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Palaeoenvironment and ecology of the middle Cretaceous Grebenka flora of northeastern Asia

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Abstract

The Grebenka flora, from the main exposure of the Albian–Cenomanian Krivorechenskaya Formation in northeastern Russia, represents a range of plant communities from pioneer to mature forest that grew close to the mid-Cretaceous North Pole (> 72°N). The diversity of this flora is dominated by angiosperms followed by conifers, ferns and other plant groups. The age is constrained by $^{40}Ar/^{39}Ar$ analyses of associated volcaniclastics (~ 96.5 Ma), coupled with biostratigraphic correlation of the plant-bearing non-marine beds with marine units of the Krivorechenskaya Formation and the overlying Dugovskaya Formation. Limited palaeosol development and pronounced episodic floodplain aggradation indicate that the 100-m-thick plant-bearing volcaniclastic floodplain succession was deposited rapidly, resulting in excellent trapping and preservation of the plant communities, but dilution of the palynoflora. Analysis of the megaflora (> 100 foliage taxa, plus woods and fructifications) provides a 'snapshot' of the mid-Cretaceous climate, and offers reliable quantitative climatic signals of conditions near the mid-Cretaceous North Pole. Multivariate analysis of leaf physiognomy (Climate Leaf Analysis Multivariate Program) on the whole flora suggests that the plants experienced a mean annual temperature of 13.0 ± 1.8°C and a cold month mean temperature of 5.5 ± 3.3°C. However, analyses of individual florules yield slightly different results that help constrain the uncertainties inherent in such an approach. These and other foliar physiognomic data are compared across the Arctic. © 2002 Published by Elsevier Science B.V.

Keywords: Cretaceous; northeastern Russia; palaeobotany; palaeoenvironment; palaeoecology; palaeoclimate

1. Introduction

The characterisation of polar climates is critical for understanding the global climate system. Land-based climate proxies give a direct reading of atmospheric conditions, but often the precise age of non-marine sediments is difficult to pinpoint. Moreover, sediment accumulations used as proxies may take many thousands to millions of years to form and thus represent climate aver-

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aged over that time. Plant fossils, however, are capable of capturing environmental data on much shorter time-scales within the lifetime of the organism, but in order to provide useful climatic information populations of plant material are required that, like sediments, need to be temporally well-defined.

The present study was conducted to reconstruct a 'snapshot' of ancient northeastern Asian maritime onshore palaeoclimate and palaeoenvironmental conditions close to the middle Cretaceous North Pole, in a remote region from which very few well-constrained palaeoclimate proxy data have been reported. We have focussed on climate signals of plant-leaf physiognomy because these provide the widest range of quantitative palaeoclimate parameters. In order to minimise uncertainties we also established a robust taphonomic, sedimentary, stratigraphic and palaeogeographic framework for the flora.

The Grebenka flora has been regarded as the most important mid- to Late Cretaceous palaeofloristic record in northeastern Asia (Terekhova, 1988), and during the last 40 yr every publication discussing northeastern Asian regional phytostratigraphy and palaeobotany has referred to it. Moreover, the Grebenka flora seems to be one of the most diverse middle Cretaceous floras of Eurasia, and possibly of the world, despite its position within the Cretaceous Arctic Circle. However, the age of the flora is controversial with estimates ranging from the late Albian (Terekhova, 1988) to as young as the Turonian (Samylina, 1974), or even the Coniacian (Krassilov, 1975). The Grebenka flora (Chukotka, northeastern Asia: Fig. 1) is so called because the plant remains come from a number of localities along the Grebenka River, a right tributary of the Anadyr River. The locality with the most abundant and taxonomically diverse fossil flora occurs on the right bank of the Grebenka River, at an exposure of the Krivorechenskaya Formation (Fig. 2). This locality was discovered by Yelisseev (1936) and is now referred to by his name. Plant fossils collected by Yelisseev were first studied and published by Kryshtofovich (1958), but Baikovskaya (1956) discussed an earlier unpublished report of Kryshtofovich and this same report was subsequently referred to again by Vakhrameev (1966). In the 1950–1960s, geologists of the

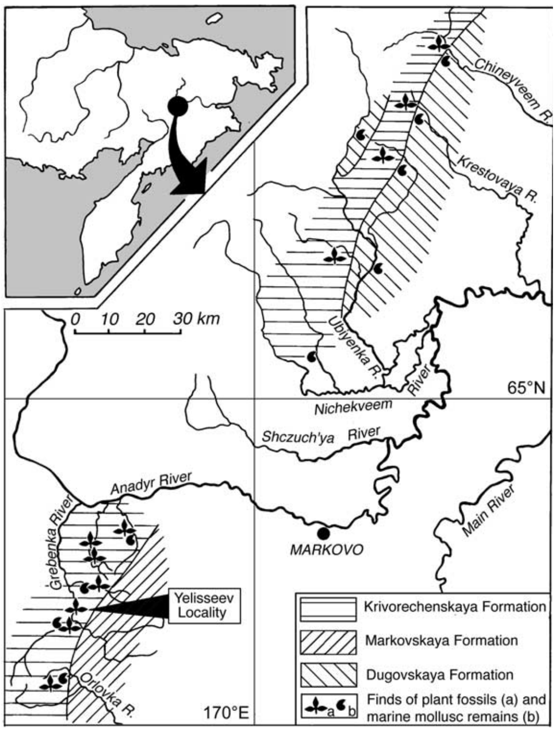

Fig. 1. The distribution of plant-bearing deposits of the Krivorechenskaya Formation and the overlying Markovskaya and Dugovskaya formations, northeastern Asia.

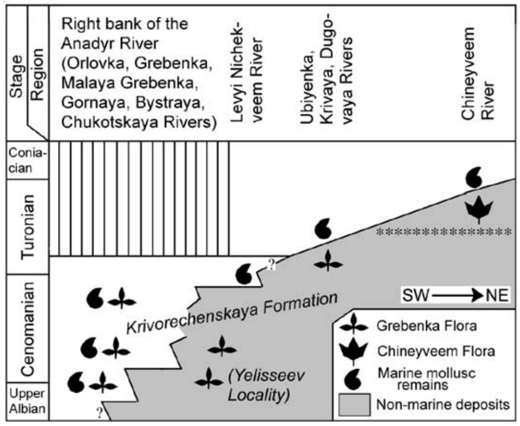

Fig. 2. Correlation of non-marine deposits of the Krivorechenskaya Formation with marine rocks in the middle reaches of the Anadyr River (asterisks indicate the upper boundary of the Grebenka flora).

USSR Geological Survey made numerous plant fossil collections from the Krivorechenskaya Formation that were subsequently studied by Samylina (1974), Krassilov (1975) and Budantsev (1983). New field studies and palaeobotanical work on the Grebenka flora were made by Devyatilova et al. (1980), Filippova (1978a,b, 1979, 1982, 1984, 1989, 1998), Filippova and Abramova, (1993), and E.L. Lebedev (1987).

Ankudinov, Devyatilova and V.V. Lebedev (1982–1983; unpublished survey reports) collected marine mollusc fossils from the Krivorechenskaya Formation and from overlying deposits along the middle reaches of the Anadyr River and Terekhova (1988) and Pokhialainen (1994) used these molluscs to better define the age of the formation. Ammonites and inoceramids, ocurring together with some plant impressions in the marine deposits, were also used for age determinations by Alabushev and Pokhialainen (1990, personal communication; see Table 2). Plant fossils and samples for palynological and palaeomagnetic analyses were collected and examined from continental and marine strata of the Krivorechenskaya Formation (Shczepetov and Herman, 1990; Samylina and Shczepetov, 1991; Herman and Shczepetov, 1992; Shczepetov et al., 1992; Spicer and Herman, 1996; Herman, 1999a,b). Palaeomagnetic analysis of the Yelisseev Locality succession yielded a predominantly reversed polarity (Lozhkina and Shczepetov, 1994). However, it is unclear if this result reflects the primary magnetisation, or a subsequent overprint. Prior to this study all existing museum collections of the Grebenka flora were analysed using early versions of the Climate Leaf Analysis Multivariate Program (CLAMP) technique (Spicer et al., 1996; Spicer and Herman, 1998).

The Yelisseev Locality was the major target of our study because:

(1) Existing Yelisseev Locality plant fossil collections are very rich. Approximately 130 plant taxa have been reported, and most were recovered from the Yelisseev Locality. From earlier, primarily taxonomic, studies the reason for this diversity is not apparent, due to a lack of palaeoenvironmental understanding. For instance, the diversity could have resulted from broad time averaging (i.e. the sediments exposed at the locality accumulated over a long time and therefore sampled an evolutionary gradation of taxa), or from the preservation of numerous different plant communities, or both. In view of the diversity and palaeolatitude of this flora, the previously inferred late Albian–earliest Cenomanian age is interesting, because in neighbouring Alaska where such diversity is unknown the earliest angiosperm occurrences are thought to be no older than late Albian (Smiley, 1966, 1969a,b).

(2) The plant-bearing sediment pile is quite thick. The large number of individual florules observed at numerous sites within the locality suggests that it may be possible to document repeated plant assemblage and depositional environment associations, and thereby obtain valuable insights into near-polar Cretaceous plant communities at this critical time in angiosperm evolutionary radiation.

(3) The sediment thickness is sufficient to get reliable palaeomagnetic data to determine the palaeolatitude of the locality, and to investigate any possible reversals in polarity to help constrain the age.

(4) Although entirely non-marine, the plant-bearing strata have been traced laterally to areas where marine biostratigraphy can be used to constrain the age of the flora.

(5) Tuffaceous rocks are known to be present, and $^{40}Ar/^{39}Ar$ analysis has the potential to provide independent age determination of the succession.

The results of our 1997 field study of the Yelisseev Locality are presented in this paper. Here we describe, for the first time, the sedimentology of the sedimentary succession exposed at this locality, we present new palaeomagnetic data defining its palaeolatitude, define its absolute age by means of $^{40}Ar/^{39}Ar$ analysis, and interpret the palaeoenvironments and the palaeoecology of the ancient plant communities.

To avoid unnecessary stratigraphical revisions and misunderstandings, we herein use the established obligatory Russian hierarchical stratigraphic nomenclature and translation principles (Zhamoyda, 1992). Thus, formations ('suites' in Russian language) are subdivided into subformations ('sub-suites'), and in turn into members ('pachka'), with capitalisation of their formal names.

2. Geological setting

The Yelisseev Locality is situated approximately 50 km to the south and east of the Okhotsk–Chukotka volcanogenic belt, which was active from late Aptian times through the Late Cretaceous. The succession was deposited in a fore-arc basin, during the accretion of the Kony–Murgal Arc onto the northeastern Asian continental margin, i.e. the final closure of the Mongol–Okhotsk Ocean (Nockleberg et al., 1998). The Krivorechenskaya Formation reflects depositional environments of alluvial to coastal plains and adjacent shallow marine basins. The geology of the region is dominated by the influence of the nearby volcanogenic belt (Belyi, 1994), which was the source of the clastic material that entombs the fossil flora.

The Krivorechenskaya Formation is widely exposed in two areas along the middle reaches of the Anadyr River (Figs. 1 and 2). The lithological composition of the Krivorechenskaya Formation and overlying deposits, as well as palaeontological remains from them, differ in the two areas, and they are therefore here considered separately.

2.1. Geology of right bank of the Anadyr River

On the right bank of the Anadyr River, the plant-bearing deposits of the Krivorechenskaya Formation extend through the basins of the Orlovka, Grebenka, Chukotskaya and Bystraya rivers (Figs. 1 and 3). The deposits containing the Grebenka flora overlie Valanginian and Hauterivian rocks with an angular discordance, and are divided into two subformations (Devyatilova et al., 1980). The Lower Krivorechenskaya Subformation is 400–600 m thick, and largely composed of conglomerates with subordinate coarse-grained sandstones. It is devoid of fossils, except for fragmented plant debris. The Upper Krivorechenskaya Subformation is represented by continental conglomerates, sandstones and siltstones yielding plant remains, and marine beds containing molluscs. It also contains fewer conglomerates than the Lower Krivorechenskaya Subformation.

Devyatilova et al. (1980) suggested that on the right bank of the Anadyr River the Upper Krivorechenskaya Subformation is divisible into two members, although certain publications treat these members as subformations (Terekhova, 1988). The Lower Member is 400–600 m thick and composed exclusively of continental deposits (conglomerates and sandstones), while the 300–350-m-thick Upper Member differs from the lower by the presence of sandstones and siltstones with a marine fauna. According to Devyatilova et al. (1980), the Yelisseev Locality belongs to the Lower Member of the Upper Krivorechenskaya Subformation. No marine fossils have been found at the Yelisseev Locality.

A locality of the Upper Krivorechenskaya Subformation that contains both plant and marine mollusc remains is situated in the middle reaches of the Gornaya River, 7 km to the northeast from the Yelisseev Locality (Fig. 3). Fossil plants similar to those of the Yelisseev Locality (Table 1) have been found here together with marine molluscs. The molluscs indicate that the locality belongs to the *Mantelliceras* zones of the standard scale (Pokhialainen, 1994; Gradstein et al., 1994) and to the *Hypoturrilites gravesianus* ammonite zone and *Inoceramus dunveganensis aiensis* inoceramid zone of northeastern Asia (Table 2), which correspond to beds with *I. dunveganensis* in Alaska (lower Cenomanian). The age determination of the Gornaya River Locality is critical to the understanding of the Yelisseev Locality age, because these successions can be correlated directly with the Yelisseev Locality succession by combining field observations and information from aerial photographs. From these it appears that the Yelisseev Locality is stratigraphically just below the Gornaya River Locality succession (Fig. 3) and thus probably not younger than the early Cenomanian (the latest Albian to earliest Cenomanian interval was regarded most probable according to Shczepetov et al. (1992) and Herman (1999a,b)).

In the vicinity of the Yelisseev Locality, two other exposures of the Upper Krivorechenskaya Subformation are known where marine mollusc

Table 1
Fossil plants from the Yelisseev Locality

Thallites sp.
Thallites sp. cf. *Marchantites jimboi* (Krysht.) Krysht.
Equisetites sp.
Gleichenia pseudocrenata E. Lebed.
Gleichenites zippei (Corda) Sew.
Gleichenites asiatica Philipp.
Birisia jelisejevii (Krysht.) Philipp.
Birisia ochotica Samylina
Birisia (?) *oerstedtii* (Heer) E. Lebed.
Coniopteris anadyrensis Philipp.
Coniopteris (*Birisia*?) *grebencaensis* Philipp.
Coniopteris (?) sp.
Arctopteris penzhinensis E. Lebed.
Asplenium dicksonianum Heer
Hausmannia bipartita Samyl. et Shczep.
Cladophlebis aff. *septentrionalis* Hollick
Cladophlebis sp. 1
Cladophlebis sp. 2
Cladophlebis sp. 3
Sphenopteris sp. 1
Sphenopteris sp. 2
Sagenopteris variabilis (Velenovsky) Velenovsky
Cycadites hyperborea (Krysht.) E. Lebed.
Nilssonia alaskana Hollick
Nilssonia serotina Heer
Nilssonia yukonensis Hollick
Nilssonia sp.
Nilssoniocladus chukotensis Spicer et Herman
Ginkgo ex gr. *adiantoides* (Unger) Heer
Ginkgo ex gr. *lepida* Heer
Sphenobaiera vera Samyl. et Shczepetov
Pseudotorellia (?) sp.
Phoenicopsis ex gr. *angustifolia* Heer
Cephalotaxopsis ex gr. *heterophylla* Hollick
Cephalotaxopsis intermedia Hollick
Florinia (?) sp.
Araucarites anadyrensis Krysht.
'*Araucarites*' sp. (cone-male)
'*Araucarites*' sp. (cone-female)
Pagiophyllum triangulare Prynada
Pseudolarix (?) sp.
Pityophyllum ex gr. *nordenskioldii* (Heer) Nath.
Pityophyllum ex gr. *staratschinii* (Heer) Nath.
Pityospermum aff. *piniformis* Samylina
Pityospermum semiovale Samylina
Pityostrobus sp. 1
Pityostrobus sp. 2
Sequoia cf. *minuta* Sveshnokova
Sequoia ex gr. *reichenbachii* (Geinitz) Heer
Sequoia sp. (cone)
Sequoia sp. (cone scale)
Tollia sp.
Elatocladus smittiana (Heer) Seward
Magnoliaephyllum alternans (Heer) Seward
Menispermites marcovoensis Philipp.
Menispermites minutus (Krysht.) Herman
Menispermites ex gr. *septentrionalis* Hollick
Platanus louravetlanica Herman
Platanus sp.
Platanus sp. (reproductive structures)
Pseudoprotophyllum cf. *boreale* (Dawson) Hollick
Platanofolia gen. indet.
'*Diospyros*' aff. *steenstrupi* Heer
Sorbites asiatica Philippova
Myrtophyllum acuminata (Philipp.) Herman
Celastrophyllum sp.
'*Araliaephyllum*' *dentatum* Philippova
Araliaephyllum medium (Philippova) Herman
Scheffleraephyllum venustum (Philipp.) Philipp.
Sapindophyllum sp.
Scheffleraephyllum sp.
Trochodendroides arctica (Heer) Berry
'*Zizyphus*' sp.
Dalbergites sp.
Cissites sp. 1
Cissites sp. 2
Cissites sp. 3
Dalembia vachrameevii E. Lebed. et Herman
Grebenkia anadyrensis (Krysht.) E. Lebed.
Dicotylophyllum cf. *Palaeonuphar nordenckioldii* (Heer) Bell
Dicotylophyllum sp. 1
Dicotylophyllum sp. 2
Dicotylophyllum sp. 3
Dicotylophyllum sp. 4
Carpolithes sp.

remains accompany plant fossils (Figs. 1 and 2). At the Malaya Grebenka River Locality, fossil molluscs indicate a late Albian to earliest Cenomanian age (*Neogastroplites americanus* ammonite zone) (Terekhova, 1988; Pokhialainen, 1994) (Table 2). According to Devyatilova et al. (1980), the Malaya Grebenka Locality is also situated stratigraphically above the Yelisseev Locality, but poor exposure renders this conclusion insecure (Shczepetov et al., 1992; Filippova, 1998). At the Orlovka Mountain locality, near the Orlovka River (see Fig. 1), the inoceramid *Pergamentia* indicates a late Cenomanian to early(?) Turonian age interval (the *Pergamentia reduncus* and, possibly, *Inoceramus labiatus* inoceramid zones) (Pokhialainen, unpublished data). Cenomanian(?) inoceramid remains are also known from the Bystraya River area (Figs. 2 and 3) (Terekhova, 1988).

