Island Arc

Island Arc 2017; 26: e12171

Research Article

The Aptian–Cenomanian flora of the Razdolnaya coal Basin (Primorye region, Russia)

ELENA VOLYNETS* AND EUGENIA BUGDAEVA

Institute of Biology and Soil Science, FEB RAS, 159, Prospect 100-letiya, Vladivostok 690022, Russia

Abstract Taxonomic composition of the Aptian-Cenomanian flora collected from the Razdolnaya coal Basin, Primorye, is described along with a geological description of sediments containing fossil plants. This is the first report of finding the fossil angiosperms *Dicotylophyllum* sp. and some indeterminable platanoids in the upper part of the Lipovtsy Formation (Late Lipovtsy floral assemblage), the age of which is determined as the Aptian-Early Albian. The deposits of the overlying Korkino Group were paleobotanically characterized for the first time.

Key words: Albian, Aptian, Cenomanian, floral assemblages, fossil plants, Primorye region, Razdolnaya coal Basin.

INTRODUCTION

The Early Cretaceous floras of the Razdolnaya coal Basin in the Primorye region attracted outstanding paleobotanists (Kryshtofovich & Pavlov 1928; Kryshtofovich 1928, 1929; Krassilov 1967; Vakhrameev 1991).

Kryshtofovich (1921) divided the Mesozoic flora of Primorye into the ancient Mongugay flora (the Triassic) and the younger Nikan flora (the Early Cretaceous). He found in the Lower Cretaceous deposits of the Razdolnaya (former Chinese name Suifun) coal Basin the monocots *Pandanophyllum ahnertii* Krysht. and early dicots *Aralia lucifera* Krysht. as well as *Cissites prodromus* Krysht. in the Partizansk (Suchan) coal Basin. These findings convinced him of the Cretaceous age of the Nikan flora (Kryshtofovich 1928, 1929; Kryshtofovich & Pavlov 1928).

In the middle 1960s Krassilov (1967) elaborated the detailed stratigraphy of the Lower Cretaceous of the Razdolnaya Basin, which is relevant until now. He divided the Nikan Group into the Ussuri (Barremian), Lipovtsy (Aptian) and Galenki (Albian) Formations based on the study of the Early Cretaceous flora of South Primorye.

Our data on the Aptian–Cenomanian flora of the Razdolnaya coal Basin give grounds to specify the stratigraphic position of some strata and to extend our knowledge of taxonomic composition of this flora.

The Aptian–Cenomanian was a very important time in the history of the vegetable kingdom, during which the early flowering plants appeared in the geologic record. At the end of the terminal Albian the replacement of gymnosperms by angiosperms took place. Moreover, among ferns and gymnosperms the representatives of evolutionary advanced "young" plants appeared.

MATERIALS AND METHODS

Our study is based on the fossil plant collections from the Razdolnaya coal Basin stored in the Institute of Biology & Soil Science FEB RAS (Vladivostok).

These fossils were collected by the authors, as well as by colleagues (Nevolina S. I., Shorokhova S. A., Krassilov V. A., Markevich V. S.) and by geologists from the Primorye Geological Survey (Amelchenko G. L., Lushnikov V. F., Mudrov V. L., Naydenko A. N., Okovityi V. N., Kovalenko S. V.,

*Correspondence: Institute of Biology and Soil Science, FEB RAS, 159, Prospect 100-letiya, Vladivostok 690022 Russia (email: volynets61@yandex.ru).

Received 13 April 2015; accepted for publication 9 July 2016.

doi: 10.1111/iar.12171

Oleynikov A. V., Golozubov V. V., Kandaurov A. T., Gussakov L. A.). Plant megafossils were collected from more than 100 localities in the study area (Fig. 1). They are represented mainly by leaf imprints, leafy shoots, mineralized trunks, wood, fruits and seeds. The preservation of the fossil

