Ammonite and inoceramid radiations after the Santonian–Campanian bioevent in Sakhalin, Far East Russia

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Study of several marine Santonian–Campanian successions from Sakhalin Island, Far East Russia, has revealed that evolution of the ammonites and inoceramid bivalves proceeded at different rates after the major faunal turnover at the (locally defined) Santonian–Campanian boundary. Sometimes changes in the inoceramid assemblages were more frequent and rapid than changes in the ammonite assemblages, and sometimes vice versa. Significant levels of inoceramid turnover and radiation events have been identified at the (locally defined) Santonian–Campanian and lower-upper Campanian boundaries. Changes in ammonite and inoceramid diversity, and in the proportions of endemic and cosmopolitan species, were investigated in the context of the local relative sea-level curve and inferred environmental changes. In Far East Russia, the main ammonite and inoceramid radiation after the local Santonian–Campanian faunal turnover occurred in the early Late Campanian *Pachydiscus (P.)* aff. *egertoni* ammonite Zone and the coeval *Schmidticeramus schmidti* inoceramid Zone. This condensed interval of ammonite and inoceramid maximum diversity provides a perfect stratigraphic marker that is recognizable in Sakhalin, North-East Russia and Japan. The succession of Santonian–Campanian assemblages identified in Sakhalin enabled the establishment of seven ammonite and six inoceramid zones, which correlate relatively well with those of North-East Russia and Japan. The problems of placing the Santonian–Campanian boundary in Sakhalin and in the adjacent Japanese island of Hokkaido are reviewed. ☐ *Ammonites, Campanian, diversity, endemism, inoceramids, radiation, Sakhalin, Santonian.*

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The Cretaceous faunas from Sakhalin (Fig. 1) are characterized by a high degree of endemism, which complicates stratigraphic interpretation and reconstruction of the paleogeography. However, the taxonomic diversity and abundance of the fossils enable phylogenetic studies and the identification of globally significant bioevents in the evolution of the different faunal groups. These bioevents facilitate correlation within and outside the Pacific Realm, in spite of the predominance of endemic forms.

One of the sharpest faunal turnovers in the Cretaceous of Sakhalin occurs at the local Santonian–Campanian boundary (Yazykova 1996). This bioevent occurred in a Coniacian–Campanian period of generally elevated sea level (Kauffman & Hart 1996) and is located near to a 3rd-order sequence boundary (Kauffman 1985).

Santonian–Campanian successions are widely distributed in Sakhalin. The sequence is composed mainly of marine deep water, slope to basinal sediments, but regressive shallow water sandstone deposits occur at certain levels. The succession has been studied in more than 10 sections in the West Sakhalin Mountains. The studied interval extends from Member 8 of the Bykov Formation up to Member 3 of the Krasnoyarka Formation (Fig. 2) – an interval that is generally more then 1000 m thick (Poyarkova 1987). The lithologies comprise mudstones interbedded with siltstones, sandstones, and tuffaceous sandstones. At the base of the Krasnoyarka Formation there is a conglomerate (Zonova *et al.* 1993). Numerous fossils, predominantly ammonites and inoceramids, were collected throughout the succession, mostly from calcareous concretions. Ammonites and inoceramids are the two most common fossil groups in the Santonian–Campanian of the Pacific region and are potentially important biostratigraphic tools because of their rapid evolutionary rates. The succession of Santonian–Campanian assemblages from Sakhalin, in conjunction with comparative material from North-East Russia, was used to establish complementary ammonite and

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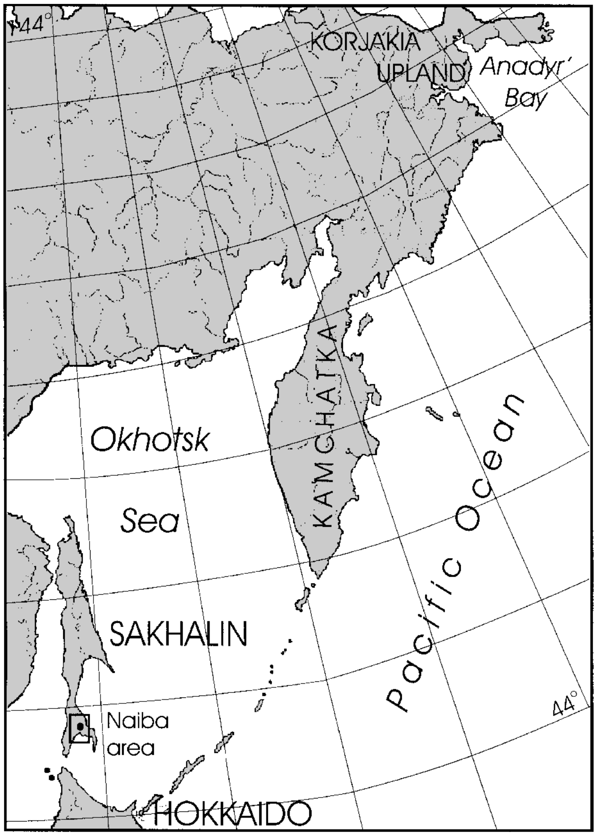

Fig. 1. Location map of the Sakhalin Island and study area (river Naiba area), Far East Russia. The Nabia area is situated in the southern part of the West Sakhalin Mountains. The West Sakhalin Mountains extend from the south-western part of the Sakhalin Island and northward for about 640 km.

inoceramid zonal schemes for this interval. Significant levels of inoceramid turnover and radiation events have been identified. Changes in ammonite and inoceramid diversity, and in the proportions of endemic and cosmopolitan species, were investigated in the context of the relative sea-level curve established by Zakharov *et al.* (1996) for this region (Fig. 3).

