Campanian integrated biostratigraphy and palaeocommunities of Sakhalin Island (Far East Russia)

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YAZYKOVA, E., ZONOVA, T. & KAZINTSOVA, L., 2002: Campanian integrated biostratigraphy and palaeocommunities of Sakhalin Island (Far East Russia). – In: WAGREICH, M. (Ed.): Aspects of Cretaceous Stratigraphy and Palaeobiogeography. – Österr. Akad. Wiss., Schriftenr. Erdwiss. Komm. 15: 269–292, 7 Figs., Wien.

Abstract: The lithology and palaeontology of the Campanian succession of Sakhalin Island is described. The Campanian interval of the Cretaceous succession in Sakhalin Island (Far East Russia) presents a rich record of fairly well preserved ammonites, inoceramids, radiolarians, benthic foraminifers, gastropods and non-inoceramid bivalves, consisting of mostly endemic species and a few cosmopolitan forms. Changes in the faunal biodiversity were investigated within a context of relative sea-level changes and other environmental changes published elsewhere. The maximum diversity of planktic and nektic groups is established at the base of the lower Campanian. The peak of diversity of benthic groups is recorded at the base of the upper Campanian and associated with high diversity of planktonic groups. The end of the Campanian was a time of low diversity of all faunal groups in the Sakhalin palaeobasin. A high-resolution, integrated biostratigraphic zonation based on ammonites, inoceramids and radiolarians is proposed and correlated with adjacent areas. The zonal scheme comprises four ammonite zones, four inoceramid zones and two radiolarian zones. The definition of the Campanian stage and substage boundaries in Sakhalin and some possibilities for global correlation are discussed: the first occurrence of *Anapachydiscus (Neopachydiscus) naumanni* (YOKOYAMA) and *Desmophyllites diphylloides* (FORBES) are the main index taxa for the base of the Campanian Stage in Sakhalin; the F.O. of *Anapachydiscus arrialoorensis* (STOLICZKA) defines the base of the upper Campanian; occurrences of *Pachydiscus (P.) subcompressus* MATSUMOTO and *Pachydiscus (P.) gollevillensis* (D'ORBIGNY) are the main criteria for base of the Maastrichtian Stage.

Keywords: Biostratigraphy, Event Stratigraphy, Palaeocommunity, Ammonites, Inoceramids, Radiolarians, Campanian, Sakhalin Island, Russia

1. INTRODUCTION

The present work forms part of a larger research programme undertaken by workers at VSEGEI, VNIGRI (St. Petersburg, Russia) and the University of Silesia (Sosnowiec, Poland). The production of a detailed biostratigraphic scheme for the Cretaceous succession of the northwestern province of the Pacific is the main aim of this research. The existing Cretaceous biostratigraphic scheme for this province was published in 1974.

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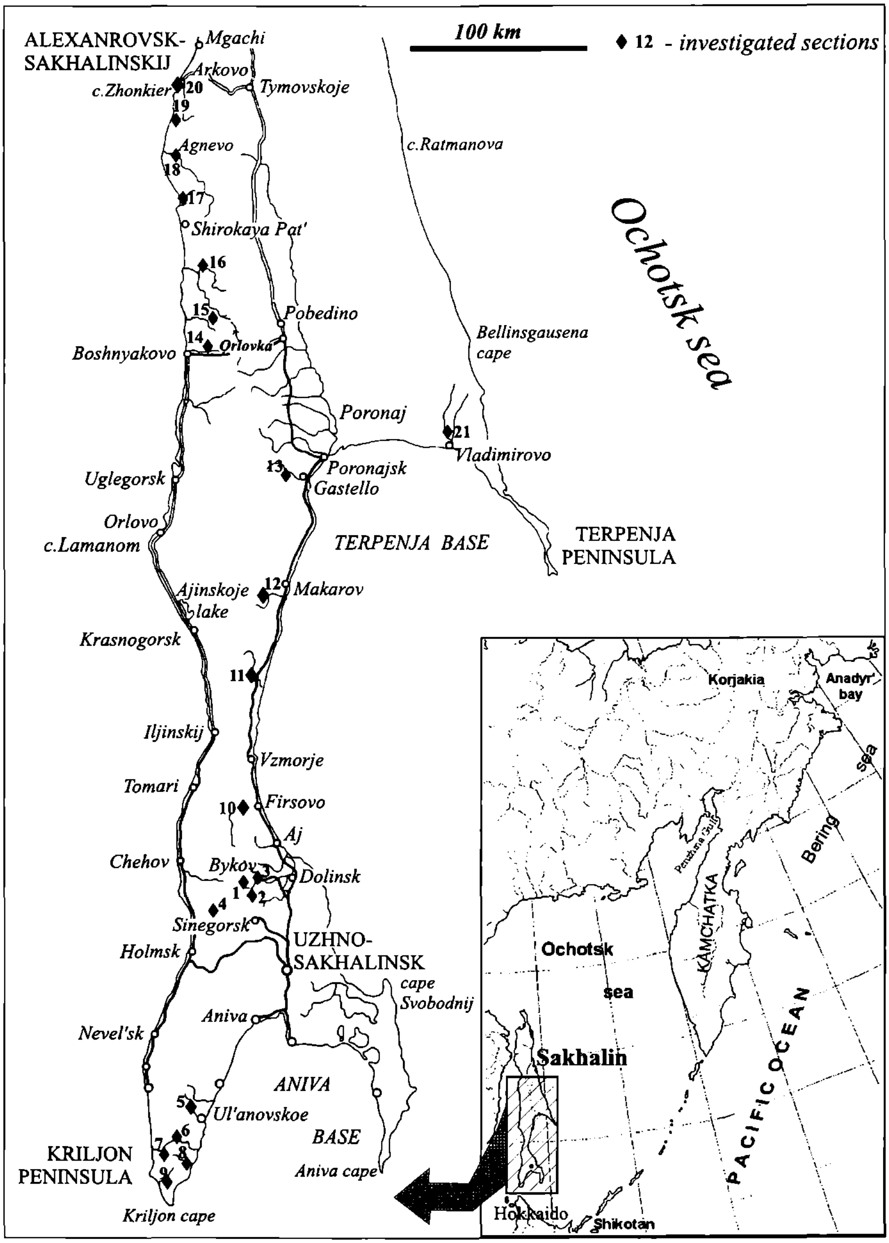


Fig.1: Locality map of investigated sections in Sakhalin Island. 1 – river Naiba; 2 – river Krasnoyarka; 3 – river Sejm; 4 – road Yuzhno-Sakhalinsk - Holmsk; 5 – river Ul'anovka; 6 – river Kura; 7 – river Saharovka; 8 – river Naicha; 9 – river Gorbusha; 10 – area of river Firsovka; 11 – area of river Manuj; 12 – area of river Makarova; 13 – area of river Gastello; 14 – area of river Bol'shaja Orlovka; 15 – river Avgustovka; 16 – area of river Pilevka; 17 – river Naj-Naj; 18 – river Agnevo; 19 – river Popovskaya; 20 – cape Zhonkier; 21 – river Vladimirovka.

During the last two decades the authors have published interim results from the new research: POYARKOVA (1987), ZONOVA (1992), KAZINTSOVA (1992), YAZYKOVA (1992, 1996, 2002), ZONOVA et al. (1993), KAZINTSOVA (2000) etc. Based on detailed analysis of the Sakhalin Santonian – Campanian (S-C) fossil associations, YAZYKOVA described the S-C boundary event and recovery, followed by the radiation of the ammonite and inoceramid faunas during the post-crisis period.

It is important to integrate the biostratigraphy, event stratigraphy and palaeoecological analyses of different faunal groups from this region. The Cretaceous succession of Sakhalin Island is typical of the whole of Far East Russia in the high endemism of faunas, the very thick and monotonous character of terrigenous marine rocks, and the marked lateral facies changes. These factors hinder biostratigraphic subdivision, regional and interregional correlation of Cretaceous strata, and biogeographic comparisons with the European and Tethyan Realms. Because of the complex tectonic structure of the region, fossils are generally rare and commonly poorly preserved. For these reasons, every fossil has a biostratigraphic significance, whatever the state of preservation.

2. METHODS

2.1. Material

The inoceramids were determined by ZONOVA (St. Petersburg, Russia), the ammonites were identified and revised by YAZYKOVA (Sosnowiec, Poland), and the radiolarians were described by KAZINTSOVA (St. Petersburg, Russia). This study is based mainly on material from the authors' personal collections; material is housed in the CNIGR Museum (St. Petersburg, Russia). For high-resolution faunal analysis and palaeoecological reconstructions, data on gastropods, non-inoceramid bivalves and foraminifers were taken mostly from POYARKOVA (1987). In addition, data on foraminifers were taken from VASILENKO (1965) and SEROVA (KALISHEVICH et al., 1981); non-inoceramid bivalves from KALISHEVICH (KALISHEVICH et al., 1981); and gastropods from NAGAO (1939), KANIE (1977) and SHIGETA et al. (1999). Recent data on palaeotemperature and palaeomagnetostratigraphy (ZAKHAROV et al., 1996, 1998; KODAMA et al., 2000), based on sections in the southern part of Sakhalin Island, were also incorporated.

