Taxonomic study of Ordovician (Llanvirn-Caradoc) Radiolaria from the Southern Uplands (Scotland, U.K.)

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ABSTRACT
Over 100 years ago, Hinde (1890a, b) described Radiolaria in thin sections from Ordovician cherts of the Southern Uplands of Scotland and established for the first time the presence of the group in the Early Palaeozoic. Radiolarians from the Southern Uplands have now been successfully extracted by hydrofluoric acid leaching and the systematic palaeontology of some of the yielded morphotypes is discussed herein. The studied fauna come from two outcrops of radiolarites: one at upper Hawkwood Burn and the other north-west of the village of Crawford. Amongst the radiolarians extracted from the latter outcrop, the genera *Inanibigutta* and *Protoceratoikiscum* are common. The presence of the species *Inanibigutta diffusa* (Hinde), *Inanibigutta* (?) *minuta* Wang and *Inanibigutta* sp. cf. *I. verrucula* (Nazarov) allows the correlation of the Crawford fauna with the *Haplentactinia juncta-Inanigutta unica* assemblage in Nazarov's (1988) biozonation, of upper Llanvirn (Llandeilian)-Caradoc age, and with the assemblage documented by Wang (1993) in China, of earliest Caradoc age.

KEY WORDS
Radiolaria, Ordovician, Llanvirn, Caradoc, Southern Uplands, Scotland, United Kingdom, Iapetus Ocean, Caledonides, radiolarian chert.

RÉSUMÉ

Étude taxonomique des radiolaires ordoviciens (Llanvirnien-Caradocien) de Southern Uplands (Écosse, R.U.).

Des radiolaires ordoviciens ont été extraits à l'acide fluorhydrique des radiolarites de l'unité structurale des Southern Uplands en Écosse. Étudiés en lame-mince il y a plus d'un siècle (Hinde 1890a, b) ceux-ci ont servi comme témoin de la présence certaine de ce groupe dans le Paléozoique inférieur. La faune ici étudiée vient de deux affleurements: l'un des radiolarites rouges brunâtres à Hawkwood Burn, l'autre des radiolarites grises qui affleurent au nord-ouest du village de Crawford. La paléontologie systématique de certaines formes intéressantes est ici discutée. Les genres *Inanibigutta* et *Protoceratoikiscum* sont communs parmi les radiolaires extraits des radiolarites de Crawford. La présence des espèces *Inanibigutta diffusa* (Hinde), *Inanibigutta* (?) *minuta* Wang et *Inanibigutta* sp. cf. *I. verrucula* (Nazarov) permet la corrélation de la faune de Crawford avec l'association *Haplentactinia juncta-Inanigutta unica* de la biozonation de Nazarov (1988), d'âge Llanvirnien supérieur (Llandeilien)-Caradocien, ainsi qu'avec l'association décrite par Wang (1993) en Chine, d'âge Caradocien basal.

MOTS CLÉS
Radiolaires,
Ordovicien,
Llanvirnien,
Caradocien,
Écosse,
Royaume Uni,
radiolarites,
Océan Iapetus,
Calédonides.

INTRODUCTION

Despite significant improvements in our understanding of Palaeozoic Radiolaria over the last 35 years, Early Palaeozoic assemblages are still poorly documented (Noble & Aitchison 1995). As a result, our knowledge of the early stages of evolution of this significant planktonic group remains limited. The oldest radiolarian fossils come from late Cambrian shallow-water limestones of China, from which one species has been recently described (Dong *et al.* 1997). Diversification markedly increased during the Ordovician and from the limited work that has been done so far, it is clear that radiolarian evolutionary change during this time was more rapid than previously believed (Renz 1990). The group has therefore the potential to become a valuable biostratigraphic tool for the yet poorly explored Early Palaeozoic interval, with an increasing number of easily identifiable, diagnostic taxa (Aitchison & Noble 1997; Aitchison 1998; Aitchison *et al.* 1998).

There are relatively few localities in the world where well-preserved Ordovician assemblages are known and most of them represent carbonate platform/slope environments (Fortey & Holdsworth 1971; Nazarov & Popov 1980; Webby & Blom 1986; Renz 1990; Wang 1993). Radiolaria of oceanic affinity are common, but less well preserved, in rocks of deep water origin such as radiolarites (ribbon radiolarian cherts with shaly intervals) which are often associated with remnants of oceanic crust in accretionary prisms of ancient subduction zones. They reflect the significant biogeochemical role that Radiolaria started to play in the oceans (i.e. the silica cycle) from the Early Palaeozoic.