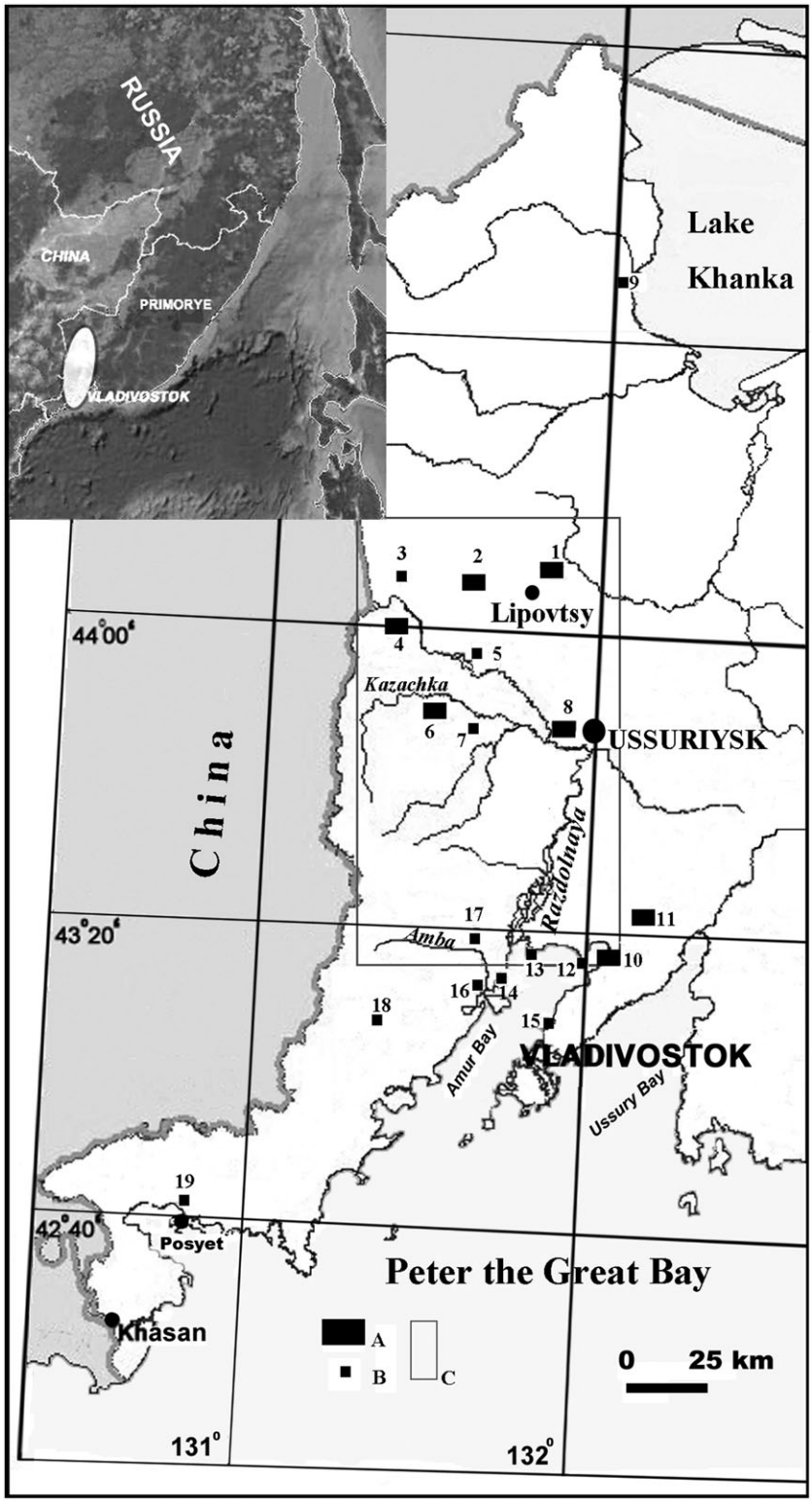

Fig. 1 Study area in the south-western Primorye region. A, coal fields; B, low-coal occurrences: 1, Lipovtsy; 2, Ilyichevka; 3, Fadeevka; 4, Konstantinovka; 5, Sinelovka; 6, Alexee-Nikolsk; 7, Kazachka; 8, Ussuriysk; 9, Lake Khanka; 10, Podgorodnenka; 11, Surazhevka; 12, De-Fries; 13, Rechnoi Peninsula; 14, west coast of Amur Bay; 15, Firssov Cape, Vladivostok City; 16, lower course of the Amba River near Provalovo Village; 17, Zanadvorovka Village; 18, Ovchinnikovo Village (Barabash River Basin); 19, estuary of the Gladkaya River (Posyet Bay).

plant material is satisfactory, that allows to observe the fine details of structures of the plant organs.

STRATIGRAPHIC SETTING

The Razdolnaya coal Basin extends from the north-west (from the Lake Khanka) to the southwest as far as the Posyet Bay. It represents an area of distribution of mostly Cretaceous sediments (Fig. 2), which are divided into the Nikan (Barremian–late Albian) and the Korkino (late Albian–Cenomanian) Groups.

The Nikan Group consists of the Ussuriysk (Barremian), Lipovtsy (Aptian–early Albian), and Galenki (early–late Albian) Formations (Fig. 2). The latter is overlain conformably by the Korkino Group (Krassilov 1967; Markevich 1995; Volynets 2005, 2006, 2013, 2014; Golozubov 2006).

THE LIPOVTSY FORMATION

This formation conformably overlies the Ussuriysk Formation. Based on lithologic composition, the Lipovtsy Formation is divided into two

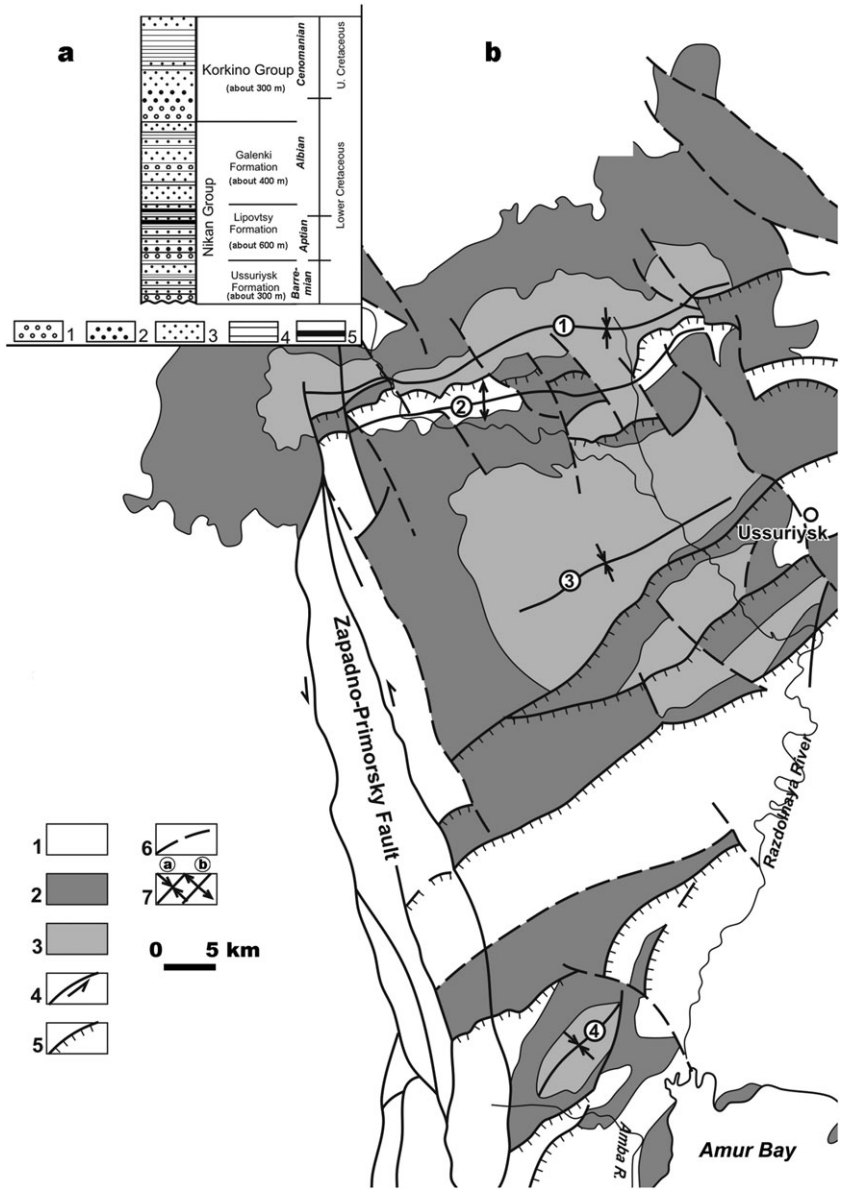

Fig. 2 Distribution of the Cretaceous deposits in the Razdolnaya Basin. 1, Pre-Cretaceous rocks; 2, Nikan Group; 3, Korkino Group; 4, strike-slip fault; 5, thrust; 6, normal fault; 7, syncline axis (a) and anticline axis (b): 1, Lipovtsy-Fadeevka syncline; 2, Korf-Galenki anticline uplift; 3, Putsylovka; 4, Zanadvorovka syncline (Golozubov 2006, with additions authors). Inset A: Schematic sequence of the Cretaceous deposits. 1, conglomerate, gravelstone; 2, coarse-grained sandstone; 3, medium- and fine-grained sandstone; 4, siltstone; 5, coaly mudstone and coal.

subformations: Lower Lipovtsy (K_1 *lp₁*) and Upper Lipovtsy (K_1 *lp₂*). On siltstones of the Ussuriysk Formation the coarse-grained gravelly sandstones of the Lipovtsy Formation (Lower Lipovtsy Subformation) are deposited, and they show a new sedimentary cycle (Fig. 2). The thickness of this formation is nearly 500 m (Krassilov 1967).