2.2. Stratigraphy

In the river Naiba area, Kriljon Peninsula, on the southern coast of the Terpenja Peninsula and through much of the south of the West-Sakhalin Mountains (Fig.1), the Campanian Stage is represented by the interval from the upper part of Member 10 of the Bykov Formation to Member 3 of the Krasnoyarka Formation (Fig. 2) (POYARKOVA, 1987). In the northern part of the West-Sakhalin Mountains, from the river Bol'shaja Orlovka to Cape Zhonkier (Fig.1, section numbers 14–20), the Zhonkier Formation is the lateral equivalent of the upper part of Member 10 of the Bykov Formation (POYARKOVA, 1987) and is, therefore, lower Campanian. In general, much of the entire Cretaceous succession in Sakhalin is represented by mudstones with rhythmic intercalations of siltstone, sandstone and tuffaceous sandstone (Fig. 2) (POYARKOVA, 1987). In addition, lenses and layers of coal occur in the Zhonkier Formation (YAZYKOVA, 1996). Calcareous concretions and

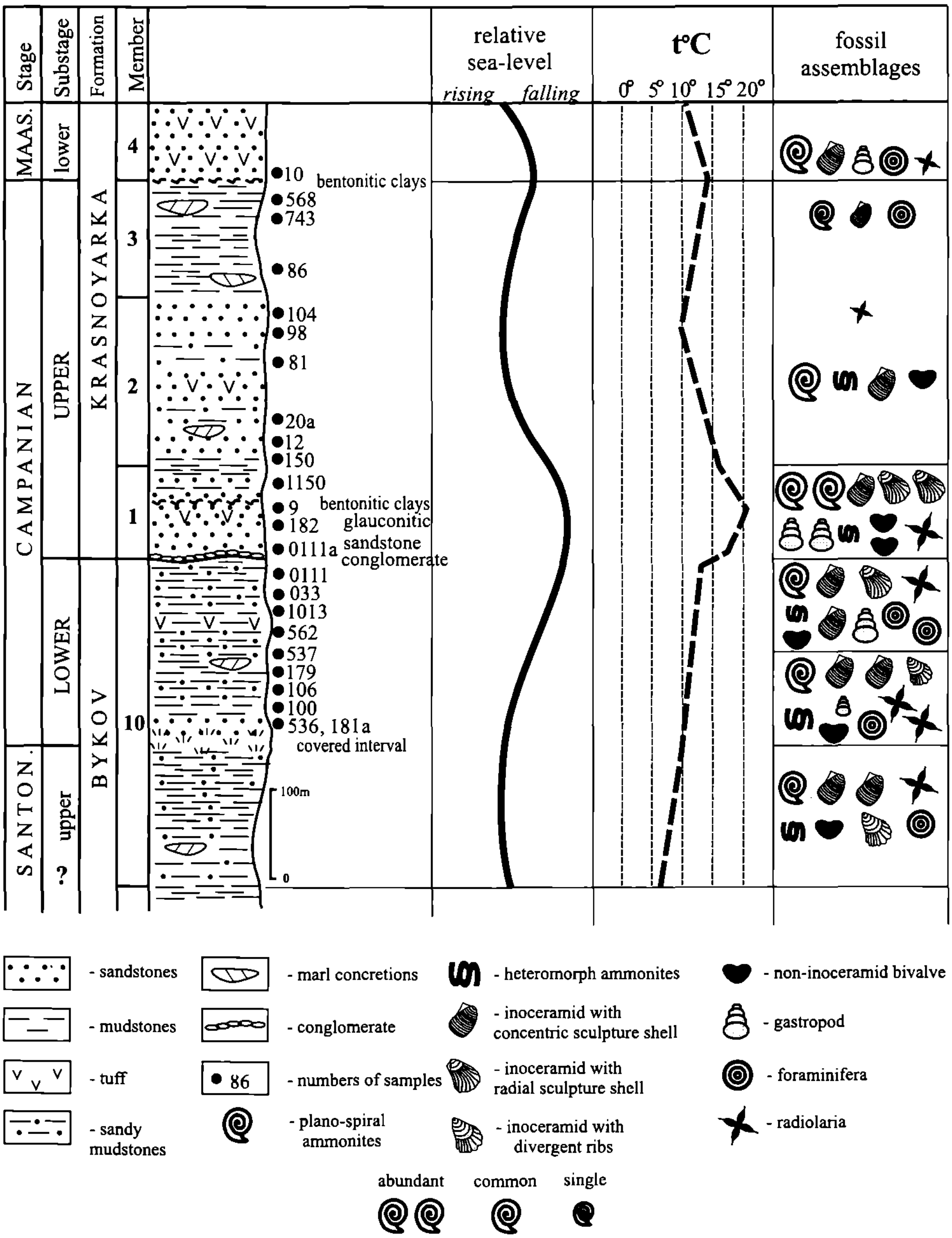


Fig. 2: Fossil assemblages and lithostratigraphy of the generalized Campanian succession of the Naiba area basin (river Naiba, streams: Krasnoyarka, Sejm, Susuja, Sara and road Yuzhno-Sakhalinsk – Holmsk); relative sea-level (MATSUMOTO, 1977b; ZAKHAROV et al., 1996) and palaeotemperature curves (modified after ZACHAROV et al., 1996, 1998).

concretionary layers, which sometimes yield well-preserved fossils, are a typical feature of all the sections. In comparison to other Cretaceous intervals in Sakhalin, the studied part is the most richly fossiliferous.

Within the mudstones of Member 10 of the Bykov Formation, the presence of a coarse sandstone layer may mark a hiatus that eliminates some part of the Upper Santonian, although this cannot be confirmed because the immediately underlying strata are obscured (Fig. 2). Furthermore, in the northern part of the West-Sakhalin Mountains (Fig. 1, section numbers 14, 15), there are no indications of a hiatus at the contact of the Zhonkier and underlying Verbluzhegorsk formations (YAZYKOVA, 1996).

The contact between the Bykov and Krasnoyarka formations and, in the north, between the Zhonkier and Krasnoyarka formations is characterized by conglomerates overlain by glauconitic sandstones with thin beds of tuff and bentonitic clay (Fig. 2). From the presence of the conglomerates, previous authors have inferred a hiatus at this level (YAZYKOVA, 1996, 2002).

Member 1 of the Krasnoyarka Formation is characterized by an abundance of diverse fossils that in places form coquina beds up to 2 meters thick. This member corresponds to a well defined stratigraphic interval of high benthic diversity that can be traced from Japan through Sakhalin to northeastern regions of Russia, Alaska and California (MATSUMOTO, 1959, 1977; KANIE, 1977; ZONOVA, 1984; ZONOVA et al., 1993; TOSHIMITSU et al., 1995; YAZYKOVA, 1996, 2002).

Member 2 is represented by a monotonous sequence of sandstone with interlayers of mudstone and rare calcareous concretions. Member 3 of the Krasnoyarka Formation is black mudstone. The interval from Member 2 through Member 3 is characterized by a decrease in fossil diversity and by the disappearance of most of the Campanian taxa. The boundary between members 3 and 4 of the Krasnoyarka Formation is established at a bentonitic clay bed (Fig. 2). Further along the river, a waterfall-forming massive sandstone marks the base of the Lower Maastrichtian.