Table 2
Stratigraphic position of the plant fossil localities in relation to marine fossil zones in the area surrounding the Yelisseev Locality (according to Shchepetov et al. (1992) and data of Pokhialainen (1994) and Alabushev)

Stage	International zonal standard (Pokhialainen, 1994)	Ammonite zones of the North-eastern Russia (Pokhialainen, 1994)		Inoceramid zones of the North-eastern Russia (Pokhialainen, 1994)		Stratigraphic position of the plant fossil localities (Shczepetov and Herman, 1990): According to ammonites and inoceramids	Stratigraphic position of the plant fossil localities (Shczepetov and Herman, 1990): According to palynology and palaeomagnetic data
Turonian	*Mammites nodosoides*	*Marshalites tumefactus*		*Inoceramus labiatus*			
	Watinoceras coloradoensis						
Cenomanian	*Neocardioceras juddi*			*Pergamentia reduncus*		Orlovka Mountain locality	
	Metoicoceras geslinianum						
	Cacycoceras querangeri						
	Alternacanthoceras jukesbrownei						
	Acanthoceras rhomomagense	*Turrilites costatus*		*Pergamentia pressulus*			
	Mantelliceras dixoni	*Neogastroplites americanus*	*Hypoturrilites gravesianus*	*Gnesioceramus comancheanus*	*Inoceramus dunveganensis ajensis*	Gornaya River locality	
	Mantelliceras mantelli						Grebenka River locality (Yelisseev locality)
Albian	*Stoliczkia dispar*		*Pseudhelicoceras mordax*		*Inoceramus concentricus sulcatus*	Malaya Grebenka River locality	
	Mortoniceras inflatum						

The approximately 100-m-thick uppermost part of the Upper Krivorechenskaya Subformation, is represented by conglomerates and coarse-grained sandstones with large-scale cross-bedding. According to Devyatilova et al. (1980), the total thickness of the Upper Krivorechenskaya Subformation is about 700–900 m, and the Krivorechenskaya Formation is disconformably overlain by deposits of Senonian(?)–Maastrichtian to Eocene age.

2.2. Geology of the left bank of the Anadyr River

On the left bank of the Anadyr River, the Krivorechenskaya Formation can be divided into two subformations. The Lower Krivorechenskaya Subformation consists predominantly of conglomerates, whereas the Upper Krivorechenskaya Subformation is represented by conglomerates, sandstones and siltstones (Devyatilova et al., 1980). In the Nichekveem River basin (Figs. 1 and 2) marine molluscs of latest Cenomanian and probably early Turonian age were found in the Upper Krivorechenskaya Subformation (Terekhova, 1988). The total estimated thickness of the Krivorechenskaya Formation in this region is about 1600 m (Devyatilova et al., 1980).

The Upper Krivorechenskaya Subformation plant remains in the Krivaya, Vetvistaya and Dugovaya rivers (the Ubiyenka River basin) were studied by Filippova and Abramova (1993) and Filippova (1998) who equated them to those of the Grebenka flora.

Up to 600-m-thick marine deposits of the Dugovskaya Formation conformably overlie the Upper Krivorechenskaya Subformation (Terekhova, 1988). Mollusc remains indicate a late Turonian age (Terekhova, 1988). However, Terekhova (1988) and Pokhialainen (1994) regard the boundary between continental (Upper Krivorechenskaya Subformation) and marine (Dugovskaya Formation) deposits as diachronous (Fig. 2). The

Dugovskaya Formation in the Ubiyenka River basin contains *Inoceramus concentricus costatus* of early to late Turonian age, whereas *Inoceramus hobetsensis* remains from the Dugovskaya Formation in the Krestovaya and Chineyveem Rivers are of late Turonian and possible Coniacian age.

3. Material and methods

3.1. Field strategy

The Yelisseev Locality was documented photographically, and this record was used as a field reference. Vegetation cover prevented measurement of the whole exposure, so some horizons yielding plant fossils were excavated as isolated sites, within a defined framework. Some sites studied in 1996 equal those in Herman and Shczepetov (1992) and Shczepetov et al. (1992) and where this is the case, the current site number is followed by the 1992 site number in parentheses. The positions of plant assemblages within the sedimentary succession were recorded. Plant fossils were excavated by hand, sediment details and taxonomic composition were noted, and plant specimens were cleaned and photographed in the field. Representative specimens were collected.

3.2. Sedimentological methods

Sedimentological logs were constructed to reflect the vertical development of the sedimentary succession, and photopanoramas were made for a two-dimensional (2D) overview. The strata were subdivided and facies-coded in accordance with Miall (1978, 1996), and assigned to the alluvial architectural elements of Miall (1996), although there were inevitable limitations imposed by restricted lateral and three-dimensional (3D) exposure. General sandstone classification was conducted according to Pettijohn et al. (1982), and the nomenclatural schemes of Fischer and Schmincke (1984) and McPhie et al. (1993) were used for pyroclastic sediment classification. The sorting scheme of Folk (1974) was also utilised. Selective petrographic sampling (40 samples) was conducted to gain information on depositional processes and history. Compositions and textures of the samples were mainly determined by thin-section light microscopy, together with backscatter electron image analysis (BSE) of polished thin sections. During BSE work elemental analysis of detrital components was obtained for mineral identification using energy dispersive X-ray analysis.

3.3. $^{40}Ar/^{39}Ar$ analysis

Biotite grains were separated from the loosely cemented samples by hand-picking and the least kinked and altered samples were selected. Biotite grains were generally around 0.5–1.0 mm in diameter. Initially single laser spot analyses were undertaken and yielded uniform ages in the range 94–96 Ma, indicating that a multiple age population, due to reworking of older volcaniclastic deposits, is not present. The minor diagenetic alteration in these grains is generally parallel to cleavage (Pickles et al., 1997) and step-heated single grains were thus chosen on the basis of the initial spot analyses. Samples were heated in the same manner as in Kelley et al. (1999) using a defocused multimode beam from a continuous Nd-YAG laser running at the fundamental 1064-nm frequency for 60-s heating steps. Data were corrected for mass spectrometer discrimination and irradiation interferences. Ages are quoted relative to the international biotite standard GA1550 with an age of 98.9 Ma (Renne et al., 1998).

3.4. Palaeomagnetic studies

In order to get more reliable data on the palaeomagnetic properties of the succession, oriented rock samples were taken throughout the Yelisseev Locality succession, as well as from fine-grained and medium-grained sandstone lenses in the conglomerates of the Lower Krivorechenskaya Subformation. In total 80 oriented samples were taken from 71 sites, most of them at the Yelisseev Locality. In addition, three samples were taken from site G975, and four samples from site G976. These sites are situated on the Grebenka River 1 and 3 km downstream from the mouth of the Gornaya River (Fig. 3).

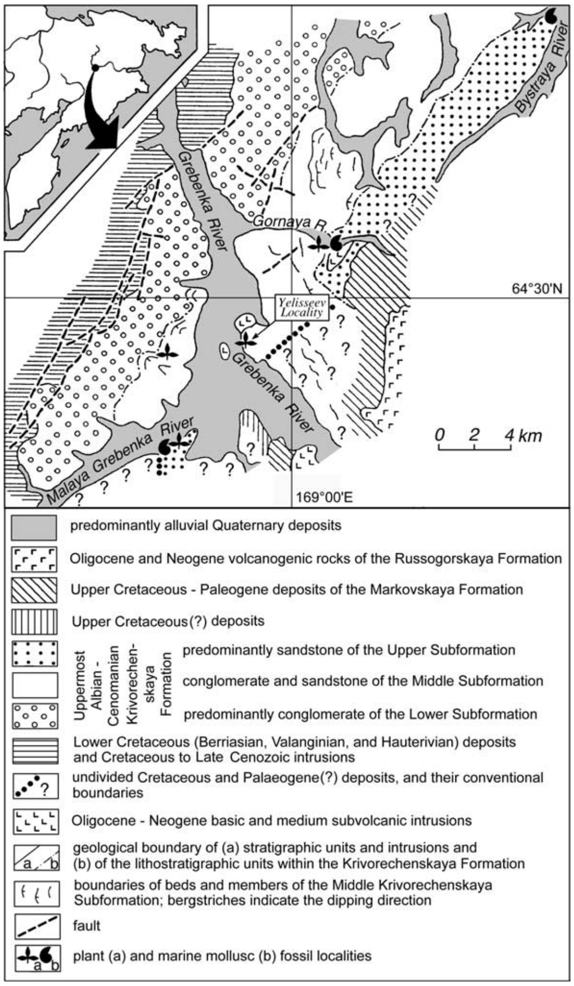

Fig. 3. Schematic geological map derived from photo-interpretation and field observations of the area surrounding the Yelisseev Locality.

The oriented samples were each made into several (from two to five) cubes of 8 cm^3 each, prior to measurements of magnetic susceptibility (K) and natural remnant magnetisation (NRM). The (K)-measurements were performed on a KLY-2 instrument with an accuracy of 10^{-8} of SI units. The NRM measurements were performed on a JR-4 instrument with an accuracy of 1×10^{-8} A/M. To identify the characteristics of the initial magnetisation vector, samples were subjected to temperature and alternating magnetic field demagnetisation. Thermal demagnetisation was performed in 50°C steps up to 600–650°C, but at temperatures higher than 500°C the step was 20–30°C. Samples were heated in an Aparin furnace placed in a set of Helmholtz coils. The magnetic field within the furnace was less than 10 nT. The quality of demagnetisation was checked with duplicate cubes placed antiparallel in the furnace. During thermal demagnetisation magnetic susceptibility was constantly checked because it reflects changes in magnetic minerals under heating conditions. Demagnetisation by virtue of the alternating magnetic field method reached an amplitude of 60 mT, in 5-mT step increments.

3.5. CLAMP technique

The CLAMP technique of Wolfe (1993) was used to obtain palaeoclimatic data from the leaf flora. In CLAMP the architecture of woody dicot leaves from modern-day vegetation growing under known climatic conditions is used as a reference data set against which to compare the architecture of leaves found in a fossil assemblage. The scoring of leaf physiognomy was conducted according to Wolfe (1993) and the same reference data set was used as in Spicer and Herman (1998). This data set consists of 103 modern Northern Hemisphere sites scored for eight climate variables, including mean annual temperature (MAT), warm month mean temperature (WMMT), cold month mean temperature (CMMT), mean annual precipitation (MAP), mean growing season precipitation (MGSP), mean monthly growing season precipitation (MMGSP), precipitation during the three consecutive driest months (3DRIMO), and length of the growing season (LGS). Climate vectors in physiognomic space were determined by canonical correspondence analysis (ter Braak, 1986) using the computer program CANOCO (ter Braak, 1987–1992). Default values in CANOCO were used throughout. In addition to analysing the total Yelisseev Locality flora, analyses were also performed on individual sites within the Yelisseev Locality representing specific plant communities. This was done to determine the magnitude of uncertainties in climate retrodictions due to taphonomic and palaeoecological overprints. To be statistically reliable CLAMP requires the scoring of at least 20 leaf morphotypes at any given fossil site. It was not possible, therefore, to analyse leaves from all sites separately. Instead we analysed the whole flora combining many different communities at different stages of seral development, a florule from a single site representing a floodplain pond, and a combination of several florules from spatially and stratigraphically closely situated sites representing similar floodplain palaeoenvironments.

4. Observations: the Yelisseev Locality

4.1. Sedimentary petrography

As is common for ancient pyroclastic deposits, diagenetic processes have profoundly changed the mineralogical composition and the depositional texture, and bedding is therefore to some extent obscured. The diagenetic overprint includes cementation and replacement of less stable original sediment components by palagonite, calcite, chalcedony, quartz and clay minerals. However, the properties of more resistant sedimentary particles and their pseudomorphs provided useful information. Volcanic glass shards, or obvious secondary porosity derived from them, are not observed in the Yelisseev Locality material. However, the analysed samples show a clay content incompatible with the physical processes responsible for the sedimentary structures of these beds. Tentatively, this suggests that sand-sized glass shards probably were abundant, and subsequently diagenetically altered to clay (Fig. 4B).

In the Yelisseev Locality, the framework clasts of the conglomerates are epiclastic, i.e. composed of reworked pre-existing volcanic rocks of the Okhotsk–Chukotka volcanoigenic belt. Most sandstones are dominated by volcanic rock fragments and are thus categorised as lithic arenites. These rock fragments exhibit a plethora of shapes and compositions, but each grain is typically dominated by a fine-grained groundmass of plagioclase laths (Fig. 4D,E). Single-crystal, euhedral plagioclase grains with characteristic volcanic embayments, faint zonations and vacuoles constitute the second most common detrital component (cf. Scholle, 1979; McPhie et al., 1993). In three samples they clearly outnumber the volcanic rock fragments, i.e. they form arkoses, which also are rich in hornblende and biotite (Fig. 4A,B). These accessory minerals are comparably fresh and only slightly abraded (angular to subangular; Fig. 4C), and were therefore regarded suitable for radiometric dating (see Fig. 4G). Quartz grains are only occasionally present. The recorded detrital compositions broadly correspond with that of the inferred andesitic sediment sources of the Ochotsk–Chukotka volcanogenic belt. Organic matter is present in most samples, as solitary detrital particles of silt and sand size, or as large wood fragments (Fig. 4I). In situ rootlets were observed in a few thin sections (Fig. 4H), as were rare cases of pedogenic textures (Fig. 4F). Siltstones are dominated by fragmented angular framework grains, and are throughout rich in dispersed organic matter (Fig. 4G). Mudstone beds are rare in the Yelisseev Locality, and clay mineralogical analysis is not regarded useful, particularly considering the diagenetic overprint of the sediments.

The studied sediments show a pronounced volcanic affinity. The nomenclature of such sediments has been confusing in the past (see discussion in Orton, 1996). In accordance with the schemes of Fischer and Schmincke (1984) and McPhie et al. (1993), the Yellisseev Locality conglomerates and lithic arenites should be regarded ‘epiclastic’ and ‘volcanogenic sedimentary’, respectively. Hence, they were formed from the weathering and erosion of pre-existing volcanic rocks. The few arkosic sandstones (three beds) observed at the Yelisseev Locality are primarily composed of ejecta which suffered little textural modification during rapid alluvial re-sedimentation, and are therefore regarded as ‘secondary pyroclastic’ or ‘re-sedimented syneruptive volcaniclastic’ (cf. Fischer and Schmincke, 1984; McPhie et al., 1993). The Yelisseev Locality, however, is probably situated too far from the sedimentary source to yield true single-source sediments, and a mixture between the two volcanic sand grain populations is represented in each sample. Sand grain angularity ranges from well-rounded epiclastic lithic fragments to more angular pyroclastic particles, indicating multiple sedi-

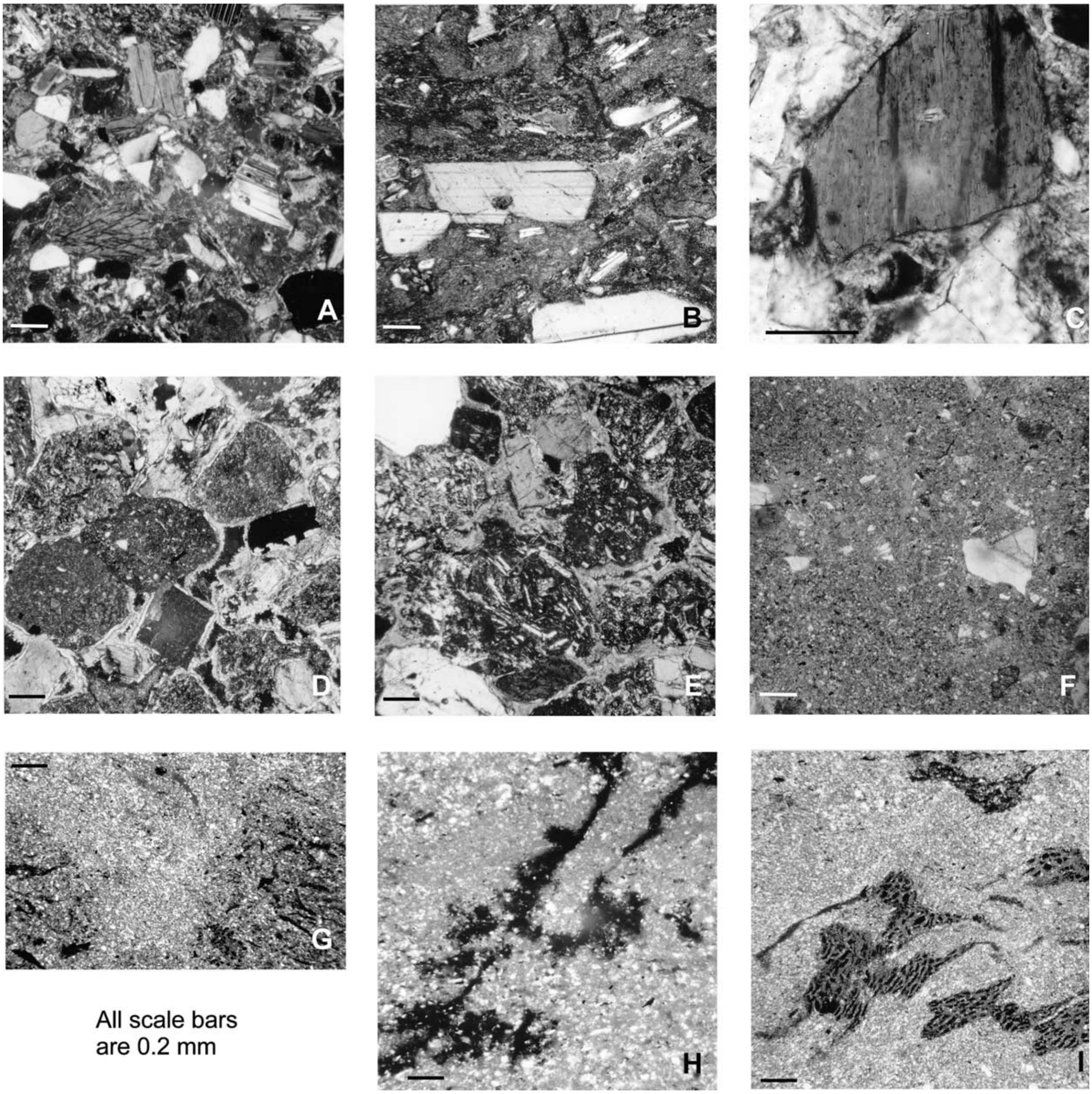

Fig. 4. Thin-section photomicrographs from the Yelisseev Locality. All scale bars represent 0.2 mm. (A) Plagioclase-dominated arkose with hornblende and biotite grains (sample G973-24, site 18, level 2.80 m). (B) Arenite dominated by splintered angular plagioclase laths in clay mineral ground mass (sample A97-6, site 9, level 0.90 m). (C) Subangular hornblende grain from hyperconcentrated flow deposit (sample G973-24, site 18, level 2.80 m). (D and E) Arenites dominated by well-rounded lithic fragments derived from erosion of magmatic rocks ((D) sample G973-4, site 7, level 1.00 m; (E) sample G973-12, isolated outcrop 5 m below site 10). (F) Rooted palaeosol showing texture with floating sand grains in mud matrix (sample G973-19, isolated outcrop 6 m below site 18). (G) Burrow within the site 9 plant-bearing bed, level −0.10 m (sample A97-4a). (H) Hollow rootlet obliquely penetrating siltstone (sample G973-53, site 22, plant-bearing bed). (I) Wood remains from the site 9 plant-bearing bed, level −0.10 m (sample A97-4a).