The Lower Lipovtsy Subformation is represented by coarse deposits - conglomerates and coarse-grained gravelly sandstones. Coal seams are absent.

Its most complete section was studied on the watershed of the Krestyanka-2 and Krestyanka-3 rivers, in the Ilyichevka coalfield and in the vicinity of Ussuriysk City (Krassilov 1967; Kutub-Zade 2010). The thickness of the subformation varies from 110 to 260 m.

The Upper Lipovtsy Subformation consists mainly of fine-grained sandstones, siltstones, mudstones, and coals. The lower coal seam "Rabochii" (up to 19 m thick) has industrial significance, while the superposed coal seam "Gryaznyi" (1–2 m thick) does not have commercial value. The coals mined in the northern part of the Razdolnaya coal basin are humic and liptobiolithic (resinous). The thickness of the subformation is 50–350 m (Kutub-Zade 2010).

In the 1920s these resinites were studied by Kryshtofovich (1928), who describes "… coal is compact, hard, brownish-black, opaque, heavy, overfilled, or rather mostly consisting of thin resin needles, transpiercing the coal in all directions and shining in split…". He recognized a special type of coal composed of small sticks of resin bodies and named this coal as rhabdopissite (from Greek ράβδος meaning small stick and πίσσα–resin), suggesting that these substances are simply resin filling or gum of resin ducts of trees, conifers or rather cycadophytes, i.e., probably bennettites.

Recently Bugdaeva & Markevich (2009) revealed the plants that produced resinous coals of the Lipovtsy coal field. The remains of leaves *Mirovia orientalis* (Nosova) Nosova compose that coal. These plants belong mainly to the enigmatic extinct group Miroviaceae. The miroviaceous leaves usually contain numerous resin ducts, that probably served as the basis for the origin of rhabdopissites. The coal-forming plants also comprise ginkgoalean *Pseudotorellia krassilovii* Bugdaeva and cyatheaceous and gleicheniaceous ferns (palynospectra from coals are dominated by their spores).

THE GALENKI FORMATION

This formation conformably overlies the Lipovtsy Formation. It consists mainly of polymictic fine- to medium-grained sandstones, lesser siltstones, tuffites, conglomerates, coaly mudstones, and andesites. A specific feature of sediments of the formation is the admixture of tuffaceous material along all sequences of this stratigraphic unit. Its thickness is 250–380 m (Kutub-Zade 2010). The plant remains occur mostly in the middle and upper parts of the section of this formation.

THE KORKINO GROUP

The Korkino Group unconformably overlies the Galenki Formation. The boundary between them is defined on the basal part layer of conglomerates or coarse-grained tuffstones commencing the new sedimentation rhythm. The typical feature of sediments of this Group is abundant intercalations of red beds (tuffaceous siltstones and tuffites), rarely psammitic tuffs and whitish-grey tuffstones. Its thickness is up to 300 m (Kutub-Zade *et al.* 2002).

THE FLORISTIC ASSEMBLAGES OF THE RAZDOLNAYA COAL BASIN

EARLY LIPOVTSY FLORAL ASSEMBLAGE

The fossil plants were collected from several localities: in Mt. Salnikov near Ussuriysk City, in a lower course of the Amba River near Provalovo Village, in Muravyov-Amurskii Peninsula near Vladivostok City, as well as from sections of boreholes 1c, 2c, 3c, 7c, 10c (in the territory between Kazachka, Borissovka and Razdolnaya rivers), 24, 53, 54 (in a lower course of the Slavyanka River, Ussuriysk City) (Fig. 1).

The Early Lipovtsy floral assemblage involves *Thallites* sp., *Lycopodites nicanicus* Krassil., *Isoetites* sp., *Equisetites* ex gr. *burejensis* (Heer) Krysht., *E. ramosus* Samyl., *Coniopteris burejensis* (Zal.) Sew., *Coniopteris* sp., *Alsophilites nipponensis* (Oishi) Krassil., *Onychiopsis psilotoides* (Stok. et Webb) Ward, *Cladophlebis matonioides* Oishi, *C. frigida* (Heer) Sew., *Cladophlebis* sp., *Lobifolia novopokrovskii* (Pryn.) Rasskaz. et E. Lebed., *Sphenopteris* ex gr. *fontainei* Sew., *Sagenopteris* sp., *Pterophyllum burejense* Pryn., *P. manchurense* (Oishi) Krassil., *Pterophyllum* sp., *Dictyozamites cordatus* (Krysht.) Pryn., *Nilssoniopteris robusta* (Krysht. et Pryn.) Krassil., *Nilssonia* ex gr. *brongniartii*

(Mant.) Dunk., *N. densinervis* (Font.) Berry, *N. nicanica* Pryn., *Nilssonia* sp., *Baiera ahnertii* Krysht., *Podozamites* ex gr. *lanceolatus* (Lindl. et Hutt.) Schimp., *Podozamites* sp., *Pityophyllum* sp., *Elatides* ex gr. *curvifolia* (Dunk.) Nath., *E. asiatica* (Yok.) Krassil., *Athrotaxites berryi* Bell, *Athrotaxopsis expansa* Font. emend. Berry, *Brachyphyllum japonicum* (Yok.) Oishi, *Brachyphyllum* sp.

This assemblage consists of 34 taxa which belong to the ferns (9 taxa), cycadophytes (9 taxa), and conifers (9 taxa). The age of this floral assemblage based both on the paleobotanical and palynological data is the Aptian (Verbitskaya *et al.* 1965; Krassilov 1967; Markevich 1995).

LATE LIPOVTSY FLORAL ASSEMBLAGE

Numerous localities of fossil plants in the basin are located in the Lipovtsy, Ilyichevka, Konstantinovka, Alexee-Nikolsk, Ussuriysk, Podgorodnenka and Surazhevka coalfields, as well as in many outcrops (e.g. near villages Sinelovka, Fadeevka, Zanadvorovka, Ovchinnikovo, Kazachka) (Fig. 1). Moreover, the phytofossils are known from the localities situated at the mouth of the Gladkaya River (Posyet Bay), in the Rechnoi and De-Fries peninsulas near Vladivostok and Firssov Cape (Vladivostok City).