The evolutionary development of these two faunal groups in Sakhalin after the faunal turnover at the local Santonian–Campanian boundary proceeded at different rates. In contrast to the changes in the ammonite assemblages, changes in the inoceramid assemblages were generally more rapid. However, sometimes the ammonites reacted faster to the environmental changes. On the other hand there are some parts of the succession where the ammonite diversity decreases or does not change at all, and the inoceramid diversity increases, or vice versa (Fig. 3). Detailed analysis of successive assemblages collected bed by bed throughout the succession has shown that the major bioevents occurred during periods of significant environmental changes. The influence of three factors (drop in temperature, oxygen deficit and eustatic sea-level fluctuations) is inferred to have been the main reason for appearances and disappearances in the ammonites and inoceramids.

The problem of defining the Santonian–Campanian boundary in Far East Russia and Japan

None of the three criteria recommended at the Second International Symposium on Cretaceous Stage Boundaries, Brussels, 1955 – namely the extinction of the crinoid genus *Marsupites*, the first appearance of the ammonite *Placenticeras bidorsatum* and the evolutionary first appearance of the belemnite *Gonioteuthis granulataquadrata* (see Hancock & Gale 1996) – can be applied in North-East Russia, Far East Russia or Japan, because the taxa in question have not been recorded in these areas.

The local Santonian–Campanian boundary in Far East Russia as currently understood is placed in Member 10 of the Bykov Formation of the south Sakhalin sections. It is recognized by the first appearance of the inoceramid bivalve *Inoceramus nagaoi* and the ammonite *Anapachydiscus (Neopachydiscus) naumanni*. The entry of the former is used as the marker for the stage, because it is morphologically similar and interpreted as vicarious to *I. azerbaijanensis*, a Campanian taxon of both the Boreal and Tethyan realms. Numerous finds of both of the Sakhalin zonal index taxa have been made throughout Sakhalin as well as in the Korjakia Upland in the north of Far East Russia (Fig. 1); the two taxa are also known from Japan. The base of the local Campanian can additionally be traced in Sakhalin (Poyarkova 1987; Zonova *et al.* 1993) as well as in the adjacent Japanese island of Hokkaido (Matsumoto 1977; Toshimitsu *et al.* 1995) by the last appearance of *Texanites* and by the first appearance of *Desmophyllites diphylloides* and *Phyllopachyceras ezoense* (Toshimitsu *et al.* 1995; Yazykova 1996).

However, in northwestern Hokkaido, which is in the same biotic province as Sakhalin, Toshimitsu & Kikawa (1997) have placed the local Santonian–Campanian boundary at the boundary between the *Inoceramus amakusensis* Zone and the *Inoceramus (Platyceramus) japonicus* Zone, at the first occurrences of the ammonites *Submortoniceras* cf. *condamyi* or *Menabites mazenoti*. In the zonal scheme of the present article (Fig. 7), the boundary betweeen the *Inoceramus amakusensis* Zone and the *Inoceramus (Platyceramus) japonicus* Zone is actually taken in Sakhalin to mark the base of the upper Santonian Substage rather than the top of the Santonian Stage. Furthermore, neither

