BioOne RESEARCH EVOLVED

A revised heterostracan-based ichthyostratigraphy of the Wood Bay Formation (Lower Devonian, Spitsbergen), and correlation with Russian Arctic archipelagos

Author(s): Vincent N. Pernègre and Alain Blieck
Source: Geodiversitas, 38(1):5-20.
Published By: Muséum national d'Histoire naturelle, Paris
https://doi.org/10.5252/g2016n1a1
URL: http://www.bioone.org/doi/full/10.5252/g2016n1a1

BioOne (www.bioone.org) is a nonprofit, online aggregation of core research in the biological, ecological, and environmental sciences. BioOne provides a sustainable online platform for over 170 journals and books published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Web site, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at www.bioone.org/page/terms_of_use.

Usage of BioOne content is strictly limited to personal, educational, and non-commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

A revised heterostracan-based ichthyostratigraphy of the Wood Bay Formation (Lower Devonian, Spitsbergen), and correlation with Russian Arctic archipelagos

Vincent N. PERNÈGRE
Muséum national d'Histoire naturelle,
Direction des collections, Unité de gestion des collections de paléontologie
case postale 38, 57 rue Cuvier, F-75231 Paris cedex 05 (France)
pernegre@mnhn.fr

Alain BLIECK
Université de Lille – Sciences et technologies
UFR des Sciences de la Terre (SN5)
UMR 8198 du CNRS « EvoEcoPaléo »
F-59655 Villeneuve d'Ascq cedex (France)
alain.blieck@univ-lille1.fr

Published on 25 March 2016

urn:lsid:zoobank.org:pub:9CD2D098-6C9F-4FA1-9E19-D53662122EE1

Pernègre V. N. & Blieck A. 2016. — A revised heterostracan-based ichthyostratigraphy of the Wood Bay Formation (Lower Devonian, Spitsbergen), and correlation with Russian Arctic archipelagos. *Geodiversitas* 38 (1): 5-20. http://dx.doi.org/10.5252/g2016n1a1

ABSTRACT
Spitsbergen shows a several kilometers thick, mostly siliciclastic Devonian sequence. In this sequence, the Wood Bay Formation represents a typical Old Red Sandstone megafacies unit of Early Devonian age (Pragian-Emsian). It outcrops in the Andrée Land Block (often wrongly designated as the "main Devonian graben") in NW Spitsbergen. Its stratigraphy has been mostly established in two areas of this block, that is, in the Woodfjorden area in the north, and in the Dicksonfjorden-Austfjorden area in the south. A revision of the pteraspidiform heterostracan vertebrates has been carried out in both areas. Eight different fossil assemblages are defined, five for the Woodfjorden area (WA), and three for the Dicksonfjorden-Austfjorden area (DAA), that enable the correlation of the Sigurdfjellet and Kapp Kjeldsen "faunal divisions" of the lower Wood Bay Formation (in WA) with the Austfjorden Member (in DAA), and the Keltiefjellet "faunal division" of the upper Wood Bay Formation (in WA) with the Dicksonfjorden Member (in DAA). Unfortunately, pteraspids do not help with correlation between the uppermost parts of the Wood Bay Formation in the north and south of the Andrée Land Block. These results are used also for a more precise correlation with the heterostracan-bearing, Early Devonian, Old Red Sandstone series of Novaya Zemlya and Severnaya Zemlya in the Russian Arctic. They also confirm that Spitsbergen and those Russian archipelagos were elements of the Early Devonian, palaeobiogeographic Arctic Province.

KEY WORDS
Old Red Sandstones,
Pragian-Emsian,
Heterostraci,
vertebrates,
Svalbard,
Novaya Zemlya,
Severnaya Zemlya.

RÉSUMÉ
Révision de l'ichtyostratigraphie fondée sur les hétérostracés de la Formation de Wood Bay (Dévonien inférieur du Spitsberg) et corrélations avec les archipels arctiques russes.
Le Spitsberg présente une série sédimentaire dévonienne qui est principalement siliciclastique et épaisse de plusieurs kilomètres. Au sein de celle-ci, la Formation de Wood Bay se présente sous un mégafaciès Vieux Grès Rouges typique d'âge éodévonien (Praguien-Emsien). Elle affleure dans le Bloc d'Andrée Land (souvent désigné sous le nom incorrect de « graben dévonien principal ») du NW du Spitsberg. Sa stratigraphie a été étudiée essentiellement dans deux régions : celle du Woodfjord dans le nord et celle du Dicksonfjord-Austfjord dans le sud. Nous avons mené une révision des vertébrés hétérostracés ptéraspidiformes dans ces deux régions. Huit assemblages fossiles différents sont définis : cinq pour la région du Woodfjord (WA) et trois pour celle du Dicksonfjord-Austfjord (DAA). Ceci permet de corréler les « divisions fauniques » de Sigurdfjellet et Kapp Kjeldsen de la partie inférieure de la Formation de Wood Bay (dans WA) avec le Membre de l'Austfjord (dans DAA), ainsi que la « division faunique » de Keltiefjellet de la partie supérieure de la Formation de Wood Bay (dans WA) avec le Membre du Dicksonfjord (dans DAA). Par contre, les ptéraspides ne sont d'aucune aide pour corréler les parties les plus supérieures de la Formation de Wood Bay entre elles, entre le nord et le sud du Bloc d'Andrée Land. Ces résultats autorisent également des corrélations plus précises avec les Vieux Grès Rouges à hétérostracés d'âge éodévonien de Nouvelle Zemble et de Terre-du-Nord, dans l'Arctique Russe. Ils confirment l'appartenance du Spitsberg et de ces archipels russes à la province paléobiogéographique arctique au Dévonien inférieur.

MOTS CLÉS
Vieux Grès Rouges,
Praguien-Emsien,
Heterostraci,
vertébrés,
Svalbard,
Nouvelle Zemble,
Terre-du-Nord.

INTRODUCTION

Spitsbergen shows, mainly in its north-western part, a several kilometers thick, mostly siliciclastic sequence of Devonian age which corresponds to the late- and post-orogenic molasse of the late Caledonian (Haakonian-Svalbardian) orogeny in the Svalbard archipelago. In this sequence, the Wood Bay Formation represents a typical Old Red Sandstone megafacies unit of Early Devonian age (Pragian-Emsian). It outcrops in the Andrée Land Block (ALB), in NW Spitsbergen (often wrongly designated as the "main Devonian graben"). Its stratigraphy has been established in two areas of this block, i.e. in the Woodfjorden area in the north, and in the Dicksonfjorden-Austfjorden area in the south, based upon a variety of bio- and litho-stratigraphic informations. This has led to correlation problems between both areas (e.g., Blieck *et al.* 2000). So, a revision of the most significant biological markers in both series has become necessary, in order to propose a more precise correlation between them. Ichthyostratigraphy has been defined by Blieck *et al.* (1995) as an ichthyofauna-based biostratigraphy, and was first applied to the Late Silurian – Early Devonian succession of Artois – Ardenne (N France and S Belgium). The term is here applied to the Early Devonian succession of Spitsbergen. The most recent ichthyostratigraphic results for the Lower and Middle Devonian of Spitsbergen was based upon thelodonts from the Andrée Land Group (Žigaitė *et al.* 2013, 2014). The present work is a new synthesis of the heterostracan biostratigraphy of the Wood Bay Formation. It is based upon the preliminary works of Pernègre (2004c) and Pernègre & Dupret (2004), and is updated by new data recently obtained by the junior author (Pernègre 2004b).

Abbreviations

CNRS	Centre national de la Recherche scientifique;
MNHN	Muséum national d'Histoire naturelle;
IPEV	Institut Paul-Émile Victor.

GEOGRAPHICAL AND GEOLOGICAL SETTING

The main island of the Norwegian Svalbard archipelago is Spitsbergen. It is located in northern Europe, between 75° and 80° (Fig. 1). The Devonian of Spitsbergen outcrops in three main regions: two are located in the northern part of the island; the third one, located in the southern part (Hornsund), is smaller (Fig. 1B). There are also other minor areas with remnants of Devonian rocks. The Devonian from the first area in the north-west outcrops in a half graben limited southward by the Raudfjorden Fault Zone and eastward by the pre-Devonian basement in the Friedrichbreen Fault Zone (McCann 2000: fig. 3). The Devonian of the second main area, in the centre-north, outcrops in a wide north-south graben-like structure (Friend & Moody-Stuart 1972). It is limited westward by the Breibogen Fault Zone and eastward by the Billefjorden Fault Zone (Harland 1997: fig. 8.1; Blomeier *et al.* 2003a: fig. 1b).

The Devonian succession can be understood in a sequence stratigraphic context. Its thickness is estimated at 9000 meters (Blomeier *et al.* 2003a) and it is composed of the following stratigraphical units, from the base to the top: the Siktefjellet Group, the Red Bay Group and the Andrée Land Group (Fig. 2). The base is located at the base of the Siktefjellet Group, and is precisely defined by an angular unconformity above metamorphic, Precambrian basement. The age of the unconformity, however, is not precisely defined. The Siluro-Devonian (S/D) boundary occurs, for some authors, between



Fig. 1. — Geographical and geological setting: **A**, geographical location of Svalbard and Russian Arctic archipelagos: **1**, Svalbard; **2**, Novaya Zemlya; **3**, Severnaya Zemlya; **B**, location of the Devonian outcrops in Spitsbergen, modified from Pernègre (2003, 2004c); **C**, geographical and stratigraphical location of the studied localities from the Woodfjorden area, simplified geological map after Blomeier *et al.* (2003a); **D**, geographical and stratigraphical location of the studied localities from the Dicksonfjorden-Austfjorden area, simplified geological map after Blomeier *et al.* (2003a).

the Lilljeborgfjellet and Albertbreen formations (Murashov & Mokin 1976, 1979; McCann 2000) or into the Lilljeborgfjellet Formation (Harland 1997; Blomeier *et al.* 2003a). There are in fact no precise data for establishing that S/D boundary. The age of the other formations is estimated from their miospore, plant and vertebrate (fish) contents (Blieck *et al.* 1987; McCann 2000: 570).