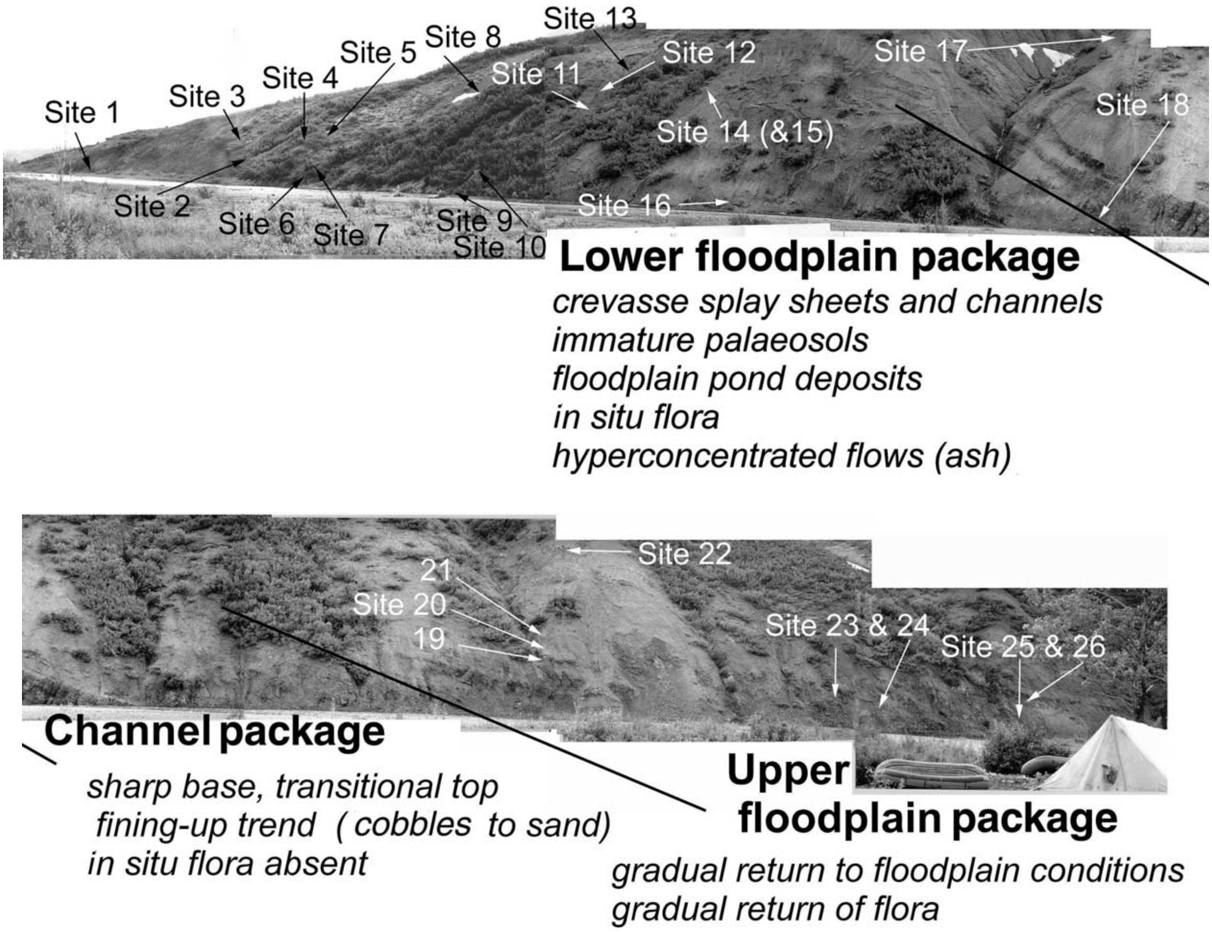

Fig. 5. Panorama of the Yelisseev Locality, showing site locations and characteristics of the main sedimentary packages.

ment sources and sediment recycling (Fig. 4D). Accordingly, all of the studied arenites may be termed 'tuffaceous sandstones' (cf. Fischer and Schmincke, 1984; McPhie et al., 1993).

The investigated conglomerates are matrix-rich, clast-supported and moderately to well-sorted. The clasts are typically well-rounded and of a high sphericity, whereas the matrices uniformly are composed of moderately to well-sorted coarse-grained sandstone which compositionally and texturally corresponds to most sandstones of the section.

The detrital grains of the Yelisseev Locality sandstones indicate original moderate to good sorting (Fig. 4D,E), despite the clay mineral replacements of detrital grains.

4.2. Facies analysis

In the Yelisseev Locality an approximately 100-m-thick succession of sediments are exposed, or partly exposed. Each bed is typically traceable laterally for a few metres, at most 50 m (Fig. 5). Despite a strong diagenetic overprint (see 4.1. Sedimentary petrography), the following facies associations and alluvial architectural elements were identified (Fig. 6).

4.2.1. Gravelly stream channel deposits

Description: this facies association is dominated by tabular, horizontally and at places very slightly trough-shaped, crudely stratified beds of clast-supported, sand matrix-rich conglomerates

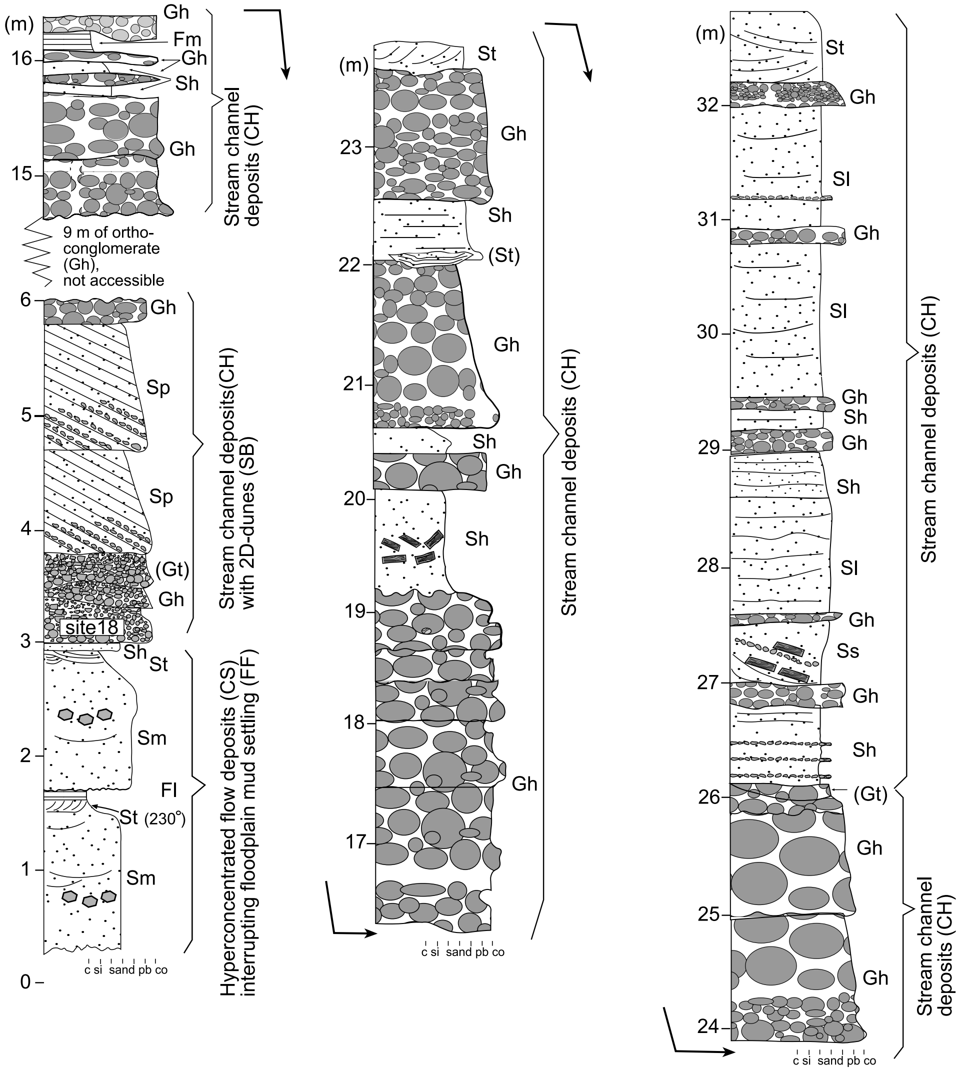

Fig. 6. Sedimentary logs of the continuously outcropping sections of Yelisseev Locality.

(facies Gh), particularly within the lower part of the channel package (see Fig. 5). Clast imbrication is apparent only in very few beds, due to the pronounced sphaericity of the clasts. The maximum clast diameter varies up to 25 cm, and seems independent of bed thickness, although some beds are not completely preserved. Rare intercalations of very angular pebbles occur. The conglomerate beds are typically massively or horizontally bedded, and normally graded. Lateral exposure did not allow measurements of the widths of the conglomerate units, but they appear to be in the order of 100 m. In the middle part of the Yelisseev Locality succession, at the base of the channel package, the oldest conglomerate beds are vertically stacked, forming multistorey units several metres thick, and are very rarely amalgamated with low-angle surfaces scoured into the substrate. Horizontally stratified or trough crossbedded lenses of coarse-grained sandstone (facies Sh and St) are upwards increasingly abundant within the conglomerates. The sandstone lenses are 1–3 m in width and less than 20 cm in thickness. From a petrographical

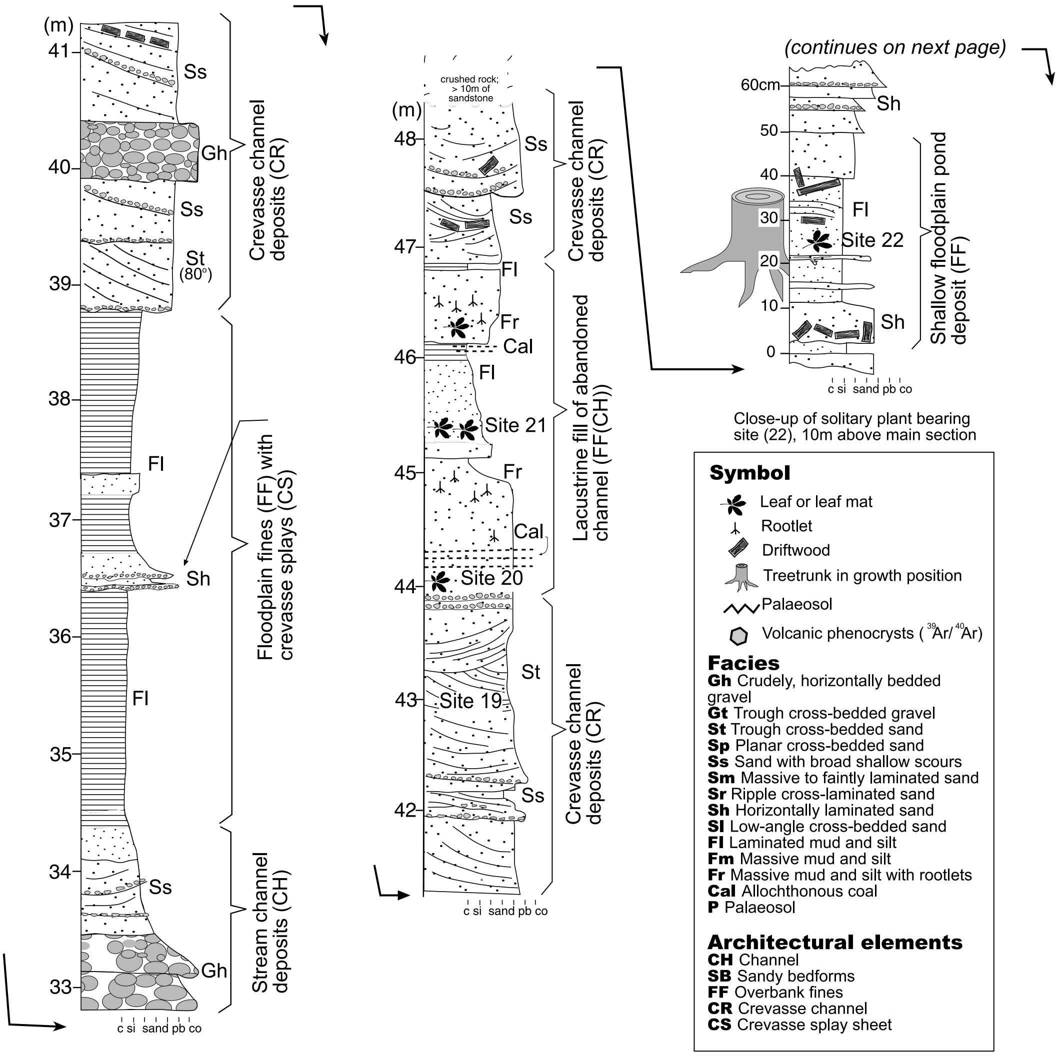

Fig. 6 (*Continued*).

point of view these arenites also resemble the matrixes of the conglomerates.

Interpretation: the crudely horizontally stratified clast-supported conglomerates of this facies association were probably deposited by unsteady traction currents on flat pavements, as channel lag deposits of laterally mobile braided channels (cf. Steel and Thompson, 1983). Occasional normal grading may be attributed to waning flow or gradual channel abandonment. Channel bar deposits are probably represented within the conglomerates, but no apparent leeside foresets were observed to support this. The sandstone lenses probably represent the fill of less active channels of the braidplain. Although similar sheet-like conglomerates may be produced by repeated catastrophic floods, the conglomerate beds show no features typical of ephemeral flashfloods (Nemec and Steel, 1984). Thus, there is a lack of matrix-support (although the conglomerates are matrix-rich) and of a linear correlation between maximum clast size and bed thickness for conglomerate beds preserved in their entire thickness. The very rare incursions of beds dominated by angular

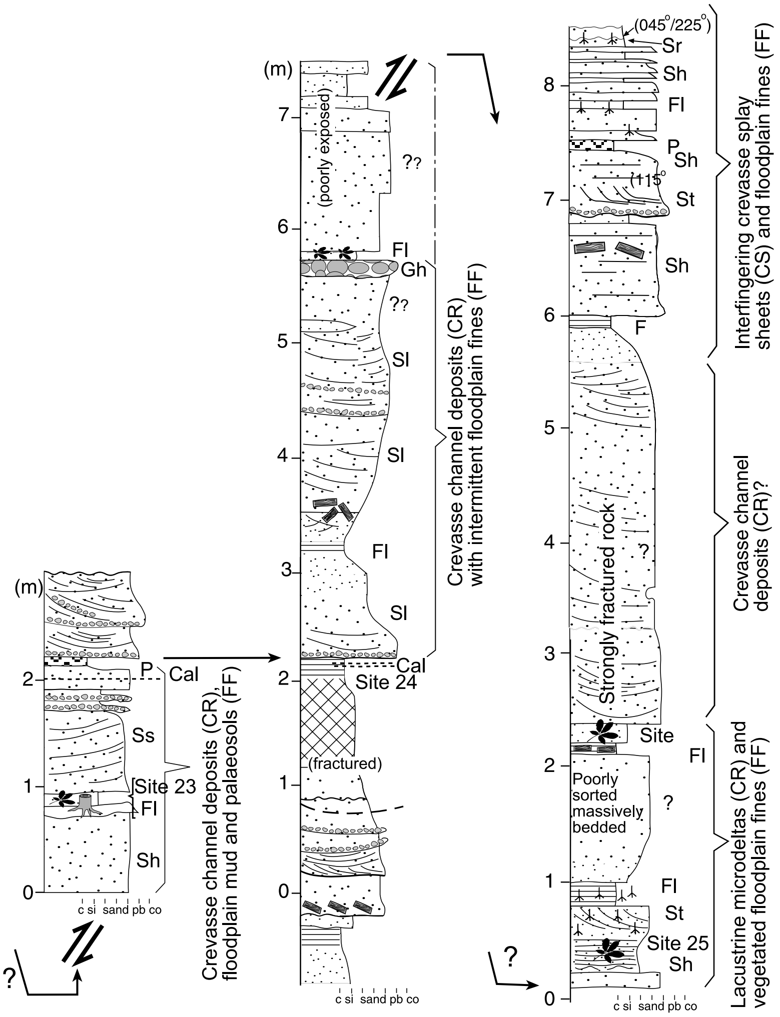

Fig. 6 (*Continued*).

gravel probably reflect the proximity to talus cones and proximity to steep palaeorelief (cf. Tanner and Hubert, 1991). The channel conglomerates are referred to the architectural element CH, as it is not possible to break them down into downstream or lateral accretion units (elements DA, LA).

4.2.2. Sandy stream channel deposits

Description: most of these sandstones constitute $<$1-m-thick irregular sheets, or isolated channel-fills within gravelly facies, within the channel package (see Fig. 5). The sandstones are medium- to very coarse-grained, and typically poorly to moderately sorted. Some sandstone beds show normal grading. They are dominated by shallow, low-angle troughs (facies Sl), commonly with pebble lags, but do also include horizontally laminated sandstone beds (facies Sh). Scour-and-fill units also occur (facies Ss). The facies association includes very few tabular and trough cross-bedded cosets (facies Sp and St) and a notable lack in rippled beds. Dune foreset migration palaeodirections ($n = 3$) indicate broadly southward sediment transport when corrected for tectonic tilt. Reworked (size-sorted and abraded) fossil logs are abundant along some bedding planes, and consitute the only observed biota.

This facies association commonly shows a sharp, slightly erosive base, and is interbedded with stream channel conglomerates.

Interpretation: this facies association is intimately associated (interfingers) with the gravelly stream channel facies association (see 4.2.1. Gravelly stream channel deposits), and is here interpreted to represent sandy stream channel deposition. The interbedding between horizontal (Sh) and low-angle cross-bedding (Sl) indicate high-energy unidirectional flow, and the formation of dune-like bedforms at or near critical flow conditions. The rare tabular and trough cross-bedding (facies Sp and St) is referred to in-channel fluvial downstream migration of 2D and 3D dunes, although some inclined beds in the section may represent mesoforms (lateral river bank migration). The scour-and-fill facies (Ss) probably represent episodes of low river discharge, leading to erosion and reworking of previous bedforms. The facies association includes deposits of the architectural elements CH and SB.

4.2.3. Crevasse channel deposits

Description: the crevasse channel facies association is dominated by scour-and-fill sandstone (facies Ss), but occasionally also contains rare, trough cross-bedded sandstone beds (facies St) and horizontally stratified sandstone (facies St). Stratification is generally poorly defined, and the sorting is at places poor. These sandstone units contain abundant pebble lags, accumulations of large (5–50-cm-long) pieces of branchwood, leaf mats and very thin (1–2 cm) discontinuous coal laminae, and show at places intensive rooting. Despite limited lateral exposure, the width of at least one of these sandstone-dominated units is estimated to be 50–100 m. The thicknesses of the units are >5 m. The crevasse channel facies association units are found interbedded with mud-dominated pedogenic facies, within the lower and upper floodplain packages (see Fig. 5), commonly with a sharp, slightly erosive, base and a gradual return to mudstone and immature palaeosols (facies Fl and P).

Interpretation: the trough cross-bedding (facies St) and scour-and-fill (facies Ss) features indicate mainly deposition in unidirectionally flowing water. This is most obviously expressed in the lower parts of these units. Although the discrimination in part may be arbitrary, the crevasse channel facies association was distinguished from stream channel facies associations (4.2.1. Gravelly stream channel deposits and 4.2.2. Sandy stream channel deposits). This was based on the dominance of scour-and-fill structures, the interfingering and close association with floodplain facies (see 4.2.5. Floodplain pond and microdelta deposits and 4.2.6. Floodplain fines and palaeosols), the abundant delicate plant remains, and the more pronounced textural immaturity. Hence, crevasse channel deposition interrupted abruptly mud deposition and pedogenesis, and occurred only periodically. The abundant mud matrix content of the channel-fill sandstones (mainly facies Ss) may be related to limited reworking of floodplain fines into the crevasse channels (cf. Miall, 1996), whereas the gradual returns to typical floodplain facies (Fl and P) can be be attributed to crevasse channel abandonment. The crevasse channel facies association is accordingly referred to as the alluvial architectural element CR.