3. THE CAMPANIAN STAGE ON SAKHALIN ISLAND

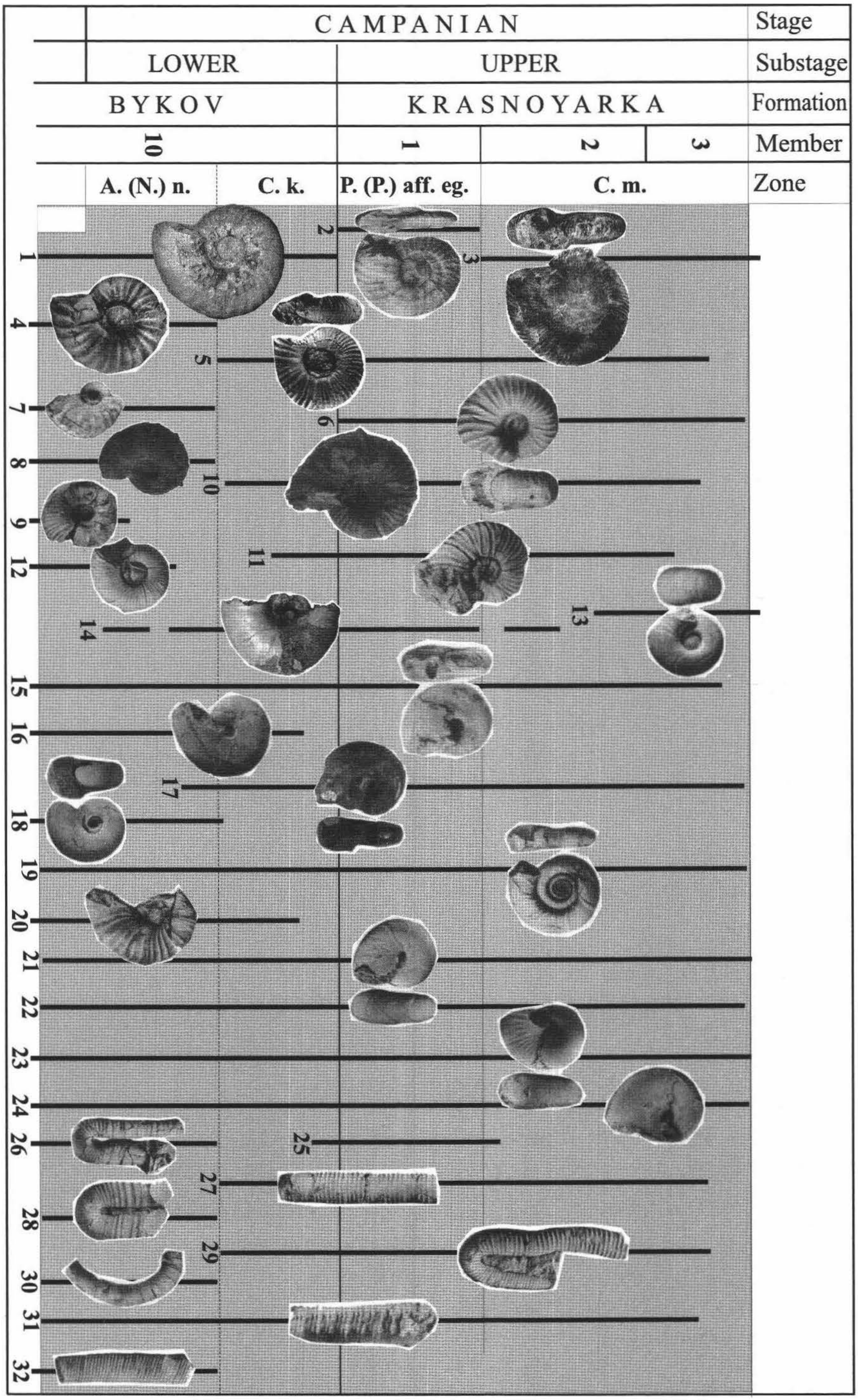
The high degree of endemism of the Pacific fauna makes it difficult to recognize and apply the European Cretaceous stages. Consequently, for many years a scheme of regional series and stages was used for Pacific palaeobasins. These regional stratigraphic units were also further subdivided using local formations, zones and fossiliferous strata. For instance, the Cretaceous sequences on Sakhalin and northeastern regions of Russia were divided into the Giliak (approximately Cenomanian – Turonian) and Orochen (approximately Coniacian – Danian) series (VERESCHAGIN et al., 1965), following KRISHTOFOVICH (1932). In Japan, the Gyliakian (approximately Cenomanian – Turonian), Urakawian (approximately Coniacian – lower Campanian) and Hetonaian (approximately Campanian – Maastrichtian) series were used (MATSUMOTO, 1959c, 1977a). At the present time, however, only regional lithostratigraphic units, such as formations, and local biostratigraphic units, such as provisional zones and beds (intervals or strata), are recognized in Sakhalin and the regional series have been abandoned. Global correlations are based mainly on rare finds of cosmopolitan taxa associated with endemic species. It is possible that the abandonment of regional series was premature, although this debate is beyond the scope of the present study. Herein, we discuss all of the evidence for recognition of the Campanian Stage in Far East Russia, in particular Sakhalin Island, using all faunal data as well as palaeomagnetostratigraphy.

Detailed discussion of the Santonian – Campanian boundary in Sakhalin, and the biotic event at this level, have been described elsewhere (YAZYKOVA, 1996; YAZYKOVA, 2002). The biotic event is termed the Regional Biotic Event and is known from many different regions of the world (RBE *sensu* KAUFFMAN & HART, 1995).

Following many previous works (MATSUMOTO, 1959c, 1977a; VERESCHAGIN et al., 1965; POYARKOVA, 1987; ZONOVA, 1992; YAZYKOVA, 1992; ZONOVA et al., 1993; YAZYKOVA, 1996, 2002; KAZINTSOVA, 2000; and others) the Santonian – Campanian boundary in Sakhalin is placed at the base of the *Inoceramus nagaoi* inoceramid Zone, *Anapachydiscus (Neopachydiscus) naumanni* ammonite Zone and *Spongostaurus* (?) *hokkaidoensis – Hexacontium* sp. radiolarian zones (Figs. 3–6). This position corresponds approximately to the covered interval within Member 10 of the Bykov Formation (Fig. 2) in the southern and central sections, and to the base of the Zhonkier Formation in the northern part of the West-Sakhalin Mountains. It is recognized by the first occurrences of the ammonites *Desmophyllites diphylloides* (FORBES) and *Anapachydiscus (Neopachydiscus) naumanni* (YOKOYAMA), and the inoceramid *Inoceramus nagaoi* (MATSUMOTO & UEDA). In northeastern regions of Russia, this boundary is placed at the base of the same zones and, in Japan, at the base of the *Anapachydiscus (Neopachydiscus) naumanni* Zone (Fig. 6).

The 34n/33r palaeomagnetic boundary is placed approximately at the same level in the southern sections (ZAKHAROV et al., 1996; KODAMA et al., 2000). Above this, a few cosmopolitan taxa suggest a Campanian age, notably *Saghalinites cala* (FORBES), *Diplomoceras notabile* (WHITEAVES) and *Ryugasella ryugasense* WRIGHT & MATSUMOTO. Moreover, the radiolarian complex *Spongostaurus* (?) *hokkaidoensis – Hexacontium* sp. also indicates an early Campanian age in Sakhalin as well as in Japan (TOSHIMITSU et al., 1995).

Fig. 3: Stratigraphic distribution of the main Campanian ammonite species and zonal division in the Sakhalin sections. 1 – *Anapachydiscus (Neopachydiscus) naumanni* (YOKOYAMA); 2 – *Pachydiscus (P.)* sp. aff. *egertoni* (FORBES); 3 – *Canadoceras multicostatum* MATSUMOTO; 4 – *Eupachydiscus haradai* (JIMBO); 5 – *Canadoceras kossmati* MATSUMOTO; 6 – *Anapachydiscus arrialoorensis* (STOLICZKA); 7 – *Menuites japonicus* MATSUMOTO; 8 – *Menuites naibutiensis* MATSUMOTO; 9 – *Menuites menu* (FORBES); 10 – *Canadoceras yokoyamai* (JIMBO); 11 – *Canadoceras mysticum* MATSUMOTO; 12 – *Neopuzosia ishikawai* (JIMBO); 13 – *Pseudophyllites indra* (FORBES); 14 – *Anapachydiscus fascicostatus* (YABE); 15 – *Damesites damesi* JIMBO;16 – *Damesites sugata* (FORBES); 17 – *Tetragonites popetensis* YABE; 18 – *Tetragonites epigonus* (KOSSMAT); 19 – *Gaudryceras tenuiliratum* YABE; 20 – *Gaudryceras denseplicatum* (JIMBO); 21 – *Desmophyllites diphylloides* (FORBES); 22 – *Phyllopachyceras ezoense* (YOKOYAMA); 23 – *Phyllopachyceras forbesianum* (D'ORBIGNY); 24 – *Neophylloceras ramosum* (MEEK); 25 – *Saghalinites cala* (FORBES); 26 – *Subptychoceras yubarense* (YABE); 27 – *Ryugasella ryugasense* WRIGHT & MATSUMOTO; 28 – *Subptychoceras vancouverense* (WHITEAVES); 29 – *Diplomoceras notabile* WHITEAVES; 30 – *Scalarites venustum* (YABE); 31 – *Pseudoxybeloceras lineatum* GABB; 32 – *Pseudoxybeloceras quadrinodosum* (JIMBO). ➔