The Wood Bay Formation (Holtedahl 1914 cited in Friend 1961; Friend *et al.* 1966) forms the base of the Andrée Land Group (Fig. 2). It overlies the Ben Nevis Formation of the

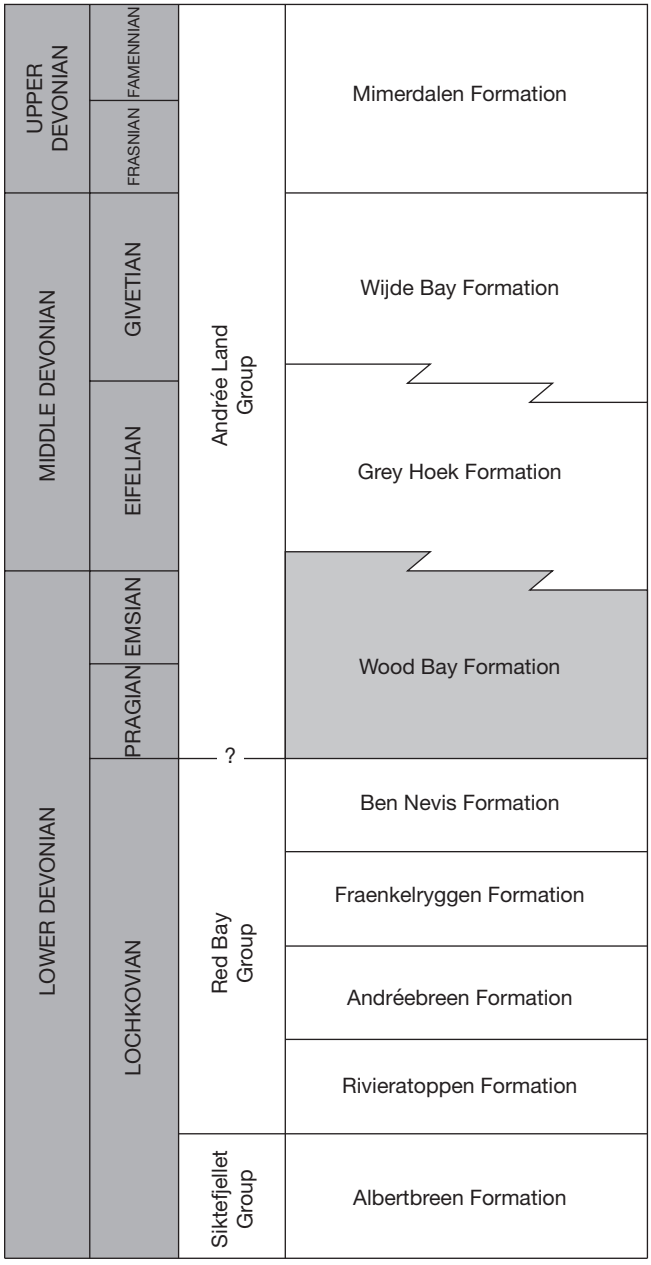


Fig. 2. — Stratigraphical section of the Andrée Land Block of northern Spitsbergen, after Harland (1997) and Blomeier *et al.* (2003a). Ages after Blieck *et al.* (2000, 2002) and McCann (2000). Note that: 1) it is common to subdivide the lowermost part of the Red Bay Group into Wulffberget, Rabotdalen (locally present) and Princesse Alicefjellet formations instead of only the Rivieratoppen Formation, according to Murashov & Mokin (1976, 1979) – this subdivision being applicable throughout the Devonian of northern Spitsbergen (Blomeier *et al.* 2003a, b); and 2) the Grey Hoek and Wijde Bay formations are considered as lateral equivalents and Eifelian in age by Schweitzer (1999); however, Schweitzer's idea that the Grey Hoek and Wijde Bay formations are of equal age is certainly not true along Wijdefjorden, where one lies on top of the other with a depositional boundary; upper parts of the Grey Hoek Formation in the Woodfjorden area may be coeval with the Wijde Bay Formation farther east (Blomeier *et al.* 2003a, b; W. Dallmann, pers. comm. 2007).

Red Bay Group (Kiaer 1916 cited in Friend 1961). A continuity of sedimentation between both formations was proposed by Føyn & Heintz (1943) and accepted by Friend (1961), Goujet (1984) and Blieck *et al.* (1987). The age of the boundary between the Ben Nevis and the Wood Bay formations is still uncertain, and tentatively assigned to the Lochkovian/Pragian boundary (Blieck 1984; Blieck *et al.* 2000). This uncertainty is probably due to the Monacobreen deformation phase that occurred between both formations, based upon the occurrence of a polymictic conglomeratic unit at the base of the Andrée Land Group at Sigurdfjellet (McCann 2000). However, the idea that the Wood Bay Formation overlies the Ben Nevis Formation with a polymictic conglomerate is probably not true. The conglomerate at Sigurdfjellet may be a fault-bound conglomerate of an earlier stage, which occurs at several places along the Breibogen Fault farther north. The boundary between both formations is not exposed. There is still a certain probability of a tectonic phase due to the quite different styles of deformation in the Red Bay and Andrée Land groups (Piepjohn *et al.* 2000) (W. Dallmann pers. comm. 2007). Moreover, the age and correlation of the Wood Bay Formation in the northern and southern parts of the ALB has been a subject of discussions, varying from the Lochkovian/Pragian or "Siegenian" to the Pragian/Emsian or Givetian (Blieck *et al.* 2000: fig. 10). The top of the Devonian sequence is located at the top of the Plantekløfta Member of the Mimerdalen Formation (Fig. 2). Its suggested age is late Famennian, based on the study of its plants and miospore assemblages (Schweitzer 1999; Piepjohn *et al.* 2000). However, the data are very scant, based upon a few specimens of *Retispora lepidophyta* (Kedo, 1957), and thus not very conclusive for dating (J. E. A. Marshall pers. comm. 2007).

During the Devonian, palaeomagnetic data show that Spitsbergen was in an equatorial location, and on the northern edge of Laurentia close to Baltica (Golonka 2000; Friend *et al.* 2000: fig. 6; Scotese 2002; Torsvik & Cocks 2004: fig. 5; Cocks & Torsvik 2011: figs 16, 17). Both palaeocontinents were accreted into the single Old Red Sandstone Continent.

The Wood Bay Formation

This represents the most important part of the Devonian succession in the centre-north ALB, and is characterized by its dominantly red colour.

Age and composition

The Wood Bay Formation corresponds to the upper part of the Lower Devonian (Fig. 2). It is dated as early Pragian to late Emsian (Blieck 1984; Blieck *et al.* 1987, 2000; Blomeier *et al.* 2003a). This is suggested by its vertebrate and miospore content (Allen 1965, 1967; Blieck *et al.* 1987; Mark-Kurik 1991). However, the age of its upper part is still under debate (Blieck *et al.* 2000); the top of the formation varies from an early Emsian (Steemans *in* Blieck *et al.* 2000) to a late Emsian age (Mark-Kurik 1991). It is considered here that the Wood Bay Formation occupies all of the Pragian and Emsian. Some authors place the base of the Pragian into the Fraenkelryggen Formation of the Red Bay Group (e.g., Harland 1997). This proposal seems strange because the latter author uses palaeontological results which gave a basal Pragian age for the base of the Wood Bay Formation (Blieck *et al.* 1987, 2000). However, we will not discuss this problem here. The Wood Bay Formation is essentially composed of red sandstones (the

Dicksonfjorden Member of Blomeier *et al.* 2003a: fig. 1b) with variations of grain size, from siltstones to conglomerates (Fig. 3). Variations of compaction often occur. In the southern part of the ALB (Dicksonfjorden-Austfjorden area), the oldest sandstones are green-grey with felspars and carbonate occurrence (the Austfjorden Member of Vogt 1929; also Friend 1961; Friend *et al.* 1966; see Blomeier *et al.* 2003a: fig. 1b; Fig. 3). The thickness of the Wood Bay Formation is about 3000 meters (Blomeier *et al.* 2003a).

Sedimentology

The Wood Bay Formation belongs to the Old Red Sandstone megafacies. The deposits are mostly considered as continental on sedimentological evidence, and as having originated in flood plains, rivers and lakes (Friend 1961; Critelli & Reed 1999; Blomeier *et al.* 2003a, b). On the contrary, the occurrence of fossils such as lingulids (Goujet 1984; Goujet & Emig 1985) and *Cruziana* d'Orbigny, 1842 (Goujet 1984; Harland 1997: 138) leads to the conclusion that the environment was semi-continental in "fjords" or estuaries with dominantly terrigenous material brought by rivers (Goujet 1984; Blieck 1984; Goujet & Emig 1985; Blieck & Janvier 1999). The high level of terrigenous material has been interpreted as the results of a semi-arid climate, with monsoonal periods (Dickins 1993 cited in Blomeier *et al.* 2003a). The Caledonian orogeny (Haakonian phase) is responsible for the siliclastic nature of the sediments.

History of the subdivisions of the Wood Bay Formation

For palaeontologists, the Wood Bay Formation is commonly divided into four "faunal divisions", that is, from base to top: the Sigurdfjellet, Kapp Kjeldsen, Keltiefjellet ("Lykta fauna") and Stjørdalen faunal divisions (Fig. 3). The three latter were originally proposed by Føyn & Heintz (1943) and revised by Goujet (1984) who introduced the Sigurdfjellet division. Føyn & Heintz (1943) gave the first stratigraphical description of the Wood Bay Formation. They divided it into three divisions called "Series": "Each of these three divisions is characterised by a group of guide-fossils [...]. With our present knowledge of the stratification and of the fossils, it is therefore impossible to draw distinct limits between the various divisions", and "In appearance all three divisions have certain (geological) characteristics making possible to distinguish them more or less accurately at a distance" (Føyn & Heintz 1943: 13). This first stratigraphy was faunally and lithologically characterized, but this remained quite vague. Friend (1961) confirmed Føyn & Heintz' divisions in the Woodfjorden area (north-west of the ALB). However, he quoted: "many of the vertebrates are only represented in collections by isolated fragments and have not yet been adequately described" (Friend 1961: 81). He proposed new lithological characteristics such as colour, composition, grain size and bedding as the fundamental lithostratigraphic basis for mapping. At the same time, he proposed another scheme for the Dicksonfjorden-Austfjorden area (south-east of the ALB), where the sandstones present colour variations. He described two lithostratigraphic units: the "Austfjorden Sandstone" and the "Dicksonfjorden Sandstone" (Friend 1961: 90-92). Later on, Friend *et al.* (1966) returned to the original concept of "faunal divisions", based on some publications of the Pteraspidiformes from the formation (Heintz 1960, 1962; Blieck & Heintz 1979), and they characterized each division after some guide-fossils: the genus *Gigantaspis* Heintz, 1962 characterizes the Kapp Kjeldsen faunal division, and the genus *Doryaspis* White, 1935 (with *Doryaspis nathorsti* (Lankester, 1884)) characterizes the Lykta one (later renamed Keltiefjellet). The same authors renamed the two lithostratigraphical units of the Dicksonfjorden-Austfjorden area into "Members" (Friend *et al.* 1966: 61). They described a third unit, i.e. the Verdalen Member, for the top of the formation; the latter is mainly composed of calcareous sediments and located principally in the north, with restricted extensions in the southern area. They suggested lateral correlations between the Woodfjorden and the Dicksonfjorden-Austfjorden areas, based on sedimentology, but without faunal considerations. Goujet (1984) is the most recent author to have added a subdivision in to the formation, viz., the Sigurdfjellet division at the base of the succession in the Woodfjorden area. It is supposed to be in conformity with the underlying Ben Nevis Formation, and characterized by a rich and distinctive, but still incompletely published fauna (However, see discussion here above in the "geographical and geological setting" section. This Sigurdfjellet division is characterized by abundant and well-preserved vertebrate fossils, including heterostracans, osteostracans, placoderms and thelodonts that are mostly published; the acanthodian microremains have not yet been described, only some macroremains from the Woodfjorddalen region have been published: Gagnier & Goujet 1997).

