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# Inertinite-rich Tertiary coals from the Zeya–Bureya Basin, Far Eastern Russia

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## Abstract

Selected Tertiary coals from the Zeya–Buryea Basin, Far Eastern Russia, were investigated for aspects of their coal type, rank, depositional environment and post-depositional history. The coals have been examined in outcrop (lithotype logging), microscopically (maceral, reflectance and fluorescence), and geochemically (proximate analysis). Two laterally extensive coal-bearing horizons occur: one of Palaeocene age and the other of early Miocene age. The Palaeocene coals were investigated in active open-cut mines at Raichikhinsk and Yerkovtsi and the early Miocene deposit in an abandoned open-cut mine at Cergeyevka. Palaeocene coals at Raichikhinsk and Yerkovtsi were indistinguishable from each other macroscopically, microscopically, and geochemically. The deposits were sufficiently coalified that brightness logging could be undertaken. Dull coals, with numerous fusainous wisps, were dominant. Four dulling-up sequences, which represent stacked peat deposits, were observed at Raichikhinsk. At Yerkovtsi, only a small section of the middle of the seam, which was mostly dull and muddy coal, was investigated. Petrographically, these coals were dominated by inertinite group macerals, which is unusual in non-Gondwanan coals and rare in the Tertiary. Rank classification was problematic with volatile matter (VM) content of vitrain (daf), macroscopic appearance, and microscopic textures suggesting subbituminous B rank, but carbon content, moisture content and specific energy indicating a lignite rank. Notwithstanding complications of rank, estimates of the maximum-range burial depths were calculated. Taking the VM (daf) content of vitrain as 48%, burial depth estimates range from 900 m for a high geothermal gradient and long heating time to a maximum of 3300 m for a low geothermal gradient and short heating time. These estimates are maxima as the coal rank may be lower than implied by the VM. The Cergeyevka deposit is a soft brown coal. Limited sampling of the upper-most portion indicated a high moisture content (75% daf) and an unusual, hydrogen-rich geochemistry. Lack of identifiable liptinites using either reflected light or fluorescence microscopy suggested a significant bituminite component. Otherwise, the coals appear to be typical for the Tertiary. An estimate of 125 m maximum burial depth was obtained using the bed-moisture content of the coal, which is around the present burial depth. Comparison of present-day thicknesses with inferred burial depths suggests that at least 500 m of section is missing between the Palaeocene coals and the early Miocene coals. Palaeoenvironmental considerations suggest that fire played a significant role in the accumulation of the peats at Raichikhinsk and Yerkovtsi. At Cergeyevka, peat accumulation ended by drowning of the mire. Two tuff beds were

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recognised within the seam at Raichikhinsk and one in the seam at Yerkovtsi. Correlation of the tuff beds is uncertain but they should prove useful in regional coal seam correlation and interpreting coal depositional environments. Geochemical analysis by XRF was complicated by high loss-on-ignition (LOI) values. Despite extensive alteration, an acid igneous source is implied from the presence of free quartz and $TiO_2/Al_2O_3$ ratios of 0.02 to 0.05.

*Keywords:* Tertiary coal; Russia; Inertinite; Rank; Depositional environment

## 1. Introduction

The Zeya–Bureya Basin contains economic, coal-bearing sequences of Tertiary age (Figs. 1 and 2) and is the major source of coal for large parts of Far Eastern Russia. Coal resources are estimated in excess of 60 Gt of mostly lignite. Upper and Lower Cretaceous coal-bearing sequences (Krassilov, 1992) are presently uneconomic.

A reconnaissance study of Tertiary coals at Raichikhinsk, Yerkovtsi and Cergeyevka (Fig. 1) has provided broad parameters of coal type, rank, quality, depositional environments and post-depositional history.

Deposits at Raichikhinsk and Yerkovtsi belong to the Palaeocene Kivda Formation (Fig. 2) which was extensively deposited in the basin but its present distribution is controlled by post-depositional erosion. The modern Zeya River has dissected the basin, leaving behind a series of at least four terraces (Fig. 1) with associated loess deposits. Coal is present beneath terrace number II at Yerkovtsi, but has been eroded during the formation of terraces III and IV (the lowermost).

A single seam, of total thickness around 4 m, is being mined at Raichikhinsk. At Yerkovtsi, a total coal thickness of around 4 m is also mined but the seam is in places split into two almost equal portions by up to 2 m of carbonaceous mudstone. The upper split has been eroded in places resulting in a net reduction of mineable coal. Controls on the splitting and its nature have not been investigated. It is likely that the same seam is represented at both Raichikhinsk and Yerkovtsi.

At Cergeyevka, a single early Miocene coal is present. The extensive seam is 10–15 m thick but is not currently exploited and exposures are very poor. Only one outcrop of the top of the seam was examined in an abandoned open-cut mine.

## 2. Tectonic development of the Zeya–Bureya Basin

Tectonic structures of the Russian Far East were formed as the result of Mesozoic and Cenozoic collision between the southern margin of the Siberian (North Asian) craton and the Amur composite terrane. Within the latter, separate tectonic blocks (terranes) are distinguished (the Badzhal, Baladek, Bureya, Gonzha, Mamyn, Oldoy, Un'ya-Bom, and Ul'ban Terranes; Fig. 3). The contemporaneous Mongolian–Okhotsk Belt is considered to be a relic accretion complex between the southern margin of the Siberian continent and the Amur microcontinent.

In the Early Mesozoic, during the closure of the Mongolian–Okhotsk ocean, several periods of subduction occurred which were characterized by different directions. Subduction periods alternated with continental transform environments (A.I. Khanchuk, personal communication) and resulted in formation of the Late Jurassic–Early Cretaceous calc-alkaline and alkaline volcanics, volcano-plutonic belts along the converging continental margins. Accretion systems of the Mongolian–Okhotsk belt were significantly reworked by the Late Mesozoic and Cenozoic strike-slip movements.

Palaeotectonic reconstructions indicate three types of basin existed in the early stages of the Late Triassic–Jurassic collision, viz. (1) residual oceanic basins in gaps between continental margins and which contain flysch-like deposits of the Ul'ban and Un'ya-Bom structural zones; (2) hinterland basins formed along the margins of the overlapping plate (the Uda trough); and (3) foreland basins formed along the margin of the subsiding plate (the Upper Amur, Zeya-Dep, Bureya troughs).

During the same stage, a chain of the South Tukuringra late-collision depressions (the Urkan, Pikan Basins, etc.) formed within the collision zone. Distant from it occur N–S trending rift-like structures

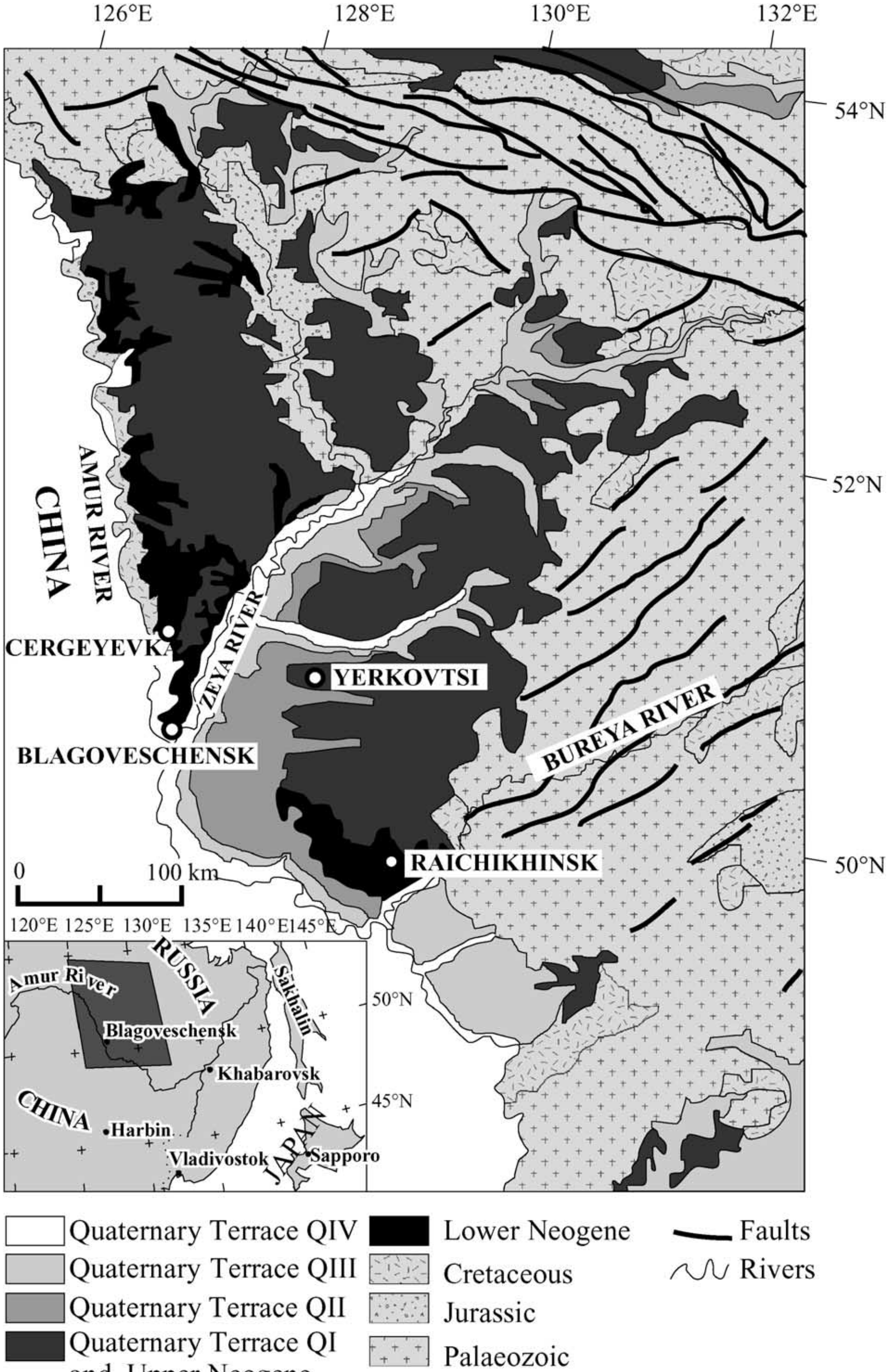
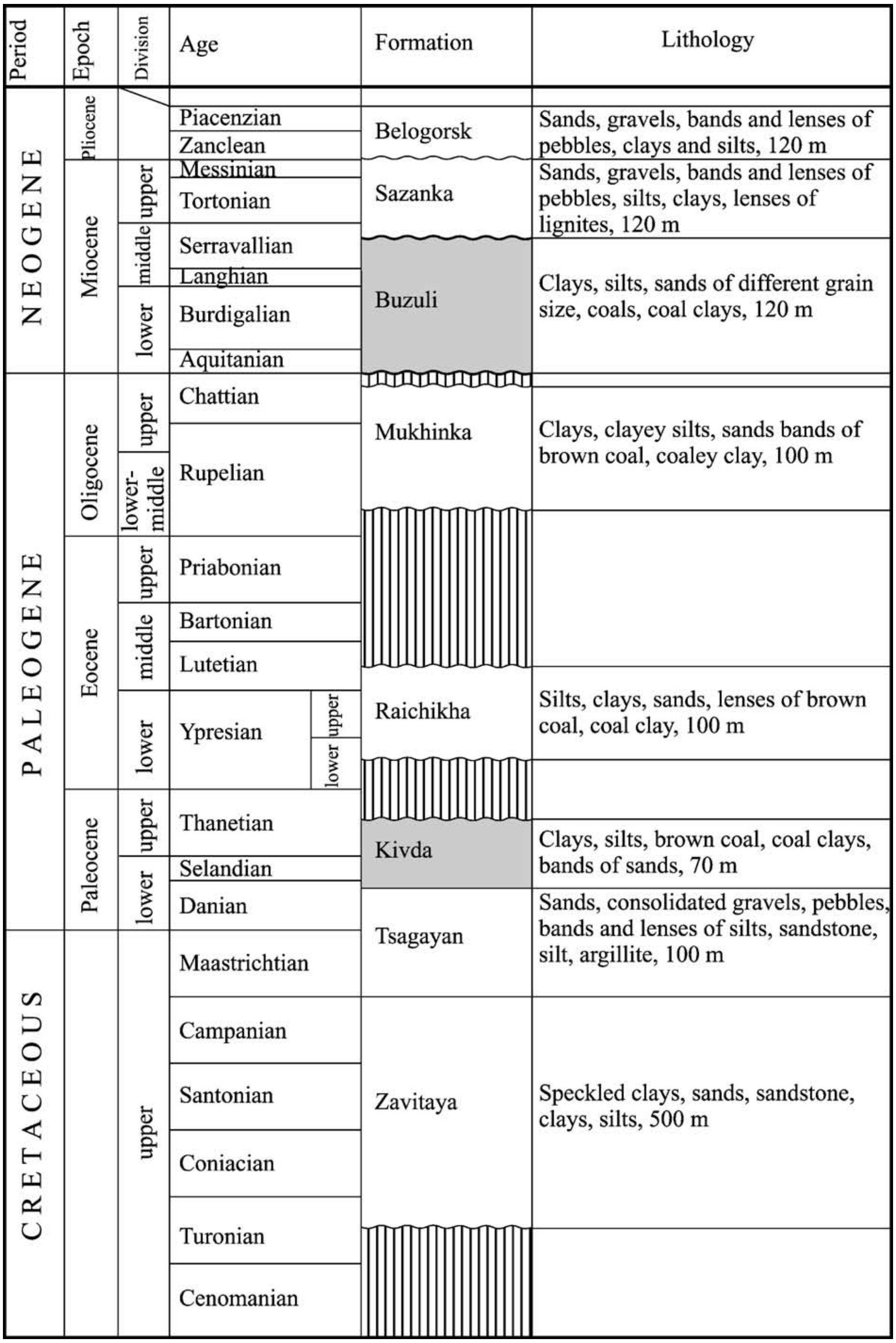