CAMPANIAN
Stage
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Substage
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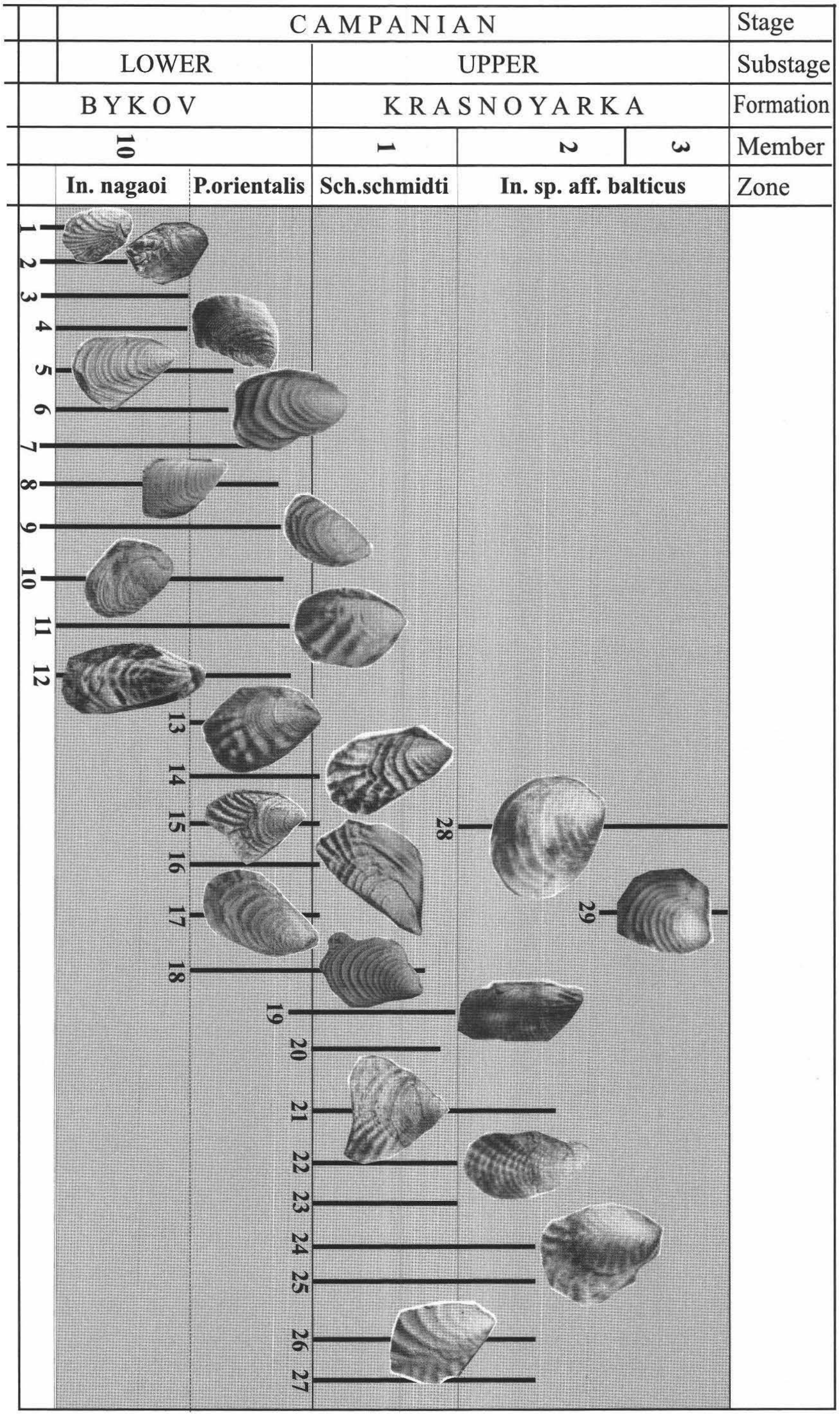
The lower/upper Campanian boundary is recognized by the first appearance of *Anapachydiscus arrialoorensis* (STOLICZKA) (POYARKOVA, 1987; ALABUSHEV & WIEDMANN, 1997; YAZYKOVA, 2002) and is placed at the base of the *Pachydiscus* (*P.*) sp. aff. *egertoni* and *Schmidticeramus schmidti* zones (Fig. 6). In Japan (TOSHIMITSU et al., 1995) the lower/upper Campanian boundary is placed at the base of the *Anapachydiscus fascicostatus* and *Mytiloides shimanukii* zones (Fig.6). In Sakhalin, the stratigraphic range of *Anapachydiscus fascicostatus* is too long to allow its use in defining this boundary: it occurs near the middle part of the lower Campanian and disappears at the end of the upper Campanian. On the other hand, *Mytiloides shimanukii* has been recorded from the upper Campanian (*Schmidticeramus schmidti* Zone) of the Kriljon Peninsula in southern Sakhalin (SHIGETA et al., 1999).

The Campanian/Maastrichtian boundary in Far East Russia and Japan is defined by the first occurrence of *Pachydiscus (P.) subcompressus* MATSUMOTO and *Pachydiscus (Neodesmoceras) japonicus* MATSUMOTO; its position is suggested by a few finds of *Pachydiscus (P.) gollevillensis* (D'ORBIGNY) and *P. (P.) neubergicus* (HAUER) on Sakhalin (VERESCHAGIN et al., 1965; ZONOVA et al., 1993; YAZYKOVA, 1994). More detailed consideration of this boundary will be covered elsewhere.

4. AMMONITE, INOCERAMID AND RADIOLARIAN BIOSTRATIGRAPHY

Ammonites, inoceramids and radiolarians are the most important, biostratigraphically useful Cretaceous faunal groups on Sakhalin Island, in the Korjakia-Kamchatka region and throughout much of the Pacific region (Fig. 6). Although these groups commonly occur as fossils in the same bed, in life they had their own habitat preferences and represent different biofacies.

Fig. 4: Stratigraphic distribution of the main Campanian inoceramid species and inoceramid zonation for the Campanian in Sakhalin Island: 1 – *Inoceramus (Pl.) japonicus hokkaidoensis* NODA; 2 – *Inoceramus (Pl.) japonicus higoensis* NODA; 3 – *Inoceramus lophopterus* ZONOVA; 4 – *Inoceramus transitorius* ZONOVA; 5 – *Inoceramus cuneus* ZONOVA; 6 – *Inoceramus nagaoi* MATSUMOTO & UEDA; 7 – *Inoceramus subyokoyamai* ZONOVA; 8 – *Inoceramus naumanni* YOKOYAMA; 9 – *Inoceramus yokoyamai* NAGAO & MATSUMOTO; 10 – *Inoceramus talovensis* PERGAMENT; 11 – *Inoceramus elegance elegance* SOKOLOV; 12 – *Inoceramus eleganse pseudosulcatus* NAGAO & MATSUMOTO; 13 – *Pennatoceramus laciniosus* ZONOVA; 14 – *P. orientalis orientalis* (SOKOLOV); 15 – *P. orientalis matsumotoi* (ZONOVA);16 – *P. clarus* (GLASUNOV); 17 – *P. orientalis vagus* (PERGAMENT); 18 – *Inoceramus shuvaevi* ZONOVA; 19 – *Inoceramus shutovae* ZONOVA; 20 – *Inoceramus ampambaensis* SORNAY; 21 – *Schmidticeramus schmidti* (MICHAEL); 22 – *Ordinatoceramus ordinates* (PERGAMENT); 23 – *Ordinatoceramus bicentralis* ZONOVA; 24 – *Sachalinoceramus sachalinensis* (SOKOLOV); 25 – *Sachalinoceramus subsachalinensis* ZONOVA; 26 – *Sachalinoceramus broncus* (PERGAMENT); 27 – *Sachalinoceramus subbroncus* ZONOVA; 28 – *Inoceramus* sp. aff. *balticus* BÖHM; 29 – *I. balticus toyajoanus* NAGAO & MATSUMOTO. ➔


CAMPANIAN
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The ammonite zonal succession (Figs. 3,6) is based on the family Pachydiscidae (YAZYKOVA, 1996, 2002), which appeared at the end of the Santonian and dominated ammonite faunas through the Campanian – Maastrichtian interval worldwide. Each ammonite zone is based on the first appearance of an index-species. The pachydiscids are widespread and well preserved. The litho- and biofacies in which they commonly occur suggest that they lived in near- to offshore, moderately deep waters. The same was true of the superfamily Desmoceratacea (MATSUMOTO, 1977a; TANABE, 1979). The inoceramid zonal scheme (Figs. 4,6) was developed by ZONOVA (ZONOVA et al., 1993). These benthic bivalves are also widespread, occurring in both sandy and muddy lithofacies. The inoceramid zones were also established on the first appearances of an index-species. The phylogenetic scheme of the Santonian – Campanian inoceramids has already been described in previous work (YAZYKOVA, 2002). The Campanian succession of Radiolarian zones (Figs. 5,6) was established by KAZINTSOVA (2000). Some representatives of two distinct assemblages are figured (Fig. 5). This planktic group lived in offshore deep waters. The integration of zones from more than one faunal group allows greater biostratigraphic precision and greater confidence in age determinations than zonations based on a single group.

4.1. Lower Campanian

4.1.1. Ammonites

(Fig. 3)

The *Anapachydiscus (Neopachydiscus) naumanni* Zone (MATSUMOTO, 1959c) has been described in Sakhalin by YAZYKOVA (ZONOVA et al., 1993). It occurs within the middle part of Member 10 of the Bykov Formation (Fig. 2). Representatives of the index species are widespread in the northern Pacific province and, as a rule, are well preserved, large, and in some cases gigantic. *Anapachydiscus (Neopachydiscus) naumanni* (YOKOYAMA) is closely allied to *Eupachydiscus levyi* (GROUSSOUVRE) from the lower Campanian of Europe and Tethys. In total, the zonal assemblage includes 22 species belonging to 11 genera. The assemblage is largely endemic, with only five cosmopolitan species: *Damesites sugata* (FORBES), *Tetragonites epigonus* (KOSSMAT), *Phyllopachyceras forbesianum* (D'ORBIGNY), *Desmophyllites diphylloides* (FORBES), *Subptychoceras vancouverense* (WHITEAVES), *Pseudoxybeloceras lineatum* GABB. The same zone occurs in northeastern Russia (VERESCHAGIN et al., 1965) and Japan (Fig. 6) (TOSHIMITSU et al., 1995).