The Late Lipovtsy floral assemblage consists of 136 taxa. The most significant are ferns (38 taxa), among which abundant *Nathorstia pectinata* (Goepp.) Krassil. (Fig. 3), *Alsophilites nipponensis* (Oishi) Krassil., *Onychiopsis psilotoides* (Stok. et Webb) Ward (Fig. 3), accompanied by *Coniopteris burejensis* (Zal.) Sew., "*Polypodites*" *polysorus* Pryn., *Teilhardia tenella* (Pryn.) Krassil., *Cladophlebis frigida* (Heer) Sew. Rarely *Osmunda denticulata* Samyl., *Birisia onychioides* (Vassilevsk. et Kara-Mursa) Samyl. occur.

Among conifers (33 taxa) *Araucariodendron heterophyllum* Krassil., *Podozamites* ex gr. *lanceolatus* (Lindl. et Hutt.) Schimp., *Elatides asiatica* (Yok.) Krassil., *Athrotaxopsis expansa* Font. emend. Berry takes significant part. They are accompanied by *Pityophyllum* ex gr. *nordenskioldii* Heer, *Sequoia* ex gr. *reichenbachii* (Gein.) Heer, *Torreya nicanica* Krassil. (Fig. 3), *Mirovia orientalis* (Fig. 3). The presence of cycadophytes is significant (30 taxa), namely Bennettitales (17 taxa) and Cycadales (13 taxa).

Among Bennettitales *Pterophyllum burejense* Pryn. (Fig. 3), *Zamiophyllum ivanovii* (Krysht. et Pryn.) Krassil. (Fig. 3), *Cycadites sulcatus* Krysht. et Pryn. are numerous. They are accompanied by *Pterophyllum sutschanense* Pryn. (Fig. 3), *Dictyozamites cordatus* (Krysht.) Pryn., *Nilssoniopteris rhitidorachis* (Krysht.) Krassil. (Fig. 3).

Among Cycadales the presence of *Ctenis yokayamae* Krysht., *Nilssonia densinervis* (Font.) Berry, *N.* ex gr. *brongniartii* (Mant.) Dunk, *N.* ex gr. *orientalis* Heer, *N. nicanica* Krassil. is significant.

Also there are diverse Lycopodiales (*Lycopodites prynadae* Krassil., *L. nicanicus* Krassil., *L. multifurcatus* Lee, *Lycopodites* sp., *Isoetites* sp.), Caytoniales (*Caytonia orientalis* Krassil., *Sagenopteris variabilis* (Velen.) Velen., *S. mantellii* (Dunk.) Schenk (Fig. 3), *Sagenopteris* sp.), and Ginkgoales (*Ginkgo concinna* Heer, *G. pluripartita* (Schimp.) Heer, *G.* ex gr. *adiantoides* (Ung.) Heer, *Pseudotorellia* sp., *P. krassilovii*), rather rare Equisetales (*Equisetites* sp., *E. ramosus* Samyl., *E. burejensis* (Heer) Krysht.), single Czekanowskiales (*Czekanowskia* ex gr. *rigida* Heer), Bryales (*Marchantites yabei* Krysht. et Pryn., *Thallites* sp.) and disperse cuticle of Gnetales (Volynets 2005, 2014; Bugdaeva *et al.* 2014).

Extremely rare are angiosperms, which appear in Podgorodnenka and Ilyichevka coal fields. They are represented by leaves of *Dicotylophyllum* sp. (Fig. 4) and by dispersed cuticle of indeterminable platanoids (Fig. 5). The specimen of angiosperm leaf shown on the left in Figure 4 is better-preserved, whereas other specimens in Figure 4 are not well-preserved. The former leaf is small, about 1.5 cm long and more than 1 cm wide. Primary venation is pinnate, the primary vein thinns noticeably between the base and the apex which is unknown. Secondary veins (probably 7 or 9 pairs) are thin to moderate, often decurrent on midvein. Such details of morphology, as leaf lamina outline, venation pattern, leaf margin are not preserve, therefore, these leaves are assigned here to the artificial genus *Dicotylophyllum* of unknown taxonomic position.

The outstanding feature of this floral assemblage is the presence of *Nathorstia pectinata, Dictyozamites cordatus, Cycadites sulcatus, Torreya nicanica,* with the significant role of "young", evolutionary the most advanced taxa, *Osmunda denticulata, Birisia onychioides, Sequoia* ex gr. *reichenbachii, Taxites brevifolius,* as well as the first appearance of flowering plants.

Based on our research we have revealed that in the late Aptian–early Albian, the main components of the swamp plant communities were conifers Miroviaceae, Araucariaceae, taxodialeans, ginkgoaleans