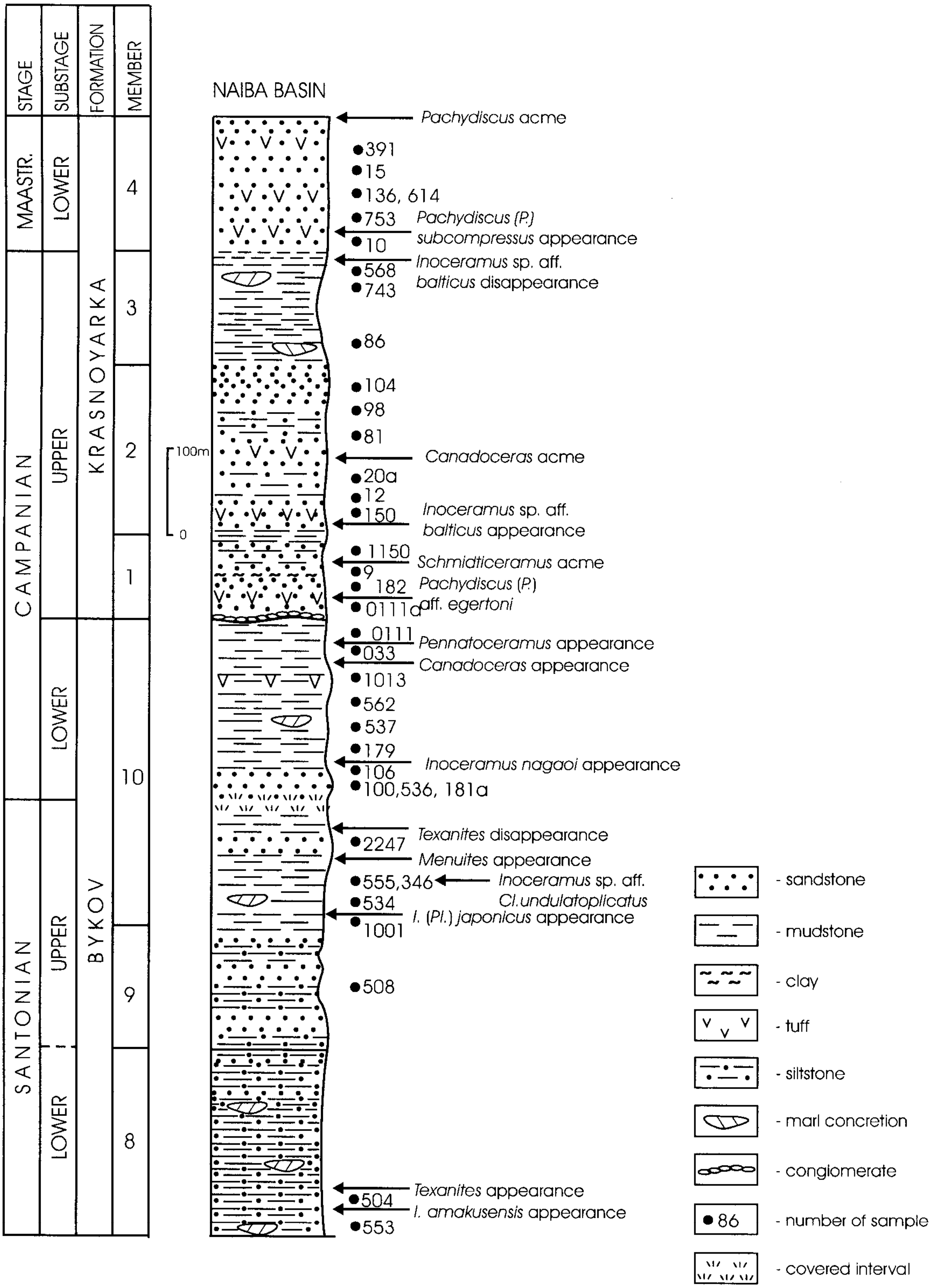

Fig. 2. Composite Santonian–Campanian stratigraphic section of Sakhalin (Poyarkova 1987).

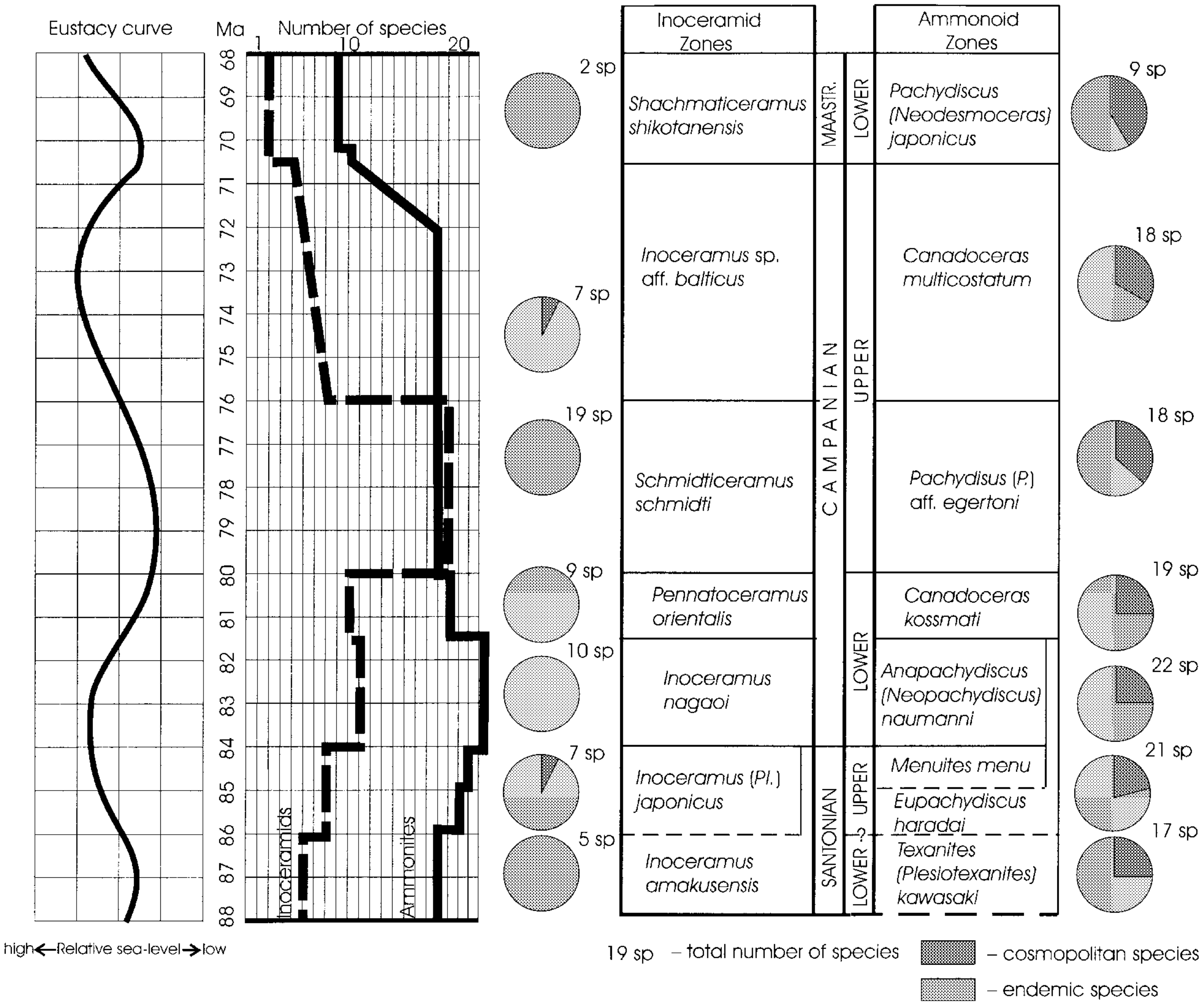

Fig. 3. Relative sea level (Zakharov *et al.* 1996), ammonite and inoceramid species diversity, proportions of endemic and cosmopolitan species and zonal schemes for the Santonian-lower Maastrichtian sequences in Sakhalin.

of the two above-mentioned Japanese ammonite species has been found in Sakhalin.