The *Canadoceras kossmati* Zone was established from Hokkaido (MATSUMOTO, 1977) and has since been recorded from Sakhalin (YAZYKOVA, 2002). It corresponds to the uppermost part of Member 10 of the Bykov Formation (Fig. 2). *Canadoceras kossmati* MATSUMOTO is the oldest and most widespread representative of *Canadoceras* in Sakhalin and the Korjak–Kamchatka region. Within this zonal fauna, the degree of endemism is slightly higher than in the underlying *Anapachydiscus (Neopachydiscus) naumanni* Zone. In total, 19 species belonging to 11 genera are recorded, including four species that are distributed widely in circum-Pacific regions: *Saghalinites cala* (FORBES), *Diplomoceras notabile* WHITEAVES, *Ryugasella ryugasense* WRIGHT & MATSUMOTO and *Pseu-*

doxybeloceras lineatum GABB. The same zone (Fig. 6) has been included in the recent biostratigraphic scheme for Japan (TOSHIMITSU et al., 1995).

4.1.2. Inoceramids

(Fig. 4)

The *Inoceramus nagaoi* Zone (ZONOVA et al., 1993) has been established elsewhere on the Pacific coast of Russia (VERSCHAGIN et al., 1965; YAZYKOVA, 2002). It corresponds to the *Anapachydiscus (Neopachydiscus) naumanni* ammonite zone. Representatives of the index taxon are numerous and well preserved, and are widespread in Far East Russia as well as in Japan. *Inoceramus nagaoi* MATSUMOTO & UEDA is closely allied to the Campanian taxon *Inoceramus azerbajanensis* ALIEV, which occurs in the Crimea and central Asia. The zonal fauna is totally endemic and includes 11 species. The taxonomic composition of the zone overlaps those of the *Inoceramus (Pl.) japonicus* and *Sphenoceramus schmidti, Sph. orientalis, I. (Pl.) chicoensis* zones (Fig. 6) in Japan. It is necessary to note the discrepancy between the concepts of the *Inoceramus (Platyceramus) japonicus* Zone as applied in the Japanese island of Hokkaido (TOSHIMITSU et al., 1995) and in the adjacent Sakhalin. In Sakhalin, authors placed the *Inoceramus (Pl.) japonicus hokkaidoensis* Zone (Fig.6) in the upper Santonian, because the representatives of zonal species and associated *Inoceramus (P.) japonicus higoensis* Noda appear at the same time as the ammonite *Eupachydiscus haradai*, occurring together with *Texanites*. Records of *I. (Pl.) japonicus hokkaidoensis* or *I. (Pl.) japonicus higoensis* together with the lower Campanian *Anapachydiscus (Neopachydiscus) naumanni* are rare. It is not possible to correlate the lower boundaries of the *Anapachydiscus (Neopachydiscus) naumanni* and *Inoceramus (Pl.) japonicus hokkaidoensis* zones. In Japan, on the other hand, that zone has the late Campanian age, but *Inoceramus (Pl.) japonicus hokkaidoensis* Noda appears in the late Santonian (NODA, 1983; HASEGAWA & TOSHIMITSU, 1993). The present authors would argue against changing the position of the lower boundary of the *Inoceramus (Pl.) japonicus hokkaidoensis* Zone in Sakhalin to match that in Japan.

The *Pennatoceramus orientalis* Zone (Fig. 4) was first established in Sakhalin (ZONOVA, 1974), then in Hokkaido (MATSUMOTO, 1977a) and was described in detail by ZONOVA later (ZONOVA et al., 1993). It corresponds to the *Canadoceras kossmati* ammonite Zone (Fig. 6). Representatives of the zonal index are widespread in the Sakhalin – Japan region as well as in the Korjak-Kamchatka region (VERESCHAGIN et al., 1965). The zonal assemblage contains 15 species, all of which are endemic. Five species of *Pennatoceramus* (Fig. 4) are the oldest representatives of the radiate-ribbed inoceramids of the subfamily Sachalinoceraminae (*sensu* ZONOVA et al., 1993). The stratigraphic distribution of *Pennatoceramus orientalis* in Sakhalin overlaps with that in Hokkaido (*see* TOSHIMITSU et al., 1995, fig. 3). The *Pennatoceramus orientalis* Zone corresponds to the upper part of the *Sphenoceramus schmidti, Sph. orientalis, I. (Pl.) chicoensis* Zone in Japan (TOSHIMITSU et al., 1995).

4.1.3. Radiolaria

(Fig. 5)

The *Spongostaurus* (?) *hokkaidoensis* – *Hexacontium* sp. Zone occurs in the lower Campanian part of Member 10 of the Bykov Formation. A detailed description of this biostratigraphic unit was published by KAZINTSOVA (ZONOVA et al., 1993). This assemblage contains close to 20 taxa, including 16 which are illustrated in Fig. 5 and are representatives of the genera *Cromyomma, Hexacontium, Spongostaurus, Grucella, Phaseliforma, Patulibracchium, Stichomitra, Amphipyndax,* and *Saturniforma*. *Spongostaurus* (?) *hokkaidoensis* is also the index-species for a lower Campanian radiolarian zone (Fig. 6) in Japan (TAKETANI, 1982; TOSHIMITSU et al., 1995).

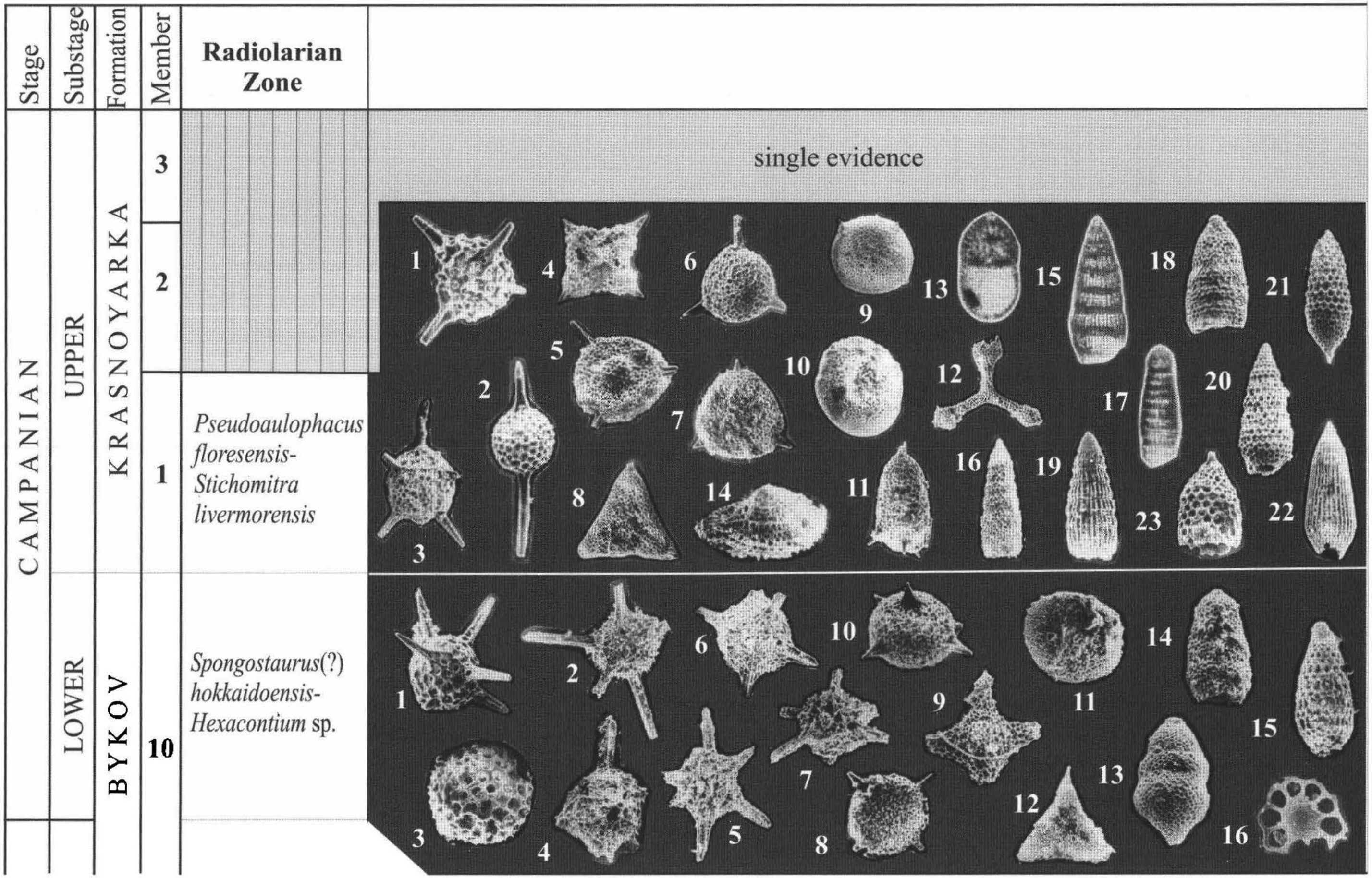
4.2. Upper Campanian

4.2.1. Ammonites

(Fig. 3)