Fig. 1. Simplified geology of the Russian sector of the Zeya–Bureya Basin and surrounding regions (modified from 1:2,500,000 Geological Map, 1986). No geology is indicated for China.



| Period | Epoch | Division | Age | Formation | Lithology |
|---|---|---|---|---|---|
| NEOGENE | Pliocene | | Piacenzian | Belogorsk | Sands, gravels, bands and lenses of pebbles, clays and silts, 120 m |
| | | | Zanclean | | |
| | Miocene | upper | Messinian | Sazanka | Sands, gravels, bands and lenses of pebbles, silts, clays, lenses of lignites, 120 m |
| | | | Tortonian | | |
| | | middle | Serravallian | Buzuli | Clays, silts, sands of different grain size, coals, coal clays, 120 m |
| | | | Langhian | | |
| | | lower | Burdigalian | | |
| | | | Aquitanian | | |
| PALEOGENE | Oligocene | upper | Chattian | Mukhinka | Clays, clayey silts, sands bands of brown coal, coaley clay, 100 m |
| | | lower-middle | Rupelian | | |
| | Eocene | upper | Priabonian | | |
| | | middle | Bartonian | | |
| | | | Lutetian | | |
| | | lower | Ypresian upper | Raichikha | Silts, clays, sands, lenses of brown coal, coal clay, 100 m |
| | | | lower | | |
| | Paleocene | upper | Thanetian | Kivda | Clays, silts, brown coal, coal clays, bands of sands, 70 m |
| | | lower | Selandian | | |
| | | | Danian | Tsagayan | Sands, consolidated gravels, pebbles, bands and lenses of silts, sandstone, silt, argillite, 100 m |
| CRETACEOUS | | upper | Maastrichtian | | |
| | | | Campanian | Zavitaya | Speckled clays, sands, sandstone, clays, silts, 500 m |
| | | | Santonian | | |
| | | | Coniacian | | |
| | | | Turonian | | |
| | | | Cenomanian | | |

Fig. 2. Stratigraphy of the Zeya–Bureya Basin. Coal-bearing formations of interest are shaded in grey. Vertical lines in formation column indicate missing sections.

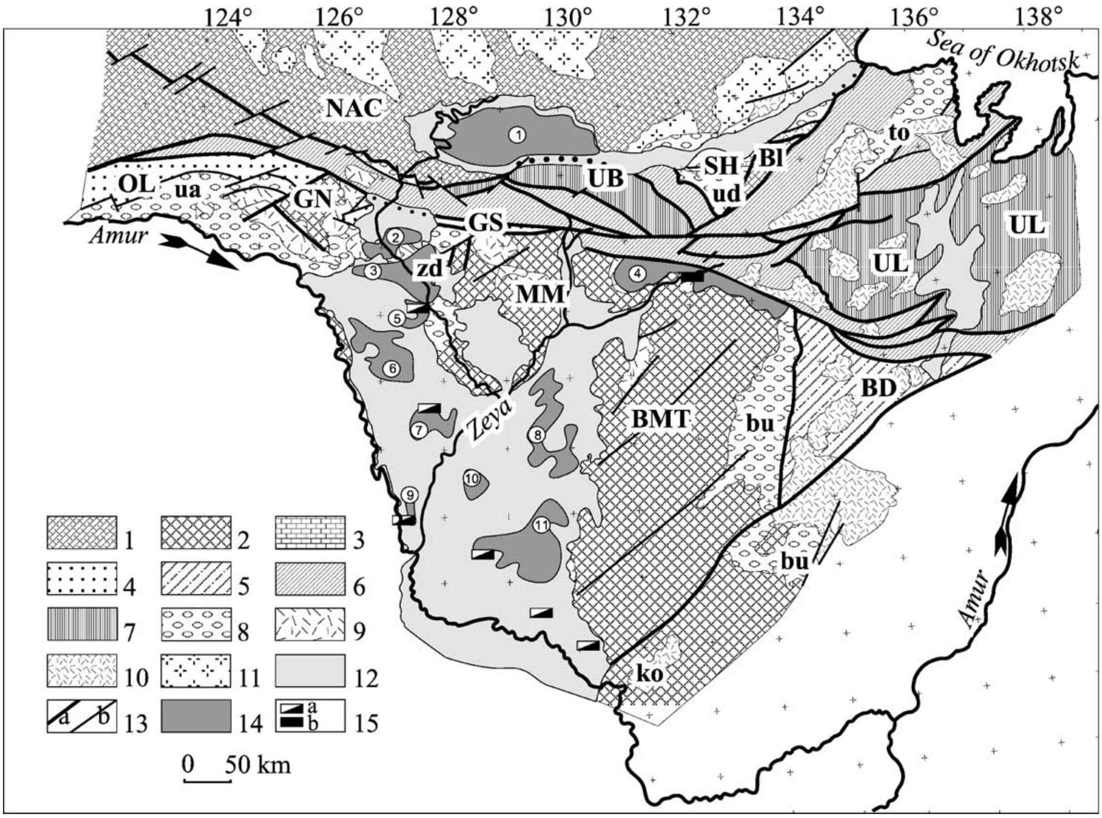


Fig. 3. Tectono-stratigraphic terrane and overlapping assemblages of the Amur Region (compiled by A.A. Sorokin and A.P. Sorokin). (1) Craton margin, craton terrane; (2) continental margin arc terrane; (3) Early–Middle Palaeozoic passive continental margin terranes; (4) Silurian–Devonian passive continental margin terranes; (5) Triassic–Middle Jurassic rock complexes (accretion wedge and subduction zone terranes); (6) Middle–Upper Paleozoic rock complexes (accretion wedge and subduction zone terranes); (7) Upper Triassic–Middle Jurassic residual turbidite basin terranes; (8) Mesozoic foreland basin, inter- and intramontane depression; (9) Upper Jurassic volcano-plutonic belt; 10. Early–Late Cretaceous volcano-plutonic belt; (11) Upper Jurassic–Early Cretaceous plutonic belt; (12) Cenozoic sedimentary rock units; (13) Faults (a—bounding terranes; b—major postcollision); (14) Coal fields; (15) Coal deposits (a—brown, b—hard). NAC = North Asian craton, terranes: BD = Badzhal, BL = Baladek, BM = Bureya, GN = Gonzha, MM = Mamyn, OL = Oldoy, UB = Un'ya-Bom, UL = Ul'ban. Overlapping sedimentary basins: bu = Bureya, to = Torom, ua = Upper Amur, ud = Uda, zd = Zeya-Dep. Circled numbers indicate the names of coal fields: (1) Upper Zeya; (2) Pikan; (3) Dep; (4) Gerbikan–Ogodzha; (5) Olga; (6) Sivaki–Ul'ma–Mukhinka–Bureya; (7) Klimoutsy–Semyonovka–Yukhta; (8) Selemdzha–Margaritovka–Tom; (9) Zagorniy–Sergeyevka; (10) Belogorsk; (11) Yerkovtsy–Romny–Zavitinsk.