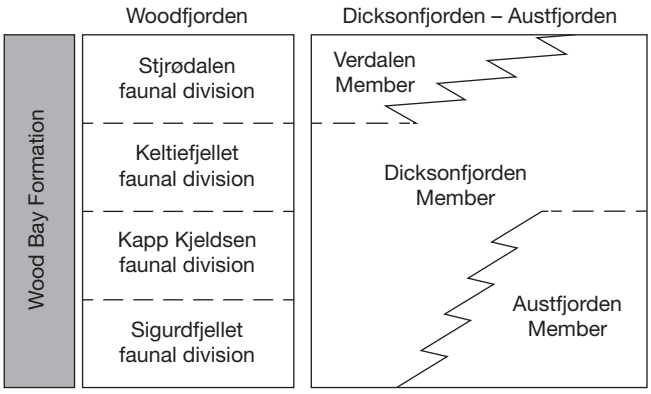


FIG. 3. — Biostratigraphic scale (faunal divisions) of the Wood Bay Formation in the Woodfjorden area, after Goujet (1984), Harland (1997) and Blieck *et al.* (2000), and lithostratigraphic section of the Wood Bay Formation in the Dicksonfjorden-Austfjorden area, after Blomeier *et al.* (2003a).

Present lithostratigraphic scheme

The Norsk Polarinstitutt geological map describes three members for the Wood Bay Formation, viz., from base to top: the Austfjorden, Dicksonfjorden and Verdalen members (Dallmann *et al.* 2002; Blomeier *et al.* 2003a). Green-grey well-cemented sandstones compose the Austfjorden Member, which is only

TABLE 1. — Macrovertebrate content of the different localities of the Wood Bay Formation in the Woodfjorden area, and their attribution to Assemblages 1 to 5. Pteraspidiforms after Pernègre (2002, 2003, 2004a, c, 2005, 2006), Pernègre & Dupret (2004); placoderms after Goujet (1973, 1984, and pers. comm.); osteostracans after Janvier (1985). For locality abbreviations, see text.

	Localities	Pteraspidiforms	Placoderms	Osteostracans
Assemblage 1	B_{IV}	*Doryaspis arctica* Pernègre, 2002 *Gigantaspis minima* Pernègre & Goujet, 2007 *Xylaspis prima* (Pernègre, 2003) *Woodfjordaspis felixi* Pernègre, 2006	*Sigaspis lepidophora* Goujet, 1973 *Arctaspis* sp.	*Boreaspis rostrata* Stensiö, 1927 *Boreaspis intermedia* Wängsjö, 1952 *Boreaspis ceratops* Wängsjö, 1952 *Boreaspis ginsburgi* Janvier, 1977 *Cephalaspis curta* Wängsjö, 1952 *Norselaspis glacialis* Janvier, 1981 *Axinaspis whitei* Wängsjö, 1952
	B_{II}	*Doryaspis arctica* *Gigantaspis minima* *Xylaspis prima*	*Arctaspis* sp. *Sigaspis lepidophora*	
	B_i	*Doryaspis arctica* *Gigantaspis minima*		*Diademaspis* sp.
	B_J	*Gigantaspis minima*		
	A_{11}	*Xylaspis prima*		
	$B_{I'}$	*Doryaspis arctica* *Gigantaspis minima*		
Assemblage 2	B_I	*Doryaspis arctica* *Gigantaspis isachseni* Heintz, 1962		
	A_{1-4}	*Doryaspis arctica* *Gigantaspis isachseni* *Gigantaspis bocki* Heintz, 1962		
	B_L	*Doryaspis arctica* *Gigantaspis isachseni* *Gigantaspis bocki*		
	B_O	*Doryaspis arctica* *Gigantaspis isachseni*	*Arctaspis* sp.	*Diademaspis poplinae* Janvier, 1985 *Parameteoraspis moythomasi* (Wängsjö, 1952)
Assemblage 3	H_{1-3}	*Gigantaspis isachseni* *Doryaspis nathorsti* (Lankester, 1884)	*Heintzosteus* sp.	
	B_G	*Gigantaspis isachseni* *Doryaspis lyktensis* (Heintz, 1960)	*Arctolepis* sp.	
	B_C	*Doryaspis nathorsti* *Gigantaspis isachseni*	*Arctaspis* sp.	
Assemblage 4	B_E	*Doryaspis nathorsti* *Doryaspis* sp. 1	*Arctolepis decipiens* (Woodward, 1891) *Arctaspis maxima* Heintz, 1929	
	C_4	*Doryaspis nathorsti* *Doryaspis* sp. 1	*Arctolepis decipiens*	*Parameteoraspis lanternaria* (Wängsjö, 1952)
	B_d	*Doryaspis nathorsti* *Doryaspis* sp. 1	*Arctaspis maxima* *Arctolepis* sp.	
Assemblage 5	B_H	*Doryaspis nathorsti*	*Arctolepis decipiens*	
	A_{16}	*Doryaspis nathorsti*	*Arctaspis* sp.	*Parameteoraspis oblongata* (Stensiö, 1927) *Parameteoraspis* sp.

present in the south-eastern part of the ALB (Fig. 3). The red sandstones are grouped into the Dicksonfjorden Member, which is diachronous within the basin (Fig. 3). It comprises the main part of the sediments in the north, and overlies the Austfjorden Member in the south-east (Blomeier *et al.* 2003a: fig. 2). The Verdalen Member is discontinuous and outcrops mainly in the north (Fig. 3). It has been shown to be ichthyostratigraphically equivalent to both the lower Grey Hoek Formation in the north, and uppermost Wood Bay Formation in the south (Blieck *et al.* 1987: fig. 8).

The Norsk Polarinstitutt maps use a purely lithostratigraphic subdivision, with lateral (highly diachronous) boundaries between the Austfjorden and Dicksonfjorden members. The reason is that many years of mapping in Andrée Land have shown that it is impossible to assign the faunal divisions (see above) to certain lithological characteristics. Although there are differences in places, there is no critical parameter that can be used to subdivide the strata in accordance with its faunal divisions throughout the Devonian outcrop area. Thus, most of the Wood Bay Formation (except for the Verdalen Mem-

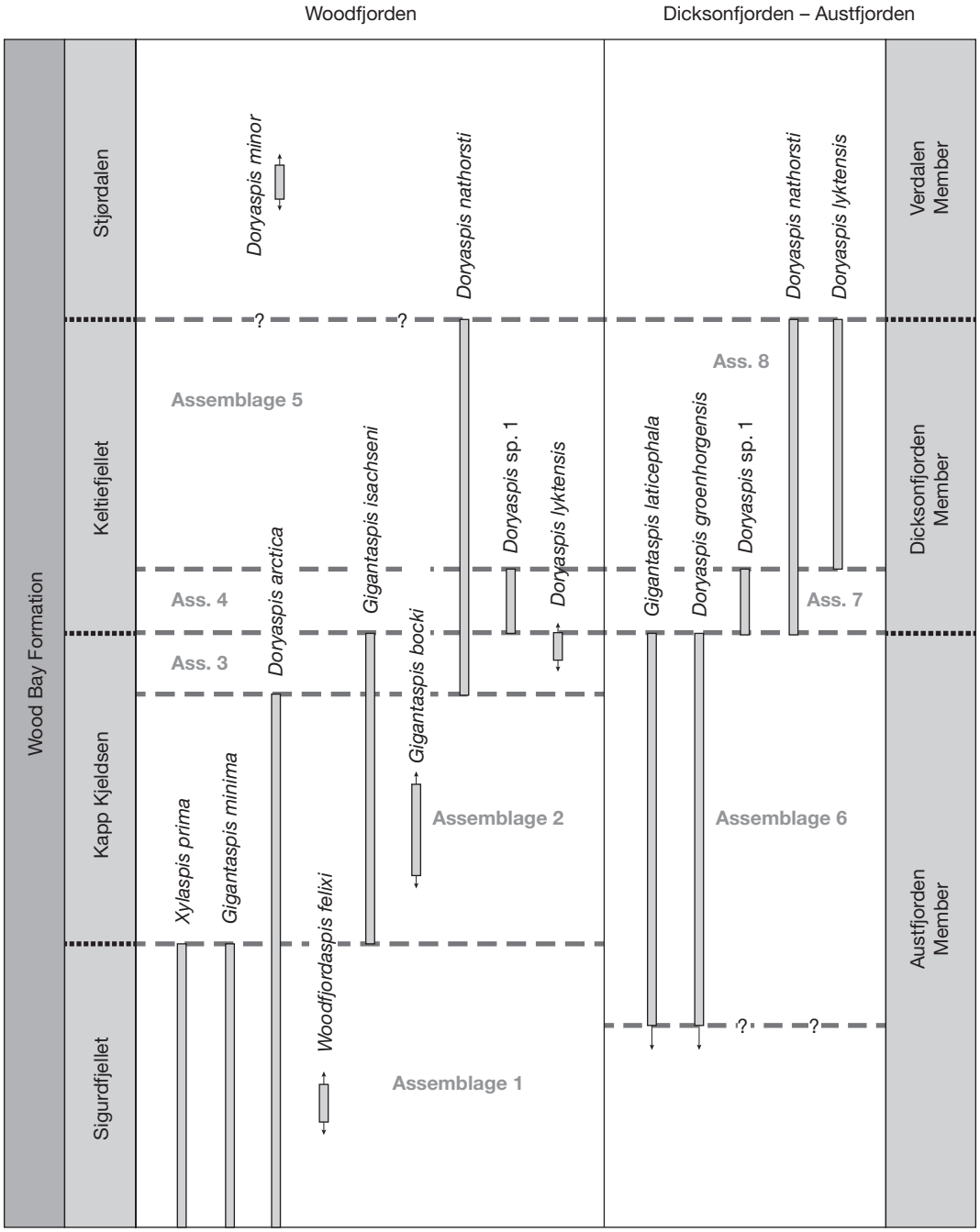


FIG. 4. — New stratigraphic distribution of the pteraspidiform species and assemblages in the Wood Bay Formation, both in the Woodfjorden and the Dicksonfjorden-Austfjorden areas.

ber) in northern and northwestern Andrée Land belongs to the Dicksonfjorden Member with red to greenish coloured, mostly calcite-free, fine-grained sand- and silt-stones. The Austfjorden Member occurs only in the southeastern part of the area, is coarser grained, with yellow to greenish and calcite-rich sandstones and gritstones. Chronostratigraphically it corresponds to the lower part of the Dicksonfjorden Member in the north and west, and interfingers with it in relatively narrow zones across a stratigraphic interval of several hundred meters (see Blomeier *et al.* 2003a, b; and W. Dallmann pers. comm. 2007).