The *Pachydiscus* (*P.*) sp. aff. *egertoni* Zone (POYARKOVA, 1987; ZONOVA et al., 1993) occurs within Member 1 of the Krasnojarka Formation and, as mentioned previously, is a raedily correlated marker. Fossils are abundant and diverse within this interval, although preservation is commonly poor. The total fauna comprises 18 species belonging to 12 genera, including 5 species that are distributed widely in circum-Pacific regions: *Desmophyllites diphylloides* (FORBES), *Phyllopachyceras forbesianum* (D'ORBIGNY), *Saghalinites cala* (FORBES), *Ryugasella ryugasense* WRIGHT & MATSUMOTO and *Anapachy-*

Fig. 5: Biostratigraphic division by radiolarian assemblages of the Campanian in Sakhalin sections. ➔ Lower Campanian – *Spongostaurus* (?) *hokkaidoensis* – *Hexacontium* sp. Zone: 1 – *Cromyomma* (?) *nodosa* PESSAGNO; 2, 4–7 – *Hexacontium* sp.; 3, 10 – Gen. et sp. indet; 8 – *Spongostaurus* (?) *hokkaidoensis* TAKETANI; 9 – *Grucella* sp.; 11 – *Phaseliforma* ? sp.; 12 – *Patulibracchium petroleumensis* PESSAGNO; 13 – *Stichomitra* sp. A; 14 – *Stichomitra manifesta* Foreman; 15 – *Amphipyndax stocki* (CAMPBELL & CLARK); 16 – *Saturniforma abastrum* PESSAGNO. Upper Campanian – *Pseudoaulophacus floresensis* – *Stichomitra livermorensis* Zone: 1 – *Cromyomma* (?) *nodosa* PESSAGNO; 2 – *Sphaerostylus hastatus* CAMPBELL & CLARK; 3 – *Stylodictya stellaris* KAZINTSOVA; 4 – *Crucella espartoensis* PESSAGNO; 5 – *Pseudoaulophacus floresensis* PESSAGNO; 6 – *Spongotripus crassus* KAZINTSOVA; 7 – *Spongotripus morenoensis* CAMPBELL & CLARK; 8 – *Patulibracchium petroleumensis* PESSAGNO; 9 – *Crucella zonovae* (KAZINTSOVA); 10 – *Orbiculiforma* (?) *sempiterna* PESSAGNO; 11 – *Stylodruppa bifascicula* KAZINTSOVA; 12 – *Patulibracchium vereshagini* KAZINTSOVA; 13 – *Diacanthocapsa rotunda* KOZLOVA; 14 – *Sciadiocapsa* (?) *rumseyensis* PESSAGNO; 15 – *Dictyomitra* ex gr. *multicostata* ZITTEL; 16 – *Xitus* (?) sp. D (IWATA & TAJIKA, 1986); 17 – *Theocampe altamontensis* (CAMPBELL & CLARK); 18 – *Stichomitra manifesta* FOREMAN; 19 – *Dictyomitra formosa* SQUINABOL; 20 – *Lithostrobus* sp. A (IWATA & TAJIKA, 1986); 21 – *Stichomitra livermorensis* (CAMPBELL & CLARK); 22 – *Archaeodictyomitra squinaboli* PESSAGNO; 23 – *Clathrocyclas hyronia* FOREMAN.


Stage
Substage
Formation
Member
Radiolarian Zone
CAMPANIAN
UPPER
LOWER
KRASNOYARKA
BYKOV
3
2
1
10
single evidence
Pseudoaulophacus floresensis-Stichomitra livermorensis
Spongostaurus(?) hokkaidoensis-Hexacontium sp.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

discus arrialoorensis (Stoliczka). *Pachydiscus (P.)* sp. aff. *egertoni* (Forbes) is a cosmopolitan taxon, but sadly the preservation of material from Sakhalin precludes confident identification with the type specimen from India. From the total fauna, this zone is confidently correlated with the *Anapachydiscus fascicostatus* Zone in Hokkaido (Fig. 6) (Toshimitsu et al., 1995). Representatives of *Anapachydiscus fascicostatus* (Yabe) occur also in Sakhalin within the uppermost part of Member 10 of the Bykov Formation up to the lower part of Member 2 of the Krasnoyarka Formation (Fig. 3) (Poyarkova et al., 1987; Zonova et al., 1993; Yazykova, 1996, 2002).

The *Canadoceras multicostatum* Zone was first established in the river Naiba area and has since been identified in Japan (Matsumoto, 1959c; 1977a) and described in detail by Zonova et al. (1993). It occurs within members 2 and 3 of the Krasnoyarka Formation. In total, 18 species belonging to 13 genera are known from the zone, including six cosmopolitan taxa: *Desmophyllites diphylloides* (Forbes), *Phyllopachyceras forbesianum* (d'Orbigny), *Saghalinites cala* (Forbes), *Anapachydiscus arrialoorensis* (Stoliczka), *Ryugasella ryugasense* Wright & Matsumoto and *Diplomoceras notabile* Whiteaves. At the present time, two new zones have been adopted in Japan in place of the *Canadoceras multicostatum* Zone (Fig. 6), but their faunal assemblages are apparently identical to those of the *Canadoceras multicostatum* Zone in Sakhalin. Representatives of zonal taxa from Japan, *Pachydiscus (P.) awajensis* and *Patagiosites laevis*, have still not been found in Sakhalin.

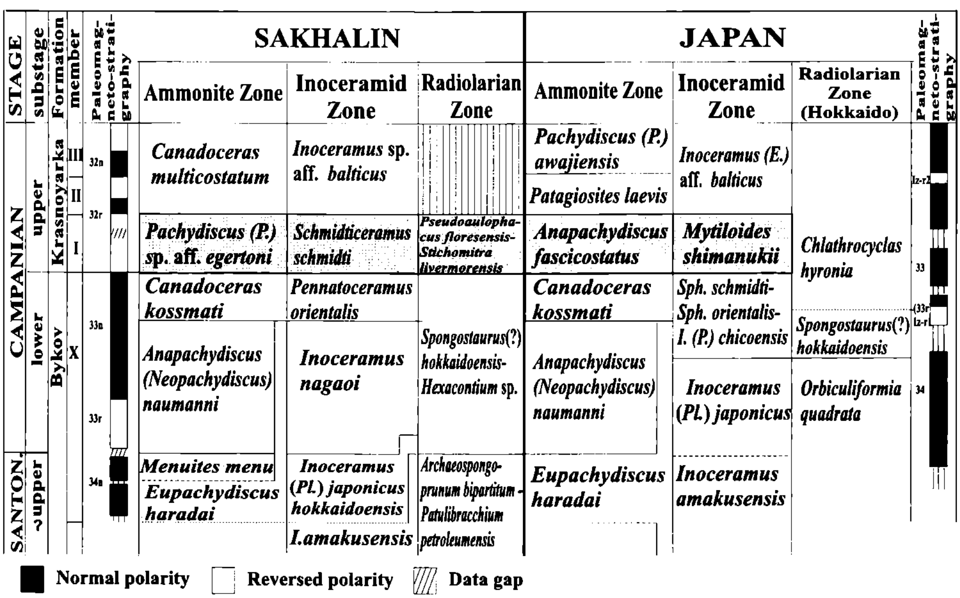


Fig. 6: Ammonite, inoceramid and radiolarian zones for the Campanian of Sakhalin by authors; ammonite, inoceramid, radiolarian zones and palaeomagnetostratigraphy for Japan by Toshimitsu et al. (1998); palaeomagnetostratigraphy for South Sakhalin by Kodama et al. (2000).

4.2.2. Inoceramids

(Fig. 4)

The *Schmidticeramus schmidti* Zone (Matsumoto, 1959c; Zonova et al., 1993) occupies the same interval as the *Pachydiscus* (*P.*) sp. aff. *egertoni* ammonite Zone and Member 1 of the Krasnoyarka Formation (Fig. 6). This interval contains a high diversity and density of inoceramids and represents a time of flourishing of the subfamily Sachalinoceraminae (*sensu* Zonova et al., 1993), which consists of four genera (Fig. 4): *Pennatoceramus, Schmidticeramus, Sachalinoceramus, Ordinatoceramus*. The interval can be traced over thousands of kilometers within the West Pacific province, i.e. Japan, Sakhalin, Kamchatka, Korjakia, Alaska (Matsumoto, 1959a,b,c; 1977a; Kanie, 1977; Zonova, 1984; Zonova et al., 1993; Toshimitsu et al., 1995; Yazykova, 1996, 2002). In Japan (Fig. 6), this level corresponds to the *Mytiloides shimanukii* Zone, which has the same taxonomic composition as the *Schmidticeramus schmidti* Zone in Sakhalin and northeastern regions of Russia (Vereschagin et al., 1965). The stratigraphic distribution of *Schmidticeramus schmidti* in Sakhalin coincides with that in Hokkaido (see Toshimitsu et al., 1995, fig. 3). *Mytiloides shimanukii* also has radial ribs and has been found in Sakhalin at the same level as in Japan (Shigeta et. al., 1999).