The occurrence of radiolarians in cherts of the Southern Uplands terrane (Fig. 1) has been known for over a century. It was on material from this region that Hinde (1890a, b) first established the definite presence of Radiolaria in the Early Palaeozoic. Outcrops of radiolarian cherts were extensively discussed by Peach & Horne (1899), who were responsible for a major mapping compilation of the geology of Southern Scotland. Radiolaria from the Southern Uplands have also been reported by Nicholson (1889) and Smith (1900). The techniques available at

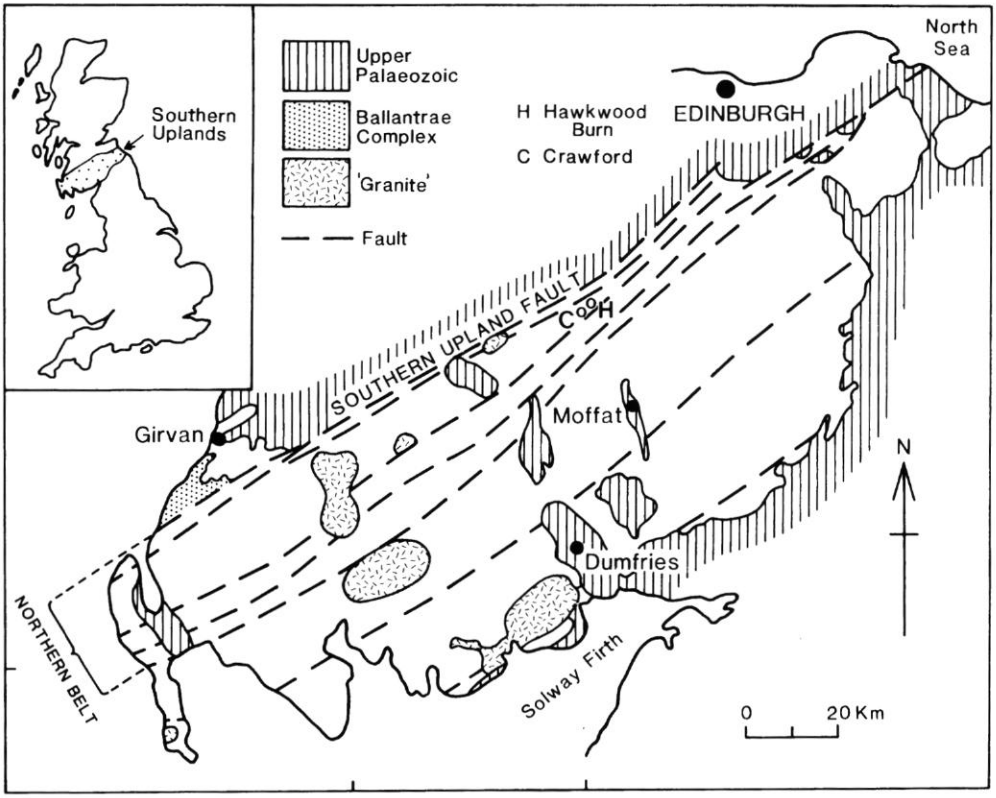

FIG. 1. — Geological outline of the Southern Uplands. Based on McAdam *et al.* (1993).

that time only allowed for study of Radiolaria in thin section, which provided very limited information on their morphology. This was naturally the case for the single previous taxonomic work of Radiolaria from the Southern Uplands (Hinde 1890b) in which 23 new species were described. Recognising the potential of radiolarian studies in the Southern Uplands, a number of radiolarian chert outcrops have already been examined and the results briefly reported (Danelian & Clarkson 1998). This paper focuses on the systematic study of some of the yielded morphotypes based on modern radiolarian taxonomy (e.g., Nazarov & Popov 1980; Nazarov 1988). It attempts to link matrix-free forms to the species described originally by Hinde and to gradually build a detailed and integrated picture of the radiolarian assemblages occuring in these historically important Scottish localities.