Present palaeontological context

Since the stratigraphic work of Føyn & Heintz (1943), the Pteraspidiformes have been used as references for the faunal divisions, due to abundant *in situ* material and richness of the resulting collections. These Pteraspidiformes are easily identifiable at the generic level (Heintz 1962, 1968; Pernègre 2002, 2003). However, the other elements of the fauna are of less value for biostratigraphical correlations, except thelodonts. The osteostracans are quite rare both in the collections and *in situ*, which is a restricting factor for their stratigraphical potential: species are often known from a single specimen only (Janvier

TABLE 2. — Macrovertebrate content of the different localities of the Wood Bay Formation in the Dicksonfjorden-Austfjorden area, and their attribution to Assemblages 6 to 8. Pteraspidiforms after Pernègre (2002, 2003, 2004a, c, 2005, 2006), Pernègre & Dupret (2004); placoderms after Goujet (1973, 1984, and pers. comm.); osteostracans after Janvier (1985).

	Localities	Pteraspidiforms	Placoderms	Osteostracans
Assemblage 6	BD & BD'	*Doryaspis groenhorgensis* Pernègre, 2005 *Gigantaspis laticephala* (Blieck & Goujet, 1983)	*Dicksonosteus arcticus* Goujet, 1975 *Heintzosteus brevis* (Heintz, 1929) *Lehmanosteus hyperboreus* Goujet, 1984	
	B_S	*Doryaspis groenhorgensis* *Gigantaspis laticephala* ?		*Nectaspis areolata* Wängsjö, 1952 *Hildenaspis* sp.
Assemblage 7	142	*Doryaspis* sp. 1		
	BR_{1-3}	*Doryaspis nathorsti* (Lankester, 1884) *Doryaspis* sp. 1	*Arctaspis maxima* Heintz, 1929 *Dicksonosteus* sp.	*Parameteoraspis lanternaria* (Wängsjö, 1952)
Assemblage 8	C_{17}	*Doryaspis nathorsti* *Doryaspis lyktensis* (Heintz, 1960)		
	B_T	*Doryaspis nathorsti* *Doryaspis lyktensis*		
	C_{18}	*Doryaspis nathorsti* *Doryaspis lyktensis*		*Diademaspis poplinae* Janvier, 1985
	C_{19}	*Doryaspis nathorsti* *Doryaspis lyktensis*	*Arctaspis maxima*	
	B_Y	*Doryaspis nathorsti* *Doryaspis lyktensis*	*Arctolepis decipiens* (Woodward, 1891)	*Nectaspis peltata* Wängsjö, 1952
	132	*Doryaspis nathorsti*		

1985), so that their stratigraphic and geographic distributions are poorly known. This also applies to the placoderms. Although their specimens are abundant *in situ* (Heintz 1929; Goujet 1973, 1984), many forms remain undescribed and those named by Heintz (1929) now require revision. Hence, placoderms could probably be used for biostratigraphy, but not at the present state of knowledge. So, the new ichthyostratigraphy of the Wood Bay Formation is mainly based on the distribution of the pteraspidiform heterostracans. Other data are used here when they are available, after publications by Janvier (1981, 1985) and Goujet (1973, 1984).

Definition of new Pteraspidiform assemblages and index-taxa

Localities

The 37 studied localities were collected during various French expeditions, initially during the 1964 and 1969 CNRS-MNHN expeditions lead by Prof. J.-P. Lehman, and subsequently during the 2002-2003 IPEV expeditions lead by Prof. D. Goujet. These localities can be easily plotted on the geological map of Blomeier *et al.* (2003a). They belong to both the Woodfjorden and the Dicksonfjorden-Austfjorden areas (Fig. 1 C-D). The localities have been coded during the field expeditions for quick marking of the specimens. These codes are still used in collection. For the 1964-1969 expeditions, different teams were constituted (A, B, C…) and each one harvested different localities, so called A, B, C… Each team selected its own labelling of the localities (a, b, c; I, II, III; 1, 2, 3… plotted after the letter of the team). This explains the diversity of codes found in collections (e.g., B_{IV}, B_L, C_4). During the 2002-2003 expeditions a single number was given to each locality where fossils were found (e.g., '142').

In the Woodfjorden area, all localities belong to the Dicksonfjorden Member (red sandstones; Figs 1C and 3). This area was investigated only in 1969. The vertebrate content of the localities is given in Table 1. B_{iv} is the richest locality, where the specimens are only represented by isolated elements. Specimens in articulation are known in the B_i, B_J, and B_I localities, where isolated elements are also known (Fig. 1C). A single specimen comes from the A_{11} locality. Only isolated elements have been found in the $B_{I'}$, A_{1-4}, B_L, B_O, H_{1-3}, B_G, B_C, B_E, C_4, B_D, B_H and A_{16} localities (Fig. 1C and Table 1).

In the Dicksonfjorden-Austfjorden area, localities were visited in 1964, 1969 and 2002-2003. The vertebrate content of these localities is given in Table 2. The BΔ, BΔ' and B_S localities are in the Austfjorden Member (grey-green sandstones; Fig. 3). The two first ones are close to each other and belong to the same outcrop level, having been collected in 1964 and 1969 respectively. Rare specimens are anatomically articulated (except in the BD locality with *Gigantaspis laticephala* (Blieck & Goujet, 1983)), isolated elements represent the main material. A badly preserved disc is attributed to *Gigantaspis laticephala* in the B_S locality. The BR_{1-3} and '142' localities are close to the Austfjorden

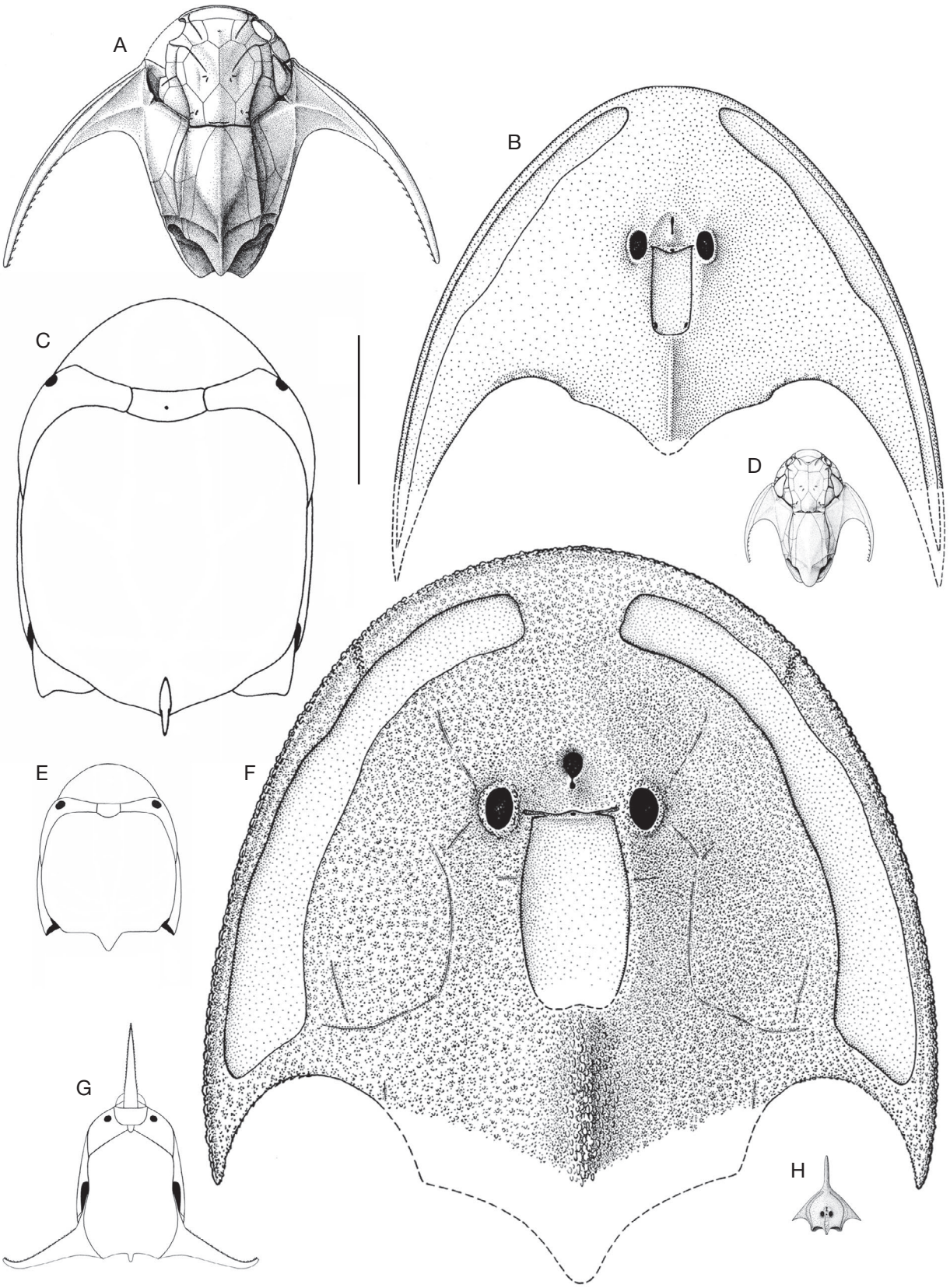


FIG. 5. — Illustrations of some representatives of the main genera of vertebrates in the Wood Bay Formation: **A**, *Arctolepis* Eastman, 1908; **B**, *Parameteoraspis* Blieck, Goujet & Janvier, 1987; **C**, *Gigantaspis* Heintz, 1962; **D**, *Dicksonosteus* Goujet, 1975; **E**, *Xylaspis* Pernègre, 2004; **F**, *Diademaspis* Janvier, 1985; **G**, *Doryaspis* White, 1935; **H**, *Boreaspis* Stensiö, 1927; **A**, **D**, placoderms; **B**, **F**, **H**, osteostracans; **C**, **E**, **G**, heterostracans. Scale bar: 5 cm.