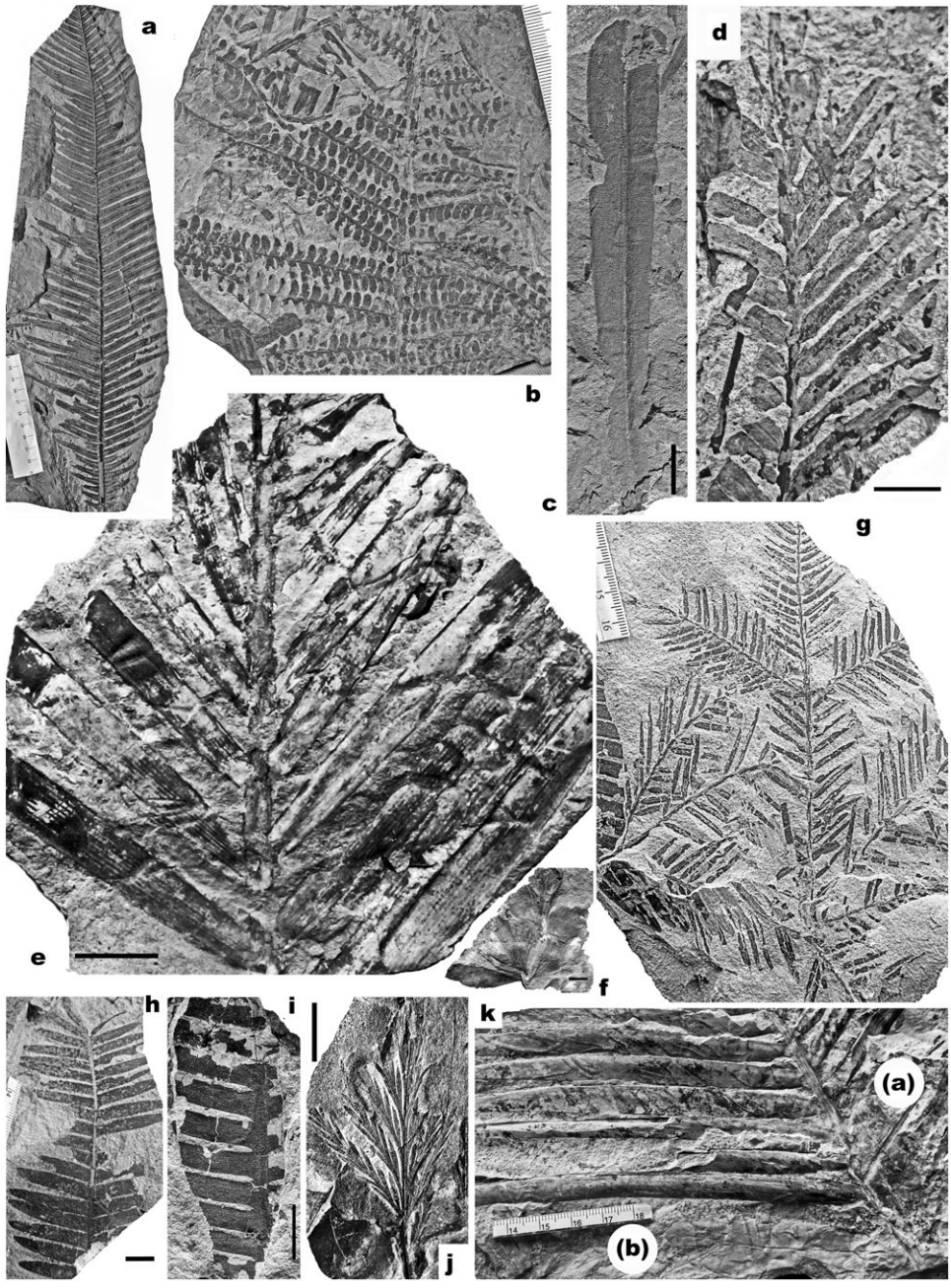

Fig. 3 The typical fossil plants of the Late Lipovtsy floral assemblage (upper part of the Lipovtsy Formation). a, *Nathorstia pectinata* (Goepp.) Krassil., Lipovtsy Coalfield; b, *Gleicheniopsis sujfunensis* Krassil., Lipovtsy Coalfield; c, *Nilssoniopteris rhitidorachis* (Krysht.) Krassil., Lipovtsy Coalfield; d, *Mirovia orientalis* (Nosova) Nosova, Lipovtsy Coalfield; e, *Zamiophyllum ivanovii* (Krysht. et Pryn.) Krassil., Ilyichevka Coalfield; f, *Adiantopteris sewardii* (Yabe) Vassilevsk., Podgorodnenka Coalfield; g, *Torreya nicanica* Krassil., Lipovtsy Coalfield; h, *Pterophyllum burejense* Pryn., Lipovtsy Coalfield; i, *P. sutschanense* Pryn., Lipovtsy Coalfield; j, *Onychiopsis psilotoides* (Stok. et Webb) Ward, Podgorodnenka Coalfield; kA, *Zamiophyllum buchianum* (Ett.) Sew.; kB, *Sagenopteris mantellii* (Dunk.) Sew., Ilyichevka Coalfield (scale bar 1 cm).

(*Pseudotorellia krassilovii*), bennettites, as well as gleicheniaceous and cyatheaceous ferns. These plants supplied the material for the accumulation of resinite coals on the territory of Razdolnaya Basin (Bugdaeva *et al.* 2015).

The age of this assemblage is the late Aptian–early Albian (Volynets 2006, 2013, 2014; Bugdaeva *et al.* 2014).

GALENKI FLORAL ASSEMBLAGE

This assemblage is divided into three subassemblages: early, middle and late.

The early subassemblage was revealed in the lower part of the Galenki Formation. The localities with fossil plants are known in the middle course of the Razdolnaya River near Sinelnikovo Village

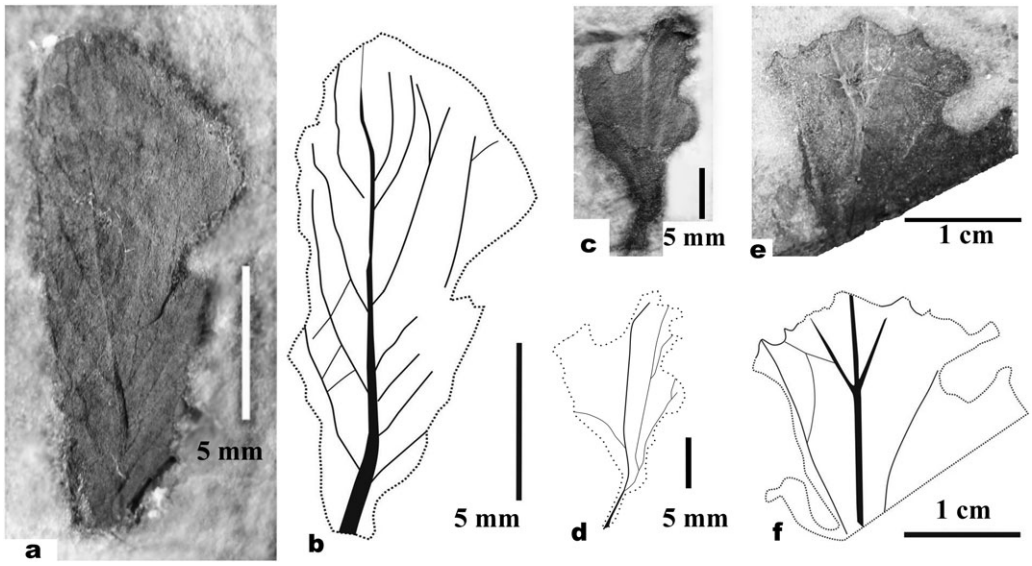

Fig. 4 The angiosperms of the Late Lipovtsy floral assemblage (upper part of the Lipovtsy Formation). a, b, *Dicotylophyllum* sp. 1 (image and its drawing); c, d, *Dicotylophyllum* sp. 2 (image and its drawing); e, f, *Dicotylophyllum* sp. 3 (image and its drawing), all findings are from Podgorodnenka Coalfield.

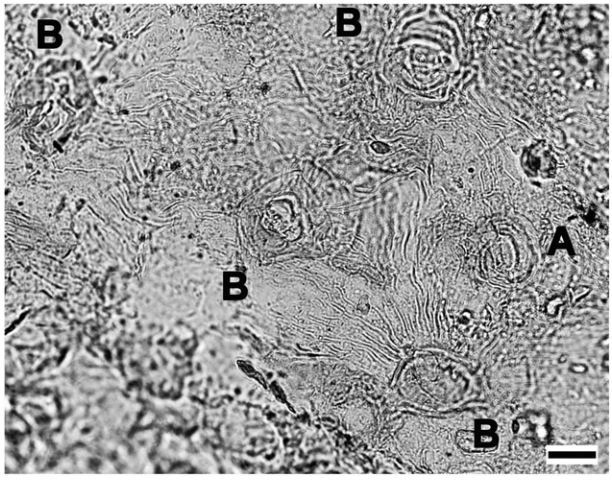

Fig. 5 Lower cuticle of a leaf of probable platanoids (upper coal seam in upper part of the Lipovtsy Formation, Porechye Coal Mine). A, stoma; B, radiostriate hair bases, light microscope (scale bar 20 μm).