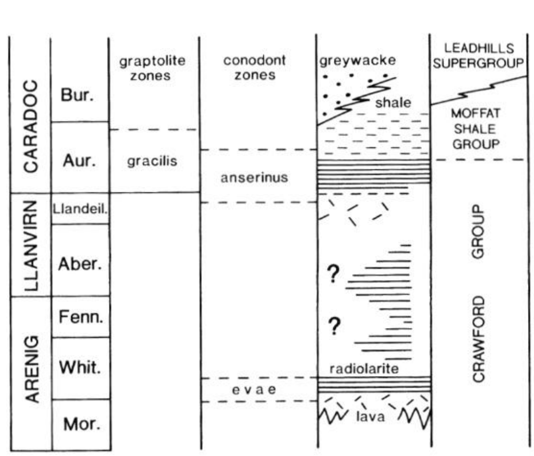

FIG. 2. — Simplified stratigraphy for the Lower-Middle Ordovician of the Southern Uplands, focusing on the Crawford Group. Lithostratigraphic terminology according to Floyd (1996). Chronostratigraphy and biostratigraphy from Fortey *et al.* (1995).

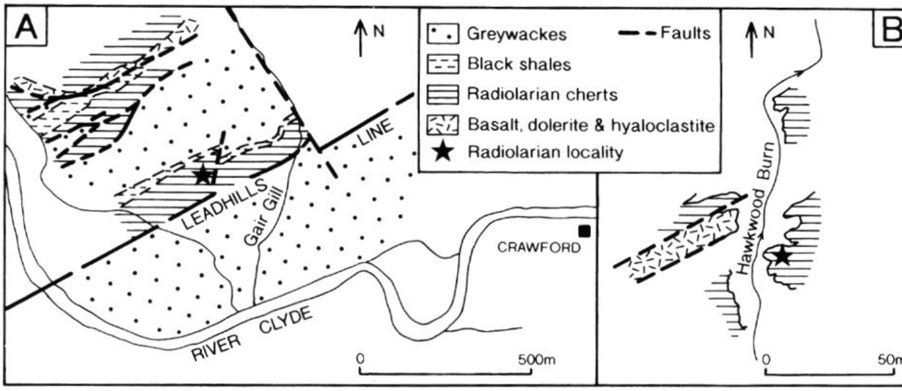

FIG. 3. — Geological map of the studied localities. **A**, north-west of the village of Crawford (after Leggett & Casey 1980); **B**, at Hawkwood Burn (after Clarkson *et al.* 1993).

STRATIGRAPHICAL FRAMEWORK

The Southern Uplands consist largely of Ordovician and Silurian sedimentary rocks of deep-water origin. The oldest rocks at the base of the succession are composed mainly of basaltic lavas, radiolarian cherts and siliceous mudstones. A formal lithostratigraphy for the Ordovician has recently been defined by Floyd (1996). The lavas and radiolarites are part of the Crawford Group of Arenig-Llanvirn age (*sensu* Fortey *et al.* 1995), although based on recent conodont evidence the Group probably extends into the Caradoc (Armstrong *et al.* 1990, 1996). The overlying graptolitic shales of the Moffat Shale Group (Caradoc-Llandovery) are in turn succeeded by the greywacke successions of the Leadhills Supergroup (Fig. 2).

Until recently, the various outcrops of radiolarian cherts in the Southern Uplands were considered as being part of a single continuous stratigraphical sequence, spanning the Arenig and Llanvirn, and overlain by the early Caradoc (*Nemagraptus gracilis* graptolite biozone) Moffat Shale Group (Leggett 1978, 1987). However Armstrong *et al.* (1996), after an extensive revision, suggested that radiolarian cherts could represent two distinct sedimentary events: one during the mid Arenig (*Oepikodus evae* conodont biozone), and one of latest Llanvirn to earliest Caradoc age (*Pygodus anserinus* conodont biozone).

BIOSTRATIGRAPHICAL DISCUSSION

The fauna discussed herein were extracted from two chert samples, one from an outcrop along the lower part of a trackside cutting, north-west of the village of Crawford (National Grid Reference NS 941 215; Figs 1, 3A) and the other from radiolarites cropping out at upper Hawkwood Burn (NS 972 248), a tributary of the Wandel Burn (Figs 1, 3B). Samples were processed with the laboratory technique of hydrofluoric acid (Dumitrica 1970; Pessagno & Newport 1972).