Member – Dicksonfjorden Member boundary (Fig. 1D). They are composed of grey (BR_1; Austfjorden Member) or grey-red sandstones (BR_3 and '142'; Dicksonfjorden Member). Only isolated elements are found in the $C_{17\text{-}19}$, B_Y and '132' localities, whereas subcomplete specimens (e.g., spécimen MNHN.F.SVD870) were collected in the B_T locality (Fig. 1D and Table 2).

New pteraspidiform assemblages

In the Woodfjorden area, the Wood Bay Formation is mainly represented by red sandstones of the Dicksonfjorden Member (Fig. 3). The faunal divisions, originally described in this area (Føyn & Heintz 1943; Friend *et al.* 1966; Goujet 1984; Fig. 3) were previously based on two Pteraspidiformes, *Gigantaspis* and *Doryaspis*. *Gigantaspis* was the index-fossil for the Kapp Kjeldsen and Sigurdfjellet divisions (*Gigantaspis* sp. *in* Blieck *et al.* 1987), whereas *Doryaspis nathorsti* was the index-fossil for the Keltiefjellet and Stjørdalen divisions (Friend *et al.* 1966; Goujet 1984; Blieck *et al.* 1987). However, results from the investigated localities suggest new characteristic assemblages, with new species distributions, and a redefinition of the biostratigraphical subdivision of this region. Assemblage 1 (Table 1) contains *Gigantaspis minima* Pernègre & Goujet, 2007, *Xylaspis prima* (Pernègre, 2003) and *Doryaspis arctica* Pernègre, 2002 in the B_{IV}, B_{II}, B_i, B_J, A_{11} and $B_{I'}$ localities, as well as *Woodfjordaspis felixi* Pernègre, 2006 in locality B_{IV} (Pernègre 2006). Characteristic of the base of the Wood Bay Formation, it corresponds to the *Gigantaspis*, *Zascinaspis* Stensiö, 1958 and *Doryaspis* assemblage of Blieck *et al.* (1987: 203). It is equivalent to the Sigurdfjellet faunal division (Fig. 4), previously characterized by a distinctive but incompletely published fauna in Goujet (1973; 1984: 26; also Blieck *et al.* 1987; Harland 1997: 295, fig. 16.5; Žigaitė *et al.* 2013, 2014). Assemblage 2 (Table 1) contains *Doryaspis arctica* and *Gigantaspis isachseni* Heintz, 1962 in the B_I, $A_{1\text{-}4}$, B_L et B_O localities, plus *G. bocki* Heintz, 1962 in locality $A_{1\text{-}4}$. It corresponds to the *Gigantaspis* and *Doryaspis* sp. assemblage proposed by Blieck *et al.* (1987: 203, 206; Fig. 4 here). Assemblage 3 (Table 1) contains *Gigantaspis isachseni* and *Doryaspis nathorsti* in the $H_{1\text{-}3}$ and B_C localities, while *D. nathorsti* is replaced by *D. lyktensis* in the B_G locality. It corresponds to the *Gigantaspis* and *Doryaspis nathorsti* assemblage of Blieck *et al.* (1987: 203, 206; Fig. 4). Assemblages 2 and 3 are considered as equivalent to the Kapp Kjeldsen faunal division, as redefined by Goujet (1984: 26) and Blieck *et al.* (1987: 203, 206). It is based on the occurrence of *Gigantaspis isachseni* in both assemblages. Assemblage 2 is correlated to the lower part of the Kapp Kjeldsen division, while Assemblage 3 is equivalent to its upper part (Fig. 4), due to the occurrence of *Doryaspis nathorsti* as proposed by Friend *et al.* (1966), Goujet (1984) and Blieck *et al.* (1987). Assemblage 4 (Table 1) contains *Doryaspis nathorsti* and *Doryaspis* sp. 1 (unpublished) in localities B_E, C_4 and B_D. It is strictly equivalent to the *Doryaspis nathorsti* and the "huge species of *Doryaspis*" assemblage mentioned by Blieck *et al.* (1987: 206; Fig. 4 here). Assemblage 5 (Table 1) is not a well defined assemblage, it contains a single pteraspidiform species, *Doryaspis nathorsti*. It is found in the B_H and A_{16} localities (Fig. 4). Assemblages 4 and 5 equal the Keltiefjellet division as defined by Blieck *et al.* (1987) and Harland (1997). The former one characterizes the lower part of the faunal division by the occurrence of *Doryaspis* sp. 1 (unpublished), while the latter one represents its upper part with only *Doryaspis nathorsti* (Fig. 4). The diversity of the Pteraspidiformes decreases towards the top of the Wood Bay Formation, as it was presumed by Føyn & Heintz (1943), Friend *et al.* (1966), Goujet (1984), Blieck *et al.* (1987) and Harland (1997).

In the Dicksonfjorden-Austfjorden area, the Wood Bay Formation is divided in two lithological members characterized by different fossil data. Assemblage 6 (Table 2) contains *Doryaspis groenhorgensis* and *Gigantaspis laticephala* in the BD, BD' and B_S localities which belong to the Austfjorden Member (Fig. 4). It can be correlated with Assemblages 1, 2 and 3 defined in the Woodfjorden area, by the co-occurrence of *Doryaspis* and *Gigantaspis*. Assemblage 7 (Table 2) contains *Doryaspis nathorsti* and *Doryaspis* sp. 1 (unpublished) in the $BR_{1\text{-}3}$ and '142' localities, at the base of the Dicksonfjorden Member. This assemblage is equivalent to Assemblage 4 proposed in the Woodfjorden area. Assemblage 8 (Table 2) contains *Doryaspis nathorsti* and *Doryaspis lyktensis* in the $C_{17\text{-}19}$, B_T, B_Y and '132' localities, in the Dicksonfjorden Member. A possible equivalent in the Woodfjorden area is the poorly defined Assemblage 5 (Fig. 4).

Index-taxa

Concerning the faunal divisions of the Woodfjorden area, after the pioneer works of Føyn & Heintz (1943) and Friend *et al.* (1966), it is possible to propose new assemblages (Fig. 4) and to define new index-taxa (Fig. 5). The Sigurdfjellet faunal division at the base of the formation does correspond to Assemblage 1 with two guide-fossils, *Xylaspis prima* and *Gigantaspis minima* (Figs 4 and 5E). The Kapp Kjeldsen faunal division, originally characterized by the occurrence of the genus *Gigantaspis* (Føyn & Heintz 1943; Friend *et al.* 1966), in fact equals Assemblages 2 and 3 with *Gigantaspis isachseni* as new guide-fossil (Fig. 5C). The Keltiefjellet faunal division, first named "Lykta division" by Føyn & Heintz (1943) and Friend *et al.* (1966), and renamed by Friend (1961; also in Blieck *et al.* 2000; Harland 1997), corresponds to Assemblages 4 and 5. The base of the division is characterized by the occurrence of *Doryaspis* sp. 1 (unpublished). *Doryaspis nathorsti* has also been reported throughout the whole division, but cannot be considered as a guide-fossil due to its presence at the top of the underlying division (Fig. 4). No pteraspidiform has been recently collected from the Stjørdalen faunal division. The samples collected in 1969 do not contain representatives of this order. The studied samples in the Oslo collections contain only rare fragments of possibly *Doryaspis*. *Doryaspis minor* was mentioned from this division by Heintz (1960) (Fig. 4). However, this species is the most poorly known of the