(the Tarakon, Priamuriye, Zeya–Selemdzha, Yekaterinoslavka, Arkhara Depressions). These structures combined to form the Zeya–Bureya depression.

The late collision depressions are composed of the Lower Cretaceous, Upper Cretaceous and Cenozoic deposits with thickness up to 2000 m. Rift-like basins are distributed within the southern portion of the Amur microcontinent. The rift infill (up to 2500 m) is composed of the Upper Jurassic and Lower Cretaceous volcano-sedimentary deposits of the Yekaterinoslavka, Itikut, and Poyarkovo suites; and the plate infill (epiriftic) (1500 m) is composed of sedimentary rocks of the Zavitaya, Tsagayan, Kivda, Raichikha, Mukhinka, Buzuli, Sazanka, and Belogorsk suites. These complexes form various positive and negative structures within the plate which differ in morphology and types of tectonic movements, with depths of occurrence of basement rocks ranging from 3 to in excess of 4 km. They comprise systems of small troughs, primarily filled with sandy-argillaceous rocks and effusive layers at the base and on the rims of those structures.

The key structure of the Zeya–Bureya Basin is the Zeya–Selemdzha zone, which is limited by deep faults in the west and east, which confine the Zeya River valley. This structure consists of alternating NE-trending horsts and grabens. Troughs in the western portion of the zone (e.g., Lermontovka, Dmitrievka, Komissarovka, Koz'modem'yanovka, Belogorsk, Konstantinogradovka, Sapronovka Troughs) have a cover thickness exceeding 4 km and are considered to be the best prospects for liquid hydrocarbons. The Mikhailovka, Yekaterinoslavka, Romny, Arkhara and South Arkhara troughs are located in the eastern portion of the Zeya–Bureya basin, which comprises the Yekaterinoslavka and Arkhara zones (Lishnevsky, 1968; Sorokin, 1972).

The Lower Zeya basin is limited in the east by the Turan uplift and in the northwest by the Amur–Mamyn uplift. Behind the latter is located the Amur–Zeya (the Ushumun) depression, with a 1- to 4-km-thick cover of volcanic and sedimentary rocks, and with the same stratigraphic units as the Lower Zeya depression. In the north, the basin is limited by the Gonzha uplift and by the Upper Amur and Zeya-Dep depressions, which are composed of the Jurassic and Lower Cretaceous marine, coastal marine, and continental deposits formed within the Mongolian–Okhotsk region.

Table 1
Additional coal samples not described by Fig. 4

| Sample no. | Location | Notes |
|---|---|---|
| Z1A | Raichikhinsk Open Cut | Coalified wood from claystones of the Raichika Formation approx. 20 m above main seam |
| ZB32 | Cergeyevka | Medium—dark lithotype from top of seam in disused open cut mine |
| ZB34 | Cergeyevka | Xylite from near base of seam; sample stored for several years in air at Blagoveschensk |
| ZB35 | Cergeyevka | Medium—dark lithotype from near base of seam; sample stored for several years in air at Blagoveschensk |

## 3. Methods

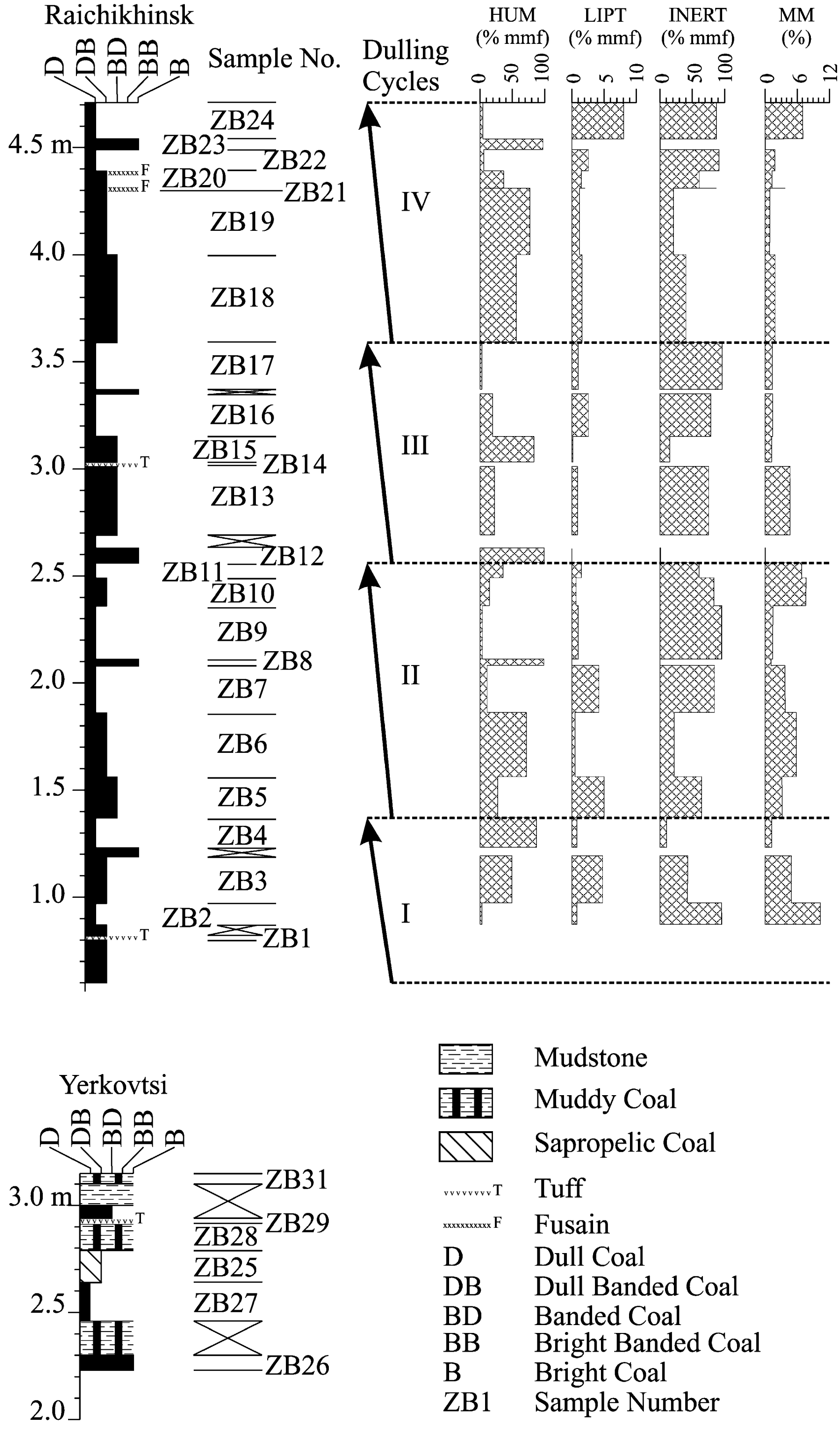
Coal samples were obtained from the deposits at Raichikhinsk, Yerkovtsi and Cergeyevka (Figs 1 and 4; Table 1). Where possible, lithotype profiles were made prior to sampling. Random blocks of coal 3–5 cm in length were collected from each lithotype section. Samples designated for rank determination (i.e., all bright coals, samples Z1A and ZB32) were wrapped in plastic film to minimise moisture loss. At Raichikhinsk, most of the seam profile was available for sampling (Fig. 4). An additional sample of coalified wood (sample Z1A) was collected from the Raichika Formation, approximately 20 m above the main seam. At Yerkovtsi, only the central portion of the seam was accessible (Fig. 4) but this was sampled in a similar manner to the Raichikhinsk seam. At Cergeyevka, only the top 60 cm was available from limited outcrop in an abandoned open-cut mine exposure (sample ZB32). Additional material from near the base of the seam (samples ZB34, ZB35) was obtained from The Russian Academy of Sciences, Far East Branch. These additional samples had been in open-air storage for several years and were not considered suitable for geochemical analysis.

In addition to the coals, three tuff horizons were identified (two at Raichikhinsk and one at Yerkovtsi) and sampled for petrographic and geochemical analysis.

Lithotype profiles were obtained for most of the seam thickness at Raichikhinsk and for the central part of the seam at Yerkovtsi. Despite being brown coals, the seams were sufficiently coalified that the colour profiles characteristic of soft brown coals (dark to pale) were no longer discernible and a brightness profile scheme (Standards Association of Australia, 1986) was adopted.

No lithotype profile was possible at the Cergeyevka deposit due to limited outcrop but samples were categorised according to brown coal (lignite)

Fig. 4. Measured coal lithotype profiles from open cut mines at Raichikhinsk and Cergeyevka. Lithotype sections from which coal samples were collected for petrographic and geochemical analyses are indicated by sample numbers ZB1 to ZB31. Four dulling up cycles identified at Raichikhinsk are indicated by arrows and Roman numerals I to IV. Coal macroscopically identified as sapropelic was later shown to be woody. Scale indicates estimated height above base of seam. HUM = Huminite; LIPT = Liptinite; INERT = Inertinite; MM = Mineral Matter.


Raichikhinsk
D DB BD BB B
Sample No.
Dulling Cycles
HUM (% mmf) 0 50 100
LIPT (% mmf) 0 5 10
INERT (% mmf) 0 50 100
MM (%) 0 6 12
4.5 m
4.0
3.5
3.0
2.5
2.0
1.5
1.0
F
F
T
T
ZB24
ZB23
ZB22
ZB20
ZB21
ZB19
ZB18
ZB17
ZB16
ZB15
ZB14
ZB13
ZB12
ZB11
ZB10
ZB9
ZB8
ZB7
ZB6
ZB5
ZB4
ZB3
ZB2
ZB1
IV
III
II
I
Yerkovtsi
D DB BD BB B
3.0 m
2.5
2.0
T
ZB31
ZB29
ZB28
ZB25
ZB27
ZB26
Mudstone
Muddy Coal
Sapropelic Coal
Tuff
Fusain
D Dull Coal
DB Dull Banded Coal
BD Banded Coal
BB Bright Banded Coal
B Bright Coal
ZB1 Sample Number

lithotype nomenclature (Standards Association of Australia, 1986), which uses the colour of the groundmass and smaller plant fragments.