At Hawkwood Burn, the radiolarian cherts are of red-brownish colour and were recently described by Clarkson *et al.* (1993). From the base of these cherts a conodont faunule of late Llanvirn (Llandeilian)-earliest Caradoc age was reported (Armstrong *et al.* 1990, 1996). Although radiolarian preservation here does not allow any confident identification of established species, the fauna seem to be comparable to the *Haplentactinia juncta-Inanigutta unica* assemblage of Nazarov's biozonation (Llandeilian-Caradoc: Nazarov 1988; Nazarov & Ormiston 1993), which is consistent with the age given on the basis of conodonts.

In the second locality, near the village of Crawford, the radiolarites are mainly greenish-grey in colour. No biostratigraphic data other than that provided by the radiolarians exist for the age of this outcrop. The presence of the genus *Protoceratoikiscum* is important because it suggests a Llanvirn-Caradoc interval (*sensu* Fortey *et al.* 1995) as a first approximation for the age of these cherts (Danelian & Clakson 1998). The presence of the species *Inanibigutta diffusa*, established herein (Fig. 4A-D), now allows the correlation of the Crawford fauna with the *Haplentactinia juncta-Inanigutta unica* assemblage of Nazarov's biozonation of late Llanvirn (Llandeilian)-Caradoc age. Moreover, the identification of *Inanibigutta* (?) *minuta* (Fig. 4F-G) and *Inanibigutta* sp. cf. *I. verrucula* (Fig. 4H) allows the correlation of the Crawford assemblage with the one documented by Wang (1993) from the Pingliang Formation, dated as of earliest Caradoc age (common interval between the *N. gracilis* and *P. anserinus* biozones).

SYSTEMATIC PALAEONTOLOGY

Subclass RADIOLARIA Müller, 1858
Superorder POLYCYSTINA Ehrenberg, 1838
emend. Riedel, 1967
Order SPUMELLARIA Ehrenberg, 1857
Family INANIGUTTIDAE
Nazarov & Ormiston, 1984

Genus *Inanibigutta* Nazarov, 1988

Inanibigutta Nazarov, 1988: 56. – Nazarov & Ormiston 1993: 35.

TYPE SPECIES. — *Entactinosphaera aksakensis* Nazarov, 1975.

Inanibigutta diffusa (Hinde, 1890b)
(Fig. 4A-D)

Stauroplegma diffusum Hinde, 1890b: 50, pl. 4, fig. 4.
Entactinosphaera ? *diffusa* (Hinde) – Nazarov & Popov 1980: 37, 38, text-fig. 16, pl. 2, fig. 4, pl. 13, fig. 8.
Inanibigutta diffusa (Hinde) – Nazarov 1988, fig. 31.

OCCURRENCE. — Middle Ordovician (Llandeilan to Lower Caradoc) Bestomakskaya Suite, Eastern Kazakhstan, southwestern foothills of the Chingiz Range, Chagan River (Nazarov & Popov 1980); Broughton Heights, Peebleshire, Southern Uplands (Hinde 1890b); grey radiolarites of the Crawford track, Southern Uplands, this study.

MEASUREMENTS (one specimen). — Diameter of the flattened part of the outer shell, 133-136 µm; diameter of the elongated part of the outer shell, 152-154 µm; length of main spines, 40-50 µm; diameter of inner shell, 63-66 µm.

DESCRIPTION

A nearly spherical outer shell bearing six radiating main spines positioned with hexagonal symmetry. The outer shell is perforated by circular to oval pores of various dimensions. The main spines are robust, rod-like, and gently tapering distally. They are almost half the length of the diameter of the outer shell. A number of needle-like secondary spines cover the surface of the outer shell. The inner shell is relatively small, perforated and linked to the outer shell through radial beams that continue as main spines outside the outer shell. Its position is eccentric in relation to the center of the outer shell (Fig. 4C-D).