Toshimitsu & Kikawa (1997) established a K-Ar age of 82 ± 0.6 Ma for a tuff in the lower part of the *Inoceramus (Pl.) japonicus* Zone in the southern part of Hokkaido, which correlates approximately with the most recently published boundary age of 83.5 ± 0.5 Ma (Gradstein *et al.* 1999). Unfortunately there have been no corresponding investigations in Sakhalin using the K-Ar method, and we are consequently unable to change the position of the boundary at present on the basis of the data from Japan.

At the Brussels Symposium it was additionally recommended that the base of the Campanian should be linked directly or indirectly to the 33R/34N palaeomagnetic boundary. On the basis of palaeomagnetic data (Toshimitsu *et al.* 1995), the base of the Campanian in Japan should be placed at the top of the *Inoceramus (Platyceramus) japonicus* Zone as that zone is used in Japan, rather than at the base (Fig. 7). Recent palaeomagnetic data from the south Sakhalin sections (Kodama *et al.* 2000) show a gap in data between the 33R and 34N palaeomagnetic zones within Member 10 of the Bykov Formation, approximately in the upper part of the *Inoceramus (Pl.) japonicus* Zone. This part of the succession is covered (Fig. 2) and extends from the last occurrence of *Texanites* to the first occurrence of *Inoceramus nagaoi.* It is possible that a hiatus is present at this palaeomagnetic boundary interval (e.g. Toshimitsu & Kikawa 1997). In any case, these results indirectly substantiate the relative position of the Santonian–Campanian boundary in Sakhalin at the base of the *Inoceramus nagaoi* inoceramid Zone and the *Anapachydiscus (Neopachydiscus) naumanni* ammonite Zone.

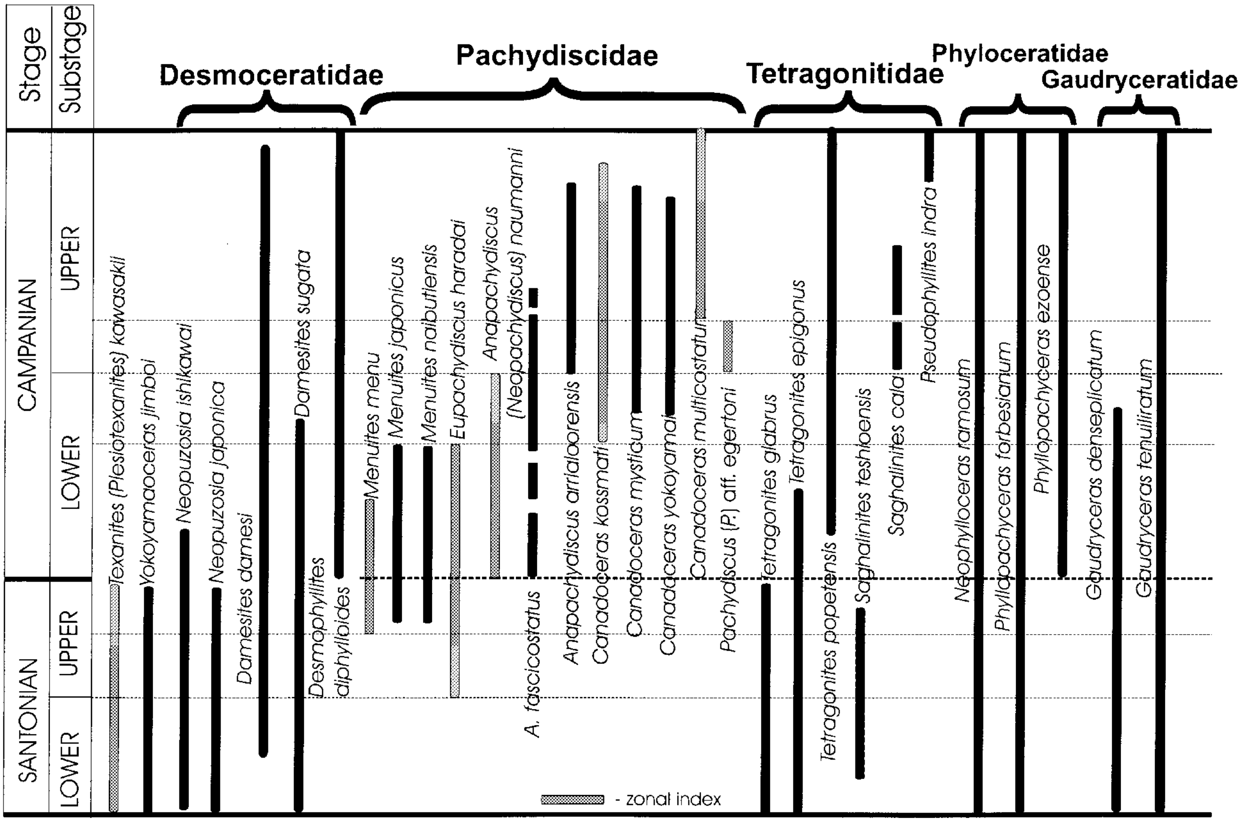

Fig. 4. Stratigraphic distribution of the Santonian–Campanian non-heteromorph ammonite species in Sakhalin.

Ammonite and inoceramid assemblages in the Santonian–Campanian of Sakhalin

Santonian

During the Santonian–Campanian, the Sakhalin basin was part of a marginal sea (Kirillova 1997). The Early Santonian global regression (Haq *et al.* 1987) was reflected here by a relative fall in sea level and by shallow-water sedimentation of the sandy siltstone of Member 8 and the coarse sandstone of Member 9 of the Bykov Formation (Figs 2, 3). During the late Santonian global sea-level rise, a transgressive cycle of sedimentation is observed in the Naiba section, recorded by the finely-stratified mudstones with marl isolated concretions of the lower part of Member 10 (Fig. 2).