(Fig. 1). Taxonomic diversity of the subassemblage is not great (31 taxa). In this subassemblage cycadophytes predominate: *Dictyozamites*, *Pterophyllum*, *Leptopterophyllum*, *Nilssonia*. The most numerous plants are *Dictyozamites cordatus*, *Leptopterophyllum pterophylloides* (Pryn.) Krassil., *Nilssonia densinervis*, *N.* ex gr. *orientalis*, as well as the ferns, among them *Onychiopsis psilotoides*, *Teilhardia tenella*, *Anemia dicksoniana* (Heer) Krassil. are also abundant.

Ginkgoaleans are represented mainly by *Ginkgo* ex gr. *adiantoides*, lycopods by *Lycopodites prynadae*, conifers by *Podozamites tenuinervis* Heer, caytonialeans by *Sagenopteris mantellii*.

The specific feature of the early subassemblage is the predominance of cycadophytes (30%) as well as the increased presence of "young" fern genera - *Teilhardia*, *Anemia*, *Birisia*.

The age of this subassemblage is the early Albian (Volynets 2006, 2011, 2014).

The middle subassemblage of the Galenki floral assemblage is revealed in the middle part of the Galenki Formation (Volynets 2005, 2013, 2014). In the localities near Fadeevka, Porechye, Ilyichevka (the Ilyichevka coal field), Konstantinovka (the Konstantinovka coal field), Bolotnyi stream (Barabasch River Basin), in De-Fries and the Muravyov-Amurskii peninsulas (the Podgorodnenka coal field) the most abundant megafloral remains occur.

This subassemblage is characterized by considerable taxonomic diversity (69 taxa), with predominance of the ferns (27 taxa), among which *Birisia alata* (Pryn.) Samyl., *Anemia dicksoniana*, *Lobifolia novopokrovskii* (Pryn.) Rasskaz. et Lebed. The subdominants are conifers (14 taxa), among which *Podozamites tenuinervis*, *Taxites brevifolius*, *Sequoia reichenbachii* are common in this assemblage.

Cycadophytes (10 taxa) are represented by abundant remains of *Neozamites denticulatus* (Krysht. et Pryn.) Vachr., *Pterophyllum sutschanense*, *Nilssonia canadensis* Bell, *N.* ex gr. *orientalis*. The presence of dicots *Sapindopsis*, *Dicotylophyllum*, *Cercidiphyllum*, *Laurophyllum* is typical in this assemblage.

The remains of ginkgoaleans (*Pseudotorellia* sp.), gymnosperms of unknown taxonomic position (*Sujfunophyllum dichotomum* Krassil.), monocots (*Pandanophyllum ahnertii* Krysht.), and fruits of angiosperms (*Onoana* and *Nyssidium*) are rare.

The particular feature of this subassemblage is the predominance of the ferns (39.2%) and conifers (20.4%), as well as considerable amount of *Birisia*, *Anemia*, *Dicksonia*, *Adiantopteris*, *Taxites*, *Sequoia*. But the angiosperms (8.5%) are still rare.

The age of this subassemblage is the middle Albian (Volynets 2006, 2011, 2014).

The late subassemblage of the Galenki floral assemblage was found from/in the upper part of the Galenki Formation (Volynets 2005). The localities with abundant fossil plants are known from the west lakeside of the Lake Khanka, from vicinity of Porechye Village (the Ilyichevka coal field), at Konstantinovka Village (the Konstantinovka coal field), in the Amba River Basin (Zanadvorovka Village and the west coast of Amur Bay), near the coal fields of the Podgorodnenka (Sokol Bay, Dachnyi stream, Peschanka River) and from Surazhevka coal field (Surazhevka Village) (Fig. 1).

The taxonomic diversity of this subassemblage is rather high (86 taxa). The ferns (27 taxa) and cycadophytes (25 taxa) predominate. The representatives of ferns *Coniopteris*, *Anemia*, *Osmunda* are the most diverse. *Osmunda denticulata*, *Anemia dicksoniana*, *Gleichenites porsildii* Sew., *Birisia oerstedtii* (Heer) E. Lebed. *Lobifolia novopokrovskii* are common.

Cycadophytes are represented by numerous *Pterophyllum burejense*, *P. sutschanense*, *Leptopterophyllum pterophylloides*, *Encephalartopsis vachrameevii* Volyn., *Nilssonia canadensis*, *N.* ex gr. *brongniartii*. The genus *Ctenis* (4 species) occurs rarely.

Among conifers (13 taxa) *Sequoia reichenbachii*, *Taxites acuminatus*, *T. brevifolius*, *Athrotaxopsis expansa* are common. Caytoniales (*Caytonia orientalis*, *Sagenopteris variabilis*), Ginkgoales (*Ginkgo* ex gr. *adiantoides*, *G. pluripartita*, *Baiera ahnertii* Krysht., *B. manchurica* Yabe et Oishi) and flowering plants (*Sapindopsis* sp., *S. variabilis* Font., *Menispermites* sp., *Araliaephyllum* sp.) are rare.

For this floral subassemblage against the ferns (31.2%) and cycadophytes (29.1%) the diversity increases, and the angiosperms are scanty (5.7%). Its age is the beginning of the late Albian.

The age of Galenki Formation as a whole is the early Albian to early–late Albian (Volynets 2006, 2011).

KORKINO FLORAL ASSEMBLAGE

This assemblage was revealed from the deposits of the Korkino Group distributed on Markovskii Cape, in the basin of Peschanka River on the Muravyov–Amurskii Peninsula, as well as in the Amba River Basin. It was recognized as two subassemblages.

The early subassemblage was studied in the lower part of this Group section on the Muravyov–Amurskii Peninsula, as well as in the Amba River Basin (South Primorye). Its taxonomic diversity is low (25 taxa). Conifers dominate in this subassemblage (11 taxa), accompanied by ferns (9 taxa), single cycadophytes (2 taxa) and angiosperms (2 taxa), as well as by plants with unclear taxonomic position (2 taxa).

Among conifers *Elatides asiatica* and *Elatocladus obtusifolius* Oishi are numerous and *Sequoia* ex gr. *reichenbachii* are common. Ferns are represented by abundant *Gleichenites* aff. *porsildii* and *Anemia dicksoniana*, but such genera as *Osmunda*, *Arctopteris*, *Birisia* and *Dicksonia* occur very rarely. The presence of cycadophytes *Nilssonia* ex gr. *brongniartii* and *N.* ex gr. *orientalis* is not significant.