REMARKS

The eccentric position of the inner shell was pointed out by Nazarov (*in* Nazarov & Popov 1980) and can be observed on the holotype illustrated by Hinde (1890b), which is obviously a section through an equatorial plan encompassing four spines. Only one specimen in our sample was identifiable with certainty. Nevertheless, several other naturally broken but incomplete specimens may belong to this species (Fig. 4E). The dimensions of our specimen correspond precisely to the ones measured by Hinde (1890b). However, Nazarov (*in* Nazarov & Popov 1980) accepted a larger variability of size for this species, especially as far as the length of spines is concerned. The latter author also mentioned that a spongiform texture was observed on the outer shell of some of his specimens from Kazakhstan.

Inanibigutta* (?) *minuta Wang, 1993
(Fig. 4F-G)

Inanibigutta minuta Wang, 1993: 100, pl. 6, figs 9-12.

OCCURRENCE. — Middle part of the Pingliang Formation, Gansu Province, China (Wang 1993); grey radiolarites of the Crawford track, Southern Uplands, this study.

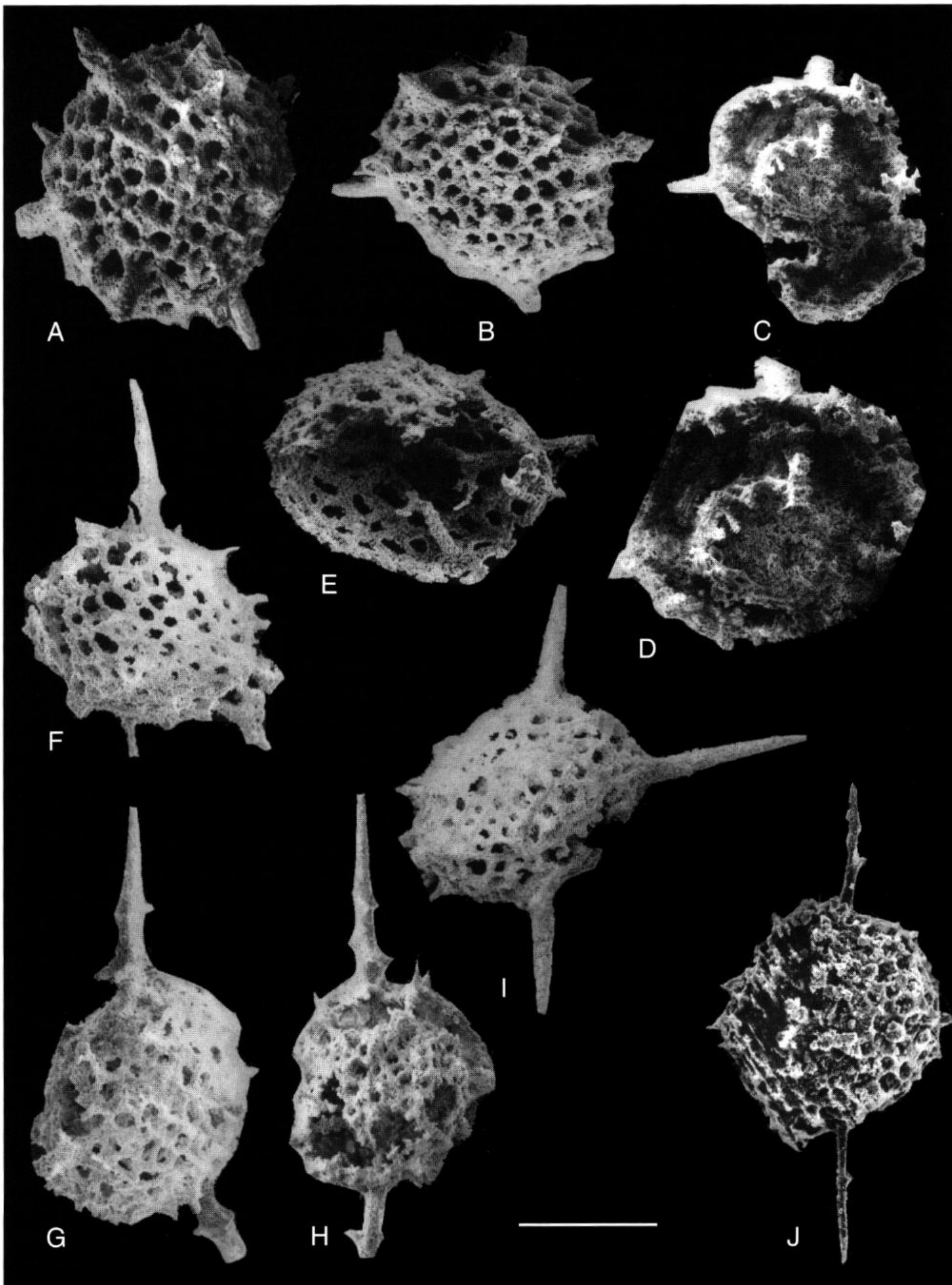

FIG. 4. — Scanning electron micrographs of radiolaria extracted from cherts of the Southern Uplands. **A-D**, *Inanibigutta diffusa* (Hinde), different views of the same specimen; **C-D**, view of internal structure after the shell was broken with a razor; **E**, ? *Inanibigutta diffusa* (Hinde); **F-G**, *Inanibigutta* (?) *minuta* Wang; **H**, *Inanibigutta* sp. cf. *I. verrucula* (Nazarov); **I**, *Inanibigutta* sp. cf. *I. aksakensis* (Nazarov); **J**, *Inanibigutta* (?) sp. A. Scale bar: A, 82 µm; B, 89,5 µm; C, 106 µm; D, 70 µm; E, 76 µm; F, G, 94 µm; H, 124 µm; I, 83 µm; J, 129 µm.

REMARKS

The observed morphotypes are identical to *Inanibigutta minuta* as described and illustrated by Wang (1993). They possess nearly spherical outer shells with numerous secondary spines, distally tapering main spines with apophyses in their proximal part and both the outer shell and main spines have appropriate dimensions. Nevertheless, the attribution of this species to *Inanibigutta* is questionable because in neither the type-series (holotype and paratypes), nor in our material has the exact number of main spines ever been observed.