4.2.4. Levee and crevasse sheet sandstone

Description: this facies association includes thin (a few dm), horizontally stratified (facies Sh), or trough cross-bedded (facies St), non- or normally graded sandstone beds, in places with basal pebble lags. Large tree trunks (up to 30 cm in diameter) and rootlets in growth position are common. The sandstone beds are in places thicker (several dm), stacked and slightly amalgamated into each other, but typically fine and thin away distally, interfingering conformably with laminated mudstone or weakly developed palaeosols (facies Fl and P). Three of these sheet-shaped sandstone beds are distinctly different from the others, as they are very rich in subangular to angular, broken plagioclase and hornblende grains (see 4.1. Sedimentary petrography). These three beds show flat basal scouring surfaces with pebble lags, followed by massively bedded, normally graded, coarse-grained sandstone with faint internal scouring surfaces (facies Sm), in turn followed by trough cross-bedded fine- to medium-grained sandstones (St) and final gradation into mudstones (facies Fl).

Interpretation: this facies association generally indicates unidirectionally flowing water (facies St and Sh), but at the same time these sediments constituted the growth environment for large trees. This, and the interfingering with floodplain fines (facies Fl and P), indicate episodes of high-energy deposition in proximal, higher levees (stacked sandstone beds with erosive contacts) to more distal lower floodplain settings (conformably interfingering with fine-grained deposits (facies Fl, P)). Hence, proximal overbank floods passed between mature trees growing on the levee (architectural element LV). This slowed down overbank flows, stimulated rapid sand deposition, and hindered further erosion of the levees. The flows then continued to lower, more distal interfluve areas. As they lost their remaining energy, sand deposited rapidly as crevasse splay sheets. The three beds with unusually uniform detrital composition (arkosic wackes; see 4.1. Sedimentary petrography), are interpreted as syn-eruptive volcanic ash deposits, which experienced only very limited reworking into crevasse splays. In volcanic settings such beds are commonly the result of stream channel ash choking and subsequent floodplain flooding (Orton, 1996). Whether directly related to volcanic eruptions or not, all the observed levee and crevasse splay deposits are assigned to the alluvial architectural element CS.

4.2.5. Floodplain pond and microdelta deposits

Description: this facies association is dominated by well-sorted siltstone beds, 10–20 cm thick (facies Fl). These are typically horizontally laminated, and within them leaf mats with very delicate foliar taxa are excellently preserved. In places, branches and large in situ tree trunks are found together with the leaves. Occasionally, the laminated siltstones (facies Fl) grade upwards into trough cross-bedded sandstone (facies St), or sandstone subjected to incipient rooting (facies Fr), and weak palaeosol development (facies P). The thin beds belonging to this facies association are found repeatedly within successions of horizontally laminated, coarse-grained tuffaceous sandstones (facies Sh) or laminated mudstones (facies Fl) within the lower and upper floodplain packages (see Fig. 5).

Interpretation: the close relationship of this facies association with horizontal, vertically accreted deposits, plant growth and pedogenesis generally implies floodplain deposition. The textural maturity of the laminated siltstones is conspicuously higher than that of surrounding sandstone beds, possibly due to aeolian winnowing and redeposition of silt. The well-preserved leaves indicate minimal transport, and oxygen depletion of the sediment. Possibly, leaf mats formed in shallow, poorly oxygenated pools of standing water beyond the levees, which trapped aeolian silt and preserved fallen and wind-transported leaves. The coarsening upwards trend of the cross-bedded sandstone may in this context be due to lacustrine microdelta progradation, i.e. pond infilling, which introduced stream transported leaves and provided shallow water and sub-aerial surfaces for pioneer plants and the onset of pedogenic processes. The deposits of the lacustrine pond and microdelta facies association are assigned to the alluvial architectural element FF.

4.2.6. Floodplain fines and palaeosols

Description: the upper and lower floodplain packages (Fig. 5) contain a facies association of homogeneous, horizontally laminated mudstone (facies Fl) and rare, rather weakly horizontally stratified mudstone beds (facies Fm). At places, the latter contain rhizomes, rootlets, leaf mats of pioneer to mature forest communities, and tree trunks in growth position. This facies association forms tabular-shaped vertically accreted successions, up to several metres thick, which in places are interrupted by sandstone sheets of the levee and crevasse splay sheet sandstones (architectural element LV and CS).

Interpretation: the horizontally laminated mudstone is interbedded with rootlet beds and palaeosols, i.e. within vertically accreted floodplain deposits. In this context they are interpreted as lacustrine pools of standing water on the floodplain. Pedogenesis appears concentrated to certain levels within the succession, and represents emergent conditions on the floodplain. However, the pedogenic overprint appears slight in most palaeosols, because neither clear horizonation nor pronounced destratification is developed in most cases. This represents the very weak to weak stages of palaeosol development sensu Retallack (1988). Both the floodplain fines and palaeosol facies association are assigned to the alluvial architectural element FF.

4.3. Plant occurrences in sedimentological context

The full megafossil plant diversity recorded here, and from earlier collections, is given in Table 1. Below, only the plants that repeatedly occur throughout a range of palaeoenvironments are presented, because repeated occurrence is required for reliable community reconstruction. Where possible this is followed by an interpretation of the ecological associations and growth environment represented by each site.

4.3.1. Site 1

Sedimentary context: conglomerate bed, tabular, massive, clast-supported, cobble-sized clasts.

Plant remains: no plant material recorded.

4.3.2. Site 2 (25 and 25a)

Sedimentary context: these small exposures probably represent a lateral equivalent to the section represented by sites 9–13 (see below). Fine-to medium-grained plant-bearing sandstone is underlying a conglomerate.

Plant remains: *Birisia jelisejevii* (Krysht.) Philipp., *Birisia ochotica* Samyl., *Coniopteris* (*Birisia*?) *grebencaensis* Philipp, *Arctopteris penzhinensis* E. Lebed., *Asplenium dicksonianum* Heer, *Nilssonia serotina* Heer, *Cephalotaxopsis heterophylla* Hollick, *Cephalotaxopsis intermedia* Hollick, *Araucarites anadyrensis* Krysht., *Pseudolarix*? sp., *Pityophyllum* ex gr. *nordenskioldii* (Heer) Nath., *Pityospermum* aff. *piniformis* Samyl., *Pityostrobus* sp. 2, *Menispermites minutus* (Krysht.) Herman et Shczep., *Menispermites* ex gr. *septentrionalis* Hollick, *Platanus louravetlanica* Herman, *Araliaephyllum dentatum* Philipp., *Scheffleraephyllum venustum* (Phillipp.) Phillipp., *Trochodendroides arctica* (Heer) Berry, *Grebenkia anadyrensis* (Krysht.) E. Lebed.

Ecological interpretation: lack of exposure prevented a reliable interpretation of the sedimentological context. The composition and preservation state of the floral assemblage, however, suggest an allochthonous sample of a semi-mature floodplain community consisting of a mixed conifer and angiosperm tree/shrub component with a fern and cycadophyte understorey.

4.3.3. Site 3 (28)

Sedimentary context: this is a small exposure which probably represents a lateral equivalent to sites 9–13 (see below). Medium- to coarse-grained sandstones occur just above a sharp contact with a mudstone.

Plant remains: *Thallites* sp. cf. *Marchantites jimboi* (Krysht.) Krysht., *Gleichenia zippei* (Corda) Sew., *Birisia jelisejevii* (Krysht.) Philipp., *Coniopteris*? sp., *Arctopteris penzhinensis* E. Lebed., *Hausmannia bipartita* Samyl. et Shczep., *Ginkgo* ex gr. *adiantoides* (Ung.) Heer (very abundant), *Cephalotaxopsis heterophylla* Hollick, *Cephalotaxopsis intermedia* Hollick, *Araucarites anadyrensis* Krysht., *Pityophyllum* ex gr. *staratchinii* (Heer) Nath., *Pityostrobus* sp. 2, *Sequoia* spp. (cone and cone scale), *Elatocladus smittiana* (Heer) Sew., *Grebenkia anadyrensis* (Krysht.) E. Lebed.

Ecological interpretation: this assemblage is dominated by conifers, probably trees, with a minor angiosperm component (*Grebenkia*). The stature of *Grebenkia* is unknown but it may have been a shrub. The paucity of angiosperms may suggest a more mature seral phase than that represented by site 2. The understorey was dominated by a variety of ferns. Also represented here is a pond or stream margin component consisting of the water fern *Hausmannia* and cf. *Marchantites*, a coloniser of wet mud surfaces.

4.3.4. Site 4 (30a)

Sedimentary context: a small exposure, probably a lateral equivalent to part of the section represented by sites 9–13 (see below). Medium-to coarse-grained sandstones occur, and the beds appear laterally equivalent to those of site 3.

Plant remains: *Birisia ochotica* Samyl., *Coniopteris anadyrensis* Phillipp., *Coniopteris* (*Birisia*?) *grebencaensis* Phillipp., *Asplenium dicksonianum*

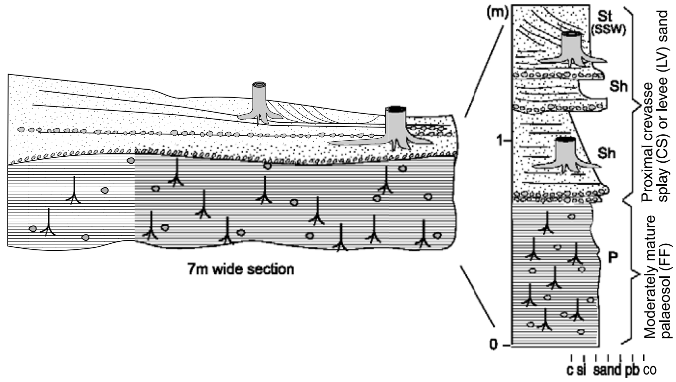

Fig. 7. Log and sketch from site 7, of a relatively mature palaeosol superimposed by stacked crevasse splays with in situ tree trunks.

Heer, *Nilssonia serotina* Heer, *Cephalotaxopsis intermedia* Hollick, *Araucarites anadyrensis* Krysht., *Pagiophyllum triangulare* Pryn., *Pityophyllum* ex gr. *nordenskioldii* (Heer) Nath., *Pityophyllum* ex gr. *staratchinii* (Heer) Nath., *Sequoia* cf. *minuta* Sveshn., *Tollia* sp., *Elatocladus smittiana* (Heer) Sew., *Menispermites* ex gr. *septentrionalis* Hollick, *Sorbites asiatica* Phillipp., *Myrtophyllum acuminata* (Phillipp.) Herman, *Araliaephyllum dentatum* Phillipp., *Scheffleraephyllum venustum* (Phillipp.) Phillipp.

Ecological interpretation: this appears to be another sample, as with site 2, of a semi-mature floodplain community consisting of a mixed conifer and angiosperm tree/shrub component with a fern and cycadophyte understorey. The assemblage is rich in well-preserved conifer shoot remains, suggesting limited in-stream transport of its components.

4.3.5. Site 5 (30)

Sedimentary context: a very small exposure, probably a lateral equivalent to a part of the section at sites 9–13 (see below). Isolated small siltstone outcrop with no sedimentary structures recorded.

Plant remains: *Birisia jelisejevii* (Krysht.) Phillipp., *Birisia ochotica* Samyl., *Birisia*(?) *oerstedtii* (Heer) E. Lebed., *Coniopteris anadyrensis* Phillipp., *Coniopteris* (*Birisia*?) *grebencaensis* Phillipp., *Asplenium dicksonianum* Heer, *Cladophlebis* sp. 1, *Cephalotaxopsis heterophylla* Hollick, *Pagiophyllum triangulare* Pryn., *Sequoia* ex gr. *reichenbachii* (Gein.) Heer, *Sequoia* sp.

Ecological interpretation: this assemblage lacks an angiosperm component but displays a diversity of ferns, amongst the remains of three conifer genera. It is interpreted to represent a mature conifer-dominated forest, with a fern understorey.

4.3.6. Site 6 (31)

Sedimentary context: a small isolated exposure, probably a lateral equivalent to part of the section represented by sites 9–13 (see below). Medium-grained sandstones.

Plant remains: *Birisia*? *oerstedtii* (Heer) E. Lebed., *Coniopteris* (*Birisia*?) *grebencaensis* Phillipp., *Asplenium dicksonianum* Heer, *Elatocladus smittiana* (Heer) Seward, *Scheffleraephyllum venustum* (Phillipp.) Phillipp.

Ecological interpretation: this depauperate assemblage is too limited to interpret.

4.3.7. Site 7

Sedimentary context (Fig. 7): at a cliff section amalgamating levee, or proximal crevasse splay, pebbly sandstones, with in situ tree trunks and roots are overlying a palaeosol with intensive rooting and destratification. The section demonstrates that as the overbank floods passed, adult trees growing on the river bank survived, and continued growing. The trees slowed down the overbank flow profoundly, and caused rapid sediment deposition and limited erosion of the levee.

The rather strong pedogenic overprint of the palaeosol at this section is untypical for the Yelisseev Locality.

Ecological interpretation: this represents a mature riparian community dominated by trees. The lack of identifiable preserved plant material prevents a detailed taxon-based interpretation of the community.

4.3.8. Site 8 (33)

Sedimentary context: a small isolated sandstone exposure with poorly preserved plant remains and no visible sedimentary structures, probably a lateral equivalent to part of the section represented by sites 9–13.

Plant remains: *Phyllites* sp. *Equisetites* sp., *Gleichenites asiatica* Phillipp., *Birisia jelisejevii* (Krysht.) Phillipp., *Birisia ochotica* Samyl., *Coniopteris* (*Birisia*?) *grebencaensis* Phillipp., *Asplenium dicksonianum* Heer, *Hausmannia bipartita* Samyl. et Shczep., *Sphenopteris* sp. 2, *Florinia*? sp., *Menispermites* ex gr. *septentrionalis* Hollick, *Platanus* sp., *Scheffleraephyllum venustum* (Phillipp.) Phillipp., *Grebenkia anadyrensis* (Krysht.) E. Lebed.

Ecological interpretation: this poorly preserved assemblage appears to have undergone a marked degree of stream transport and, although information on the sedimentary context is limited, the sandstone may thus represent a channel fill. The community represented is almost devoid of conifers and is made up of water plants (*Hausmannia*), early pioneer plants of disturbed river banks such as *Equisetites*, together with plants of slightly more stable settings such as the ferns *Gleichenites* and *Birisia*. The angiosperm component is typical of a shrub community in a frequently disturbed riparian setting.

4.3.9. Site 9

Sedimentary context: the locality is situated in a small gulley formed by stream action. Site 9 is located at the base, with sites 10–13 at successively higher levels up the gulley. Site 9 comprises a coarsening-upward succession (Fig. 8). At the base, an organic-rich, ripple-drift cross-laminated and horizontally laminated siltstone occurs, which includes rootlets, 3D preserved plant remains, and invertebrate trace fossils. The siltstone grades into a current rippled (A-ripples) and horizontally laminated coarse-grained sandstone, with floating large plagioclase grains in a mud matrix at the top. This is followed abruptly by massively bedded mudstone, and massively bedded coarse-grained sandstone. Petrographical evidence and sedimentary context suggest that the increasing grain-size was caused by increased sedimentation on the floodplain due to influx of volcanic ash (Figs. 4B and 8).

Plant remains: *Equisetites* sp., *Ginkgo* sp., *Nilssonia serotina* Heer, *Nilssonia yukonensis* Hollick, *Araucarites anadyrensis* Krysht., *Cephalotaxopsis intermedia* Hollick, *Elatocladus smittiana* (Heer) Sew., *Pagiophyllum triangulare* Prynada, *Sequoia* ex gr. *reichenbachia* (Gein.) Heer, *Sequoia* sp. (cone), *Pityophyllum* ex gr. *staratchinii* (Heer) Nath., *Pityophyllum* ex gr. *nordenskioldii* (Heer) Nath., *Menispermites* ex gr. *septentrionalis* Hollick, angiosperm leaf fragment.

Ecological interpretation: the plant remains are well-preserved, minimally transported, and indicate that a mature forest was growing in the vicinity. Conifers dominate the assemblage and those with some xeromorphic features (*Araucarites*, *Pagiophyllum*, *Sequoia reichenbachii* and *Elatocladus*) are particularly abundant. Ferns are absent while cycadophytes and angiosperms are rare. The association with small in situ roots suggests that a herbaceous or pioneer community was also growing proximally and may be the source of some components of the assemblage (e.g. *Equisetites*). The increased sedimentation rate indicated by the sedimentary succession may explain why this forest community with a semi-dry aspect is preserved. Extraneous sediment influx, a sudden increase in discharge, or fall in

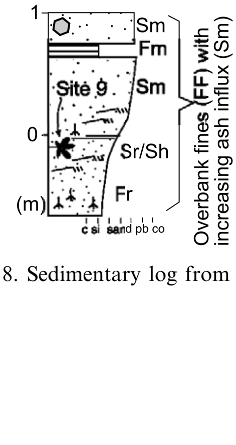

Fig. 8. Sedimentary log from site 9.

the relative position of the valley floor, would have raised the water table and allowed erosion, transport and deposition of forest material from a previously well-drained setting to be captured in the fossil record.

4.3.10. Site 10

Sedimentary context: isolated coarse-grained siltstones and fine-grained sandstones with no records of sedimentary structures.

Plant remains: *Equisetites* sp., *Coniopteris* (*Birisia*?) *grebencaensis* Philipp., *Birisia ochotica* Samyl., a possible tree fern rhizome (vertical stem) with scale leaf marks and rachis scars.

Ecological interpretation: *Equisetites* is particularly abundant at this site and, together with the limited fern component, suggests an immature pioneer community, possibly similar to an Albian alaskan *Birisia* marsh (Spicer and Herman, 2001).

4.3.11. Site 11 (53)

Sedimentary context: small outcrop of fine-grained, well-sorted sandstone that is wave rippled and cross-laminated. The leaves drape ripple surfaces. Some iron-stained root traces occur.

Plant remains: *Gleichenites asiatica* Philipp., *Gleichenites zippeii* (Corda) Sew., *Birisia jelisejevii* (Krysht.) Philipp., *Birisia ochotica* Samyl., *Coniopteris* (*Birisia*?) *grebencaensis* Philipp., *Asplenium dicksonianum* Heer., *Nilssonia alaskana* Hollick, *Cladophlebis* sp., *Hausmannia bipartita* Samyl. et Shczep., *Platanus louravetlanica* Herman, platanoid fruits, *Menispermites markovoensis* Philipp., *Sapindophyllum* sp., *Menispermites* sp., *Araliaephyllum*? sp.

Ecological interpretation: this assemblage lacks conifers but contains early colonisers such as the ferns *Gleichenites* and *Birisia*, plants of open water such as *Hausmannia*, and angiosperms typical of semi-mature communities of frequently disturbed riparian environments. Some compound-leaved angiosperms (*Sapindophyllum* sp.) were found with leaflets intact, suggesting minimal transport prior to deposition.

4.3.12. Site 12 (52)

Sedimentary context: fine-grained well-sorted sandstone. Plant material not only oriented parallel to bedding but also crossing bedding surfaces, although these surfaces are more or less obscured by plant material.