Three ammonite zones and two inoceramid zones are assigned to the Santonian in this report (Figs 3, 7). The oldest ammonite zone, the *Texanites (Plesiotexanites) kawasakii* Zone, contains *Texanites, Yokoyamaoceras, Neopuzosia, Damesites, Tetragonites, Saghalinites, Neophylloceras, Phyllopachyceras* and *Gaudryceras* (Fig. 4) as well as the heteromorph genera, *Polyptychoceras, Subptychoceras* and *Pseudoxybeloceras* (Fig. 5). The percentage of cosmopolitan species is relatively moderate, approximately 45%. The species of *Yokoyamaoceras, Neopuzosia, Saghalinites* and *Gaudryceras* belong to endemic lineages. *Texanites* appeared in south Sakhalin at the onset of the Early Santonian regression. This genus is not known from northern territories (Korjakia Upland, north-western coast of Kamchatka Peninsula, Anadyr' Bay) of Far East Russia. It is possible (cf. Cobban 1993) that *Texanites* was a migrant from Texas or Mexico, where the genus is common. The *Texanites (Plesiotexanites) kawasakii* Zone is characterized by long-ranging ammonite species, with only three species appearing at the base of the Santonian. The coeval *Inoceramus amakusensis* Zone is likewise marked by the appearance of only three new species: *Inoceramus amakusensis, I. ezoensis, I. subyokoyamai*, and the whole assemblage is totally endemic (Fig. 3). Such a low degree of origination could be explained by environmental changes which took place in the earliest Santonian. For example, Zakharov *et al.* (1998) recorded a low temperature at this time based on positive values of δ^{18}O in the aragonite of ammonite shells from south Sakhalin.

At the beginning of the global late Santonian

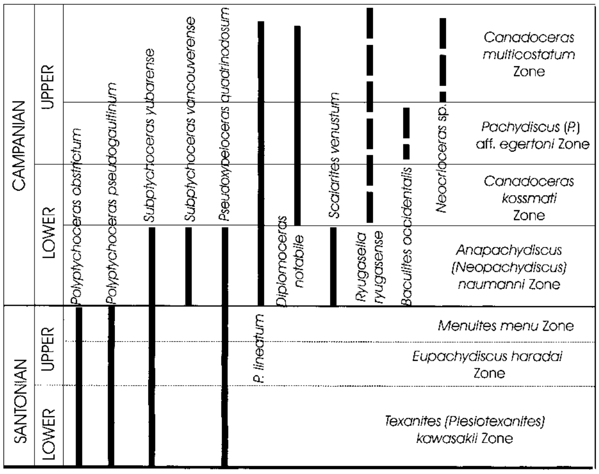

Fig. 5. Stratigraphic distribution of the Santonian–Campanian heteromorph ammonite species in Sakhalin.

transgression (Haq *et al.* 1987) in the Sakhalin palaeobasin, new species of inoceramids with a new type of radial shell sculpture appeared (the eponymous index *Inoceramus (Platyceramus) japonicus* and single records of '*Inoceramus*' sp. aff. *Cladoceramus undulatoplicatus*) (Figs 6, 7). These were probably the predecessors of a large late Campanian inoceramid group with radial shell sculpture (Zonova 1984). However, in contrast to that of their descendants, the structure of the ligament apparatus of these two taxa was still the same (two-component) as that in the majority of the Santonian inoceramids with concentric shell sculpture (Zonova 1984).

Practically simultaneously with the entry of *I. (Pl.) japonicus* the first representatives of the family Pachydiscidae appeared: first, *Eupachydiscus haradai*, followed, a little later, by *Menuites menu* (Fig. 4). This family dominated the ammonite assemblages and reached its taxonomic acme in the late Campanian–Maastrichtian. Zakharov *et al.* (1998) recorded negative δ^{18}O values probably indicating some increase in temperature aproximately in the early late Santonian.

The heteromorph ammonite assemblage hardly changed at all during the Santonian. The whole complex consists of four endemic species, two of which disappeared at the local Santonian—Campanian boundary, with three new taxa appearing in the early Campanian (Fig. 5). In general, heteromorph ammonites are rare from the Santonian to the