Coal blocks approximately 3–5 cm long were cut, freeze dried to remove any moisture, and then mounted in polyester resin for polishing. Following polishing, the samples were point counted for maceral analysis, examined in blue-light fluorescence for liptinite characterisation and reflectance was determined of huminite (vitrinite) and inertinite.

Point counting was performed under oil immersion at 500× magnification, with a minimum of 500 points at a stage distance of 0.6 mm counted across the bedding. Brown coal terminology (ICCP, 1963, 1971) was adopted for coals on the basis of maceral texture, reflectance, and chemistry. However, with the exception of the Cergeyevka samples, strong affinities are noted with black coals for many of the macerals described.

Fluorescence examination of all samples used both blue light and UV excitation. The main purpose was evaluation of liptinite types present or any other notable fluorescence characteristics. Samples were not point-counted in this mode nor were quantitative fluorescence measurements made.

Mean random reflectance of humotelinite was determined for rank evaluation. Only the hand-picked bright coals for which geochemical parameters were also available were selected. Since rank evaluation was the primary objective, eu-ulminite was targeted specifically along with the co-existing, higher reflecting, huminitic cell-infillings, i.e. phlobaphinite. Samples with high inertinite contents, and for which geochemical analysis was available, were used for determining the range of reflectances of inertinite group macerals. Forty semifusinite and 40 fusinite grains were measured for random reflectance. It proved impossible to collect a statistically valid set of reflectance distributions because of the small size of most of the inertinites (either as inertodetrinite or thin-walled semifusinite and fusinite). Reflectance techniques followed standard procedures (Standards Association of Australia, 1981).

Selected samples, representing the range of lithotypes, have been characterised by proximate analysis. Proximate analysis was performed on as received coal by a commercial laboratory according to Australian Standard AS1038.3.

## 4. Lithotype analysis

### 4.1. Palaeocene coals at Raichikhinsk and Yerkovtsi

Macroscopic logging indicated the Palaeocene coals at Raichikhinsk and Yerkovtsi could be characterised using brightness profiles traditionally used for bituminous coals (Fig. 4). Dull lithotypes dominated, with large amounts of evenly distributed fusain and minor thin (1–2 mm) fusain bands. Despite having a bituminous coal appearance, the coals had a brown streak. The range of fusain through dull coal to bright coal shows progressive increase in huminite at the expense of inertinite; liptinite is minimal (Fig. 5). Numerous small, thin, laterally discontinuous fusain bands were observed at many horizons and at least two towards the top of the seam could be traced on a mine scale. In common with all coals, the fusain represents fossil charcoal which had a petrographic composition of mostly fusinite and semifusinite. Bright coal is petrographically composed of humotelinite and represents the remains of twigs, branches, stems, and other woody material.

Of most interest is the petrographic composition of the dull coals. Dull coals can be formed from a variety of materials, usually dominated by vitrinite (huminite), inertinite, mineral matter, or mixtures of these

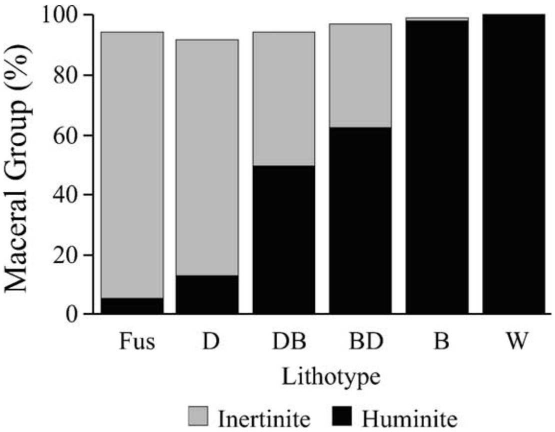


Fig. 5. Coal lithotypes at Raichikinsk and Yerkovtsy are controlled by maceral composition. Dull coals are dominated by inertinite group macerals and bright coals by huminite group macerals. Fus = fusain; D = dull; DB = dull banded; BD = banded; B = bright; W = wood tissue.

along with liptinite. The coal's dull appearance relates to the uneven fracture surface which is produced by the inhomogeneous nature of its components. These dull Palaeocene coals are dominated by inertinites with minor huminite, liptinite, and mineral matter (Fig. 5). Dull banded and banded lithotypes are mixtures of the bright and dull end members.

Four well-developed dulling-up trends were observed in the Raichikhinsk lithotype profile (Fig. 4). The lowermost section of the seam was not exposed, so the exact nature of dulling-up section I is uncertain. The other three sections show strong upwards trends from banded coals (BD), through dull banded (DB), and finally dull coal (D). Thick bright coal (B) bands do not necessarily define the base of the cycle and often occur within the dull coal sections, which is unusual compared to similar, inertinite-rich dulling-up sequences observed in Permian coals of Australia (Smythe, 1972). Each cycle is relatively uniform at about 1.0–1.5 m thick.

Dulling-up profiles are common in many coals (Dutcher, 1978; Crosdale, 1995) and are usually interpreted to represent progressively drier conditions of peat accumulation, but may also represent increasing wet conditions if accompanied by increasing amounts of mineral matter (Diessel, 1992). Each dulling-up cycle may be interpreted in terms of an individual peat unit, so the accumulation at Raichikhinsk probably represents the vertical stacking of four cycles of peat development.

The thickness of ca. 1.25 m of each cycle is not unusual. Modern peat thicknesses may, however, be up to 15 m for individual units; thicker peats are usually stacked individual bodies. Compaction ratios for peat to coal may be as large as 10:1, so that 1.5 m of coal could be derived from 15 m of peat. However, much smaller compaction ratios of as little as 1.2:1 have also been advocated (Nadon, 1998). The thicknesses of the cycles observed at Raichikhinsk are therefore reasonable for stacked peat deposits.

### 4.2. Miocene coal at Cergeyevka

The Cergeyevka samples were of medium-dark brown coal lithotypes and some xylite. Additionally, the coal at Cergeyevka was very soft and friable, similar to peat, supporting a significantly lower rank than that of the Palaeocene coals.

## 5. Maceral analysis

### 5.1. Palaeocene coals at Raichikhinsk and Yerkovtsi

Textures of the huminite (vitrinite) component of the Raichikhinsk and Yerkovtsi coals are intermediate between brown coals and black coals. Gelification is incomplete and woody tissues show well-preserved structure, including partly open cell lumina, porous cell infillings, and higher-reflecting cell infillings (Fig. 6C). However, groundmass material is well gelified, although still partly porous, such that its detrital nature is no longer clearly discernable (Fig. 6D).

The most prominent feature of the Palaeocene coals is the very large amounts of inertinite. Mean petrographic composition, weighted for lithotype thickness, of the seam at Raichikhinsk (Table 2) gives an inertinite composition of 55%. Inertinite is generally rare ( < 5%) in Tertiary and younger coals (Black, 1980; Moore et al., 1990; Moore and Ferm, 1992; Newman et al., 1997; Vasconcelos, 1999) and appears to be uncommon in most Russian coals (Lapo and Drozdova, 1989). Inertinite is generally uncommon in non-Permian coals (Vasconcelos, 1999; Scott, 2000). However, some Lower Cretaceous coals in Canada have comparable inertinite concentrations (Lamberson et al., 1991; Marchioni and Kalkreuth, 1991; Bustin and Dunlop, 1992; Langenberg et al., 1992).

Within the inertinite group, the structured varieties, semifusinite and fusinite (Fig. 6F) predominate (Table 2). However, inertodetrinite (Fig. 6E) is also very significant, comprising up to 59% (whole coal) of some samples. Similar concentrations of inertodetrinite are found in some Australian Permian coals, such as the Blair Athol Seam in the Bowen Basin (Cain, 1998), the Hoskissons Seam in the Gunnedah Basin (Tadros, 1993), and others (Diessel, 1982; Glasspool, 2000).

Yerkovtsi sample ZB25 was described in the field as being sapropelic. Petrographic examination revealed the coal to be eu-ulminite, i.e. coalified wood tissue. True sapropelic coals have either algae (alginite) or spores (sporinite) as their major component. Spanish Jurassic jet has a similar petrographic composition (Suárez-Ruiz et al., 1993) and macroscopic appearance to ZB25. However, Spanish Jurassic jet is strongly impregnated with bitumens, giving it suppressed reflectance and elevated fluorescence inten-