Plant remains: *Asplenium dicksonianum* Heer, *Scheffleraephyllum venustum* (Philipp.) Philipp.

Ecological interpretation: this assemblage is too limited for reliable interpretation.

4.3.13. Site 13 (51)

Sedimentary context: well-sorted siltstone to fine-grained sandstone with wave ripple cross-lamination and some rooting. Plant material is sometimes oriented normal to the weakly developed bedding

Plant remains: *Thallites* sp. cf. *Marchantites jimboi* (Krysht.) Krysht., *Equisetites* sp., *Gleichenia pseudocrenata* E. Lebed., *Gleichenites asiatica* Philipp., *Gleichenites zippeii* (Corda) Sew., *Birisia jelisejevii* (Krysht.) Philipp., *Birisia ochotica* Samyl., *Cladophlebis* sp., *Coniopteris* (*Birisia*?) *grebencaensis* Philipp., *Asplenium dicksonianum* Heer, *Hausmannia bipartita* Samyl. et Shczep., *Cephalotaxopsis* ex gr. *intermedia* Hollick, *Menispermites* ex gr. *septentrionalis* Hollick, *Scheffleraephyllum venustum* (Philipp.) Philipp., *Sapindophyllum* sp., *Cissites* sp.

Ecological interpretation: open-water ferns (*Hausmannia*), very early colonisers (cf. *Marchantites*, *Equisetites*), and early successional ferns (*Gleichenites* and *Birisia*) all suggest a strong wetland pioneer plant component to this assemblage. However, later successional phases such as that composed of angiosperms, and even the conifer *Cephalotaxopsis*, indicate a contribution from a nearby semi-mature floodplain community.

4.3.14. Site 14 (50)

Sedimentary context: isolated small siltstone outcrop, no records of sedimentary structures.

Plant remains: *Coniopteris* (*Birisia*?) *grebencaensis* Phillipp., *Scheffleraephyllum venustum* (Philipp.) Philipp.

Ecological interpretation: this assemblage is too limited for reliable interpretation.

4.3.15. Site 15 (54, float)

Plant remains: *Gleichenia pseudocrenata* E.

Lebed., *Gleichenites asiatica* Philipp., *Birisia jelisejevii* (Krysht.) Philipp., *Birisia ochotica* Samyl., *Birisia*? *oerstedtii* (Heer) E. Lebed., *Coniopteris* (*Birisia*?) *grebencaensis* Philipp., *Asplenium dicksonianum* Heer, *Hausmannia bipartita* Samyl. et Shczep., *Scheffleraephyllum venustum* (Philipp.) Philipp., *Cissites* sp. 2.

Ecological interpretation: no interpretation is attempted on float.

4.3.16. Site 16

Sedimentary context: isolated siltstone, no records of sedimentary structures.

Plant remains: leaf mat of *Grebenkia anadyrensis* (Krysht.) E. Lebed., *Cladophlebis* sp., *Birisia ochotica* Samyl., *Platanus louravetlanica* Herman.

Ecological interpretation: this assemblage represents a mat of leaf material derived from *Grebenkia*. Evidently the leaves fell from the plant synchronously, suggesting a deciduous habit. Although limited, the assemblage suggests a semi-mature riparian margin community.

4.3.17. Site 17 (12)

Sedimentary context: isolated small siltstone outcrop, no records of sedimentary structures.

Plant remains: *Birisia jelisejevii* (Krysht.) Philipp., *Birisia ochotica* Samyl., *Birisia*? *oerstedtii* (Heer) E. Lebed., *Coniopteris* (*Birisia*?) *grebencaensis* Philipp., *Arctopteris penzhinensis* E. Lebed., *Cycadites hyperborea* (Krysht.) E. Lebed., *Ginkgo* ex gr. *lepida* Heer, *Cephalotaxopsis intermedia* Hollick, *Araucarites anadyrensis* Kryst., *Pityophyllum* ex gr. *staratchinii* (Heer) Nath., *Menispermites markovoensis* Philipp., *Myrtophyllum acuminata* (Philipp.) Herman, *Araliaephyllum medium* (Philipp.) Herman, *Scheffleraephyllum venustum* (Philipp.) Philipp., *Scheffleraephyllum* sp., *Cissites* sp. 3, *Grebenkia anadyrensis* (Krysht.) E. Lebed.

Ecological interpretation: this assemblage represents a moderately diverse conifer community (*Araucarites*, *Pityophyllum*, *Cephalotaxopsis*) with an angiosperm shrub layer and fern and cycadophyte groundcover. Some early pioneer plants are represented also (*Birisia* species), but these taxa persist into more stable communities and may not represent an admixture of seral stages.

4.3.18. Site 18

Sedimentary context: at site 18, the mud-, silt- and sandstones of the floodplain succession are followed abruptly by an approximately 40-m-thick succession of stream channel conglomerates and sandstones, which grade into pebbly channel sandstones, followed by, and interbedded with, floodplain deposits. Site 18 is a marker bed near the base of the channel package (Figs. 5 and 6). At the base of the measured section normally graded beds were observed, going from coarse-grained sandstone to silt- and mudstone. These are massively bedded in their lower part, trough cross-laminated near the top, and are tentatively interpreted as rapidly deposited aqueous hyperconcentrated flows. The sandstones are poorly to fairly well-sorted, but grains are angular to subangular, indicating short transport from their source. To a large extent, the sandstones are composed of single-grain plagioclases, hornblendes and biotites, and to a minor degree epiclastic rock fragments. These petrographically anomalous beds are interpreted to be composed of only slightly reworked pyroclastic material samples. This was sampled for $^{39}Ar/^{40}Ar$ analysis (samples 96RAS68 and 96RAS69). The biotites are of a very narrow age interval, i.e. not derived from reworking material from multiple sources.

Plant remains: this interval is barren with respect to well-preserved fossils, only yielding rare beds rich in allochtonous drift wood and plant hash.

Ecological interpretation: notably, the first major floodplain fines after the stream channel are barren. Upsection, however, they show a gradual increase in pedogenic overprint and plant remains, i.e. repeated incipient plant colonisation.

4.3.19. Site 19

Sedimentary context: this site is situated within a crevasse channel fill in the upper floodplain package. Angular allochthonous wood pieces, 5–10 cm in length, occur. Although fragmentary, these wood remains appear not to have been transported any great distance, i.e. they are not water-worn or abraded. Site 19 is a bedding surface with transported platanoid leaves.

Plant remains: *Coniopteris* (*Birisia*?) *greben-*

caensis Philipp., *Ginkgo* ex gr. *adiantoides* (Ung.) Heer, *Cephalotaxopsis intermedia* Hollick, *Araucarites anadyrensis* Krysht., *Pityophyllum* ex gr. *staratchinii* (Heer) Nath., *Pityostrobus* sp., *Platanus louravetlanica* Herman (abundant), *Dicotylophyllum* sp., cf. *Palaeonuphar nordenskioldii* (Heer) Bell.

Ecological interpretation: this assemblage is dominated by large platanoid leaves, together with ferns, ginkgos and several conifers. The context of a channel fill suggests that the platanoids, if not the other taxa, were river margin plants and it is likely that the other more delicate leaf remains (the ferns, other angiosperms, and even *Cephalotaxopsis*) were similarly situated. The more robust components (*Araucarites* and *Ginkgo*) may have been transported further within the stream channel, but could equally have come from a more mature community incised by a cut bank.

4.3.20. Site 20 (17)

Sedimentary context: the crevasse channel sandstones of site 19 are followed by fragmentary plant horizons (Site 20). These are composed of plant hash and small wood fragments forming thin, 1-cm-thick, laminae within medium- to coarse-grained massively bedded sandstones, fining up to siltstone over 1 m. Rooting is common above these hash horizons. These beds are interpreted to represent abandonment and subsequent channel fill, with incipient palaeosol formation.

Plant remains: *Sagenopteris variabilis* (Velen.) Velen., *Nilssonia alaskana* Hollick, *Nilssonia serotina* Heer, *Cephalotaxopsis intermedia* Hollick, *Araucarites anadyrensis* Krysht., *Menispermites* ex gr. *septentrionalis* Hollick, *Dalembia vachrameevii* E. Lebed. et Herman, *Grebenkia anadyrensis* (Krysht.) E. Lebed., *Dicotylophyllum* cf. *Paleonuphar nordenskioldii* (Heer) Bell, *Dicotylophyllum* sp. B.

Ecological interpretation: this conifer/angiosperm-dominated assemblage represents the communities growing around an abandoned channel during its infill stage. This assemblage appears to have been formed during rapid influx of silt- and sand-laden water during flooding of a nearby active channel, which washed in plant material from the intervening vegetation. Ferns and early successional plants are notably absent suggesting a predominantly cycadophyte understory beneath a conifer forest with a diverse angiosperm shrub layer. Plants subsequently colonised the sediments that captured this assemblage.

4.3.21. Site 21

Sedimentary context: this is a 30-cm-thick, well-sorted horizontally laminated siltstone bed, interpreted to be a lacustrine infill of an abandoned channel, with incipient palaeosol development.

Plant remains: well-preserved accumulation of *Cycadites hyperborea* (Krysht.) E. Lebed.

Ecological interpretation: well-preserved *Cycadites* leaves form a mat within the lacustrine sediments suggesting a very local source for the leaves and a deciduous habit (seasonal leaf shedding) for the plant. The absence of other taxa suggests an isolated quiet pond, within a monospecific community bounding the pond and acting as both a source of the preserved leaves and a filter against the influx of more distally growing species.

4.3.22. Site 22 (22, 22a)

Sedimentary context: this is a small exposure with a 30-cm-thick well-sorted horizontally laminated siltstone bed with abundant plant remains (Fig. 6). Mature, poorly preserved silicified tree trunks were observed in growth position, 20 cm in diameter, branched and with nearby fallen branch remains. A single burrow was recorded, oblique-to-bedding, and 1.5 cm in width. In the uppermost part of the bed current ripples were observed indicating a main palaeocurrent direction to the south. This bed is interpreted to represent floodplain pond sedimentation. Above and below this siltstone, coarse-grained sandstones with chaotically oriented 5–6-cm-long wood fragments occur.

Plant remains: *Gleichenites asiatica* Philipp., *Birisia ochotica* Samyl., *Asplenium dicksonianum* Heer, *Coniopteris* (*Birisia*?) *grebencaensis* Philipp., *Arctopteris penzhinensis* E. Lebed., *Hausmannia bipartita* Samyl. et Shczep., *Cladophlebis* sp. 2, *Cladophlebis* sp. 3, *Sagenopteris variabilis* (Velen.) Velen., *Nilssonia serotina* Heer, *Ginkgo* ex gr.

adiantoides (Ung.) Heer, *Pseudotorellia*? sp., *Sphenobaiera vera* Samyl. et Shczep., *Desmiophyllum* sp., *Cephalotaxopsis* ex gr. *intermedia* Hollick, *Araucarites anadyrensis* Krysht., female cone of? *Araucarites* sp., *Sequoia* sp. (cone), *Elatocladus smittiana* (Heer) Sew., *Magnoliaephyllum alternans* (Heer) Sew., *Menispermites markovoensis* Philipp., *Menispermites minutus* (Krysht.) Herman, *Menispermites* ex gr. *septentrionalis* Hollick, *Diospyros* aff. *streenstrupii* Heer, *Myrtophyllum acuminata* (Philipp.) Herman, *Scheffleraephyllum venustum* (Philipp.) Philipp., *Zizyphus* sp., *Trochodendroides arctica* (Heer) Berry, *Cissites* sp. 1, *Dalembia vachrameevii* E. Lebed. et Herman, *Grebenkia anadyrensis* (Krysht.) E. Lebed. (abundant), *Dicotylophyllum* sp. cf. *Paleonuphar nordenskioldii* (Heer) Bell, *Alaliaephyllum* sp., *Sapindophyllum* sp., root fragments, branch wood.

Ecological interpretation: this leaf assemblage is the most diverse in the Yelisseev Locality for a single depositional setting. The inferred floodplain pond probably received wind-blown leaves from the surrounding communities, with most leaves being derived from the pond margin plants (cf. Spicer, 1981). The current ripples were formed by water flow, either from wind-generated circulation or by inflowing stream action. Some plant debris could have been transported to the pond by stream flow. Angiosperms are particularly diverse and are likely to have fringed the pond margin, as in many modern settings, and made up the semi-mature community colonising the pond margins. Conifers probably dominated the mature community behind them. Ferns and cycadophytes formed the ground cover along the pond edges and within the forest. This locality yielded the largest fern frond fragments which is strong evidence for minimal transport. Aquatic plants are represented by the fern *Hausmannia*.

4.3.23. Site 23

Sedimentary context: between cross-bedded, pebbly, coarse-grained crevasse channel sandstone units, a siltstone bed occurs with roots and mature trees in growth position. The tree tissues are poorly preserved. Sediments surrounding the tree trunks consist of massively bedded, poorly sorted, coarse-grained sandstone overlain by a gravelly sandstone at the level of the root flair. This in turn is overlain by a horizontally laminated well-sorted siltstone with plant remains dominated by *Araucarites anadyrensis* Krysht. shoots and branches.

Plant remains: *Cladophlebis* sp.?, *Nilssonia serotina* Heer, *Ginkgo* ex gr. *adiantoides* (Ung.) Heer, *Araucarites anadyrensis* Krysht., male cone of? *Araucarites* sp., female cone of *Araucarites* sp., branch wood of? *Araucarites* sp., *Pityophyllum staratchinii* (Heer) Nath., *Cephalotaxopsis intermedia* Hollick, *Grebenkia anadyrensis* (Krysht.) E. Lebed., *Scheffleraephyllum venustum* (Philipp.) Philipp., *Menispermites* sp., platanoid and non-platanoid angiosperm leaf fragments, fern fragments.

Ecological interpretation: this succession is interpreted to represent the inundation of a tree-vegetated palaeosurface by stream sediments, followed by the development of a shallow floodplain pond. Based on the abundance of fossil remains the vegetation was dominated by *Araucarites* with *Cephalotaxopsis* and *Pityophyllum* also being common. The shrub layer consisted of *Grebenkia* and *Shefferaephyllum* with ferns as the ground cover. The palaeosol is only weakly developed, so the forest, although mature, had not been established long enough to develop a mature soil profile. *Araucarites* shoots and branches continued to enter the sediments, showing little or no transport abrasion or sorting, which suggests they were derived from a nearby source.

4.3.24. Site 24

Sedimentary context: this site is situated laterally 12 m along a section to the south of site 23 and about 1 m above stratigraphically (Fig. 5). Here, a horizontally bedded siltstone occurs, with abundant organic material grading up into a thinly laminated carbonaceous paper shale. The development of the organic-rich horizon is terminated abruptly by pebbly crevasse channel sandstone deposits.

Plant remains: *Birisia ochotica* Samyl., *Ginkgo* ex gr. *adiantoides* (Ung.) Heer, *Nilssonia serotina* Heer, large shoots of *Cephalotaxopsis intermedia* Hollick associated with cones, *Araucarites anadyrensis* Krysht., male and female cones possibly belonging to *Araucarites anadyrensis*, *Pityophyllum* ex gr. *staratchinii* (Heer) Nath., *Sapindophyllum* sp., *Dicotylophyllum* sp. cf. *Paleonuphar nordenskioldii* (Heer) Bell., entire-margined angiosperm leaf fragments, branch wood fragments.

Ecological interpretation: a mature conifer-dominated forest forming an organic-rich immature palaeosol at the top of a channel fill. As at Site 23, the forest was dominated by *Araucarites* with *Cephalotaxopsis*, *Pityophyllum* and *Ginkgo* as subordinate elements. Angiosperms and ferns formed the understorey.

4.3.25. Site 25 (35)

Sedimentary context: at this site a fine-grained horizontally laminated sandstone grades upwards to medium-grained trough cross-bedded sandstone with abundant rootlets. This is interpreted as a microdelta infill of a shallow floodplain pond.

Plant remains: *Gleichenites asiatica* Phillip., *Sagenopteris variabilis* (Velen.) Velen., *Nilssonia serotina* Heer, *Nilssoniocladus chukotensis* Spicer et Herman, *Ginkgo* ex gr. *adiantoides* (Ung.) Heer, *Sphenobaiera vera* Samyl. et Shczep., *Phoenicopsis* ex gr. *angustifolia* Heer, *Pseudotorellia* sp., *Cephalotaxopsis* ex gr. *intermedia* Hollick, *Pityospermum semiovale* Samyl., *Sequoia* sp. (cone), *Magnoliaephyllum alternans* (Heer) Sew., *Menispermites* ex gr. *septentrionalis* Hollick, *Platanus louravetlanica* Herman, *Scheffleraephyllum venustum* (Philipp.) Philipp., *Cissites* sp. 1, *Trochodendroides* ex gr. *arctica* (Heer) Berry, *Dalembia vachrameevii* E. Lebed. et Herman, *Grebenkia anadyrensis* (Krysht.) E. Lebed., *Dicotylophyllum* sp. cf. *Palaeonuphar nordenskioldii* (Heer) Bell.

Ecological interpretation: the stream feeding the microdelta undoubtedly transported plant material to the pond, and this stream-transported component of the assemblage primarily represented stream side communities. The microdelta assemblage therefore represents both stream margin and pond margin communities. Differentiating between these is not straightforward, but the association of *Platanus* leaves with other channel-fill sediments suggests that this may have been a stream side community component. At this locality *Platanus* is closely associated with *Sphenobaiera vera* and they may have grown together. *Araucarites* is absent at this site, but the earlier phases of conifer forest development are represented in the form of *Cephalotaxopsis* and *Pityophyllum*. Angiosperms are particularly diverse and, as with Site 22, this may be a function of their predominance in pond margin plant communities.

4.3.26. Site 26 (37)

Sedimentary context: horizontally laminated, lightly rooted siltstone interpreted as an immature palaeosol developed on a microdelta pond-fill deposit. This bed is immediately overlain by a coarse-grained crevasse channel sandstone.

Plant remains: *Thallites* sp. cf. *Marchantites jimboi* (Krysht.) Krysht., *Birisia jelisejevii* (Krysht.) Philipp., *Coniopteris* (*Birisia*?) *grebencaensis* Philipp., *Asplenium dicksonianum* Heer, *Sphenopteris* sp. 1, *Nilssonia* sp., *Florinia*? sp., *Magnoliaephyllum alternans* (Heer) Sew., *Platanus louravatlanica* Herman, *Scheffleraephyllum venustum* (Philipp.) Philipp., *Dalembia vachrameevii* E. Lebed. et Herman, *Dalbergites* sp.

Ecological interpretation: this represents a delta surface pioneer community dominated by the ferns *Coniopteris* and *Birisia*, admixed with rare angiosperms derived from streamside and semi-mature pond margin communities.

4.3.27. Site 27 (42)

Sedimentary context: isolated small outcrop, fine-grained sandstones above the measured section.