The typical feature of this subassemblage is the predominance of conifers and the sharp decrease of taxonomic diversity. Its age is the terminal Albian (Volynets 2006, 2013, 2014).

The late subassemblage of the Korkino floral assemblage derived from the siltstones and mudstones of the upper part of the Korkino Group. Localities with fossil plants are known from sections along Peschanka and Saperka rivers in the north of the Muravyov–Amurskii Peninsula (Fig. 1).

Taxonomic composition of this subassemblage is poor (16 taxa). Angiosperms dominate (7 taxa), *Platanophyllum* spp. occurs often, accompanied by *Dicotylophyllum* sp. and rarely by *Sapindopsis* sp. Ferns are represented by few *Osmunda* sp., *Gleichenites* sp., *Anemia dicksoniana*, *Sphenopteris* sp. Conifers *Podozamites* sp., *Parataxodium* sp. 1, *Taxites* sp. 1, horsetails *Equisetites* sp. and seeds of *Carpolithes* sp. are rare.

The main feature of this subassemblage is the predominance (45%) of the flowering plants represented by various platanoids (Volynets 2013).

From the upper part of the Korkino Group Volynets & Markevich (2014) revealed the palynological assemblage of the late Cenomanian age.

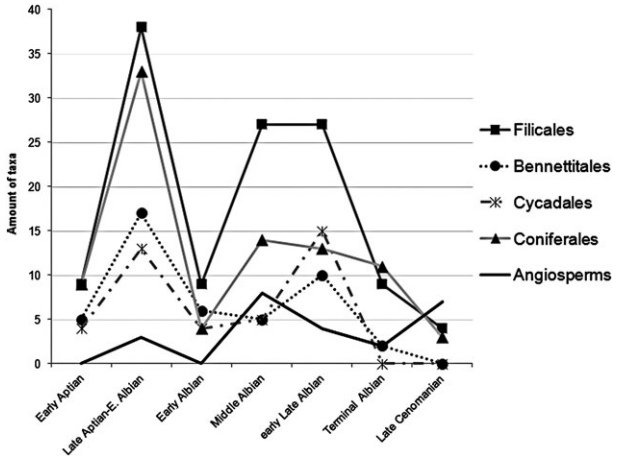

Fig. 6 Relative abundances of main groups of fossil plants in the Aptian–Cenomanian of the Razdolnaya Basin.

CONCLUSIONS

The fossil plants from the Cretaceous deposits of the Razdolnaya coal Basin were studied. Their taxonomical diversity reached a peak during the late Aptian–early Albian, after that it experienced sharp reduction, and finally increased during the middle–late Albian. At the Albian–Cenomanian boundary the most plants disappeared, and the angiosperms became dominants (Fig. 6).

Based on the contents of thermophilic elements in fossil floras (e.g. bennettites) and floral taxonomical diversity (which can reflect the existence of plants under optimal conditions) many paleobotanists believed that during the Early Cretaceous on the territory of Siberia, including the Primorye region, there were climatic optima during the Berriasian, late Aptian, early–middle Albian (e.g. Krassilov 1967, 1973; Vakhrameev 1991; Bugdaeva *et al.* 2006; Golovneva 2007).

The taxonomical diversity of the Cretaceous flora of the Razdolnaya Basin considerably changed. In the late Aptian and the early Albian. The diversity of the thermophilic ferns (*Nathorstia pectinata*, *Alsophilites nipponensis*, *Weichselia reticulata* (Stokes et Webb) Ward, *Matonidium* sp., *Gleicheniopsis sujfunensis* Krassil. (Fig. 3), *Eboracia* spp., *Adiantopteris sewardii* (Yabe) Vassilevsk. (Fig. 3), conifers (*Araucariodendron heterophyllum*, *A. oblongifolium* Krassil., *Ussuriocladus racemosus* (Halle) Krysht. et Pryn., *Torreya nicanica*, *Podocarpus* spp. *et al.*), and bennettites (*Williamsonia pacifica* Krysht., *Zamiophyllum ivanovii*, *Z. buchianum* (Ett.) Sew. (Fig. 3), *Zamites borealis* Heer, *Cycadites sulcatus*, *Nilssoniopteris robusta* (Krysht. et Pryn.) Krassil., *N. rhitidorachis et al.*) sharply increased. In the early Albian these thermophilic plants disappeared along with discontinuation of coal formation and increase of the share of volcaniclastic sediments in plant-bearing sections. In the middle–late Albian the plant diversity grows by means of appearance of moderate taxa of ferns, cycads, and conifers, inhabited in the northern Siberia–Canadian Phytogeographical Region (Vakhrameev 1991). During this time sedimentation of coal-bearing deposits with thin coal seams and volcaniclastic beds took place. The Albian–Cenomanian boundary extinction of many Mesozoic plants (e.g. bennettites and others) coincides with the accumulation in the Razdolnaya Basin of coarse-grained sediments and red beds. The latter could be formed in result of weathering of volcanic ashes (Golozubov 2006).

The changes of climates and paleoenvironments caused changes in taxonomic composition of flora, and dynamics of its diversity and abundances. The Late Lipovtsy floral assemblage consisting of 136 taxa is the most abundant; in all probability the conditions of existence of plants were favorable. It was the time of climatic optimum. The climate and environment deterioration during the Albian conditioned depletion of taxonomic composition of flora.

In the upper part of the Lipovtsy Formation (Late Lipovtsy floral assemblage) the remains of flowering plants *Dicotylophyllum* sp. and some indeterminable platanoids were found for the first time. The age of this formation was defined more precisely as the Aptian–early Albian. Thus, the time of appearance of angiosperms in this basin was older than previously considered. Molecular sequence data (Sanderson *et al.* 2004) were used to estimate divergence times in angiosperms indicating that their crown node is from the Jurassic (208–145 Ma). However, the oldest remains of angiosperms in East Asia (Mongolia, North-East China, North Korea, Japan, and Southeastern Russia) were found in the Barremian–Aptian (Krassilov 1997; Bugdaeva *et al.* 2006). The finding of *Pandanophyllum ahnertii* in the upper Aptian–lower Albian deposits of Razdolnaya Basin confirms the phylogeny of monocots proposed by K. Bremer (2000).

Taxonomic composition of the floral assemblage from the Korkino Group was analyzed for the first time. Its age is determined as the late Albian–Cenomanian.

ACKNOWLEDGEMENTS

Our research was supported by Russian Foundation for Basic Research (grant 16-04-01411). The authors are grateful to our colleagues Markevich V. S. (Institute of Biology and Soil Science FEB RAS) and Golozubov V. V. (Far East Geological Institute, FEB RAS) for their encouragement, to volunteers Lysyuk A. F., Sologub N. P., Semeykin Y. A., Lyzganov A. V., Yuferov V. V. helped us during the field works. We are indebted to the late Krassilov V. A. for fruitful discussions and advices.