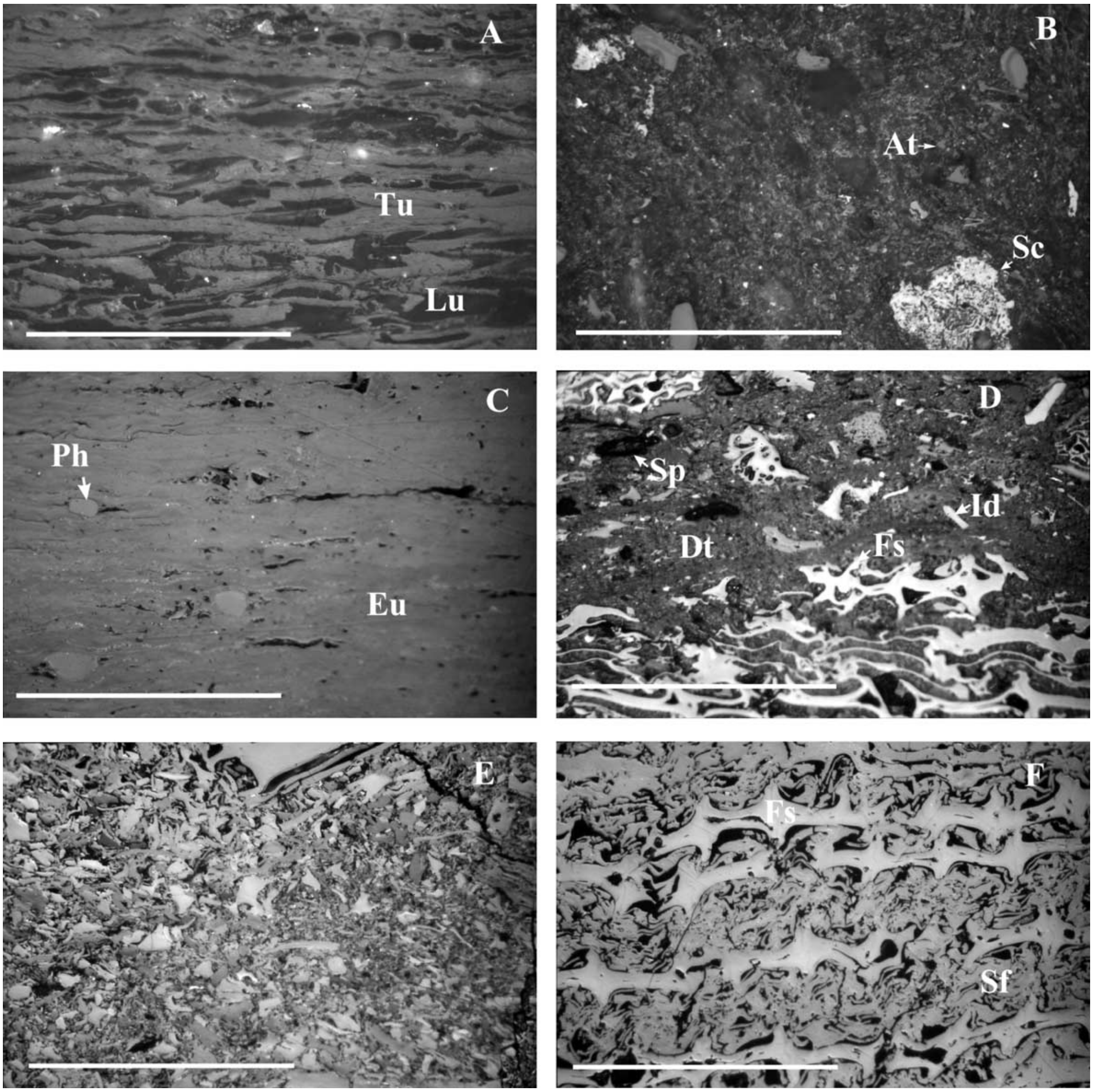


Fig. 6. (A) Texto-ulminite (Tu) showing partial swelling of cell walls with open, unfilled cell lumina (Lu). Cergeyevka (ZB34). Reflected light, oil immersion. Scale bar = 100 μm. (B)Attrinite (At) and funginite (Sc) in a mineral matter groundmass. Cergeyevka (ZB34). Reflected light, oil immersion. Scale bar = 100 μm. (C) Eu-ulminite (Eu) with remnant cell structure and partly open cell lumina with some phlobaphinite (Ph) infillings. Raichikhinsk (ZB11). Reflected light, oil immersion. Scale bar = 100 μm. (D) Fusinite (Fs), inertodetrinite (Id) and sporinite (Sp) in a groundmass of slightly porous detrogelinite (Dt). Raichikhinsk (ZB3). Reflected light, oil immersion. Scale bar = 100 μm. (E) Inertodetrinite. Raichikhinsk (ZB17). Reflected light, oil immersion. Scale bar = 100 μm. (F) Fusinite (Fs) and semifusinite (Sf). Raichikhinsk (ZB17). Reflected light, oil immersion. Scale bar = 100 μm.

sity, volatile matter, and hydrogen content (Suárez-Ruiz et al., 1993). Chemical and reflectance analyses of ZB25 do not indicate it to be bitumen impregnated and it is, therefore, not sapropelic.

### 5.2. Miocene coal at Cergeyevka

Microscopically observed textures of the Cergeyevka coals are typical of brown coals. The humin-

Table 2
Mean maceral composition of the seam at Raichikhinsk weighted for lithotype thickness

| Maceral group | Maceral sub-group | Maceral | Mean (%) | Range |
|---|---|---|---|---|
| Huminite | Humotelinite | Textinite | 0.0 | 0.0–0.0 |
| | | Texto-ulminite | 0.0 | 0.0–0.0 |
| | | Eu-ulminite | 24.2 | 94.1–1.5 |
| | Total Humotelinite | | 24.2 | 94.1–1.5 |
| | Humodetrinite | Attrinite | 1.0 | 2.6–0.0 |
| | | Densinite | 0.0 | 0.0–0.0 |
| | Total Humodetrinite | | 1.0 | 2.6–0.0 |
| | Humocollinite | Detrogelinite | 10.6 | 40.3–0.0 |
| | | Telogelinite | 0.0 | 0.0–0.0 |
| | | Eugelinite | 0.1 | 1.1–0.0 |
| | | Porigelinite | 2.2 | 13.3–0.0 |
| | | Phlobaphinite | 1.3 | 6.1–0.0 |
| | Total Humocollinite | | 14.1 | 41.6–1.7 |
| Total Huminite | | | 39.3 | 99.0–3.2 |
| Liptinite | | Sporinite | 1.3 | 4.3–0.0 |
| | | Cutinite | 0.1 | 0.6–0.0 |
| | | Resinite | 0.2 | 2.7–0.0 |
| | | Suberinite | 0.0 | 0.0–0.0 |
| | | Lamalginite | 0.3 | 5.9–0.0 |
| | | Telalginite | 0.0 | 0.0–0.0 |
| | | Liptodetrinite | 0.2 | 0.7–0.0 |
| Total Liptinite | | | 2.0 | 7.5–0.0 |
| Inertinite | | Semifusinite | 23.7 | 44.4–0.0 |
| | | Fusinite | 11.8 | 28.2–0.0 |
| | | Micrinite | 0.2 | 2.1–0.0 |
| | | Macrinite | 1.3 | 5.3–0.0 |
| | | Inertodetrinite | 18.4 | 58.6–0.0 |
| Total Inertinite | | | 55.4 | 89.8–0.6 |
| Mineral matter | | | 3.3 | 7.1–0.0 |

ite (vitrinite) component of woody material shows only partly swollen cell walls, with the cells usually open and unfilled (Fig. 6A). The huminitic groundmass is characterised by discrete attrital particles and shows little evidence of gelification (Fig. 6B). In non-woody samples (ZB32 and ZB35) difficulties were encountered in discriminating some attrinite from the mineral matter groundmass. Rare fungal bodies (funginite), typical of Tertiary and younger coals, were found (Fig. 6B). Fluorescence observations also indicated a scarcity of liptinites, with only a few spores being observed.

## 6. Reflectance analysis

### 6.1. Palaeocene coals at Raichikhinsk and Yerkovtsi

Twenty eu-ulminite readings were made by traversing the polished blocks across bedding at a 1 mm spacing. In the case of phlobaphinite, all suitable areas falling in the field of view during the traverse were measured. No difference was found in the mean random eu-ulminite reflectance between the coals at Raichikhinsk and Yerkovtsi (Table 3). Interpretation of the eu-ulminite reflectances is treated fully in the discussion of coal rank. Mean phlobaphenite reflectance was 0.03–0.10% higher than its associated eu-ulminite, but significant overlap occurs in their ranges (Table 3; Fig. 7). Phlobaphinite is, by definition, more highly reflecting than the associated huminite. Statistical analysis using the $\chi^2$ goodness-of-fit test at the 95% probability level indicates that eu-ulminite and phlobaphinite reflectances follow a normal distribution.

Forty semifusinite and 40 fusinite reflectance measurements were taken in the inertinite-rich coals from Raichikhinsk. A regular grid of 1 mm spacing was used. However, much of the inertinite was too fine grained to measure (inertodetrinite) or the cell walls too thin. The inertinite reflectances therefore give a reasonable indication of the range of values present but are not necessarily indicative of the true distribution of the reflectances. The semifusinite and

Table 3
Mean random reflectance of selected macerals

| Sample | Maceral | Mean | $n$ | $\sigma$ | Max | Min |
|---|---|---|---|---|---|---|
| ZB1A | Eu-ulminite | 0.26 | 20 | 0.011 | 0.27 | 0.23 |
| | Phlobaphinite | 0.34 | 20 | 0.017 | 0.36 | 0.29 |
| ZB8 | Eu-ulminite | 0.25 | 20 | 0.009 | 0.27 | 0.23 |
| | Phlobaphinite | 0.35 | 10 | 0.017 | 0.37 | 0.32 |
| ZB9 | Semifusinite | 0.88 | 40 | 0.184 | 1.23 | 0.48 |
| | Fusinite | 1.35 | 40 | 0.172 | 1.70 | 1.11 |
| ZB12 | Eu-ulminite | 0.29 | 20 | 0.010 | 0.31 | 0.28 |
| | Phlobaphinite | 0.32 | 20 | 0.017 | 0.35 | 0.29 |
| ZB16 | Semifusinite | 0.79 | 40 | 0.122 | 1.19 | 0.40 |
| | Fusinite | 1.27 | 40 | 0.185 | 1.81 | 1.00 |
| ZB25 | Eu-ulminite | 0.26 | 20 | 0.013 | 0.28 | 0.23 |
| | Phlobaphinite | 0.30 | 20 | 0.020 | 0.34 | 0.26 |
| ZB34 | Texto-ulminite | 0.14 | 20 | 0.011 | 0.16 | 0.12 |
| | Phlobaphinite | 0.26 | 5 | 0.007 | 0.27 | 0.25 |

Semifusinite and fusinite may not be representative of true distributions of the very large amounts of material too small to measure.