Plant remains: *Birisia jelisejevii* (Krysht.) Philipp., *Asplenium dicksonianum* Heer, *Cladophlebis* aff. *septentrionalis* Hollick, *Sagenopteris variabilis* (Velen.) Velen., *Nilssonia serotina* Heer, *Ginkgo* ex gr. *adiantoides* (Ung.) Heer, *Sphenobaiera vera* Samyl. et Shczep., *Cephalotaxopsis heterophylla* Hollick, *Cephalotaxopsis intermedia* Hollick, *Pityophyllum* ex gr. *nordenskioldii* (Heer) Nath., *Pityophyllum* ex gr. *staratchinii* (Heer) Nath., *Sequoia* sp., *Menispermites* ex gr. *septentrionalis* Hollick, *Myrtophyllum acuminata* (Philipp.) Herman, *Araliaephyllum dentatum* Philipp., *Araliaephyllum medium* (Philipp.) Herman, *Scheffleraephyllum venustum* (Philipp.) Philipp., *Trochodendroides arctica* (Heer) Berry, *Dalembia vachrameevii* E. Lebed. et Herman., *Dicotylophyllum* sp. A.

Ecological interpretation: this assemblage appears to contain representatives of most communities on the floodplain, but is biased towards early successional plants. Pioneer and understorey elements are abundant in the form of *Birisia* and *Asplenium*, but stream side components such as *Ginkgo* and *Sphenobaiera* occur admixed with representatives of semi-mature angiosperm communities typical of frequently disturbed sites, and early successional conifer forest plants such as *Cephalotaxopsis*, *Sequoia*, and *Pityophyllum*. Forest understorey elements are present as *Nilssonia* and *Sheffleraephyllum*.

4.3.28. Site 28 (45, float 10 m above site 42)

Sedimentary context: fine-grained sandstone, with no record of sedimentary structures.

Plant remains: *Cephalotaxopsis* ex gr. *intermedia* Hollick, *Pityophyllum* ex gr. *staratchinii* (Heer) Nath., *Menispermites* ex gr. *septentrionalis* Hollick.

Ecological interpretation: no ecological interpretations are attempted on float.

4.3.29. Site 29 (46, float, 20–30 m above site 24)

Sedimentary context: fine-grained sandstone with no record of sedimentary structures.

Plant remains: *Thallites* sp. cf. *Marchantites jimboi* (Krysht.) Krysht., *Birisia jelisejevii* (Krysht.) Philipp., *Coniopteris* (Birisia?) *grebencaensis* Philipp., *Cladophlebis* sp. 1, *Cephalotaxopsis intermedia* Hollick, *Araucarites anadyrensis* Krysht., *Pityophyllum* ex gr. *nordenskioldii* (Heer) Nath., *Sequoia* cf. *minuta* Sveshn., *Sequoia* sp., *Menispermites* ex gr. *septentrionalis* Hollick, *Platanus louravetlanica* Herman, *Grebenkia anadyrensis* (Krysht.) E. Lebed.

Ecological interpretation: no ecological interpretations are attempted on float.

4.4. Composition of the Yelisseev Locality flora

Based on the number of species (Table 1), the Yelisseev Locality flora is dominated by angiosperms (more than 50%) followed by conifers, ferns and other groups of plants. Among ferns, *Coniopteris* (Fig. 9F,H) and *Birisia* (Fig. 9A) are the most widespread, with *Gleichenia* (Fig. 9C), *Gleichenites* (Fig. 9B,D,K), *Hausmannia* (Fig. 9L), *Arctopteris*, *Asplenium* (Fig. 9E) and *Cladophlebis* (Fig. 9G) also being typical. Cycadophytes are numerous and *Nilssonia* (Fig. 10H) is the most diverse among them. Bedding planes occasionally have leaf accumulations of *Nilssonia alaskana* and *Cycadites hyperborea* (Fig. 9I). A short shoot of *Nilssoniocladus chukotensis* Spicer et Herman with three *Nilssonia* leaves attached has been found at the locality (Spicer and Herman, 1996). *Taeniopteris* remains are not common. Ginkgoales, i.e. the genera *Ginkgo* (Fig. 9J) and *Sphenobaiera* (Fig. 10J), are encountered frequently, whereas *Pseudotorellia* (?) remains are rare. Czekanowskiales are represented by very rare impressions of *Phoenicopsis* ex gr. *angustifolia* (Fig. 10K), and Caytoniales by the polymorphic leaflets of *Sagenopteris* (Fig. 9J).

Among conifers, *Cephalotaxopsis*, especially *Cephalotaxopsis intermedia* (Fig. 10D,K), predominates over *Araucarites*, *Elatocladus* and *Pityophyllum*. These four genera are the most typical for the Yelisseev Locality flora, particularly *Araucarites anadyrensis* Krysht. (Fig. 10A,E,F) and *Elatocladus smittiana* (Heer) Seward (Fig. 10G,M). Shoots of *A. anadyrensis* are commonly found associated with elongate female cones and tree trunks up to 40 cm in diameter. *Florinia*, *Pagiophyllum*, *Tollia*, *Sequoia* (Fig. 10C), etc. have also been reported. *Pagiophyllum triangulare* (Fig. 10B,N), represented by shoots with rigid scale-like leaves, has been found in several plant-bearing beds.

Among the angiosperm leaves, *Menispermites* (Figs. 11C and 12G,H), *Platanus*, *Araliaephyllum*, *Scheffleraephyllum* (Fig. 11D,G), *Dalembia* (Fig. 12F) and *Grebenkia* (Figs. 11A,B,E and 12C) are the most abundant. Platanoids are represented by *Platanus* and rare *Pseudoprotophyllum*. Small head-like inflorescences were found in association with *Platanus louravetlanica* Herman (Fig. 11F). Fossil leaves of *Trochodendroides* (Fig. 12B), '*Diospyros*' (Fig. 12A), *Myrtophyllum* (Fig. 12E) and *Cissites* (Fig. 12D) are few in number and several fossil leaves of dicots are tentatively assigned to the genus *Dicotylophyllum* (Fig. 11H). It should be emphasised that the real diversity of the Yelisseev Locality angiosperms is probably much high-

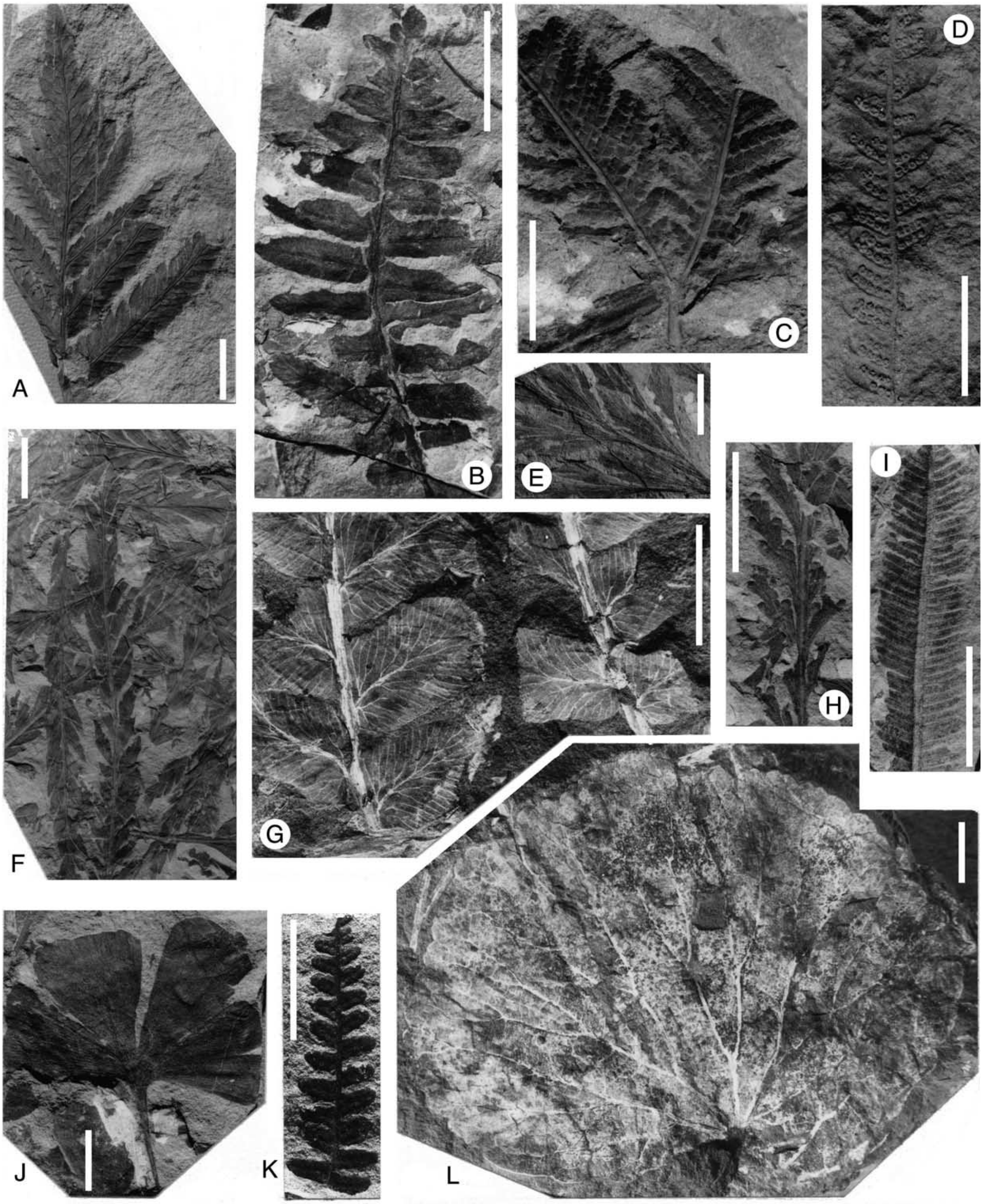
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Table 3
CLAMP results of the Grebenka flora (all sites) and two florules within it

Fossil floras	MAT (°C)	WMMT (°C)	CMMT (°C)	MAP (mm)	MGSP (mm)	MMGSP (mm)	3DRIMO (mm)	LGS (months)
Grebenka flora, all sites	13.0	20.8	5.5	1298	663	83.8	153.7	7.6
Grebenka flora, Site 22	12.3	20.2	4.7	1377	686	88.4	173.4	7.3
Grebenka flora, Sites 19–26	11.2	19.7	3.1	1381	632	86.0	177.7	6.8
Standard deviation	1.8	3.1	3.3	430	280	23	70	1.1

er. Our preliminary classification of these plant leaves shows at least 80 morphotypes (Spicer and Herman, 1998). In the Yelisseev Locality flora entire-margined (*Magnoliaephyllum*, *Myrtophyllum*, *Scheffleraephyllum*, etc.), lobed (*Platanus*, *Cissites*, *Menispermites*, *Araliaephyllum*) and compound (*Scheffleraephyllum*, *Dalembia*, *Sorbites*, *Sapindophyllum* sp.) angiosperm leaves are surprisingly numerous.

4.5. CLAMP results

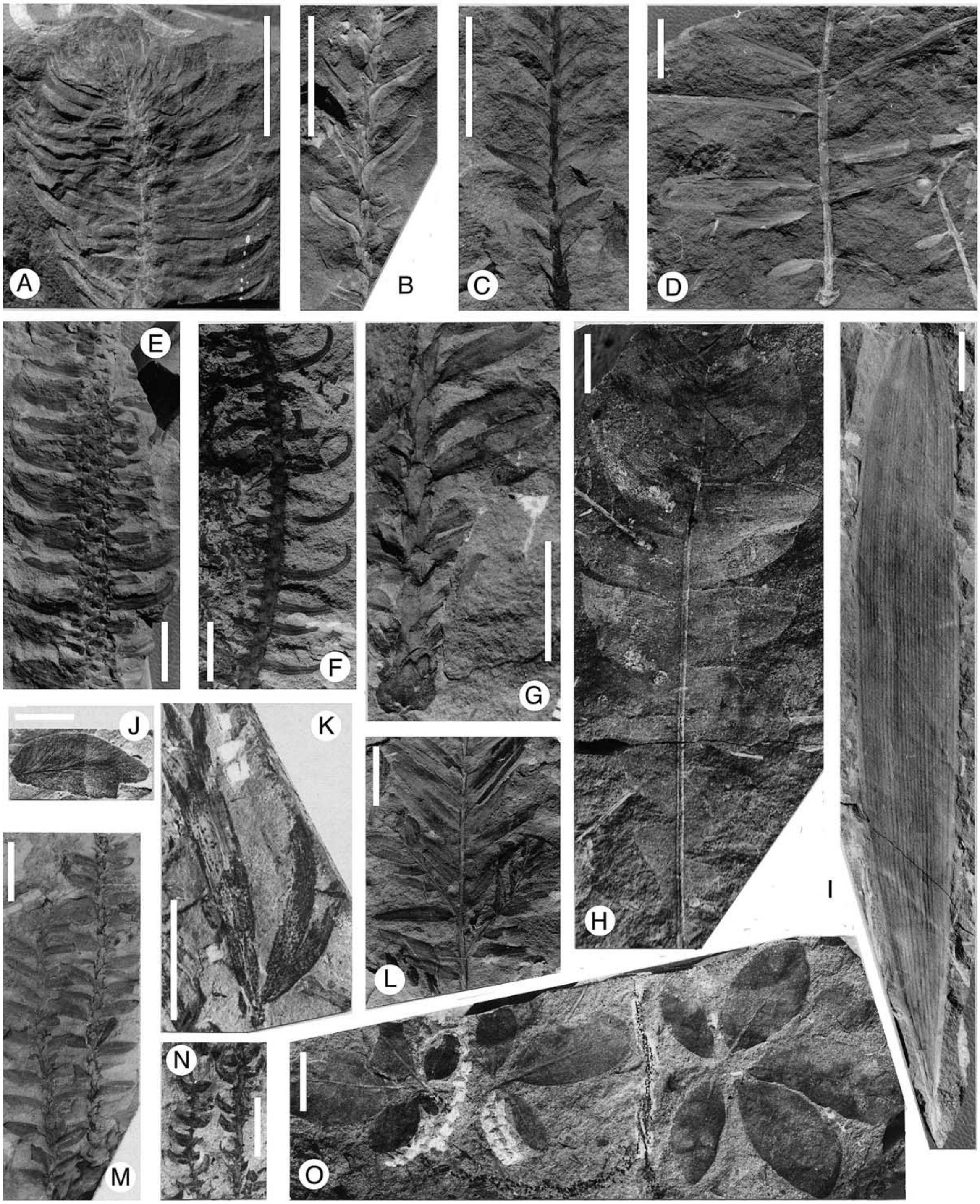
Table 3 shows the results of the CLAMP analysis of three components of the Grebenka flora. The combined flora (all sites) yields a MAT estimate of 13°C, a WMMT of almost 21°C, and a CMMT well above freezing at 5.5°C. This temperature regime is comparable to that obtained from other mid-Cretaceous Arctic floras in northeastern Asia and Alaska (Herman and Spicer, 1996, 1997). When the flora surrounding shallow floodplain lake at site 22 is analysed it gives a similar, but slightly cooler, thermal regime but the differences in all three temperature parameters derived from the florule are within the statistical uncertainty inherent in the CLAMP method. Although statistically insignificant, this coolness may be a reflection of the circum-lacustrine microclimate.

The apparent precipitation data can also be interpreted as being influenced by a local microclimate. The site 22 results indicate a wetter regime than that suggested by the whole flora, although again the differences are within the moisture regime statistical uncertainties inherent in this data set. Results from the whole flora suggest a moist regime with no pronounced dry season. However, the driest months were only slightly drier than those during the 7.6-month-long growing season, and the wettest months appear to have coincided with a period of dormancy. This is most easily explained in terms of a relatively wet winter when the light regime at these high latitudes, despite the mild temperatures (around 5°C), limited plant growth. This implies a strong winter polar high-pressure cell was not experienced by the Grebenka flora.

When the data from the continuous section (Sites 19–26) are combined, the CLAMP methodology again suggests a cooler thermal regime than the whole flora, but still within the statistical uncertainties. Again this inferred coolness could be a reflection of the microclimate in the interfluve or floodplain forests. Like Site 22, these sites represent moist floodplain communities, although locally they may have experienced slightly drier edaphic conditions than the pond margin community.

CLAMP uncertainties with respect to precipita-

Fig. 9. Ferns, cycadophytes and ginkgos from the Yelisseev Locality, collection PF-1 of the North-Eastern Integrated Scientific Research Institute, Russian Academy of Sciences, Magadan (NEISRI). (A) *Birisia jelisejevii* (Kryshtofovich) Philippova, specimen number 28-837a. (B) *Gleichenites asiatica* Philippova, specimen number 54-685a-1. (C) *Gleichenia pseudocrenata* E. Lebedev, specimen number 51-580a-2. (D) and (K) *Gleichenites zippei* (Corda) Seward: (D) specimen number 28-1023, fertile frond, (K) specimen number 28-1024, sterile frond. (E) *Asplenium dicksonianum* Heer, specimen number 30A-934. (F) and (H) *Coniopteris* (*Birisia*?) *grebencaensis* Philippova: (F) specimen number 53-817, sterile fronds, (H) specimen number 53-805a, fertile frond. (G) *Cladophlebis* sp. 2, specimen number 22-475-2. (I) *Cycadites hyperborea* (Kryshtofovich) E. Lebedev, specimen number 0-422-1. (J) *Ginkgo* ex gr. *adiantoides* (Unger) Heer, specimen number 28-857. (L) *Hausmannia bipartita* Samylina et Shczepetov, specimen number 22-469. Scale bars represent 1 cm.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tion are high, particularly in moist regimes (Wolfe, 1993; Herman and Spicer, 1997), and the differences here are not significant. Work in progress indicates, however, that for warmer and seasonally drier regimes CLAMP is able to distinguish between microclimates experienced by different florules or plant communities (Kvacek et al., 2000).