The *Inoceramus* sp. aff. *balticus* Zone has been proposed for both Sakhalin and Hokkaido Islands (Matsumoto, 1959a). Given that *I. balticus* is an important zonal taxon in the European province, this might suggest a correlation between the Pacific and European regions. Specimens of *Inoceramus* sp. aff. *balticus* have been found in Sakhalin, Korjakia (Vereschagin et al., 1965) and Japan (Fig. 6). In Sakhalin the zonal assemblage includes only seven species (Fig. 4), six of them are the last representatives of the radially-ribbed inoceramids. The *Inoceramus* sp. aff. *balticus* Zone corresponds to Member 2 of the Krasnojarka Formation and to the *Canadoceras multicostatum* ammonite Zone. Recent investigations point to a longer stratigraphic range for *Cataceramus balticus* (Böhm) (Walaszczyk, 1997). Hence the extent and significance of this zone in the northern Pacific province is open to doubt and should be a subject for further investigation.

4.2.3. Radiolaria

(Fig. 5)

The *Pseudoaulophacus floresensis – Stichomitra livermorensis* Zone corresponds to Member 1 of the Krasnojarka Formation (Fig. 5), the *Pachydiscus* (*P.*) sp. aff. *egertoni* ammonite Zone and the *Schmidticeramus schmidti* inoceramid Zone. Detailed description of this stratigraphic unit has been given by Kazintsova (in Zonova et al., 1993). This assemblage contains 37 taxa, 23 of which are illustrated in Fig. 5. The illustrated taxa represent the genera *Cromyomma, Sphaerostylus, Stylodictya, Crucella, Pseudoaulophacus, Spongotripus, Patulibracchium, Orbiculiforma, Stylodruppa, Diacanthocapsa, Sciadiocapsa, Dictyomitra, Xitus* (?), *Theocampe, Stichomitra, Lithostrobus, Archaeodictyomitra* and *Clathrocyclas*. The assemblage is unique in terms of its taxonomic composition. This assemblage differs from those below and above and includes, for example, the first appearances of *Sciadiocapsa* and *Clathrocyclas*. As noted previously

(ZONOVA et al., 1993), the assemblage resembles Late Campanian complexes of Korjakia Upland (VISHNEVSKAYA, 1987), Japan (YAMAUCHI, 1982), California (PESSAGNO, 1976) and the Atlantic (FOREMAN, 1978).

The succeeding strata of Members 2 and 3 of the Krasnoyarka Formation yield only rare and poorly preserved specimens of radiolarians. The absence of radiolarians through this interval was most probably caused by taphonomic conditions or by abrupt changes in the local environmental conditions.

5. PALAEOENVIRONMENTAL AND PALAEOECOLOGICAL INTERPRETATIONS

Based on the analysis of the fossil associations and the lithological variations, it is possible to reconstruct the broad palaeoenvironmental history of the Campanian succession on Sakhalin, which was deposited within an open shelf basin of an active marginal sea (KIRILLOVA, 1997; 2000; KIRILLOVA et al., 2000).

5.1. Lower Campanian

Global regression at the Santonian – Campanian boundary together with a rise in temperature (BARNSE et al., 1995) caused the regional biotic event that is evident in different regions of the world. In general, early Campanian assemblages of fossils in Sakhalin (*Anapachydiscus (Neopachydiscus) naumanni/Inoceramus nagaoi* Zone) represent offshore to nearshore faunas. This part of Member 10 of the Bykov Formation (Fig. 2) records initially quiet sedimentation in a relatively deep-water marine environment, as suggested by the dominance of planktic radiolarians and nektic and benthic heteromorph and plano-spiral ammonites (mostly Desmocerataceae) (MATSUMOTO, 1977a; TANABE, 1979; WESTERMANN, 1996). Non-heteromorph ammonites are relatively large and have platycone, discocone and spherocone shapes; heteromorphs have cyrtocone, orthocone and hamitocone shell shape (sensu WESTERMANN, 1996). These shell forms suggest open, offshore marine sediments (TSUJITA & WESTERMANN, 1998). The taxonomic diversity maximum of Campanian ammonites occurs at this level. The abundance of radiolarians also points to a high supply of silica and other nutrients (see RACKI & CORDAY, 2000, literature review on p.23–25). The most abundant radiolarian assemblages have been collected from siliceous mudstones in the Terpenja Peninsula, section N21 (Fig. 1). The appearance of new inoceramid species provides evidence for warm waters of normal salinity. Almost 72 taxa of foraminifers, most of which are benthic and stenobiontic, indicate a well-oxygenated basin (POYARKOVA, 1987). This interpretation is supported by the appearance of new gastropod species and the occurrence of non-inoceramid bivalves (POYARKOVA, 1987) (Fig. 7).

Fossil associations of the *Canadoceras kossmati/Pennatoceramus orientalis* Zone, in the uppermost part of Member 10 (Fig. 2,6), shows continuous changes of the local environment. Several lines of evidence suggest a well-oxygenated sea of normal salinity and a steady shallowing of water depths: a relative fall in ammonite diversity, reflected in the disappearance of some heteromorphs and the last representatives of *Menuites*; a rise in inoceramid diversity (the appearance of the first radial-ribbed *Pennatoceramus*); a rise in the abundance of foraminifers; and a decrease in radiolarian abundance. A

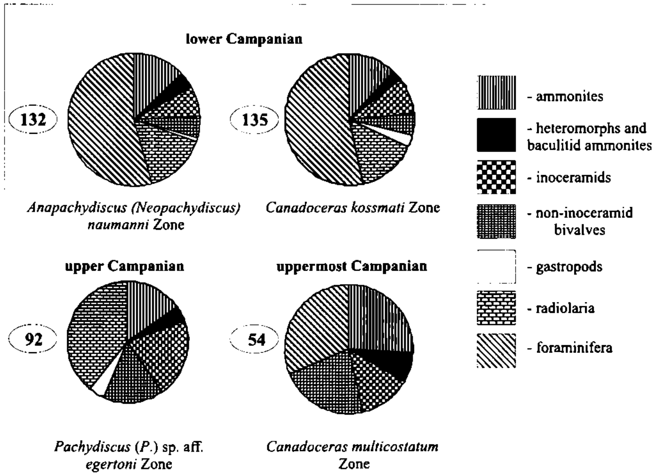


Fig. 7:
Diagrams of the macro- and microfossil content of the Campanian interval in Sakhalin Island; the total number of considered species is circled.

continuous rise of temperature in the northern Pacific region (Fig. 2) could be caused by some increase of volcanic activity (Kirillova et al., 2000), as reflected in the tuff layers of the uppermost part of Member 10 of Bykov Formation.

5.2. Upper Campanian

Member 1 of the Krasnoyarka Formation (*Pachydiscus* (*P.*) sp. aff. *egertoni*/ *Schmidticeramus schmidti* Zone) was deposited during a time of maximum regression and maximum temperature in the Campanian (Fig. 2). The occurrence of tuffaceous mudstone interlayers, glauconitic sandstones and bentonitic clays points to relatively high volcanic activity. Conglomerates at the base of Member 1 may indicate some hiatus at the lower/ upper Campanian boundary. Zakharov et al. (1998) show a relatively abrupt increase in temperature (from 13°C up to 18°C) across the conglomerates. Faunal assemblages from Member 1 record the peak of diversity of benthic organisms and a high diversity of planktic invertebrates (Fig. 7). The waters must have been relatively shallow and warm, agitated, well-oxygenated, and with normal salinity, thus allowing for the proliferation of inoceramids, gastropods and non-inoceramid bivalves. Perhaps, the gigantic sizes and radial ribs of most of the inoceramids and gastropods may furnish some evidence for high energy levels in the basin. However, the origin of radial ribbing, and the repeated evolution of radial sculpture in the inoceramids throughout the Cretaceous probably had multiple causes.