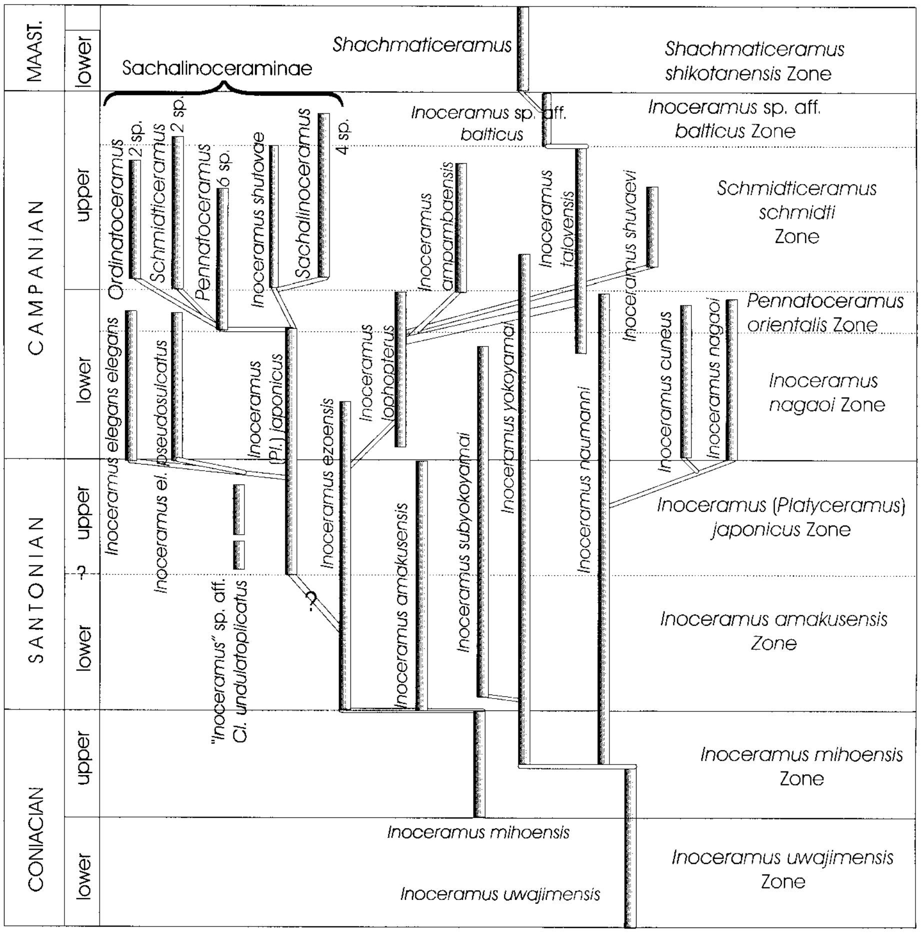

Fig. 6. Phylogeny of Santonian–Campanian Pacific inoceramid species (modified after Zonova 1984).

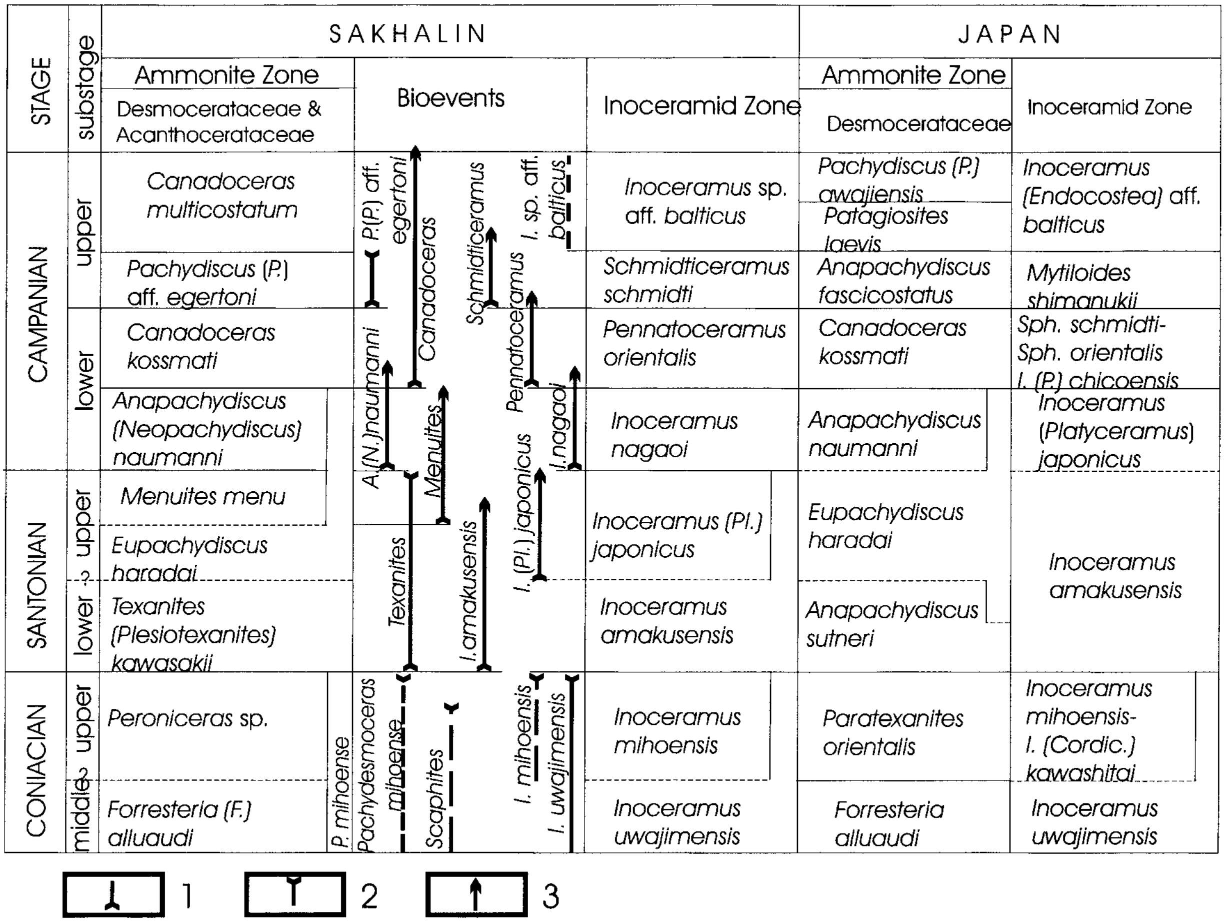

Fig. 7. Ammonite and inoceramid zonation of the Coniacian through Campanian in Sakhalin Island (by the author) and in Japan (Toshimitsu *et al.* 1995). 1 – appearance event; 2 – disappearance event; 3 – continuation into the next zone(s).