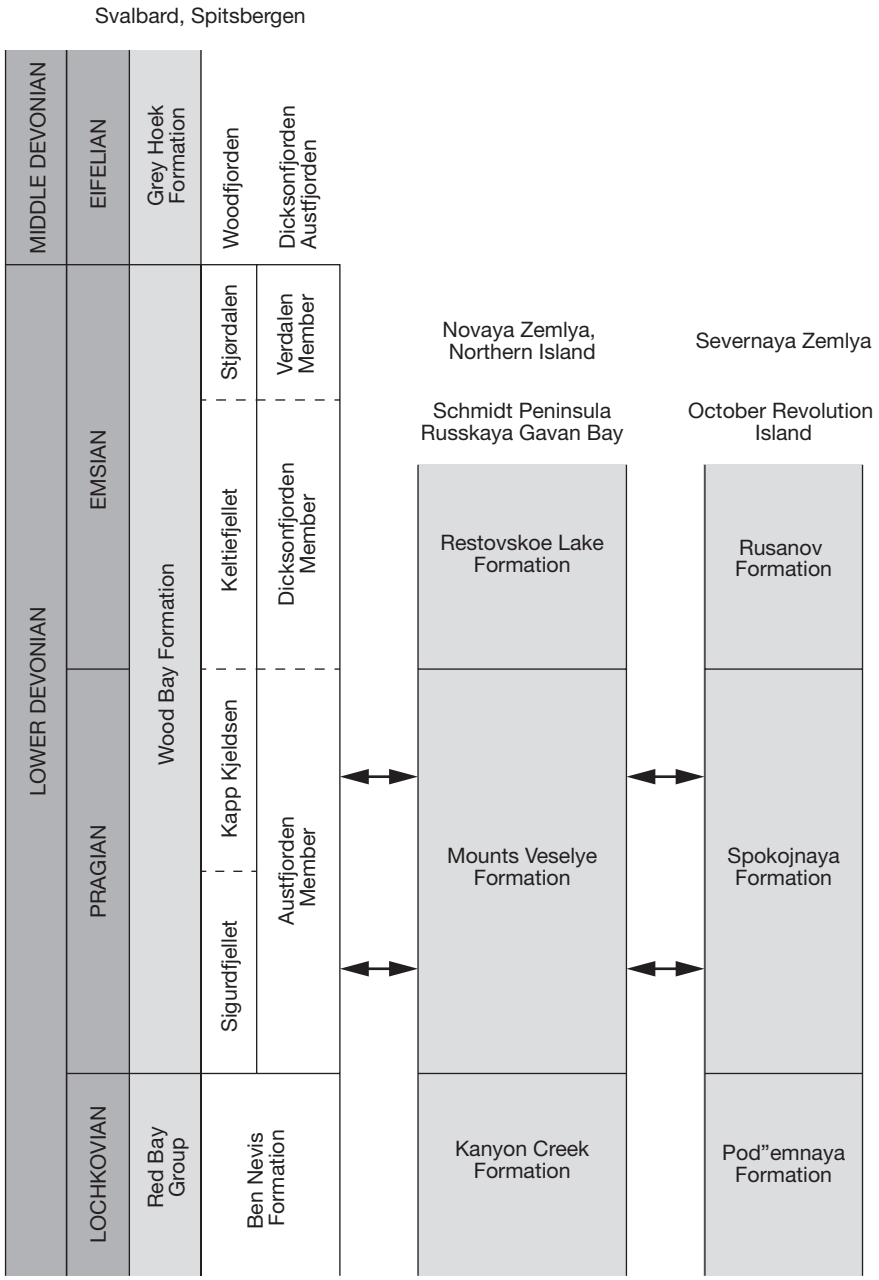


FIG. 6. — Biostratigraphic correlations of the Lower Devonian of Spitsbergen (Svalbard), Novaya Zemlya, and October Revolution Island (Severnaya Zemlya). Modified and completed from Blieck *et al.* (2002).

genus, and its distribution remains uncertain. Although pteraspidiforms are rare in the Stjørdalen division, many samples contain representatives of placoderms, a characteristic feature of this faunal division.

In the Dicksonfjorden-Austfjorden area, the Austfjorden Member equals Assemblage 6. The guide-fossil proposed here is *Doryaspis groenhorgensis* (Fig. 5G). However, the precise base of the Wood Bay Formation, and thus the Austfjorden Member remains unknown in this area (e.g., Blieck *et al.* 2000: fig. 10; Harland 1997: fig. 8.2). So, it is impossible to precisely define the basal distribution of the fauna for this member (Fig. 4). The Dicksonfjorden Member, in the Dicksonfjorden-Austfjorden area, overlies the Austfjorden Member, and its guide-fossil is *Doryaspis nathorsti* (Figs 4 and 5). Its lowermost part is characterized by the occurrence of *Doryaspis* sp. 1 (unpublished). The Verdalen Member is characterized by limestones contrary to the other divisions which are composed of siliciclastics (see e.g., Goujet 1984: 27; Harland 1997: 138). The B_P locality is from this member, but no pteraspidiform has been described yet, or even mentioned by Schultze (1968) and Ørvig (1969). So, as in the Woodfjorden area, the upper part of the Wood Bay Formation in this area seems to be characterized by the lack of pteraspidiforms.

North-west (Woodfjorden) – south-east (Austfjorden-Dicksonfjorden) correlation

The basal layers of the Wood Bay Formation in both areas show a specific regional problem. It is clear from recent geological studies that the basal part of the Wood Bay Formation does not exist in the Dicksonfjorden-Austfjorden area (Blomeier *et al.* 2003a: 160). It would be interesting to investigate the basal parts of the Wood Bay Formation where it unconformably overlies the Precambrian basement in the area between Dicksonfjorden and Kongsfjorden (W. Dallmann pers. comm. 2007). Furthermore, the lower Wood Bay Formation in the north-west (Woodfjorden area: lower Dicksonfjorden Member, Fig. 3/Sigurdfjellet faunal division) does not show any species in common with the Austfjorden Member in the south-east (Dicksonfjorden-Austfjorden area) (Fig. 4). However, the co-occurrence of the genera *Gigantaspis* and *Doryaspis* suggests that part of the Austfjorden Member (Assemblage 6) is an equivalent of the Sigurdfjellet and Kapp Kjeldsen faunal divisions (Assemblages 1 to 3) (Fig. 4). This correlation is plausible because the genus *Gigantaspis* is restricted to these assemblages in both areas. The first common species, *Doryaspis* sp. 1 (unpublished), is found at the base of the Keltiefjellet faunal division (Woodfjorden) and the Dicksonfjorden Member (Dicksonfjorden-Austfjorden) (Fig. 4). So, both levels can be considered as ichthyostratigraphically equivalent. As already said, the upper part of the Wood Bay Formation remains poorly dated because of a scarcity of pteraspidiforms, and as discussed here above, a revision is required for the placoderm fauna, which is well known in the upper parts of the Wood Bay Formation in both areas of the ALB.

DISCUSSION

The new palaeontological information, as compared to the lithostratigraphy of the ALB sediments, shows that lithological variations are related to faunal variations. The upper part of the Dicksonfjorden Member may be followed all over the ALB, where the conditions of deposition are homogeneous. The pteraspidiform fauna present in these levels is the same in both parts of the ALB and composed of *Doryaspis* sp. 1 (unpublished) and *Doryaspis nathorsti*. This may mean that the environment and conditions of life were the same. However, contrary to its upper part, the lower part of the Wood Bay Formation present different lithologies in both areas of the ALB: the Austfjorden Member in the south-east area and the Dicksonfjorden Member in the north-west area. They are both composed of sandstones, but their colour differs and the Austfjorden Member contains feldspars and micas (Friend & Moody-Stuart 1972). So, geological information would suggest that these elements come from two distinct sources: from the far south-east for the Dicksonfjorden-Austfjorden area and from the south-east for the other part of the ALB (Friend & Moody-Stuart 1972; Harland 1997: fig. 16.7D). The pteraspidiform fauna is composed of the same genera in these layers, but with different species in the Woodfjorden and the Dicksonfjorden-Austfjorden areas. Finally, the earlier phase of sedimentation in the ALB may be interpreted either as two different basins or as one basin with two areas with differential sedimentation. Additionally, the Austfjorden Member deposits laterally interfinger with the red beds of the lower Dicksonfjorden Member in the north-west (Woodfjorden area, southern Andrée Land), while they lie with a transitional boundary below the Dicksonfjorden Member in the south-east (Dickson Land) (Dallmann *et al.* 2002; Blomeier *et al.* 2003a: 160). This is certainly a major cause for difficulties in the lateral biostratigraphic correlations between both areas.

In a global context for the Arctic region, Blieck (1984) proposed a biostratigraphic scheme with a "lower *Doryaspis* zone with *Gigantaspis* and *Zascinaspis*, only known in Spitsbergen" (biozone 1d of Blieck 1984: 141 and fig. 75), and an "upper *Doryaspis* zone, also only known in Spitsbergen" (Blieck 1984: biozone 1e). Considering our new data, this biozonation can be revised and completed for Spitsbergen. The lower *Doryaspis* biozone corresponds to the distribution of the genus *Gigantaspis*, as it was originally proposed by Blieck (1984). However, the genus *Zascinaspis* is not represented in this biozone because *Z. laticephala* Blieck & Goujet, 1983 has been re-assigned to *Gigantaspis* (Pernègre 2004c; Pernègre & Goujet 2007). The lower *Doryaspis* biozone is equivalent to Assemblages 1, 2 and 3 in the Woodfjorden area (Sigurdfjellet + Kapp Kjeldsen faunal divisions) and to Assemblage 6 in the Dicksonfjorden-Austfjorden area (Austfjorden Member). The base of the upper *Doryaspis* biozone corresponds to the appearance of *Doryaspis* sp. 1 (unpublished). *Doryaspis nathorsti* which appears in the lower *Doryaspis* biozone has its acme in the upper *Doryaspis* biozone. It corresponds to Assemblages 4 and 5 in the Woodfjorden area (Keltiefjellet faunal division) and Assemblages 7 and 8 in the Dicksonfjorden-Austfjorden area (Dicksonfjorden Member) (Fig. 4).

Comparison with Russian Arctic archipelagos

The comparisons and correlations are mainly based on the pteraspidiform fauna, and among the Arctic regions, they are limited to the Russian archipelagos, because these are the only known regions which present a pteraspidiform fauna similar to the one found in the Pragian-Emsian of Spitsbergen.

Novaya Zemlya

It is the largest archipelago of the Russian Arctic (Fig. 1A), located at the east of the Barents Sea, between 70.5° and 77°, and in continuity with the Ural Mountains. It is composed of two main islands, and the studied interval comes from the northern island. The first Devonian fish remains were found by V. Bondarev in 1973, in the basal Devonian layers of the northern island (the sediments are described as "terrigenous rocks" in Mark-Kurik & Novitskaya 1977). They were found in the Schmidt Peninsula of the Russkaya Gavan Bay. The first work on the fauna (Mark-Kurik & Novitskaya 1977) was restricted to generic comparisons with

Spitsbergen. The authors mention a "large Pteraspidiforme similar to *Gigantaspis*" and another "similar to the aberrant Pteraspidiforme from the Lykta and Stjørdalen Formations" [sic], that is, *Doryaspis* (Mark-Kurik & Novitskaya 1977: 149). This preliminary work is taken into account by Novitskaya (1986): "Pteraspidiformes indet. were discovered in the lower Devonian deposits of the Northern island of Novaya Zemlya. They come from the base of the Devonian section to the East of the Russkaya Gavan Bay. The material consists of central plates, belonging mostly to a small form that resembles *Grumantaspis* Obruchev from the Wood Bay Series, Spitsbergen. Together with the above form exists a large form with characters showing similarity to *Gigantaspis* N. Heintz from the same series of Spitsbergen (Mark-Kurik & Novitskaya 1977)" (translated by E. Mark-Kurik, pers. comm. to VNP) (*Grumantaspis* is a synonym of *Doryaspis*: Blieck 1984: 183; Pernègre 2002). The Pteraspidiformes are found in the Veselye Mounts Formation which overlies the Kanyon Creek Formation, which in turn is overlaid by the Restovskoe Lake Formation (Cherkesova 1988: 674, fig. 2). Until now, there is no more detailed information on the pteraspidiform fauna from Novaya Zemlya (note that these pteraspidiform remains are not taken into consideration by Novitskaya 2004). However, comparisons with Spitsbergen are possible: a *Doryaspis-Gigantaspis* assemblage is only found in the lower Wood Bay Formation, so that the Veselye Mounts Formation can be considered as biostratigraphically equivalent to the Austfjorden Member and the Sigurdfjellet-Kapp Kjeldsen divisions. Hence, the Veselye Mounts Formation is considered here as Pragian in age (Fig. 6).