REFERENCES

BREMER K. 2000. Early Cretaceous lineages of monocot flowering plants. *Proceedings of the National Academy of Sciences* **97**, 4707–11.

BUGDAEVA E. V. & MARKEVICH V. S. 2009. The coal-forming plants of Rhabdopissites in the Lipovtsy coal field (Lower Cretaceous of Southern Primorye). *Paleontological Journal* **43**, 1217–29.

BUGDAEVA E. V., VOLYNETS E. B., GOLOZUBOV V. V., MARKEVICH V. S. & AMELCHENKO G. L. 2006. *Flora and Geological Events of the mid-Cretaceous time (Alchan Basin, Primorye)*, Dalnauka, Vladivostok (in Russian).

BUGDAEVA E. V., MARKEVICH V. S., VOLYNETS E. B., KOVALEVA T. A. & NECHAEV V. P. 2014. The Early Cretaceous coal-forming plants from the Razdolnaya Basin (Southern Primorye). *In* Baraboshkin E. Y., Markevich V. S., Bugdaeva E. V., Afonin M. A. and Cherepanova M. V. (eds.) *Cretaceous System of Russia and the near abroad: problems of stratigraphy and paleogeography*, pp. 70–2, Dalnauka, Vladivostok (in Russian).

BUGDAEVA E. V., VOLYNETS E. B. & MARKEVICH V. S. 2015. The Early Cretaceous Flora of Razdolnaya River Basin (Primorye Region, the Russian Far East). Botanica Pacifica. *A Journal of Plant Science and Conservation* **4**(2), 71–7.

GOLOVNEVA L. B. 2007. Occurrence of *Sapindopsis* (Platanaceae) in the Cretaceous of Eurasia. *Paleontological Journal* **41**, 1077–90.

GOLOZUBOV V. V. 2006. *Tectonics of the Jurassic and Lower Cretaceous Complex of the North-Western Framing of the Pacific Ocean*, Dalnauka, Vladivostok (in Russian with English abstract).

KRASSILOV V. A. 1967. *Early Cretaceous Flora of Southern Primorye and Its Stratigraphic Significance*, Nauka, Moscow (in Russian).

KRASSILOV V. A. 1973. Contributions to Stratigraphy and Paleoflora of Coal Sequence of the Bureya Basin. *In* Krassilov V. A. (ed.) *Fossil Floras and Phytostratigraphy of the Far East*, pp. 28–51, Dal'nevostochnyi Nauchnyi Centr Akademii Nauk SSSR, Vladivostok (in Russian).

KRASSILOV V. A. 1997. *Angiosperm Origins: morphological and ecological Aspects*, Pensoft, Sofia.

KRYSHTOFOVICH A. N. 1921. The discovery of equivalents of the Lower Jurassic strata of Tonkin in the Ussuri region. *Materials on Geology and Mineral Resources of the Far East* **22**, 1–30 (in Russian).

KRYSHTOFOVICH A. N. 1928. *The Lipovtsy Coal Mines in the Ussuri River Region*, Geologicheskiy Komitet (Geological Committee), Leningrad (in Russian).

KRYSHTOFOVICH A. N. 1929. The discovery of the oldest dicotyledons angiosperms and equivalents of the Potomac beds on Suchan in the Ussuri region. *Izvestiya Geologicheskogo Komiteta (Bulletin of Geological Committee)* **48**, 113–45 (in Russian).

KRYSHTOFOVICH A. N. & PAVLOV M. A. 1928. The discovery of the Aptian Beds characterized by dicotyledonous flora in the Suchan Area. *Vestnik Geologicheskogo Komiteta (Bulletin of Geological Committee)* **8**, 19–26 (in Russian).

KUTUB-ZADE T. K. 2010. *Geological sequence and mineral resources in the basins of Komissarovka, Melgunovka and Razdolnaya rivers*. Federal Geological Survey Primorye Region, Vladivostok (in Russian).

KUTUB-ZADE T. K., OLEYNIKOV A. V. & SYAS'KO A. A. 2002. *Geological structure and mineral resources in the river basins and in the area of water of Peter the Great Bay.* Federal Geological Survey Primorye Region, Vladivostok (in Russian).

MARKEVICH V. S. 1995. *The Cretaceous palynoflora of north of eastern Asia.* Dalnauka, Vladivostok (in Russian).

SANDERSON M. J., THORNE J. L., WIKSTRÖM N. & BREMER K. 2004. Molecular evidence on plant divergence times. *American Journal of Botany* **91**, 1656–65.

VAKHRAMEEV V. A. 1991. *Jurassic and Cretaceous floras and climates of the Earth*. Cambridge University Press, Cambridge.

VERBITSKAYA Z. I., DZENS-LITOVSKAYA O. A. & SHTEMPEL B. M. 1965. *The Cretaceous Vegetation and Coals of the Primorye Coal Basin*, Nauka, Moscow (in Russian).

VOLYNETS E. B. 2005. The Aptian–Cenomanian Flora of Primorye, Part 1: Floral Assemblages. *Stratigraphy and Geological Correlation* **13**, 613–31.

VOLYNETS E. B. 2006. The Aptian–Cenomanian Flora of Primorye, Part 2: Correlation of Floral Assemblages. *Stratigraphy and Geological Correlation* **14**, 200–10.

VOLYNETS E. B. 2011. Geology and conditions of forming of the Aptian–Cenomanian sediments of northwestern Primorye. Abstract of the Ph.D. thesis. Far Eastern Geological Institute, Vladivostok (in Russian).

VOLYNETS E. B. 2013. Knowledge of the Cretaceous deposits and flora of the Muravyov-Amurskii Peninsula (South Primorye). *Bulletin of the Far Eastern Branch of Russian Academy of Sciences* **5**, 62–8 (in Russian).

VOLYNETS E. B. 2014. Middle Cretaceous flora of the Razdolnaya coal Basin in Primorye. *In* Baraboshkin E. Y., Markevich V. S., Bugdaeva E. V., Afonin M. A. and Cherepanova M. V. (eds.) *Cretaceous System of Russia and the near abroad: problems of stratigraphy and paleogeography*, pp. 78–81, Dalnauka, Vladivostok (in Russian).

VOLYNETS E. B. & MARKEVICH V. S. 2013. The discovery of Cenomanian flora in the vicinity of Vladivostok city. *In* Golovneva L. B. and Gromyko D. V. (eds.) *Lectures to the memory of A.N. Kryshtofovich*, pp. 5–6, BIN RAN, St.-Petersburg (in Russian).