4.6. Palynology

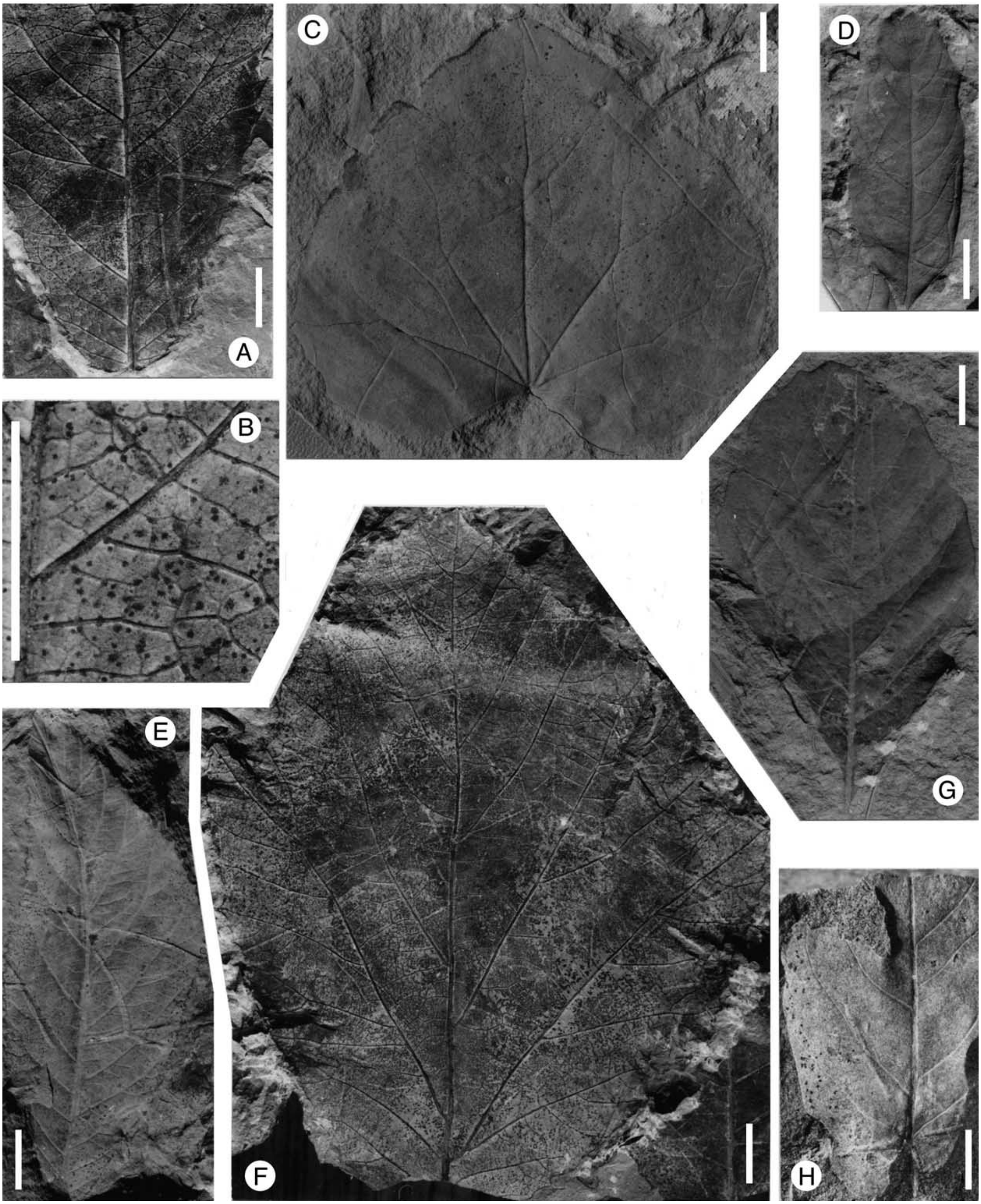
Only three playnological samples from the Yelisseev Locality have yielded identifiable material (Shczepetov et al., 1992). Sample 15 (6.7 m below site 20) is sampled from a carbonaceous, laminated siltstone with poorly preserved plant remains. The sample contains 28.2% spores (28 taxa), 60.1% gymnosperm pollen (17 taxa) and 11.7% angiosperm pollen (nine taxa), out of 684 grains counted. Sample 17 (site 20) is sampled from a siltstone with a mixture of organic matter, just below the main plant-bearing horizons. This we interpret to be equivalent to the lower part of the organic-rich incipient palaeosol at site 20. Of 746 grains counted 30.2% (26 taxa) are spores, 40.3% (18 taxa) are gymnosperm pollen, and 29.5% (10 taxa) are angiosperm pollen. Sample 42 (site 27) from the lower part of the plant-bearing bed consists of siltstone. The total grain count here is 891 of which 70.2% (40 taxa) are spores, 24.9% (17 taxa) are gymnosperm grains and 4.9% (seven taxa) are angiosperm pollen grains. Further details of the palynology of the Yelisseev Locality are given in Shczepetov et al. (1992).

4.7. $^{40}Ar/^{39}Ar$ dating

Thin section analyses show that samples 97RAS68 (site 18, level 1.0 m, see Fig. 6) and 97RAS69 (site 18, level 2.5 m, see Fig. 6), unlike samples from most other beds, are dominated by single-crystal, euhedral plagioclase grains, with significant amounts of minimally altered biotite. Sediment textures imply they represent pyroclastic fallout deposits that were subject to negligible post-eruption sediment transport (see 4.1. Sedimentary petrography). Sample 97RAS68 yielded a slightly noisy release pattern, though the age variations are around the 2σ level and do not correlate with either the atmospheric content or the $^{37}Ar/^{39}Ar$ (Ca/K) ratio. The slightly noisy plateau is similar to that reported by Lo and Onstott (1989) and indicates that this grain did experience some minor alteration. The high $^{37}Ar/^{39}Ar$ values ranging from 0.21 to 0.65 may corroborate this conclusion, but some caution must be observed because this may also have been caused by small amounts of carbonate-bearing cement in the cleavage traces. The weighted mean age of the plateau mid-temperature release (52.5% of the total) is 96.5 ± 0.6 Ma (2σ errors), calculated using Isoplot/Ex software. The spread of ages along the $^{40}Ar/^{39}Ar$ axis of the inverse isochron plot is greater than the spread towards the atmospheric intercept on the $^{40}Ar/^{39}Ar$ axis, and so no meaningful isochron age can be calculated (Table 4).

Sample 97RAS69 yielded a better constrained age with all steps falling less than 2σ from the mean age (Fig. 13). The higher atmospheric content of the lower temperature steps does not seem to correlate with lower ages, though there is greater variability. A weighted mean plateau age for all steps yields 96.2 ± 0.7 Ma and an isochron age for all points yields 96.5 ± 1.0 Ma (2σ errors). The $^{37}Ar/^{39}Ar$ ratios obtained from this sample are similar to 97RAS68 indicating the source may

Fig. 10. Cycadophytes, ginkgoales, czekanowskiales, caytoniales, conifers and angiosperms from the Yelisseev Locality, collection PF-1 (NEISRI). (A), (E) and (F) *Araucarites anadyrensis* Kryshtofovich: (A) specimen number 0-422-8, (E) specimen number 12-661-1, (F) specimen number 28-850. (B) and (N) *Pagiophyllum triangulare* Prynada: (B) specimen number 3002-215a, (N) specimen number 30-884. (C) *Sequoia* cf. *minuta* Sveshnikova, specimen number 46-852. (D) and (L) *Cephalotaxopsis intermedia* Hollick: (D) specimen number 22-472-1, (L) specimen number 35-651a. (G) and (M) *Elatocladus smittiana* (Heer) Seward: (G) specimen number 28-822, (M) specimen number 30A-898-1. (H) *Nilssonia serotina* Heer, specimen number 22-504. (I) *Sphenobaiera vera* Samylina et Shczepetov, specimen number 22-540a-1. (J) *Sagenopteris variabilis* (Velenovsky) Velenovsky, specimen number 42-565b, a leaflet. (K) *Phoenicopsis* ex gr. *angustifolia* Heer, specimen number 35-640a-1. (O) *Scheffleraephyllum venustum* (Philippova) Philippova, specimen numbers 12-673a-1, 2, 3, three compound leaves. Scale bars represent 1 cm.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have been cement in the biotite cleavage (although none were observed adhering to the sample).

Given the greater variability of the analyses of 97RAS68, we consider 96.5 ± 1.0 Ma the most reliable age determination. In addition, the age difference between the two samples is less than 0.3 Ma. This places the Yelisseev Locality sedimentary rocks in the lower Cenomanian, which is consistent with the biostratigraphy of the Yelisseev Locality (Shczepetov et al., 1992; Herman, 1999a) as discussed earlier in this paper (2.1. Geology of right bank of the Anadyr River).

4.8. Palaeomagnetic results

The magnetic susceptibility of the Krivorechenskaya Formation exhibits a wide range from 20 to 4000×10^{-5} SI units, with the highest values observed in the middle part of the Yelisseev Locality. Magnetic susceptibility changes within the Yelisseev Locality succession indicate a degree of cyclicity which may reflect the episodic depositional style as well as volcanic activity in the Okhotsk–Chukotka volcanogenic belt, from which the Krivorachenskaya Formation was sourced. The NRM of the Krivorechenskaya Formation also changes over a wide range from 2 to 640 mA/m (Table 5). These rocks may, therefore, have preserved the vector composition of their NRM, as well as the initial direction of their magnetisation. A comparison of measured samples, after 2 weeks in the position aligned with the laboratory field and opposing the laboratory field, shows that their modern viscous magnetisation reaches 30% of the NRM. However, this does not obscure the NRM of reversed polarity in the lower part of the Yelisseev Locality succession.

In order to identify the initial direction of the rock magnetisation, all samples underwent thermal cleaning, and some samples were demagnetised with an alternating magnetic field. Thermal cleaning showed that the rock magnetisation is dominated by the modern and ancient viscous components, whereas the initial magnetisation of most samples appears when they were subjected to heating higher than 400°C. The initial magnetisation accounts for 20–30% of the NRM. This is particularly typical of samples with a reversed or anomalous direction of magnetisation (sample G6). The majority of samples heated above 400°C suffered a gradual destruction of their magnetisation until they reached complete demagnetisation at the Curie temperatures, with insignificant changes in their directions (samples G14, G35, G43, G59).

According to the thermal cleaning results, deposition of the Krivorechenskaya Formation took place in a geomagnetic field of normal polarity (Table 6). This conclusion contradicts that made by Lozhkina and Shczepetov (1994), probably due to their imperfect method of determining the magnetisation components, and by the presence of rocks having a reversed magnetisation in the lower part of the Yelisseev Locality succession. A reversed magnetisation of these rocks could have resulted from secondary heating during the emplacement of dolerite intrusions, which are exposed at the northern and southern ends of the locality. Our study of oriented samples from the intrusion at the southern end of the outcrop shows reversed polarity magnetisation. Presumably, the magmatic bodies intruded the Krivorechenskaya Formation when the Oligocene(?) volcanogenic rocks of the Russogorskaya Formation were formed (Shczepetov et al., 1994). These volcanogenic rocks are widespread 20 km to the east from the Yelisseev Locality, where they make up the Russian Mountains.

In the Yelisseev Locality, an anticlinal core is exposed, with its limb having a dip to the west of 10–20° and another limb having a dip to the

Fig. 11. Angiosperms from the Yelisseev Locality, collection PF-1 (NEISRI). (A), (B) and (E) *Grebenkia anadyrensis* (Kryshtofovich) E. Lebedev: (A) specimen number 35-651b, leaf base, (B) specimen number 35-651b, venation, (E) specimen number 35-779a. (C) *Menispermites* ex gr. *septentrionalis* Hollick, specimen number 42-607. (D) and (G) *Scheffleraephyllum venustum* (Philippova) Philippova: (D) specimen number 37-980-1, a leaflet, (G) specimen number 42-580a, a leaflet. (F) *Platanus louravetlanica* Herman, holotype number 35-632a. (H) *Dicotylophyllum* sp. cf. *Palaeonuphar nordenckioldii* (Heer) Bell, specimen number 22-501-1. Scale bars represent 1 cm.

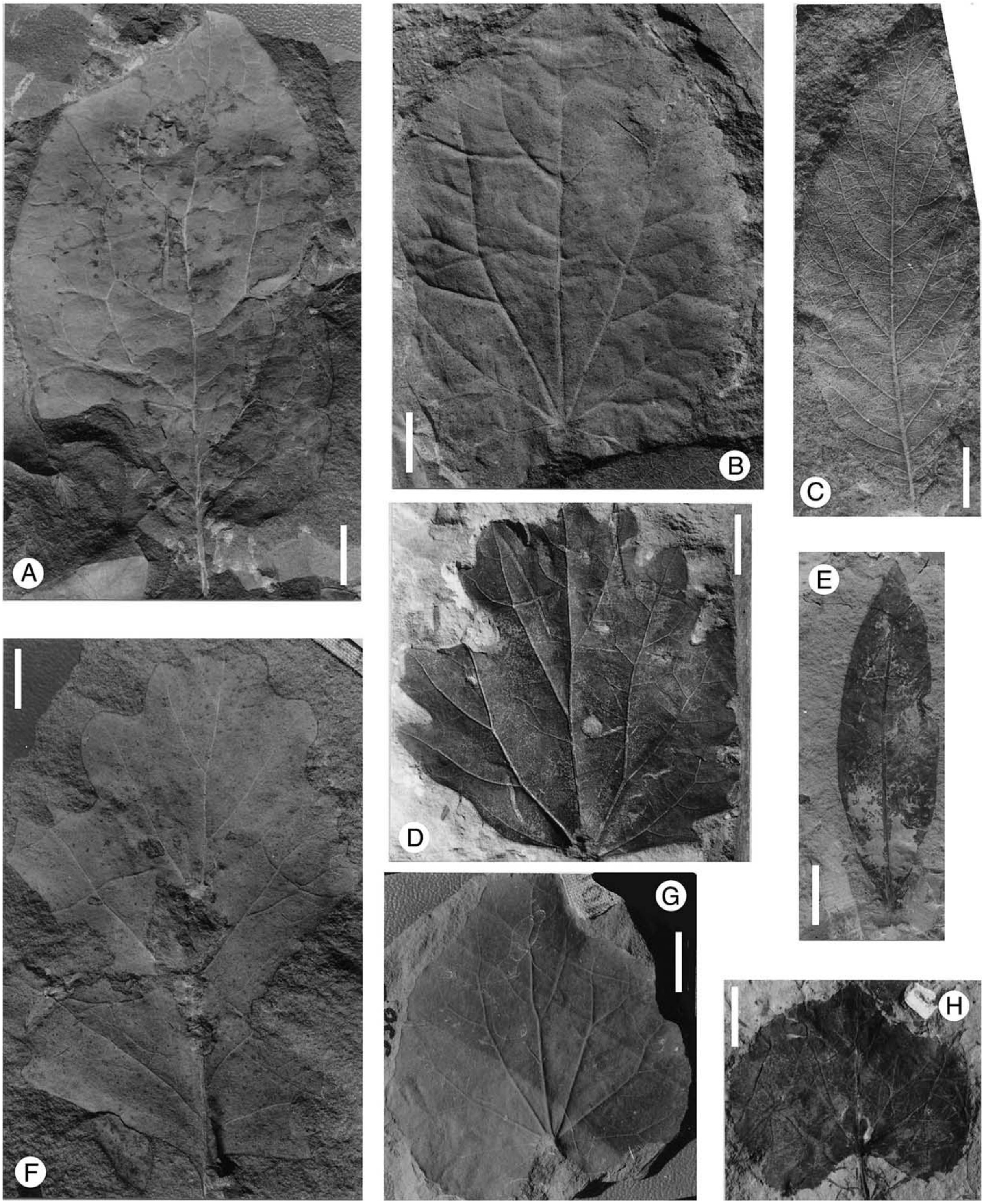
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Table 4
$^{40}Ar/^{39}Ar$ data for two individual biotite samples that were laser step-heated, data show argon isotope ratios, percent ^{39}Ar release and ages

	$^{40}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	^{39}Ar %	$^{40}Ar/^{39}Ar$	Age (Ma)	±
97RAS69, *J*-value = 0.01221 ± 0.00006								
Step 1	5.600	0.018	0.080	0.0040	6.1	4.416	94.8	1.6
Step 2	4.795	0.027	0.186	0.0095	6.3	1.989	43.3	42.1
Step 4	4.883	0.016	0.113	0.0011	9.6	4.549	97.5	2.8
Step 5	4.733	0.016	0.095	0.0000	12.1	4.733	101.4	3.7
Step 6	4.547	0.016	0.237	0.0002	40.9	4.485	96.2	0.6
Step 7	4.557	0.017	0.161	0.0002	76.0	4.506	96.6	0.5
Step 8	4.556	0.017	0.281	0.0000	76.8	4.556	97.7	10.8
Step 9	4.472	0.017	0.342	0.0000	85.2	4.469	95.9	1.2
Step 10	4.639	0.017	0.417	0.0007	93.2	4.433	95.1	1.3
Step 11	4.540	0.017	0.690	0.0003	98.9	4.465	95.8	1.6
Step 12	4.695	0.020	0.925	0.0000	99.5	4.695	100.6	13.5
Step 13	4.752	0.014	0.203	0.0000	100.0	4.752	101.8	19.3
Plateau age (100% release)							96.2	0.7
Isochron age							96.5	1.0
97RAS68, *J*-value = 0.01226 ± 0.00006								
Step 1	6.494	0.021	0.216	0.0115	0.9	3.108	67.4	3.8
Step 2	4.784	0.018	0.156	0.0017	2.1	4.270	92.1	3.0
Step 3	4.963	0.017	0.175	0.0022	3.8	4.325	93.2	2.0
Step 5	4.591	0.016	0.208	0.0005	19.3	4.448	95.8	0.5
Step 6	4.525	0.017	0.303	0.0004	22.5	4.408	94.9	1.2
Step 7	4.551	0.016	0.269	0.0001	35.1	4.531	97.5	0.6
Step 8	4.679	0.018	0.462	0.0007	37.1	4.465	96.1	1.8
Step 9	4.592	0.017	0.322	0.0002	51.4	4.545	97.8	1.0
Step 10	4.447	0.017	0.416	0.0000	54.5	4.432	95.5	1.2
Step 11	4.418	0.017	0.248	0.0001	61.6	4.399	94.8	0.7
Step 12	4.456	0.016	0.326	0.0000	71.1	4.443	95.7	0.6
Step 13	4.404	0.017	0.562	0.0002	75.7	4.341	93.6	0.9
Step 14	4.578	0.016	0.366	0.0002	77.2	4.525	97.4	2.2
Step 15	4.456	0.018	0.656	0.0001	80.6	4.426	95.3	1.1
Step 16	4.343	0.016	0.168	0.0001	86.8	4.307	92.8	0.7
Step 17	4.395	0.016	0.213	0.0001	100.0	4.380	94.4	0.6
Plateau age (52.5% release)							96.5	0.6

Data were corrected for mass spectrometer discrimination and reactor interferences (McMaster reactor, Canada) and *J*-values were measured using the GA1550 international standard with an age of 98.9 Ma (Renne et al., 1998).

south of 15–20°. Therefore, the fold test, in its incomplete form, was used to check the origin of the magnetisation. After thermal cleaning, the vectors grouped much closer in stratigraphic (ancient) coordinates, than in geographic (modern) coordinates. This confirms the existence of pre-folding magnetisation (Table 6). That thermal cleaning is revealing a true direction of original

Fig. 12. Angiosperms from the Yelisseev Locality, collection PF-1 (NEISRI). (A) *Diospyros* aff. *steenstrupi* Heer, specimen number 22-481b-1. (B) *Trochodendroides* ex gr. *arctica* (Heer) Berry, specimen number 22-508a-7. (C) *Grebenkia anadyrensis* (Kryshtofovich) E. Lebedev, specimen number 22-508a-6. (D) *Cissites* sp. 1, specimen number 35-624a-1. (E) *Myrtophyllum acuminata* (Philippova) Herman, specimen number 0-442-1. (F) *Dalembia vachrameevii* E. Lebedev et Herman, specimen number 22A-491b-1, a leaflet. (G) *Menispermites* ex gr. *septentrionalis* Hollick, specimen number 42-484. (H) *Menispermites minutus* (Kryshtofovich) Herman, specimen number 25-688a. Scale bars represent 1 cm.