Maastrichtian of Sakhalin. In the northern territories of Far East Russia they are completely absent in this interval, albeit well represented in the Turonian–Coniacian of the northwestern coast of the Kamchatka Peninsula and the Korjakia Upland (Zonova & Yazykova 1998).

In the latest Santonian, Zakharov *et al.* (1998) calculated a local gradual temperature fall based on positive δ^{18}O values. The last species of *Texanites* and *Yokoyamaoceras* disappeared during the continuous transgression at the end of the Santonian, as well as *Tetragonites glabrus, Saghalinites teshioensis* (Fig. 4) and the inoceramid *Inoceramus amakusensis* (Fig. 6).

Campanian

Four ammonite zones and four inoceramid zones are assigned to the Campanian in this report (Figs 3, 7). The affinities of the Campanian ammonite faunas of Far East Russia are virtually a continuation of the trend in the late Santonian: no collignoniceratids at all, a gradual decrease in desmoceratids and heteromorph ammonites, and an increase in the numbers and taxonomic diversity of the pachydiscids. The main evolutionary trend of the North Pacific inoceramid fauna during the Campanian was the development of a new lineage comprising the group of species characterized by radial ribs and a three-component structure of the ligament apparatus.

At a time of a temperature decrease inferred from high δ^{18}O values (Zakharov *et al.* 1996, 1998), the total number of ammonite and inoceramid species increased in the *Anapachydiscus (Neopachydiscus) naumanni* Zone and coeval *Inoceramus nagaoi* Zone (Fig. 3). The inoceramid assemblage is totally endemic and the ammonite assemblage is largely endemic, with only 6 (out of 22) cosmopolitan species. The degree of endemism is as high as before and even shows a slight increase. At this time the new species with radial ribs (*Inoceramus elegans, I. elegans pseudosulcatus*) appeared simultaneously with *I. nagaoi* close to the base of the Campanian (Fig. 6). However, these species still do not have the typical radial sculpture of the later Campanian taxa and they retain the two-component structure of the ligament apparatus. The first typical radiate-ribbed inoceramids (*Pennatoceramus)* appeared in the late early Campanian (*Pennatoceramus orientalis* Zone). *Pennatoceramus* species possessed radial ribs and a three-component structure of the ligament apparatus that is known only among Campanian radiate-ribbed inoceramids of the subfamily Sachalinoceraminae (Fig. 6) in the North Pacific (Zonova 1984). The appearance of *Pennatoceramus* was accompanied by the entry of *Canadoceras*, the next pachydiscid taxon (*Canadoceras kossmati* Zone), and the disappearance of the last *Menuites, Eupachydiscus* (Fig. 4), *Subptychoceras* and *Scalarites* (Fig. 5). In addition, six inoceramid species became extinct at the end of the early Campanian (Fig. 6).

The local lower-upper Campanian boundary in south Sakhalin is placed at the base of the Krasnoyarka Formation and recognized by the first occurrence of *Anapachydiscus arrialoorensis*. It is unclear how this definition of the boundary relates to boundary criteria used elsewhere. The author suggests that the presence of a conglomerate at the base of this formation (Figs 2, 3) indicates a hiatus resulting from the regressive cycle of the 3rd-order sea-level change. Zakharov *et al.* (1998), based on a shift in δ^{18}O values in well-preserved brachiopod shells from south Sakhalin, calculated a relatively high temperature in the lower upper Campanian (member 1 of Krasnoyarka Formation). Those authors also recorded a relatively positive shift in δ^{13}C values at this level and suggested that this might point to an increase in oceanic bioproductivity. They additionally noted the beginning of strong volcanic activity. However, in contrast to Zakharov *et al.* (1996), Kirillova (1997), Kirillova *et al.* (2000) and Filatova (1995, 1997) stated that there was a gradual decline in volcanism connected with the end of subduction of oceanic plates in the North Pacific during the late Cretaceous. In spite of this discrepancy relating to the degree of volcanism, there definitely appear to have been optimal environmental conditions at this time, which may have led to the general increase in the bioproductivity of the North Pacific at the end of the early Campanian.

The main inoceramid radiation after the Santonian–Campanian crisis occurred in the *Schmidticeramus schmidti* Zone (19 species) at the beginning of the late Campanian. On the other hand, the main ammonite radiation occurred a little earlier, in the *Anapachydiscus (Neopachydiscus) naumanni* Zone (22 species) in the early Campanian (Fig. 3). This clearly shows the differing evolutionary rates of these two groups.

The *Pachydiscus (P.)* aff. *egertoni* Zone is characterized by abundant and relatively high diverse ammonite assemblages (18 species), mainly members of the family Pachydiscidae, such as the zonal index, *Canadoceras kossmati, C. yokoyamai* and *C. mysticum* (Yazykova 1996). The coeval *Schmidticeramus schmidti* inoceramid Zone is marked by a high taxonomic diversity. Only three species, *Inoceramus ampambaensis, I. talovensis* and *I. shuvaevi,* lack radiate sculpture (Fig. 6). Among the radiate-ribbed inoceramid genera (*Pennatoceramus, Schmidticeramus, Sachalinoceramus* and *Ordinatoceramus*), there is a great variety of arrangements of radial ribs, combinations of radial and concentric ribs, shell forms, and also in the presence or absence of a wing. Coquina beds are very characteristic of this level.