Inanibigutta sp. cf. ***I. Verrucula***
(Nazarov *in* Nazarov & Popov, 1976)
(Fig. 4H)

Entactinosphaera verrucula Nazarov *in* Nazarov & Popov, 1976: 408-409, fig. 1d. – Nazarov & Popov 1980: 38-39, text-fig. 17, pl. 3, fig. 6, pl. 11, fig. 6.
Inanibigutta verrucula (Nazarov) – Nazarov 1988, fig. 31. – Wang 1993: 100, pl. 6, figs 2-3, 5-8.

OCCURRENCE. — Middle part of the Pingliang Formation, Gansu Province, China (Wang, 1993); grey radiolarites of the Crawford track, Southern Uplands, this study.

REMARKS

The illustrated specimen is comparable to *I. verrucula* as described originally by Nazarov (1976). The spherical outer shell (diameter: 185 μm) is perforated by angular to subangular pores and bears short conoidal secondary spines, as well as main spines (length of intact spine: 174 μm). However, it differs as main spines are tapering rather than cylindrical and apophyses tend to be clustered near the proximal part of the spines. My material resembles Wang's (1993) specimens in all respects. This species can be distinguished from *I.* (?) *minuta* Wang by the larger size of its outer shell, of diameter usually greater than 180 μm, and by the longer main spines (> 150 μm).

Inanibigutta sp.
cf. ***I. aksakensis*** (Nazarov, 1975)
(Fig. 4I)

Entactinosphaera aksakensis Nazarov, 1975: 68, pl. 16, figs 4-8, pl. 21, fig. 1 (not 2). – Nazarov & Popov 1980: 35, 36, text-fig. 15a-b, pl. 3, figs 8, 9, pl. 8, fig. 6, pl. 11, figs 8, 9.
Inanibigutta aksakensis (Nazarov) – Nazarov 1988, text-fig. 17, pl. 10, fig. 7-8. – Nazarov & Ormiston 1993: 36, pl. 3, fig. 1.

OCCURRENCE. — Grey radiolarites of the Crawford track, Southern Uplands, this study.

REMARKS

This morphotype has distally tapering main spines, small secondary spines on the perforated outer shell and an inner spherical shell (diameter: 70 μm approximately) comparable to *I. aksakensis*. However, the size of the outer shell (diameter less than 150 μm) is nearly half the size of the latter species. The holotype of *I. aksakensis* in Nazarov's (1975) work is the specimen illustrated on pl. 21, fig. 1 (see pl. 3, fig. 8 *in* Nazarov & Popov 1980).