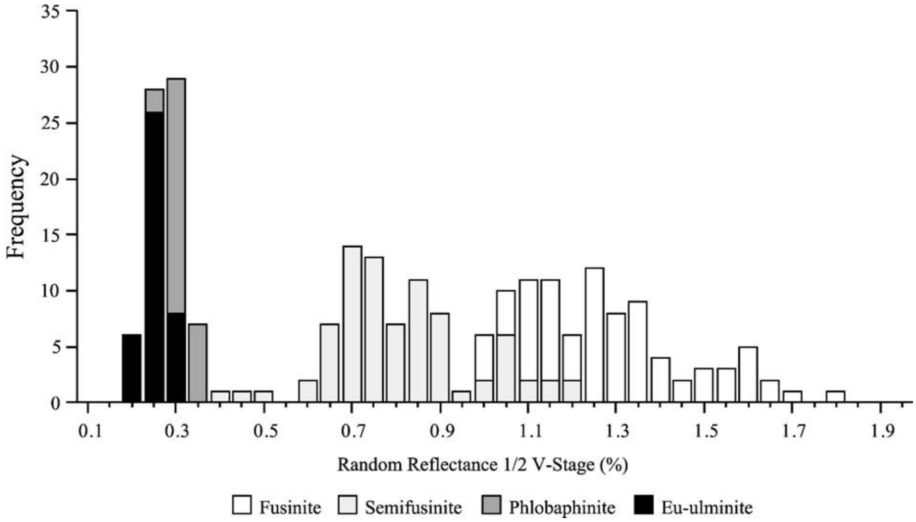


Fig. 7. All reflectance measurements for samples ZB8, ZB9, ZB12 and ZB16 from the seam at Raichikhinsk. Note the marked separation between huminite and inertinite and significant overlap within maceral groups. Data is grouped in 1/2 V-stages (e.g., 1.02 is the mid-point of the group 1.00 – 1.04%) and are not statistically representative of maceral proportions i.e. the frequency distribution does not represent a whole coal (or sample) reflectogram.

fusinite reflectance ranges overlap substantially (Table 3; Fig. 7). Optical discrimination between semifusinite and fusinite is somewhat subjective and relies on the higher reflectance of the fusinite and its more ‘brassy’ or shiny metallic appearance. Semifusinite and fusinite reflectances do not follow normal distributions as indicated by the $\chi^2$ goodness-of-fit test. Despite the low frequencies of the high reflectance values, both the semifusinite and fusinite distributions are clearly polymodal (Fig. 7).

A large gap is apparent in the reflectance distribution of huminites and inertinites (Fig. 7), which may be an artefact of data collection but it is more likely to represent a true effect. In coals of higher rank, a clear distinction is often observed between the reflectance distributions of vitrinites (huminites) and inertinites, with only limited overlap. The discrimination in distributions becomes less pronounced as rank increases, probably because the physical and chemical properties of the vitrinites change more rapidly than the inertinites. At high ranks, the vitrinites closely resemble the inertinites in many physical and chemical aspects, including reflectance, but they remain texturally distinctive. The reflectance gap may be significant in evaluating mechanisms of inertinite formation. Previously proposed mechanisms have included processes such as mouldering, bacterial and fungal attack, subaerial oxidation, as well as being related to primary plant structures (Taylor et al., 1998). The reflectance gap appears to indicate that the mechanism of inertinite formation is discrete and unrelated to vitrinite formation. Processes which may permit gradual variation in maceral properties are largely excluded; such processes may include mouldering, bacterial, and fungal attack. Instead, a mechanism is preferred in which inertinites acquire a discrete and separate set of physical and chemical properties from vitrinites with little transitional material. Such a process may be burning or charring of the peat.

The polymodal inertinite reflectance distributions observed (Fig. 7) may be attributed to formation by charring at different temperatures (Glasspool, 2000). However, different plant species also give different char reflectances for the same temperature (Scott, 2000). The complex distribution of inertinite reflectances therefore relates to both temperature of charring and the plant species involved.

### 6.2. Miocene coal at Cergeyevka

The sample collected from outcrop had no material suitable for rank determination by reflectance. A xylite sample was analysed from additional material collected at the Amur Research Centre. This sample had been in open-air storage for several years and was well oxidised. It is generally believed that this type of oxidation does not significantly affect reflectance readings (Chandra, 1958). Xylite was selected as this is woody material which, on further coalification, becomes bright coal (as used for the Palaeocene samples) and its maceral composition of texto-ulminite is the maceral precursor of eu-ulminite (as used for the Palaeocene coals). Mean random texto-ulminite reflectance at Cergeyevka of 0.14% is significantly lower than the 0.26% recorded for the Palaeocene coals and indicates a lower rank at Cergeyevka.

## 7. Coal geochemistry

### 7.1. Palaeocene coals at Raichikhinsk and Yerkovtsi

The wide range of coal chemistries (Table 4) represent substantial coal type variation for the Palaeocene samples and rank difference between the Palaeocene and Miocene coals.

Volatile matter (VM, daf) content is strongly influenced by the maceral composition (Fig. 8). Decreasing volatile matter in the isorank Raichikhinsk coals is related to increasing inertinite content. This trend is also commonly observed in Permian Gondwana coals. A very strong trend is observed for huminite contents of less than 60% (Fig. 8) which does not extrapolate to the pure vitrain samples. Huminite in most of these samples is dominated by detrogelinite which, in comparison to humotelinites, can be expected to have an elevated volatile matter content on account of its higher hydrogen content.

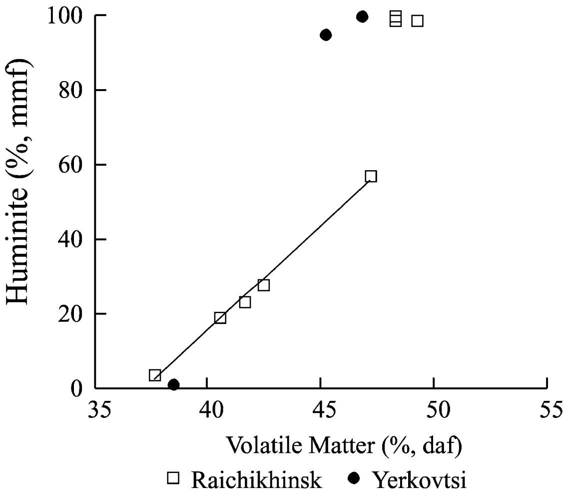


Fig. 8. Coal type, as expressed by maceral composition, strongly controls the volatile matter content (daf) of the coals at Raichikhinsk and Yerkovtsy. At Raichikhinsk, for huminite contents of less than 60%, $y = 5.6x - 208$; $n = 5$; $r^2 = 0.996$.

Table 4
Proximate analyses of selected samples

| Locality | Sample no | Lithotype | Inherent moisture (%) | Ash (%) | Volatile matter (%) | Fixed carbon (%) | Inherent moisture (%, af) | Volatile matter (%, daf) |
|---|---|---|---|---|---|---|---|---|
| Raichikhinsk | ZB1A | B | 32.2 | 1.3 | 32.1 | 34.4 | 32.6 | 48.3 |
| | ZB5 | BD | 36.0 | 5.1 | 25.0 | 33.9 | 37.9 | 42.4 |
| | ZB8 | B | 40.7 | 1.3 | 28.0 | 30.0 | 41.2 | 48.3 |
| | ZB9 | D | 35.8 | 5.0 | 22.3 | 36.9 | 37.7 | 37.7 |
| | ZB12 | B | 37.8 | 2.7 | 29.3 | 30.2 | 38.8 | 49.2 |
| | ZB13 | BD | 35.0 | 8.1 | 23.7 | 33.2 | 38.1 | 41.7 |
| | ZB16 | D | 34.2 | 7.1 | 23.8 | 34.9 | 36.8 | 40.5 |
| | ZB18 | BD | 38.6 | 4.8 | 26.7 | 29.9 | 40.5 | 47.2 |
| Yerkovtsi | ZB25 | Sap | 37.3 | 2.2 | 28.3 | 32.2 | 38.1 | 46.8 |
| | ZB26 | B | 39.1 | 2.9 | 26.2 | 31.8 | 40.3 | 45.2 |
| | ZB27 | D | 35.2 | 7.6 | 22.0 | 35.2 | 38.1 | 38.5 |
| Cergeyevka | ZB32 | MDk | 58.0 | 22.6 | 15.8 | 3.6 | 74.9 | 81.4 |

B = bright; BD = banded; D = dull; Sap = Sapropelic; Mdk = medium-dark.

### 7.2. Miocene coal at Cergeyevka

It should be noted that the Cergeyevka sample has an ash content (db) of 53.8% and is technically not coal (Table 4). The high ash content makes interpretation of results difficult, even after applying an ash to mineral matter conversion factor. Ultimate analysis results (Crosdale and Woolfe, 1998) suggest the Cergeyevka sample has type II kerogen, indicating strong algal affinities. However, alginite and other liptinites were rare ( < 5%) during petrographic examination in fluorescence mode. Bituminite has high H/C ratio, may be non-fluorescent at low rank (bituminite type III) and is optically similar to mineral matter in reflected, plane polarised light (ICCP, 1993).

## 8. Tuffs

Two thin (3–5 cm) tuffs were noted at Raichikhinsk and one at Yerkovtsi (Fig. 4). The tuffs appeared to be laterally continuous and could be traced on a mine scale. Tuff bands are often have wide areal distributions and are of great importance in regional seam correlation (Michaelsen et al., 2001; Burger et al., 2002). However, insufficient detail is known in this case to draw firm conclusions on the problems of regional seam correlation. Of the two tuffs noted at Raichikhinsk, one was towards the base of the seam and the other in the middle. The tuff at Yerkovtsi was around the middle of the seam. It is possible that the middle tuff at Raichikhinsk correlates to the middle tuff at Yerkovtsi on the basis of

Table 5
Semiquantitative XRF major and trace element geochemistry of tuff samples