Severnaya Zemlya

This archipelago is located at the east of the Kara Sea, north of the Taimyr Peninsula, between 78° and 81°, and comprises three main islands (Fig. 1A). The most important one is October Revolution Island, which has a good pteraspidiform fauna. This material is found in the Silurian-Devonian layers sampled along Recent river beds. The fauna has been mentioned by Karatajūtė-Talimaa (1983) who proposed preliminary determinations at the generic level, and identified *Gigantaspis*, *Miltaspis* and *Doryaspis*? in the Spokojnaya Formation. This enables a correlation with the Wood Bay Formation (Karatajūtė-Talimaa 1983: 25). Recently, Blieck *et al.* (2002; preliminary version by Karatajūtė-Talimaa & Blieck 1999), in a review of the Silurian-Devonian heterostracans from Severnaya Zemlya, introduced a revised determination of the genera, i.e. *Gigantaspis*?, *Miltaspis*?, and "… Protopteraspididae gen. et sp. 1 with a *Doryaspis*-like ornamentation of tuberculated dentine ridges (previously designated as *Doryaspis* sp. nov) […]" (Blieck *et al.* 2002: 812 and fig. 4). These authors propose an equivalence between the base of the Wood Bay Formation and the base of the Spokojnaya Formation. The new biostratigraphical data from the Wood Bay Formation leads us to refine this correlation. *Doryaspis* and *Gigantaspis* being only associated in the lower Wood Bay Formation, it is proposed here to correlate the Spokojnaya Formation with the Austfjorden Member and the Sigurdfjellet-Kapp Kjelden divisions (Fig. 6). However, the occurrence of *Miltaspis*? in the Russian archipelago is problematic. This genus was defined by Blieck (1981) in the Ben Nevis Formation of Spitsbergen, below the Wood Bay Formation. Other Protopteraspididae [*sensu* Blieck 1984 ; "Protopteraspididae" of Pernègre & Elliott 2008] associated with Cyathaspidiformes in Severnaya Zemlya do not correspond to the fauna of the Wood Bay Formation, thus giving uncertainty over the correlation of the base of the Spokojnaya Formation with the base of the Wood Bay Formation (Blieck *et al.* 2002: fig. 5). In conclusion, the Spokojnaya Formation can be correlated with the lower Wood Bay Formation, but its base may be older. The discussion is presently limited due to the lack of precisely known vertical distributions of the various genera in Severnaya Zemlya. The Rusanov Formation, above the Spokojnaya Formation, does not contain Pteraspidiformes, so its possible correlation with the upper part of the Wood Bay Formation is still uncertain (Blieck *et al.* 2002).

CONCLUSION

This revised ichthyostratigraphy of the Wood Bay Formation leads us to propose a new faunal characterization based upon pteraspidiform assemblages. It helps in revising correlations of lithostratigraphic units throughout the Andrée Land Block. However, the base of the Austfjorden Member in the Dicksonfjorden-Austfjorden area (Dickson Land) still remains undated, as well as the top of the formation which does not contain pteraspidiforms. Correlation with other circum-Arctic regions are only made with the Russian Arctic archipelagos, which show faunal similarities to Spitsbergen. Other regions of the Old Red Sandstone Continent contain Pragian-Emsian Pteraspidiformes, but without any taxa in common (Karatajūtė-Talimaa 1989). Some regions such as the Canadian Arctic have been correlated only with older formations in Spitsbergen (e.g., the Red Bay Group: Dineley & Loeffler 1976; Elliott 1984; Blieck *et al.* 1987, 2002). Completion and revision of the Silurian-Devonian fauna from the Russian Arctic would probably lead to refinement of the correlation with Spitsbergen. Moreover a complementary work including revision and biostratigraphy of the placoderm fauna from the Wood Bay Formation would surely lead to enlarge the circum-Arctic biostratigraphic potential of the Early Devonian succession of Spitsbergen. All these results show that, in Pragian-Emsian time, Spitsbergen, Novaya Zemlya and Severnaya Zemlya were elements of what has been called the Arctic Province of the Old Red Sandstone Continent by Blieck & Janvier (1999: fig. 9.14), a conclusion which is also drawn for Spitsbergen, Severnaya Zemlya, Chukotka and the North-West Territories of Canada in Lochkovian time (Mark-Kurik *et al.* 2013).

Acknowledgements
We thank D. Goujet (MNHN, Paris) who provided VNP with the material from Spitsbergen for his Ph. D. thesis; D. Goujet also determined some new placoderm remains. We thank P. Janvier (CNRS, Paris), D. K. Elliott (NAU, Flagstaff, Arizona) and A. de Ricqlès (Collège de France, Paris) for their critical comments on the original manuscript. VNP is grateful to IPEV that provided funds for the 2002-2003 field expeditions to Spitsbergen. Drs W. Dallmann (Norsk Polarinstitut, Oslo, Norway) and J. E. A. Marshall (University of Southampton, UK) made very detailed critical reviews of a previous version of our paper, that have been very useful. This is a contribution to both IGCP Project 591 "The Early to Middle Paleozoic Revolution: Bridging the Gap between the Great Ordovician Biodiversification Event and the Devonian Terrestrial Revolution" and IGCP Project 596 "Climate change and biodiversity patterns in the Mid-Paleozoic (Early Devonian to Late Carboniferous)". Both reviewers D. Goujet and D. K. Elliott made precise comments that greatly improved the paper.

REFERENCES

Allen K. C. 1965. — Lower and Middle Devonian spores of North and Central Vestspitsbergen. *Palaeontology* 8: 687-748.

Allen K. C. 1967. — Spore assemblages and their stratigraphical application in the Lower and Middle Devonian of North and Central Vestspitsbergen. *Palaeontology* 10: 280-297.

Blieck A. 1981. — Le genre *Protopteraspis* Leriche (Vertébré, Hétérostracé) du Dévonien inférieur Nord-Atlantique. *Palaeontographica* A 173: 141-159.

Blieck A. 1984. — *Les hétérostracés ptéraspidiformes, agnathes du Silurien-Dévonien du continent Nord-Atlantique et des blocs avoisinants : révision systématique, phylogénie, biostratigraphie, biogéographie*. *Cahiers de Paléontologie, Section Vertébrés*. Centre national de la Recherche scientifique – CNRS, Paris, 199 p.

Blieck A. & Heintz N. 1979. — The heterostracan faunas in the Red Bay Group (Lower Devonian) of Spitsbergen and their biostratigraphical significance: a review including new data. *Bulletin de la Société géologique de France*, 7e série, XXI (2): 169-181.

Blieck A. & Janvier P. 1999. — Silurian-Devonian vertebrate dominated communities, with particular reference to agnathans, *in* Boucot A. J. & Lawson J. D. (eds.), *Paleocommunities: a Case Study from the Silurian and Lower Devonian.* Cambridge University Press, 79-105.

Blieck A., Goujet D. & Janvier P. 1987. — The vertebrate stratigraphy of the Lower Devonian (Red Bay Group and Wood Bay Formation) of Spitsbergen. *Modern Geology* 11: 197-217.

Blieck A., Goujet D., Janvier P. & Meilliez F. 1995. — Revised Upper Silurian-Lower Devonian ichthyostratigraphy of northern France and southern Belgium (Artois-Ardenne), *in* Arsenault M., Lelièvre H. & Janvier P. (eds), Études sur les Vertébrés inférieurs (VIIe Symposium International, Parc de Miguasha, Québec, 9-22 Juin 1991). *Bulletin du Muséum national d'Histoire naturelle*, 4e sér., 17, C (1-4): 447-459.

Blieck A., Cloutier R., with contributions by Elliott D. K., Goujet D., Loboziak S., Reed R. C., Rodina O., Steemans P., Valiukevičius J. J., V'yushkova L., Yolkin E. A., Young V. T. 2000. — Biostratigraphical correlations of Early Devonian vertebrate assemblages of the Old Red Sandstone Continent, *in* Blieck A. & Turner S. (eds), Palaeozoic Vertebrate Biochronology and Global Marine/Non-Marine Correlation – Final Report of IGCP 328 (1991-1996). *Courier Forschungsinstitut Senckenberg* 223: 223-269.

Blieck A., Karatajūtė-Talimaa V. N. & Mark-Kurik E. 2002. — Upper Silurian and Devonian heterostracan pteraspidomorphs (Vertebrata) from Severnaya Zemlya (Russia): a preliminary report with biogeographical and biostratigraphical implications. *Geodiversitas* 24 (4): 805-820.

Blomeier D., Wisshak M., Dallmann W., Volohonsky E. & Freiwald A. 2003a. — Facies analysis of the Old Red Sandstone of Spitsbergen (Wood Bay Formation): reconstruction of the depositional environments and implications of basin development. *Facies* 49 (1): 151-174. http://dx.doi.org/10.1007/s10347-003-0030-1

Blomeier D., Wisshak M., Joachimski M., Freiwald A. & Volohonsky E. 2003b. — Calcareous, alluvial and lacustrine deposits in the Old Red Sandstone of central north Spitsbergen (Wood Bay Formation, Early Devonian). *Norwegian Journal of Geology* 83: 281-298.

Cherkesova S. V. 1988. — Lower and Middle Devonian marine deposits of the Soviet Arctic and the correlation with Arctic Canada, *in* McMillan N. J., Embry A. F. & Glass D. J. (eds), Devonian of the World (International Symposium on the Devonian System, Calgary, 1987). *Canadian Society of Petroleum Geologists*, *Memoir* 14 (III): 669-679.

Cocks L. R. M. & Torsvik T. H. 2011. — The Palaeozoic geography of Laurentia and western Laurussia: a stable craton with mobile margins. *Earth-Science Reviews* 106: 1-51.

Critelli S. & Reed W. E. 1999. — Provenance and stratigraphy of the Devonian (Old Red Sandstone) and Carboniferous sandstones of Spitsbergen, Svalbard. *European Journal of Mineralogy* 11: 149-166.

Dallmann W., Otha Y., Elvevold S. & Blomeier D. 2002. — *Bedrock Map of Svalbard and Jan Mayen*. Norsk Polarinstitutt Temakart, 33, Tromsø. Scale 1:750 000.

Dickins J. M. 1993. — Climate of the Late Devonian to Triasssic. *Palaeogeography, Palaeoclimatology, Palaeoecology* 100: 89-94.