The numerous inoceramids and ammonites of the *Schmidticeramus schmidti/Pachydiscus (P.)* sp. aff. *egertoni* Zone are associated with huge patellid gastropods (*Gigantocaplus giganteus*), which have similar radial ribs to those of the inoceramids. It is noteworthy that comparable *Patella*-like gastropods have not been observed above or below this zone in Sakhalin and Kamchatka or in Japan and Alaska (Kanie 1977; Shigeta *et al.* 1999). Kanie (1977) proposed that the radial sculpture of both the inoceramids and the gastropods was probably connected with strengthening the shell as adaptations to changing environmental conditions, which could have been shallow storm-water conditions of the continental shelf and/or the effects of submarine volcanic activity. However, it should be noted that comparable radiate ribbing in inoceramids is also found in shallow-water deposits in the lower Turonian of Brazil (genus *Rhyssomytiloides*) but in deeper water sediments, including chalks, in the lower Santonian of northern Europe and North America (*Cladoceramus undulatoplicatus*). The complex three-component structure of the ligament apparatus of the radiate-ribbed inoceramids noted above also probably served for general strengthening of the shell. Tanabe (1973) suggested these morphological changes in inoceramids came about as a result of adaptation to a change from a pseudoplanktonic (epiplanktonic) to a benthonic mode of life. However, in contrast to Zonova (1984), who derived *Schmidticeramus* from *Inoceramus (Pl.) japonicus*, he proposed that *Inoceramus naumanni* was the precursor of *I. schmidti*, i.e. *Schmidticeramus* herein. The author of the present paper follows Zonova (Fig. 6).

The ammonites in the *Schmidticeramus schmidti/Pachydiscus (P.)* aff. *egertoni* Zone also feature thicker shells, ornamented by numerous ribs and lacking any spines and tubercles. Both the inoceramids and the ammonites show a high degree of endemicity as before, the inoceramid assemblage being totally endemic (Fig. 3). The general thickness of the zone, which is coextensive with Member 1 of the Krasnoyarka Formation, is about 100 m. Member 1 is a very good marker that can be traced over thousands of kilometres inside the North Pacific region, i.e. Japan, Sakhalin, Kamchatka, Korjakia, Alaska (Matsumoto 1959, 1977; Kanie 1977; Zonova 1984; Zonova *et al.* 1993; Toshimitsu *et al.* 1995).

The majority of the radiate-ribbed inoceramids disappeared in the late Campanian (Fig. 6), with only a few species persisting into the terminal Campanian *Inoceramus* sp. aff. *balticus* Zone and the coeval *Canadoceras multicostatum* Zone. The ammonites then entered a phase of nomismogenesis (*sensu* Walliser 1995), i.e. the relatively stable stage of development, which lasted up to the middle of the late Campanian (Yazykova 1996). *Canadoceras multicostatum* and *Pseudophyllites indra* appeared in the latest Campanian (Figs 4, 5) and disappeared in the Early Maastrichtian. Throughout this zone (Member 3 of the Krasnoyarka Formation) the numbers and taxonomic diversity of both groups show a gradual decrease. This decrease follows the new local transgressive–regressive cycle (Fig. 3) and also parallels a fall in temperature calculated from increased δ^{18}O values in the aragonite of ammonite shells and the calcite of well-preserved brachiopod shells from south Sakhalin (Zakharov *et al.* 1996, 1998).

In the latest Campanian, Zakharov *et al.* (1996, 1998) noted a local regressive cycle in Sakhalin coincident with the global 3rd-order sea-level fall (Haq *et al.* 1987) and inferred a temperature minimum in the early Maastrichtian based on δ^{18}O values.

In the Maastrichtian, the northern Pacific ammonites again underwent an ‘explosion’ of new taxa, with the evolution of new species of the families Pachydiscidae and Tetragonitidae (Yazykova 1996; Hirano *et al.* 2000) during a global transgression in the late Maastrichtian. The Maastrichtian inoceramid assemblages of Sakhalin are taxonomically impoverished, being represented by the single genus *Schachmaticeramus*. This reflects the fall in generic diversity of this group following the late Campanian radiation in the *Schmidticeramus schmidti* Zone.

Conclusions

Significant levels of faunal turnover and inoceramid radiation events have been identified in the Santonian–Campanian successions of Sakhalin: (1) entry of radiate-ribbed inoceramids with simple (two-component) ligament apparatus at the base of the (locally defined) upper Santonian in the *Inoceramus (Pl.) japonicus* Zone; (2) entry of the radiate-ribbed taxa *Inoceramus elegans elegans, Inoceramus e. pseudosulcatus* and the non-radiate *Inoceramus nagaoi* at the local Santonian–Campanian boundary; (3) maximum ammonite diversity in the early Campanian *Anapachydiscus (Neopachydiscus) naumanni* Zone, and (4) initial radiation of the radiate-ribbed inoceramids with a complex three-component ligament apparatus (Subfamily Sachalinoceraminae) in the late early Campanian *Pennatoceramus orientalis* Zone, followed by the main radiation of the Sachalinoceraminae in the early late Campanian *Schmidticeramus schmidti* Zone (Fig. 6).

The level of ammonite high diversity and inoceramid maximum diversity in the early Late Campanian *Pachydiscus (P.)* aff. *egertoni* ammonite Zone and coeval *Schmidticeramus schmidti* inoceramid Zone provides an excellent stratigraphic marker that can be readily identified in Sakhalin, North-East Russia and Japan.

The sequence of fauna identified in Sakhalin enables the establishment of complementary ammonite and inoceramid zonal schemes for the Santonian–Campanian deposits. Seven ammonite and six inoceramid zones have been distinguished (Fig. 7). These zonal schemes correlate relatively well with those of North-East Russia and Japan.

There is a discrepancy between the concepts of the *Inoceramus (Platyceramus) japonicus* Zone as applied in Sakhalin and in the adjacent Japanese island of Hokkaido, and this discrepancy needs clarification.

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