| Element | Unit | Sample | | | Element | Unit | Sample | | |
|---|---|---|---|---|---|---|---|---|---|
| | | ZB 1 | ZB 14 | ZB 29 | | | ZB 1 | ZB 14 | ZB 29 |
| F | % | 3.43 | b.d. | 4.00 | Pt[a] | ppm | 1038[a] | 97[a] | 927[a] |
| $Na_2O$ | % | 0.95 | b.d. | b.d. | Ru | ppm | 657 | b.d. | b.d. |
| Na | % | – | 0.37 | – | Cd | ppm | 1009 | b.d. | b.d. |
| MgO | % | 0.64 | 0.53 | b.d. | Te | ppm | 715 | b.d. | b.d. |
| $Al_2O_3$ | % | 27.44 | 39.41 | 33.91 | BaO | % | 0.24 | – | b.d. |
| $SiO_2$ | % | 56.56 | 50.81 | 57.30 | Ba | ppm | – | 1016 | b.d. |
| P | ppm | b.d. | 245 | 479 | $Sm_2O_3$ | % | 0.15 | b.d. | b.d. |
| S | ppm | 152 | 201 | 169 | Lu | ppm | 949 | b.d. | b.d. |
| Cl | ppm | 373 | 63 | b.d. | Ta | ppm | 610 | 108 | b.d. |
| K2O | % | 1.03 | 1.4 | 0.31 | Au[a] | % | 0.51[a] | 0.05[a] | 0.52[a] |
| CaO | % | 2.97 | 2.25 | 0.73 | Pb | ppm | 795 | 200 | 450 |
| $TiO_2$ | % | 1.4 | 0.88 | 0.72 | Mn | ppm | b.d. | 802 | b.d. |
| $Fe_2O_3$ | % | 3.76 | 2.81 | 1.33 | Co | ppm | b.d. | 94 | b.d. |
| Cu | ppm | 503 | 9535 | 473 | Ni | ppm | b.d. | 93 | b.d. |
| Zn | ppm | 256 | 186 | b.d. | As | ppm | b.d. | 87 | b.d. |
| Ga | ppm | 282 | 90 | 235 | Rb | ppm | b.d. | 34 | b.d. |
| Ge | ppm | 191 | b.d. | 190 | Y | ppm | b.d. | 18 | b.d. |
| Sr | ppm | 434 | 175 | b.d. | La | ppm | b.d. | 236 | b.d. |
| Zr | ppm | 829 | 196 | 295 | Yb | ppm | b.d. | 141 | b.d. |
| Nb | ppm | 297 | b.d. | 280 | W | ppm | b.d. | 493 | b.d. |
| Pd | % | b.d. | b.d. | 0.42 | Re | ppm | b.d. | 125 | b.d. |
| In | ppm | b.d. | 138 | 417 | Bi | ppm | b.d. | 70 | b.d. |
| $CeO_2$ | % | b.d. | b.d. | 0.18 | Th | ppm | b.d. | 83 | b.d. |
| Ce | ppm | | 345 | – | U | ppm | b.d. | 41 | b.d. |
| $Tb_2O_3$ | % | b.d. | b.d. | 0.20 | | | | | |
| | | | | | Sum of concentrations (%) | | 100 | 100 | 100 |
| | | | | | LOI (%) | | 66.12 | 61.00 | 31.23 |

b.d. = below detection.

[a] Pt and Au values relate to contamination by the sample holder.

position within the seam. This correlation is supported by the immobile elements Ti and Zr (Table 5). However, the rare earth elements, which are also considered to be immobile, suggest the bottom tuff at Raichikhinsk (ZB1) might correlate to the tuff at Yerkovtsi (ZB29). Implications of tuff correlation for interpretation of the depositional environment are discussed later.

Tuffs from Raichikhinsk and Yekovtsy were characterised by semiquantitative XRF analysis (Table 5) and investigated in thin section. XRF results are considered to be indicative only and significant problems were encountered during the analysis. Of particular note are the very large loss-on-ignition (LOI) values, which relate to the presence of organic matter and water.

In thin section, all samples appeared similar. They were characterised by a graupen texture of ellipsoidal, microcrystalline (?)kaolinite (50%) with a maximum dimension of 2 mm within an organic-rich matrix (50%), which includes probable plant roots. Small amounts ( < 1%) of 10- to 50-μm diameter, angular quartz were also present. No primary volcanic textures (e.g., pumice fragments, shard fragments) were observed.

Suggested origins of graupen textures include growth as authigenic aggregates or replacement of a primary texture, such as pumice. Many graupen are considered to have been pumice lumps which have been filled with authigenic kaolinite by a process of concurrent glass solution and clay precipitation (Bohor and Triplehorn, 1993).

The type of source magma of these tonsteins is difficult to determine as most of the major and trace elements will be mobile during alteration and diagenesis (Bohor and Triplehorn, 1993). However, $TiO_2/Al_2O_3$ ratios of 0.02 to 0.05 in these samples suggest an acid igneous source (Spears and Kanaris-Sotiriou, 1979), which is supported by the presence of trace amounts of quartz visible in thin section.

## 9. Coal rank

In evaluating coal rank, a number of parameters are usually used (e.g., moisture content, volatile matter, carbon, vitrinite reflectance) as some are more sensitive than others depending on rank and type. To minimise variations related to coal type, rank is usually evaluated on the bright (vitrain) component.

### *9.1. Palaeocene coals at Raichikhinsk and Yerkovtsi*

Strong influences of coal type on geochemistry have already been noted for the coals from Raichikhinsk and Yerkovtsi. It is therefore important that only the bright (vitrain) samples be used in rank evaluation. The macroscopic appearance of the coals was similar to bituminous coal but they had a brown streak. Microscopic textures are intermediate between brown and black coals but have greater similarities with black coals.

Volatile matter (daf) of the two vitrain samples at Raichikhinsk was 48.3% and 49.2%, which is equivalent to subbituminous B (ASTM) (Russian B3). At Yerkovtsi, VM (daf) of 45.2% and 46.8% implies a slightly higher rank, equivalent to high volatile A bituminous (ASTM) (Russian D). However, carbon contents of around 64% at both locations indicate no rank difference and suggest the coals are lignite B (ASTM) (Russian B1), a much lower rank than given by the volatile matter. Moisture contents between 38% and 41% also do not indicate substantial rank differences and suggest a lignite coal rank. However, moisture content may not be a good indicator since exposure of the coals may have led to some weathering and elevated moisture contents can be expected for oxidised coals. Humotelinite reflectance is the same at both deposits, at 0.26%, and indicates a lignite rank. However, reflectance is relatively insensitive to small changes in thermal maturation at low ranks. Specific energy of 14.4 MJ/kg (moist) at Yerkovtsi also supports a low lignite rank.

Sample ZB1A, from about 20 m above the main seam at Raichikhinsk, has rank parameters consistent with those of the main seam.

No significant rank difference is interpreted between the deposits at Yerkovtsi and Raichikhinsk. A rank of lignite (ASTM) (soft brown coal (DIN), B1 (Russian)) is supported by carbon and moisture contents, specific energy and humotelinite reflectance. However, macroscopic appearance, microscopic textures, and volatile matter contents suggest a higher rank of subbituminous B (ASTM) (Bright brown coal (DIN), B3 (Russian)). The coal at Yerkovtsi is classified as Russian B2.

### *9.2. Miocene coal at Cergeyevka*

All parameters indicate the coal from Cergeyevka is distinctive and of the lowest rank. Coal lithotypes and microscopic texture are consistent with soft brown coal. In the case of the xylite sample (ZB34), the presence of swelling of cell walls and a lack of significant internal reflections indicate the coals have exceeded the rank of peat. Volatile matter (daf) (81.4%) is significantly higher than that expected for peat and but is probably related to the high hydrogen content of the sample (Crosdale and Woolfe, 1998). An ash-free moisture content (74.9%) is borderline with peat, but the sample location has been subaerially exposed for some time, increasing the potential effects of oxidation and surface run-off, both of which will have elevated the moisture content. A significant amount of moisture may also be derived form the large mineral matter (ash content = 53.8% db) component of the sample. The carbon content (66.4%) is consistent with a brown coal rank. On the basis of maceral textures and carbon content, the Cergeyevka deposit is considered to be brown coal (Australian Standards); soft brown coal (DIN); lignite (ASTM); B1 (Russian).

There is an appreciable difference in coal rank determined chemically between Cergeyevka and Raichikhinsk/Yerkovtsi, especially given that the deposits are a maximum of 200 m apart vertically. Petrographic textures also indicate significant rank differences occur between these deposits. A significant break in the depositional history of the basin is inferred.

Despite the uncertainty in the interpretation of coal rank parameters, it is clear that even the most thermally altered coals of the Palaeocene in these areas are too immature to have generated petroleum.

## 10. Depth of burial

In estimating burial depth, it is important to have an accurate understanding of the regional geological history. Good control is required on periods of subsidence versus uplift and erosion as well as control on geothermal and palaeogeothermal gradients. In the absence of deep boreholes, estimation of temperature gradients is difficult. Palaeogeothermal gradient estimates can be made based on crustal structure and basin infill or be related to the basin type, e.g. rift basin, back arc basin, intracratonic basin, etc. Despite an absence of detailed data for any of these basin history criteria, we have nevertheless attempted to constrain burial depth.

### *10.1. Palaeocene coals at Raichikhinsk and Yerkovtsi*

Vitrinite reflectance and volatile matter can be used to estimate burial depths of higher rank coals. Accurate knowledge of burial history is required as duration of heating is a critical parameter (Bostick, 1973). In the absence of basin history details and geothermal gradients, a number of different scenarios are considered in order to constrain the maximum and minimum burial depths for the Palaeocene coals (Table 6). The method of Bostick (1973) has been used and his graphs extrapolated to include the higher volatile matter content of these coals. Three scenarios of geothermal gradient are considered: low at < 20 °C/km; average at 25 °C/km and high at > 40 °C/km (Robert, 1988). It is likely that geothermal gradients may be higher than average as the underlying, conformable Cretaceous sequence is associated with extension and graben formation (Krassilov, 1992) and the presence of tuffs within the Palaeocene coals indicates contemporaneous volcanic activity.

Volatile matter content (daf) of vitrain may be used for estimating burial depth (Bostick, 1973). However, VM in this case gives a higher rank than other parameters (see discussion above) and its use may lead to an overestimation of maximum burial temperatures. It is probable that maximum temperatures are lower than those tabulated (Table 6) and limits of burial will need to be reduced.

Using the method of Bostick (1973), burial depth of the Palaeocene coals is between 600 and 2400 m at Raichikhinsk and slightly deeper at Yerkovsti (Table 6). The Raichikhinsk data is more robust as the volatile matter content is based on more samples. Some of the modelled maximum burial depths exceed 3 km and would generally be considered too high, especially when considered in conjunction with the moisture content, implying that the maximum geothermal gradient did not reach 50 °C/km. Such high geothermal gradients are generally associated with extensional regimes and it follows that

Table 6
Estimated range of burial depths for the Palaeocene coals given different burial histories and palaeogeothermal gradients using the method of Bostick (1973)

| Burial history | Effective heating time (Ma) | Geothermal gradient (°C/km) | | Raichikhinsk (48 % VM) | | | Yerkovtsi (45% VM) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Max | Min | Estimated maximum temperature (°C) | Burial depth (km) | | Estimated maximum temperature (°C) | Burial depth (km) | |
| | | | | | Max | Min | | Max | Min |
| 1. Continued, slow subsidence from earliest Palaeocene with sudden uplift in late Quaternary; coal formation in earliest Palaeocene | 65 | 50 | 20 | 28 | 1.4 | 0.6 | 52 | 2.6 | 1.0 |
| 2. As item (1) but with coal formation in latest Palaeocene | 55 | 50 | 20 | 30 | 1.5 | 0.6 | 57 | 2.9 | 1.1 |
| 3. Subsidence during Palaeogene with uplift and erosion in earliest Neogene prior to deposition of Cergeyevka deposit; only minor Neogene to Quaternary subsidence; coal formation in earliest Palaeocene | 40 | 50 | 20 | 40 | 2.0 | 0.8 | 65 | 3.3 | 1.3 |
| 4. As item (3) but with coal formation in latest Palaeocene | 30 | 50 | 20 | 48 | 2.4 | 1.0 | 73 | 3.7 | 1.5 |

Volatile matter content of 48% has been used to estimate maximum temperatures (N.B. see rank discussion). Vitrinite reflectance values of 0.27% are beyond the range of the technique.

significant crustal extension did not play an important role in Palaeogene and younger basin development.

