Patom ranges (fig. 1) and extension in the Transbaikal region is very similar to the present-day situation. Jolivet *et al.* [2013] demonstrated that the Cenozoic deformation in SE Siberia can be explained within a sinistral strike-slip system including strike-slip movement along the Bolnay and Stanovoy fault systems and pull-apart type extension in the Baikal rift and Transbaikal region (fig. 1). This deformation is driven both by the stress field generated by the India-Asia collision to the south and by the one produced by subduction processes along the Pacific trench to the east. A similar geodynamic setting could explain the Late Mesozoic tectonic evolution, involving transpression along the western (western Mongolia) and eastern (eastern Siberia) segments of the Mongol-Okhotsk suture zone and transtension in the Transbaikal area. This setting, implying an oblique closure of the Mongol-Okhotsk ocean would be superimposed on the widespread extension driven by the Izanagi subduction zone to the East.

CONCLUSIONS

The tectonic, sedimentological, palynological, floral and faunal data presented above indicate that the Transbaikal basins evolved in a continuously extensional tectonic setting from at least the Early-Middle Jurassic to the Early Cretaceous. Their evolution is characterized by an overall retrograding sedimentary environment: alluvial fan-braided river dominated systems prevailing during the Early to Middle Jurassic initial opening of the basins were progressively replaced by meandering river - lacustrine systems during the Late Jurassic - Early Cretaceous. This evolution was similar to that of the contemporaneous Choyr and

Bajanchongor basins in Mongolia. Widely distributed extension thus controlled the geodynamic evolution of SE Siberia - NE Mongolia during the Late Jurassic - Early Cretaceous. No evidence of high relief topography that could result from the Early Cretaceous Mongol-Okhotsk orogeny has been found in the Transbaikal region, although evidence for Jurassic compressive deformation exists along the Siberian platform. Compared with the Cenozoic evolution of the Baikal rift and Transbaikal region, the apparently contradictory Late Mesozoic compression and extension could be explained by a large-scale sinistral strike-slip system driven by an oblique closure of the Mongol-Okhotsk ocean. We conclude that, at least in the Transbaikal region, the closure of the Mongol-Okhotsk ocean and the docking of the Mongolia-North China continent to Siberia was a “soft collision” event that did not lead to an orogenic event implying strong crustal thickening and topography building. In that respect the notion of Mongol-Okhotsk orogeny is not appropriate for that region.

Acknowledgements. – This project was supported by the CNRS – Russian Found for Basic Research PICS program N° 13_05-91052, the Russian Found for Basic Research N° 13-05-00247 and by the Université Rennes 1 “Emerging Scientific Projects” grant. Detailed review by C. Petit, M. Buslov and N. Charles and comments by R. Augier (SGF associate editor), T. Danelian and D. Ionov largely improved the initial manuscript.

SGF associate editor: Romain Augier

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