Table 5
Magnetic properties of Krivorechenskaya Formation rocks

Sample groups	*N*	Sample No.	*K* 10^{-5} SI	In mA/m	*Q*
4	8	54–61	354	94	0.53
			153–776	29–281	0.25–0.75
3	14	41–53, 62	188	51	0.54
			20–240	16–261	0.20–2.20
2	18	22–40	698	167	0.48
			21–4500	16–642	0.2–1.58
1	21	1–21	205	57	0.56
			8–1380	2–243	0.20–4.00
GRM	7	G975-1, 2, 3	681	454	1.33
		G976-1, 2, 3, 4	316–1036	340–580	0.95–2.86

N, the numbers of samples; *K*, magnetic susceptibility; In, NRM; *Q*, Koenigsberger ratio. Note that samples G975, 1 to 3 and G976, 1 to 4 come from exposures near the mouth of the Gornaya River (sample group GRM).

magnetisation is also confirmed by the magnetic susceptibility behaviour during thermal treatment. All rock types including clays, siltstones and sandstones show a gradual decrease of 20–50% in the magnetic susceptibility compared to the initial *K*-value during their heating to 600°C. This indicates a lack of newly formed magnetic minerals. Magnetite is slowly oxidised (its presence is defined by a complete disappearance of remnant magnetisation under 580–600°C conditions), which excludes the formation of laboratory magnetisation components in an incomplete magnetic vacuum. Thus, the intrusion of magmatic rocks did not affect the rock magnetisation significantly. The ancient (initial) magnetisation was formed before folding and probably reflects a direction of a magnetic field prevalent at the time when the Krivorechenskaya Formation sediments accumulated.

5. Discussion

5.1. Sediment accomodation and deposition

Local and regional tectonics typically have strong controls on alluvial sediment accomodation in convergent-margin settings, such as the Okhotsk–Chukotka volcanogenic belt. This can

Table 6
Palaeomagnetic directions and estimated palaeo-pole positions for the Krivorechenskaya Formation rocks

Sample groups	*N*	Folded geographic coordinate				Pole			Unfolded stratigraphic coordinate				Pole		
		Dg	Ig	*k*	α95	PLat	Lat	Long	Ds	Is	k	α95	PLat	Lat	Long
4	8(7)	14	+72	26.6	11.9	57.0	79.9	299.3	254	+87	25.7	12.1	84.0	62.2	155.9
3	14(12)	17	+67	18.7	10.3	49.7	72.7	308.2	252	+89	20.5	9.8	88.0	63.7	164.0
2	19(17)	28	+75	26.1	7.1	61.8	77.2	257.1	181	+81	25.3	7.2	72.4	47.0	172.3
1	21(20)	34	+70	16.3	8.3	53.9	70.0	273.7	321	+85	19.0	7.7	80.1	71.1	148.7
GRM	7(7)	318	+78	62.7	7.7	67.0	72.9	105.7	213	+83	64.8	7.6	76.2	52.1	156.4
Fine-grained rocks	25	8	+67	24.0	6.0	49.7	74.7	328.4	309	+82	25.8	5.8	74.3	70.4	129.6

N, total number of samples (in brackets, number of samples used for calculation); Dg and Ig, declination and inclination in geographic coordinates; *k*, precision parameter; α95, radius of 95% confidence circle; Plat, palaeolatitude; Ds and Is, declination and inclination in stratigraphic coordinates; Lat and Long, coordinates of the North Pole (latitude and longitude, respectively); GRM, samples from downstream of mouth of Gornaya River. Samples, numbered from the base to the top of the Yelisseev Section, were grouped on basis of cyclical variation in magnetic susceptibility.

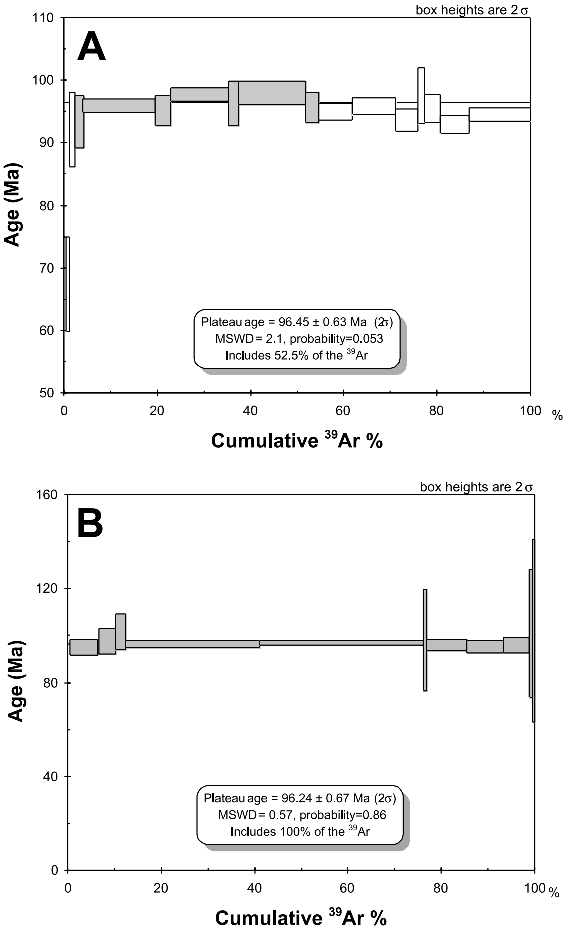

Fig. 13. Laser stepped heating ^{39}Ar release versus Ar–Ar age, for two individual biotite grains separated from samples 97RAS68 and 97RAS69. Errors are quoted at the 2σ level. (A) Sample 97RAS68 yielded a slightly scattered age spectrum with some evidence of alteration and a plateau age comprising 52.5% of the ^{39}Ar release and an age of 96.5 ± 0.5 Ma. (B) A biotite grain from sample 97RAS69 yielded a plateau age over the whole of the argon release, of 96.3 ± 0.7 Ma.

occur, for example, due to the filling and deflation of volcanic magma chambers (Miall, 1996, 1997) and we observed evidence of prominent synsedimentary tectonic activity in other Cretaceous successions close to the study area. Flexural downwarping at the margins of an ever increasingly loaded Okhotsk–Chukotka volcanogenic belt may serve as a simple model to provide the accommodation space of the Yelisseev Locality succession. From our data, it was not possible to disinguish with confidence any effects of sea-level-controlled base-level changes from those of regional tectonics in the Yelisseev Locality succession (cf. Miall, 1997).

The Yelisseev Locality succession is composed of packages of sediment reflecting switching from floodplain, to stream channel, and back to floodplain deposits. The floodplain sedimentary packages were identified by the presence of floodplain fines, in situ flora, and palaeosols. They also show evidence of rapid and frequent deposition of overbank sand and gravel, which indicate proximity to stream channels rich in sandy to gravelly bedload, and rapid floodplain aggradation. Intermittently floral communities invaded and began to stabilise the top of these splays. However, colonisation did not proceed for long enough to develop mature soils before subsequent sediment inundation took place. In the relatively warm and moist climate of the region during latest Albian to early Cenomanian time (Spicer et al., 1996; Spicer and Herman, 1998), fairly rapid palaeosol development would be expected. This all leaves a general impression of a rapid mean vertical accretion rate. Alluvial deposition is typically represented by major sediment pulses and relatively long intervals of non-deposition (Leeder, 1993). Crude estimates of mean depositional rates for fluvial systems typically vary from less than 1 to 50 m/ka, with a proposed mean of 20 m/ka (Bridge and Leeder, 1979). For overbank accretion a slower mean rate of 3 m/ka was suggested (Bridge, 1984) (see discussions in Miall (1996) and Marriott (1999)). The Yelisseev Locality channel package is dominated by gravelly bedload material, presumably deposited in braided streams. Cobble to boulder-sized maximum clast sizes indicate that the source of sediment was at most a few kilometres away (cf. Belyi, 1994), but some transport distance must have been involved to attain the high degree of clast roundness observed in the reworked pebbles of the conglomerates. Upsection, the channel package becomes sandier and eventually interfingers with floodplain deposits, and maximum clast size gradually decreases to pebble size. Palaeocurrent data are too few to trust, but broadly reflect southward sediment transport away from the volcanogenic belt. Vegetation was wiped out repeatedly during the deposition of the channel package, and recovered only after recolonisation was initiated several times, and when the alluvial system returned to previous conditions with respect to slope and discharge.

5.2. Syn- or inter-eruptive sedimentation?

The andesitic Okhotsk–Chukotka volcanogenic belt was presumably subjected to rare, short, violent, plinian eruptions ejecting material over long distances, with long inter-eruptive periods (cf. Fischer and Schmincke, 1984; Lebedev, 1987; Scarth, 1994). For most of the Yelisseev Locality succession, there is no unambiguous evidence of syndepositional volcanic activity. Instead the particle abrasion, the predominating epiclastic sediment composition, and the even dispersion of detrital organic matter, indicate continuous sediment reworking, i.e. inter-eruptive alluvial conditions. However, within the lower floodplain sedimentary package, changes in mineral composition, texture, and sedimentary structures indicate minimal reworking of volcanic ashes, i.e. primary pyroclastic sediments. This notion is reinforced by the fact that syn-eruptive periods typically promote floods, frequent avulsions and debris flows, with sand-rich, monolithologic, pyroclastic deposits. Eruptions also tend to promote alluvial aggradation, as seen for instance in the lower floodplain package of the Yelisseev Locality (cf. Smith, 1991). Inter-eruptive periods, on the other hand, are typically distinguished by gravel-dominated bedload rivers, and eventually alluvial degradation, where the degree of degradation is controlled by eruption frequency and the rate of subsidence (Smith, 1991). In the Yelisseev Locality, this could correspond to the sedimentary succession from the base of the channel package. Smith (1991) outlined an idealised three-fold series of facies geometries with syn- and inter-eruptive facies, with volcanism-driven and subsidence-driven end-members. Of these, the Yelisseev Locality succession most strongly resembles the subsidence-driven end-member with the least degradation, ideally where eruption frequency is low, and subsidence is considerable.

5.3. Sedimentation rate and preservation of plant remains

The inferred rapid, episodic vertical floodplain accretion is reflected by the exceptional diversity of the Yelisseev Locality flora. Thus, the repeated phases of colonisation and disturbance led to a mosaic of communities in different seral stages, on different substrates with different moisture contents, and different degrees of inter-plant competition. Community diversity is also reflected in taxonomic diversity. Moreover, lateral channel migration, crevasse splays, channel abandonment and pond development also provided a wealth of depositional environments in which the flora could be rapidly buried and preserved. High sedimentation rates also restricted the activity of invertebrate sediment feeders, and thus the plant material was well preserved. However, while preservation of the megafossils was enhanced, that of palynomorphs was decreased (see 4.6. Palynology). Of 20 samples processed, only three yielded sufficient grains to be worth recording. Samples 17 and 42 are from organic-rich horizons associated with low sedimentation rates, the incipient development of palaeosols, and stable communities. In other samples either the palynomorphs were not preserved or the sediments diluted their abundance. Compared to the associated leaf fossils, angiosperms are underrepresented in the palynoflora. Sample 15 is from the organic debris associated with the waning phase of a crevasse splay event, and is not associated with any identifiable megaflora. Despite this kind of depositional setting favouring broad sampling of the floodplain communities, including those rich in angiosperms, pollen grains from flowering plants are still a minor component of the palynoflora. Over-representation of spores and gymnosperm pollen is known to be a function of their high production volumes, which is reflected in the grain abundancies. However, taxonomic diversity should not be overly affected by production volumes, but even here angiosperms are in minority. This could indicate that angiosperm leaf diversity is not reflected in pollen morphology and that palynology alone may be a poor guide to flowering plant diversification and ecology.

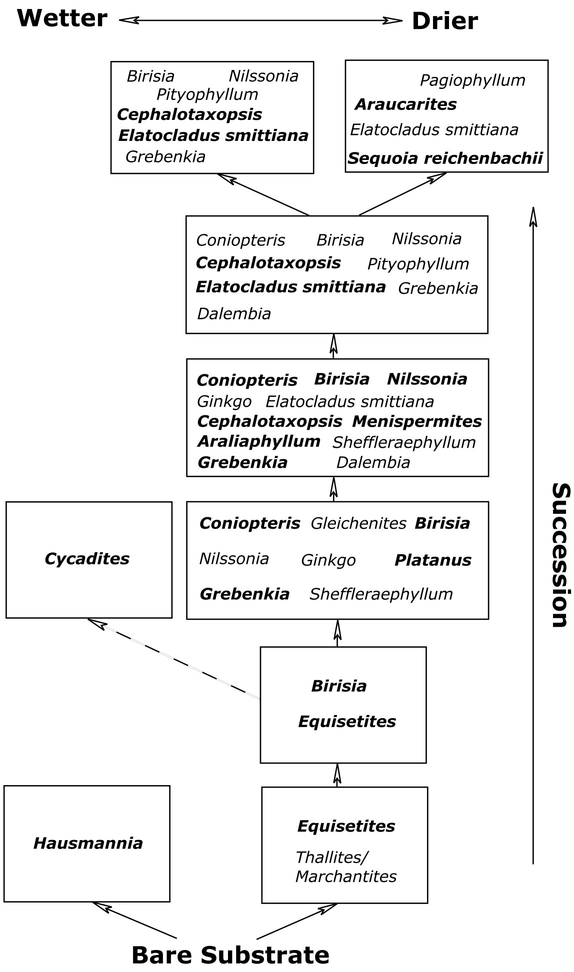

Fig. 14. Schematic representation of plant community succession in the near-polar mid-Cretaceous vegetation reconstructed from our observations at the Yelisseev Locality; dominant plant taxa are shown in bold.

5.4. Plant community reconstructions

The consistent association of particular plant remains in particular facies associations, and the juxtaposition of those environments, have allowed the reconstruction of likely seral community successions in this near-polar mid-Cretaceous vegetation. Fig. 14 illustrates typical successions from bare ground to either moist or drier mature forests. On moist subaerially exposed substrates *Equisetites* often formed dense thickets, but the first colonisers also included liverworts. In standing water the aquatic fern *Hausmannia* seemed to form a monodominant community. We have little information on later stages in the aquatic community development, but on drier sites a fern marsh typically developed similar to that recently interpreted for Alaska North Slope Albian vegetation (Spicer and Herman, 2001). In some instances, possibly on wetter substrates, a monodominant community of *Cycadites* developed instead of a more species-rich angiosperm/fern/cycadophyte shrub community. The next stage in community development was characterised by an increase in angiosperm diversity while ferns and cycadophytes remained as minor ground cover components. The stature of the angiosperms is not well-determined but based on modern analogues and leaf abundance it is likely that they reached shrub or small-tree size, but perhaps not more than a few metres in height. No obvious angiosperm wood has ever been found at the Yelisseev Locality. The more mature phases of seral succession are characterised by an ever-increasing abundance of conifers. In drier settings *Araucarites* and *Pagiophyllum* are particularly abundant. In moister environments, ferns and cycadophytes remain as ground cover beneath a canopy of taxodiaceous trees such as *Cephalotaxopsis*; conifers with rigid scale or hook-like leaves were absent. Our interpretation of the plant successions shows that angiosperms dominated and characterised early (but not the earliest) intermediate seral stages, and that mature forests were conifer-dominated, with only sometimes a minor angiosperm component.

5.5. Palaeoclimate implications

The CLAMP results are consistent with the generally accepted notion that the mid-Cretaceous was a period of pronounced global warmth most strongly expressed at high latitudes. The CMMT experienced by the Grebenka flora suggests that the mid-Cretaceous Arctic basin was probably warm enough to maintain the winter temperature in adjacent regions of northeastern Asia and Alaska above freezing. The CMMTs of all sites bordering the Arctic Ocean were at or above freezing (Herman and Spicer, 1996) despite the annual lack of solar insolation for 3–4 months. This strongly suggests that there must have been significant poleward ocean heat transport despite shallow and narrow connections with the rest of the world's ocean system (Herman and Spicer, 1996, 1997). Precipitation in northeastern Asia and Alaska is predicted to have been high, reflecting a very weak polar high-pressure cell and quite unlike that of the Present.

Apart from these broad-scale findings, these results have important general implications for the use of CLAMP at the scale of local plant communities. Although there are small differences between assemblages derived from different communities, which could be interpreted as genuinely reflecting microclimatic variations, these differences are insignificant in relation to known uncertainties inherent in the method. In moist regimes without a pronounced seasonal drought, and provided the species diversity is high such as at the Yelisseev Locality, there appears to be little significant difference in the climate signal as captured by leaves preserved in different depositional environments. This particularly applies to moisture related variables. Moreover, even at high latitudes, where there is significant seasonal temperature variation, the thermal regime is reflected well in both pond and fluvial floodplain environments. As statistical uncertainty is a function, in part, of taxonomic diversity, it is clear that where possible a better regional climate signal is obtained by combining florules from different depositional settings and vegetational communities. An important condition though is that the sedimentary package containing the florules should represent a geologically short time interval.

5.6. Palaeomagnetism

The palaeoclimatic aspects of this study need to be placed in a good palaeogeographical framework, particularly as regards palaeolatitude control. The Krivorechenskaya Formation deposits accumulated when the geomagnetic field was of normal polarity, with a steep magnetic inclination (Table 6). The palaeomagnetic pole shows different coordinates for different lithologic horizons, and the variation for the conglomerates is particularly severe (Table 6). Horizontally laminated mud- and siltstones yield the most uniform and reliable data. Nevertheless, the determined palaeomagnetic latitude values are similar for different lithologies, $>72°$N, which harmonise with other investigations (cf. Nockleberg et al., 1998). The directions obtained from fine-grained rocks of the Yelisseev Locality (which are less affected by cross-bedding) are grouped closely with respect to stratigraphic (ancient) coordinates, with the North Pole at 129.6° and 70.4°N (Table 6). Such a pole position suggests that after deposition of the succession there was a 45–50° counter-clockwise rotation of the study area in relation to the Siberian Platform.

Due to the expected normal monopolarity of the examined rocks, it is impossible to determine the age of these deposits on the basis of the palaeomagnetic data only. Latest Albian–Cenomanian times were characterised by a geomagnetic field of normal polarity (Harland et al., 1990), consistent with stratigraphic and palaeomagnetic results presented herein.

6. Conclusions

(1) The Yelisseev Locality sedimentary succession (Fig. 5) was deposited close to the Okhotsk–Chukotka volcanogenic belt, mainly between eruptions, but probably include thin incursions from one contemporaneous eruption.

(2) Radiometric dating of volcanic ash within the succession (96.5 ± 0.5 Ma; Cenomanian) confirms previous age determinations based on regional biostratigraphic correlations between the plant-bearing succession and marine incursions. These place the Yelisseev Locality to the uppermost Albian–Lower Cenomanian.

(3) The diversity of the Grebenka flora is the result of relatively rapid deposition in a subsiding floodbasin, sourced by volcaniclastics from the volcanogenic belt.

(4) Episodic influxes of sediment disturbed, and often overwhelmed the drainage system, leading to the destruction and burial of a variety of facies associations, each linked to specific plant communities. The high sediment supply and drainage

system instability resulted in the burial and preservation of a variety of seral stages of plant succession ranging from initial colonisation to mature forest. Repeated patterns of plant succession could be reconstructed and the floral dynamics inferred.

(5) Palaeomagnetic analysis demonstrated the survival of a primary (original) magnetic signal of normal polarity and suggested that at the time of deposition the vegetation was at or near 76°N, and therefore truly polar.

(6) The relatively short time span represented by the Yelisseev Locality succession means that the palaeoclimatic signal captured by the vegetation represents a snapshot of near-polar environmental conditions during a period of pronounced global warmth.

(7) CLAMP analysis suggests a MAT of 13°C with a MAT range of approximately 15°C, despite the pronounced polar insolation regime. It also implies that rainfall was moderately high and that a pronounced dry season was lacking. This reflects a very weak polar high-pressure cell and substantially different precipitation patterns to those of the present day.

(8) The absence of cold winters also meant that growth restarted very soon after sufficient daylight for photosynthesis returned in the spring. Winter dormancy lasted for no more than four and a half months and was largely controlled by light rather than temperature.

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