Using the moisture/depth of burial relationship of Suggate and Isaac (1990) a depth of ca. 1 km can be inferred for the coals at Raichikhinsk.

Sample ZB1A, from about 20 m above the main seam at Raichikhinsk in the Raichika Formation, has rank parameters similar to those of the main seam and no significant break in deposition is indicated between the Palaeocene Kivda Formation and the Eocene Raichika Formation.

The present-day sections are about 200 m thick for the Palaeogene and about 200 m thick for the Neogene + Quaternary. As it is unlikely the maximum burial depth of the Cergeyevka coal exceeded 200 m (see below), there was uplift and erosion of about 800 m of the Palaeogene sequence prior to deposition of the early Miocene Cergeyevka deposits.

Comparison with the Cretaceous coals of the Zeya–Bureya Basin would prove extremely interesting. Confined within NE–SW trending grabens are 500–800 m of Hauterivian to lower Albian sequences containing about 20 coal seams (Krassilov, 1992). The rank of these is described as brown to "transitional" (Krassilov, 1992), similar to the seams at Raichikhinsk and Yerkovtsi.

### *10.2. Miocene coal at Cergeyevka*

Moisture contents of lignites have been used to estimate burial depth in the range of up to 800 m (at 42% bed moisture) (Teichmüller, 1968; Suggate and Isaac, 1990). Using New Zealand data (Suggate and Isaac, 1990), the Cergeyevka coal with 75% bed moisture (ash-free) would have had a burial of 50 m. Macedonian peat data (Teichmüller, 1968) suggests much deeper burial of 125 m. The deposit is presently at around 125 m depth and, therefore, may be close to its maximum burial. These values would represent minimum estimates as the bed moisture content has probably been elevated, as noted previously, by either weathering processes or by contributions from mineral matter.

## 11. Depositional environment

### 11.1. Palaeocene coals at Raichikhinsk and Yerkovtsi

Palaeoenvironmental interpretation of the Palaeocene coals needs to take into account the development of dulling-up cycles (Fig. 4), the presence of large amounts of inertinite and the generally low mineral matter content (Fig. 4, Table 2). Maceral indicators (Diessel, 1982, 1992) have not been used as their interpretation is open to question (Crosdale, 1993; Wüst et al., 2001), especially for Tertiary coals.

Vertical profile trends of coal lithotypes generally show dulling-up sequences, which may be interpreted in terms of either a progressive drying of the mire (when accompanied by increasing inertinite content) or a progressive drowning of the mire (when accompanied by increased mineral matter content) (Crosdale, 1995). The vertical profile developed at Raichikhinsk showed four well-developed dulling-up cycles (Fig. 4), interspersed with occasional thick bright bands, especially in the duller portions. Insufficient data is available to speculate on the origin of the cyclicity (e.g., climate-driven, tectonic-driven), but it does not appear to directly relate to sea-level changes (e.g., Diessel, 1992; Holdgate et al., 1995) as the low sulphur content of the coal and the geologic setting suggest no marine influences.

Dulling-up trends identified at Raichikhinsk are broadly parallelled by decreasing huminite and increasing inertinite and might be interpreted in terms of progressively drier mire conditions for each cycle. However, in detail, the final stage of cycles show a decrease in inertinite and an increase in huminite which is sometimes accompanied by an increase in mineral matter. This final stage represents a return to wetter conditions and precedes a generally brighter coal section. This brighter coal might be attributed to an increase in nutrient supply associated with clastic inputs and the growth of larger plants. At Yerkovtsi, too small an interval of coal lithotypes was logged to permit inference of vertical profile trends.

Mineral matter contents at Raichikhinsk are generally low (less than 10 vol.%), with no partings, suggesting that flooding of the mire was infrequent and small in magnitude. Mineral matter contents increase towards the top of dulling-up cycles II and IV and are accompanied by thick bands of bright coal. These bright bands are related to larger vegetation (trees) which could be supported by the increased nutrient supply. However, the section observed at Yerkovsti was dominated by a mineral-rich parting which occurs around the middle of the seam and could be traced at a mine scale. The Yerkovtsi section was clearly more strongly influenced by larger scale flooding events, probably overbank flooding, than that at Raichikhinsk and was therefore closer to the mire margin. A low-lying, and not raised, mire type would be inferred. Some differences in petrographic composition may be expected at Yerkovtsi since peat normally shows progressive changes in plant communities as hydrologic conditions change during accumulation (Gore, 1983).

Tuffs are usually taken to represent single volcanic events and are commonly used in coal measure sequences to assist in seam correlation (Diessel, 1992; Bohor and Triplehorn, 1993). In coal-forming environments, individual tuff horizons may exhibit a highly variable geochemistry, but may still prove valuable in regional correlation, especially if they have distinctive geophysical signatures (Michaelsen et al., 2001). Further detailed geochemical work on the tuffs described from Raichikhinsk and Yerkovtsi (Fig. 4, Table 5) should provide a basis for widespread correlation of the Palaeocene coals and their detailed palaeoenvironmental reconstruction. For example, if the uppermost tuff at Raichikhinsk correlates with the tuff observed at Yerkovsti (based on stratigraphic position and similar concentrations of the immobile elements Ti and Zr), the mire environment at Yerkovsti was subject to relatively more inundation by river flood waters at this time as indicated by the seam splitting and muddy coal bands (Fig. 4). The mechanism for this may be increased subsidence, river migration or some other factor affecting plant growth (e.g., extensive burning of the peat) in the region of Yerkovsti. Alternatively, correlation of the basal tuff at Raichikhinsk with the tuff at Yerkovtsi (on the basis of similar concentrations of the some of the immobile rare earth elements) would indicate later commencement of the mire at Raichikhinsk.

Critical in the palaeoenvironmental interpretation is the understanding of the origin of the large inertinite component. The origin of inertinite is unresolved and four types have been recognised based on different origins viz. pyrofusinite, degradofusinite, rank fusinite, and primary fusinite (Taylor et al., 1998). Inertinite is used as a primary indicator of drier peat-forming environments when applying the coal facies diagram of Diessel (Diessel, 1982; Kalkreuth et al., 1991). However, these interpretations have been questioned (Crosdale, 1993; Wüst et al., 2001) as much inertinite may represent burning of the peat and vegetation (Glasspool, 2000; Scott, 2000) and not be related to primary plant communities or primary accumulation conditions. These facies diagrams were also developed for Permian rather than Tertiary coals.

Inertinite origins in Permian coals have been related to cold climate desiccation processes (Taylor et al., 1989), where TEM observations have revealed the presence of associated algae, suggesting periodic drying out of the peat. Similar associations have been observed in the Triassic Callide Coal Measures of Queensland (Lawson, 1997), but a fire-splay origin was deduced on regional geological grounds and the additional presence of mineral matter. Fluorescence observations did not reveal the presence of algae in the Zeya–Bureya Basin coals, but, TEM observations were not made and the process suggested by Taylor et al. (1989) cannot be precluded.

The wide range of reflectances found in the inertinites are consistent with a fire origin. Charring experiments of modern wood show mean reflectance of the char ranges from 0.49% at 340 °C up to 6.0% at 1060 °C, the temperature range of natural fires (Scott, 1989, 2000). The charcoal produced below 500 °C could be considered to be mainly semifusinite. Reflectance studies of the Raichikhinsk samples showed that nearly all inertinite had a reflectance of greater than 0.6%, consistent with a fire origin. It is likely that fires played an important role in the peat-forming environments at Raichikhinsk and Yerkovtsi.

### *11.2. Miocene coal at Cergeyevka*

Limited data from the early Miocene Cergeyevka deposit limits palaeoenvironmental interpretations. The presence of xylite from near the base of the deposit indicates that arboraceous vegetation played a role in peat accumulation, at least in the early stages. The sample from the top of the seam has a high ash content and a significant bituminite component. Some of the ash content of low rank coals is derived from cations bound to carboxylate functional groups (Brockway and Borsaru, 1985; Kiss et al., 1985), but the high ash content indicates that most is clastically derived. Bituminite is the product of degradation of algae, plankton, bacteria, etc., under anaerobic conditions (ICCP, 1993). The combination of bituminite and large amounts of clastic mineral matter at the top of the seam indicates that the late stages of peat formation occurred in open water conditions where the bottom waters were anoxic.

## 12. Conclusions

The Palaeocene and Miocene coal deposits of the Zeya–Bureya Basin are petrographically and geochemically distinct. They accumulated under different palaeoenvironmental conditions and had significantly different tectonic histories.

The Palaeocene deposits are lignite to subbituminous B in rank and are characterised by high inertinite contents, unusual for Tertiary coals. The petrographic composition strongly controls geochemistry, with increases in inertinite associated with increasing carbon content and decreasing volatile matter content. The coals were sufficiently lithified that lithotype logging could be performed and four dulling-up cycles of development were recognised which related to four episodes of peat mire development. High inertinite contents and their reflectance distribution suggest forest or peat fires may have played a significant role in the mire environment. However, the presence of clastic partings suggests the mires were not substantially raised. Geochemical parameters suggest maximum burial was in the range of 600–3300 m, with a depth of around 1000 m most likely, and that petroleum generation did not occur.

By contrast, the Lower Miocene Cergeyevka deposit is a soft brown coal. The strong contrast in rank over a short stratigraphic distance suggests a break in sedimentation, with burial and uplift of the Palaeocene coals, before deposition of this deposit. The limited samples taken had an unusually hydrogen-rich geochemistry, suggesting a large bituminite component.

Peat accumulation was terminated by drowning of the mire.

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