Inanibigutta (?) sp. A
(Fig. 4J)

OCCURRENCE. — Red-brown radiolarites at Hawkwood Burn, Southern Uplands, this study.

DESCRIPTION

The outer shell is a nearly perfect sphere perforated by relatively large circular pores. It also bears small secondary spines. Two thin rod-like main spines, positioned along an axis and almost half the length of the diameter of the outer shell, display a few thorn-shaped apophyses.

REMARKS

The nature of the thin rod-like main spines distinguishes this morphotype from all other Inaniguttidae. The exact number of spines and internal structure of the shell are unknown.

Genus *Inanigutta* Nazarov & Ormiston, 1984

Inanigutta Nazarov & Ormiston, 1984: 72, 86. – Nazarov 1988: 56.

TYPE SPECIES. — *Entactinia unica* Nazarov, 1975.

Inanigutta (?) sp. K
(Fig. 5A)

Occurrence. — Grey radiolarites of the Crawford track, Southern Uplands, this study.

Description
Small inaniguttid with six robust main spines, four of them situated on an equatorial plane and the other two along an axis perpendicular to it. The four equatorial spines are themselves positioned along two axes, perpendicular to each other. All spines are rod-like, gently tapering distally. Their bases are large, perforated and joined to the outer perforated shell in such a way as to give a bipyramidal outline. No secondary spines are visible on the surface of the outer shell.

Remarks
Uncertainty regarding generic assignement is due to the unknown internal structure of this morphotype.

Genus *Oriundogutta* Nazarov, 1988

Oriundogutta Nazarov, 1988: 57. – Nazarov & Ormiston 1993: 36, text-fig. 7b.

Type species. — *Astroentactinia ramificans* Nazarov, 1975.

?*Oriundogutta rüsti*
(Ruedemann & Wilson, 1936)
(Fig. 5B)

? *Heliosphaera rüsti* Ruedemann & Wilson, 1936: 1572, pl. 5, figs 13-15, 31, pl. 7, fig. 8.
? *Astroentactinia* ? *rüsti* (Ruedemann & Wilson) – Nazarov & Popov 1980: 46, text-fig. 24, pl. 12, figs 10-11.

Occurrence. — Red-brown radiolarites at Hawkwood Burn, Southern Uplands, this study.

Remarks
The size of the outer shell (diameter 150 µm approximately) and the presence of stout and thinner spines are comparable to *O. rüsti*. Doubts regarding taxonomic assignement remain owing to uncertainty about the internal structure.

?*Oriundogutta bella* Wang, 1993
(Fig. 5C)

? *Oriundogutta bella* Wang, 1993: 101, pl. 9, figs 1-13.

Occurrence. — Grey radiolarites of the Crawford track, Southern Uplands, this study.

Remarks
Although only six spines are visible, their distribution and angle on the spherical shell suggests that their total number is possibly eight.

Inaniguttid (?) gen. et sp. indet.
(Fig. 5D-E)

Occurrence. — Grey radiolarites of the Crawford track, Southern Uplands, this study.

Description
Star-shaped shell, lenticular in cross-section, bearing five robust conical spines. The shell is perforated by numerous pores of various sizes and shapes (subangular, oval). Pores near the base of the spines are distinctly larger and elongated, encompassing part of the spine. The internal structure is unknown.

Order ALBAILLELLARIA Deflandre, 1953
emend. Holdsworth, 1969
Family Ceratoikiscidae Holdsworth, 1969

Genus *Protoceratoikiscum*
Goto, Umeda & Ishiga, 1992

Protoceratoikiscum Goto, Umeda & Ishiga, 1992: 165.

Type species. — *Protoceratoikiscum chinocrystallus* Goto, Umeda & Ishiga, 1992.

Protoceratoikiscum sp.
aff. ***P. similistellatum*** Li, 1995
(Fig. 5F-G)

aff. *Protoceratoikiscum similistellatum* Li, 1995: 337, pl. 2, figs 2, 4.

Occurrence. — Grey radiolarites of the Crawford track, Southern Uplands, this study.