The domination of the subfamily Sachalinoceraminae and representatives of the gastropod genus *Gigantocapulus*, and the abundance of non-inoceramid bivalves, characterize this interval everywhere in the West Pacific province (WP *sensu* Page, 1996). The absence of foraminifers may have resulted from stressful life conditions and/or may be a taphonomic signature. The elevated diversity and abundance of plano-spiral ammonites, the overall domination of pachydiscids, the reduced importance of heteromorphs, and the sandy lithofacies point to rather high-energy, nearshore deposition. Interestingly, this interval is characterized by the maximum taxonomic diversity of the radiolarians (Fig. 7), an effect that could have been related to a eutrophic regime (RACKI & CORDAY, 2000, p.23–25). The richest radiolarian assemblage is from upper Campanian siliceous shale of section N21 in the Terpenja Peninsula (Fig. 1). It is possible that the East-Sakhalin Mountains sections occupied a deeper part of the basin and that the volcanic and tectonic activity was much higher there. The majority of inoceramid and ammonite records are bad-preserved and rare here. In summary, the existence of optimal environmental conditions for benthic and planktic groups can be presumed. In total, 92 taxa from six faunal groups have been identified from sediments of Member 1 of the Krasnoyarka Formation (Fig. 7).

The next depositional phase is recorded by members 2 and 3 of the Krasnoyarka Formation (Fig. 2). These members were deposited during an episode of transgression, falling temperature and probably a change of salinity level, as judged by the decrease in benthic fauna diversity (FÜRSICH et al., 1995). As compared to the underlying zone, the faunal assemblage from this interval (*Canadoceras multicostatum*/*Inoceramus* sp. aff. *balticus* Zone) is strongly reduced as a result of these environmental changes to 54 species (Fig. 7). During deposition of members 2 and 3, all of the inoceramids and ammonites gradually disappeared. Faunas in Member 2 are dominated by ammonites and contain few radiolarians. In Member 3, the proportion of ammonites is reduced, *Inoceramus* sp. aff. *balticus* appears, and 17 species of benthic foraminifers have been identified (POYARKOVA, 1987). The water were probably of variable depth, cold, poorly oxygenated, with a tendency to low levels of salinity during this depositional phase. Comparatively poor faunal assemblages characterize the upper part of the upper Campanian; a significant biotic recovery in Sakhalin is not apparent until the middle Maastrichtian.

6. DISCUSSION

At the Brussels Symposium it was recommended that the base of the Campanian should be linked directly or indirectly to the 33R/34N palaeomagnetic boundary (HANCOCK & GALE, 1996). This was the only adopted recommendation that can be applied in Sakhalin and the northeastern region of Russia given the general problems of correlating this boundary into the Pacific region (YAZYKOVA, 1996, 2002). The subject is further complicated because of the discrepancy that exists between the biostratigraphic schemes for Sakhalin and Japan, and this needs further study. In the present paper we recommend the addition of some complementary criteria for the definition of Cretaceous stage and substage boundaries in the West Pacific province. For instance, it seems possible to chose any regional criteria for stage and substage boundaries based on the morphological similarity between some Pacific and European or Mediterranean taxa and establish regional stratotypes (hypostratotypes *sensu* HEDBERG, 1976) that would facilitate interregional correlation. VERESCHAGIN (1977), COLLIGNON (1977), KAUFFMAN (1977) and ZONOVA et al. (1993) described similarities between some Pacific and European taxa. *Anapachydiscus* (*Neopachydiscus*) *naumanni* and *Inoceramus nagaoi* are examples of such taxa in the Campanian stage.

Unfortunately, the picture is confused by the publication of differing interpretations of the Campanian Stage in Sakhalin. Thus, in ALABUSHEV & WIEDMANN (1997), the base of the Campanian was defined by the first appearance of *Ryugasella ryugasensis* WRIGHT & MATSUMOTO, *Pseudophyllites indra* (FORBES), *Menuites japonicus* MATSUMOTO, *Diplomoceras notabile* (WHITEAVES) and *Pachydiscus egertoni* (FORBES). As mentioned previously (Fig. 3), *Pachydiscus* (*P.*) aff. *egertoni* has been found in Member 1 of the Krasnoyarka Formation and is not known below this level (POYARKOVA, 1987; ZONOVA et al., 1993; YAZYKOVA, 1996, 2002). *Ryugasella ryugasensis* and *Diplomoceras notabile* appear in the *Canadoceras kossmati* Zone in the upper part of the lower Campanian. *Menuites japonicus* first appears in the uppermost Santonian and its first occurrence cannot be used as a diagnostic criterion for the boundary. *Pseudophyllites indra* occurs in the upper Campanian in Sakhalin and from Santonian through Lower Maastrichtian strata of Japan, Madagascar and India. (COLLIGNON, 1977; POYARKOVA, 1987; ZONOVA et al., 1993; YAZYKOVA, 1996, and others). This species, therefore, cannot be employed as the index species for the boundary because of its long stratigraphic range. Furthermore, some authors have noted *Scaphites* finds from Santonian sequences in Sakhalin. Such records may have resulted from erroneous interpretations of the stratigraphy in key sections since the last *Scaphites* in Sakhalin occur in the lower Coniacian. The lithologically monotonous character of the strata and tectonic repetitions in the river Naiba section may have caused such problems. Specimens of *Bostrychoceras polyplocum* (ROEMER) and *Eubostrychoceras japonicum* (YABE) were not figured by ALABUSHEV & WIEDMANN (1997), and we cannot judge these records. These species have not been recorded from Sakhalin by any other workers. Thus, it appears that practically all of the cited criteria for the recognition of the Santonian/Campanian boundary in ALABUSHEV & WIEDMANN (1997) cannot be confirmed or are apparently erroneous.

Moreover, ALABUSHEV (1995) recorded a limestone (?) in the river Naiba, even though there are no limestones in this or any other sections in Sakhalin. No Campanian carbonates have been described in Sakhalin or in other north Pacific regions by any other Japanese or Russian workers (MATSUMOTO, 1959a; VERESCHAGIN et al., 1965; POYARKOVA, 1987; ZONOVA et al., 1993; YAZYKOVA, 1994; 1996; ZAKHAROV et al., 1996; SHIGETA et al., 1999; KODAMA et al., 2000; KIRILLOVA et al., 2000, and others).

Another serious error regarding the interpretation of the Campanian in Sakhalin is found in ZAKHAROV et al. (1996), where, probably as a result of misidentification, the *Anapachydiscus* (*Neopachydiscus*) *naumanni* – *Peroniceras* Zone was established in the Santonian. The key specimens, however, were not figured so it is difficult to confirm or refute the identification. From various publications it is well known that *Anapachydiscus* (*Neopachydiscus*) *naumanni* is characteristic of the lower Campanian whereas *Peroniceras* is an indicator of the Coniacian Stage. It seems that the former was mixed up with *Eupachydiscus haradai* (JIMBO), which is well known from the Santonian of Sakhalin, Korjakia, Japan (YAZYKOVA, 1992; ZONOVA et al., 1993) and Madagascar (COLLIGNON, 1938, 1955) and *Peroniceras* was probably confused with *Texanites*, a guide fossil for the Santonian in many regions in the world.

7. CONCLUSIONS

1. The Campanian interval of the Cretaceous succession in Sakhalin Island (Far East Russia) presents a rich record of fairly well preserved ammonites, inoceramids, radiolarians, benthic foraminifers, gastropods and non-inoceramid bivalves, consisting of mostly endemic species and few cosmopolitan forms.
2. A high-resolution, integrated biostratigraphic zonation based on ammonites, inoceramids and radiolarians is proposed and correlated with adjacent areas. The zonal scheme comprises four ammonite zones, four inoceramid zones and two radiolarian zones.
3. The definition of the Campanian stage and substage boundaries in Sakhalin and some possibilities for global correlation are discussed: *Anapachydiscus (Neopachydiscus) naumanni* (YOKOYAMA) and *Desmophyllites diphylloides* (FORBES) are the main index taxa for the base of the Campanian Stage in Sakhalin; The F.O. of *Anapachydiscus arrialoorensis* (STOLICZKA) defines the base of the upper Campanian; *Pachydiscus (P.) subcompressus* MATSUMOTO and *Pachydiscus (P.) gollevillensis* (D'ORBIGNY) are the main criteria for the base of the Maastrichtian Stage. *Anapachydiscus (Neopachydiscus) naumanni* (YOKOYAMA) and *Inoceramus nagaoi* MATSUMOTO & UEDA could be used as vicarious species [vicarious -i.e. similar forms found in geographically widely separated regions] for interregional correlations.
4. Changes in the biodiversity presented on figures 2–5,7 were investigated within a context of relative sea-level changes and other environmental changes published elsewhere. The dominantly shallow marine environment of the outer shelf basin as part of an active marginal sea, revealed by the palaeontological associations and sedimentary structures, probably changed from a more or less deep and cool, well-oxygenated offshore zone to a shallower, warm and agitated nearshore zone, then returning to an offshore zone but with poorly ventilated deep and cold, lower-salinity waters. The maximum diversity of planktic and nektic groups is established at the base of the lower Campanian. The peak of diversity of benthic groups is recorded at the base of the upper Campanian and associated with high diversity of planktonic groups. The end of the Campanian was a time of low diversity of all faunal groups in the Sakhalin palaeobasin.

Acknowlegements: Heartily acknowledged is James Crampton, who not only made a detailed review of our paper, but also discussed its numerous aspects and, last not least, corrected our English. We are also indebted to Chris Wood for his critical remarks, which have improved this manuscript. Thank you very much!

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