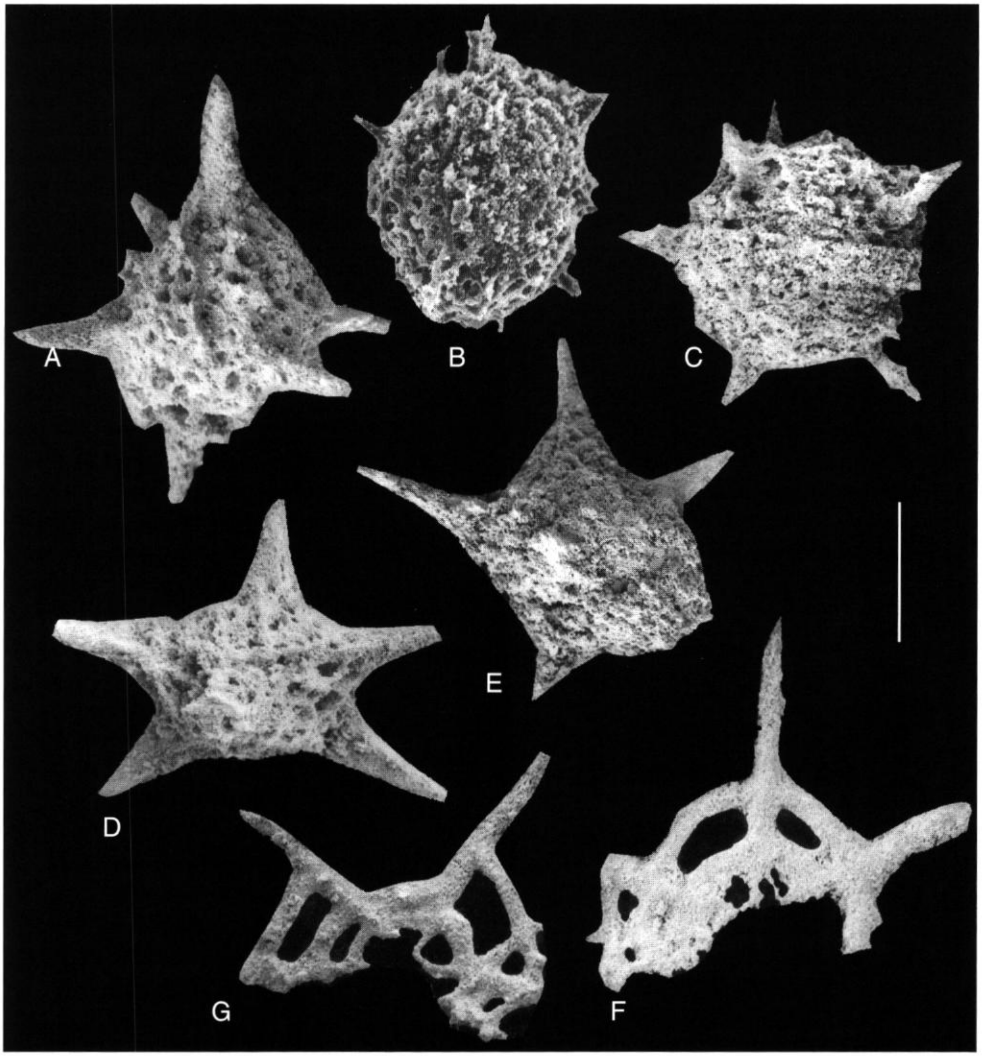

FIG. 5. — Scanning electron micrographs of radiolaria extracted from cherts of the Southern Uplands. **A**, *Inanigutta* (?) sp. K; **B**, ? *Oriundogutta rüsti* (Ruedemann & Wilson); **C**, ? *Oriundogutta bella* Wang; **D-E**, Inaniguttid (?) gen. et sp. indet.; **F-G**, *Protoceratoikiscum* sp. aff. *P. similistellatum*. Scale bar: A, 51 µm; B, 79 µm; C, 73 µm; D, 65 µm; E, 72 µm; F, 63 µm; G, 66.5 µm.

DESCRIPTION

Three to four spines distributed radially along a semi-circle formed by two to three rows of arches joining the spines. Spines taper gently distally, but also towards the centre very rapidly.

REMARKS

From the presence of arches between spines this morphotype is comparable to the species described by Li (1995). However, it differs in its smaller size and the smaller angle between adjacent spines. Only incomplete specimens were encountered in the yielded material.

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