Dineley D. L. & Loeffler E. J. 1976. — Ostracoderm faunas of the Delorme and associated Siluro-Devonian formations, North West Territories, Canada. *Palaeontology, Special Papers* 18, 218 p.

Elliott D. K. 1984. — Siluro-Devonian fish biostratigraphy of the Canadian Arctic Islands, *in* Campbell K. S. W., Ritchie A., Warren J. W. & Young G. C. (eds), Symposium on the Evolution and Biogeography of Early Vertebrates (Sydney-Canberra, 1983). *Proceedings of the Linnean Society of New South Wales* 107 (3): 197-209.

Føyn S. & Heintz A. 1943. — The Downtonian and Devonian Vertebrates of Spitsbergen. VIII. The English-Norwegian-Swedish expedition 1939. Geological results. *Norges Svalbard og Ishavs-Undersøkelser, Skrifter* 85: 1-51.

Friend P. F. 1961. — The Devonian stratigraphy of North and Central Vestspitsbergen. *Proceedings of the Yorkshire Geological Society* 33: 77-118.

Friend P. F. & Moody-Stuart M. 1972. — Sedimentation of the Wood Bay Formation (Devonian) of Spitsbergen: regional analysis of a late orogenic basin. *Norsk Polarinstitutt Skrifter* 57: 5-77.

Friend P. F., Heintz N. & Moody-Stuart M. 1966. — New unit terms for the Devonian of Spitsbergen and new stratigraphical scheme for the Wood Bay Formation. *Norsk Polarinstitutt, Årbok* 1965: 59-64.

Friend P. F., Williams B. P. J., Ford M. & Williams E. A. 2000. — Kinematics and dynamics of Old Red Sandstone basins, *in* Friend P. F. & Williams B. P. J. (eds), New perspectives on the Old Red Sandstone. *Geological Society, London, Special Publication* 180: 29-60.

Gagnier P.-Y. & Goujet D. 1997. — Nouveaux poissons acanthodiens du Dévonien du Spitsberg. *Geodiversitas* 19 (3): 505-513.

Golonka J. 2000. — *Cambrian-Neogene Plate Tectonic Maps*. Kraków b Wydawn, Uniwersytetu Jagiellonskiego, 198 p., 3 tables, 37 figs.

Goujet D. 1973. — *Sigaspis*, un nouvel Arthrodire du Dévonien inférieur du Spitsberg. *Palaeontographica* A 143 : 73-88.

GOUJET D. 1984. — *Les Poissons Placodermes du Spitsberg. Arthrodires Dolichothoraci de la Formation de Wood Bay (Dévonien inférieur). Cahiers de Paléontologie, section Vertébrés*. Centre national de la Recherche scientifique – CNRS, Paris, 254 p.

GOUJET D. & EMIG C. C. 1985. — Des *Lingula* fossiles, indicateurs de modifications de lenvironnement dans un gisement du Dévonien inférieur du Spitsberg. *Comptes-rendus de l'Académie des Sciences, Paris* 301, série II (13): 945-948.

HARLAND W. B. (ed.) 1997. — The geology of Svalbard. *Geological Society, London, Memoir* 17, xxi + 521 p.

HEINTZ A. 1929. — Die downtonischen und devonischen Vertebraten von Spitzbergen. II. Acanthaspida. *Skrifter om Svalbard og Ishavet* 22: 7-81.

HEINTZ N. 1960. — The Downtonian and Devonian Vertebrates of Spitsbergen. X. Two new species of the genus *Pteraspis* from the Wood Bay series in Spitsbergen. *Norsk Polarinstitutt Skrifter* 117: 1-13.

HEINTZ N. 1962. — The Downtonian and Devonian Vertebrates of Spitsbergen, XI. *Gigantaspis*, a new genus of family Pteraspidae from Spitsbergen. A preliminary report. *Norsk Polarinstitutt, Årbok* 1960: 22-27.

HEINTZ N. 1968. — The Pteraspid *Lyktaspis* n. g. from the Devonian of Vestspitsbergen, *in* ØRVIG T. (ed.), *Current Problems of Lower Vertebrate Phylogeny* (Nobel Symposium 4, Stockholm, 1967). Almqvist & Wiksell, Stockholm: 73-80.

HOLTEDAHL O. 1914. — On the Old Red Sandstone Series of northwestern Spitzbergen, *in* XIIth Session, International Geological Congress, compte rendu, Toronto (1913): 707-712.

JANVIER P. 1981. — *Norselaspis glacialis* n. g., n. sp. et les relations phylogénétiques entre les Kiaeraspidiens (Osteostraci) du Dévonien inférieur du Spitsberg. *Palaeovertebrata* 11 (2-3): 19-131.

JANVIER P. 1985. — Les Céphalaspides du Spitsberg. Anatomie, phylogénie et systématique des Ostéostracés siluro-dévoniens. Révision des Ostéostracés de la Formation de Wood Bay (Dévonien inférieur du Spitsberg). *Cahiers de Paléontologie, section Vertébrés*. CNRS édit., Paris, 244 p.

KARATAJŪTĖ-TALIMAA V. N. 1983. — Geterostraki nizhnego devona Severnoj Zemli i ikh korreliatsionnoje znatchenie [The Lower Devonian heterostracans from Severnaya Zemlya and their importance for correlations], *in* NOVITSKAYA L. I. (ed.), *Problemy sovremennoj paleoichtiologii* [*Extant Problems of Paleoichthyology*]. Nauka, Moskva, 22-28 (in Russian).

KARATAJŪTĖ-TALIMAA V. N. 1989. — *Skalviaspis narbutasi* gen. et sp. nov. – Novyj predstavitel' otryada pteraspidid (Heterostraci) iz nizhnego devona pribaltiki [*Skalviaspis narbutasi* gen. et sp. nov., a new representative of the Pteraspidida (Heterostraci) from the East Baltic Lower Devonian]. *Geologija* 10: 79-93 (in Russian, with Lithuanian and English abstracts).

KARATAJŪTĖ-TALIMAA V. N. & BLIECK A. 1999. — Geterostraki [Heterostraci], *in* MATUKHIN R. G. & MENNER V. V. (eds), *Stratigrafiya silura i devona arkhipelaga Severnaya Zemlya* [*Stratigraphy of the Silurian and Devonian of the Severnaya Zemlya archipelago*]. Ministerstvo prirodnykh resursov Rossijskoi Federatsii, Rossijskaya Akademiya Nauk (SNIIGGiMS), Novosibirsk: 127-131 (in Russian).

KIAER J. 1916. — Spitsbergens devoniske faunaer. *Forhandlinger Skandinavian Naturforsker-Møte* 16: 490-498 (in Norwegian).

MCCANN A. J. 2000. — Deformation of the Old Red Sandsone of NW Spitsbergen; links to the Ellesmerian and Caledonian orogenies, *in* FRIEND P. F. & WILLIAMS B. P. J. (eds), New perspectives on the Old Red Sandstone. *Geological Society, London, Special Publication* 180: 567-584.

MARK-KURIK E. 1991. — Contribution to the correlation of the Emsian (Lower Devonian) on the basis of placoderm fishes. *Newsletter on Stratigraphy* 25 (1): 11-23.

MARK-KURIK E. & NOVITSKAYA L. 1977. — Rannedevonskaya ichtiofauna na Novoj Zemle [The Early Devonian fish-fauna on Novaya Zemlya]. *Eesti NSV Teaduste Akadeemia Toimetised* 26, *Geoloogia* 2: 143-149 (in Russian, with English abstract).

MARK-KURIK E., BLIECK A., TURNER S. & BURROW C. J. 2013. — Early Devonian fishes from coastal De Long Strait, Central Chukotka, Arctic Russia. *Geodiversitas* 35 (3): 545-578. http://dx.doi.org/10.5252/g2013n3a3

MURASHOV L. G. & MOKIN J. I. 1976. — [Stratigraphical divisions of the Devonian deposits of Spitsbergen], *in Geologia Svalbardia*. Sbornik Nautchinih Trudov, Leningrad, 79-91 (in Russian).

MURASHCOV [sic] L. G. & MOKIN J. I. 1979. — Stratigraphic subdivision of the Devonian deposits of Spitsbergen, *in* WINSNES T. S. (ed.), The geological development of Svalbard during the Precambrian, Lower Palaeozoic, and Devonian (Oslo, 1975). *Norsk Polarinstitutt Skrifter* 167: 249-261.

NOVITSKAYA L. I. 1986. — *Drevnejshie beschelyustnye SSSR. Geterostraki: tsiataspidy, amfiaspidy, pteraspidy* [*The Earliest Agnatha of the USSR. Heterostraci: Cyathaspisds, Amphiaspids, Pteraspids*]. *Akademya Nauk SSSR, Trudy Paleontologicheskogo Instituta* 219. Nauka, Moskva, 160 p. (in Russian; English translation: Multilingual Services Division, Secretary of State, Canada, 284 p., 1988).

NOVITSKAYA L. I. 2004. — Podklass Heterostraci [Subclass Heterostraci], *in* NOVITSKAYA L. I. & AFANASSIEVA O. B. (eds), *Iskopaemye pozvonotchnye Rossii i sopredel'nykh stran*: *Bestchelyustnye i drevnie ryby* [*Fossil Vertebrates of Russia and Adjacent Countries*: *Agnathans and Early Fishes*]. Rossijskaya Akademiya Nauk [Academy of Sciences of Russia], Paleontologitcheskij Institut [Palaeontological Institute]. Geos, Moskva: 69-207 (in Russian).

ØRVIG T. 1969. — Vertebrates of the Wood Bay Group and the position of the Emsian-Eifelian boundary in the Devonian of the Vestspitsbergen. *Lethaia* 2 (3-4): 273-328.

PERNÈGRE V. N. 2002. — The genus *Doryaspis* White (Heterostraci) from the Lower Devonian of Vestspitsbergen, Svalbard. *Journal of Vertebrate Paleontology* 22 (4): 735-746.

PERNÈGRE V. N. 2003. — Un nouveau genre de Ptéraspidiforme (Vertebrata, Heterostraci) de la Formation de Wood Bay (Dévonien inférieur, Spitsberg). *Geodiversitas* 25 (2): 261-272.

PERNÈGRE V. N. 2004a. — *Xylaspis* n. nov., a new name for *Spitsbergaspis* Pernègre, 2003, not *Spitsbergaspis* Pribyl & Vanek, 1980. *Geodiversitas* 26 (1): 157.

PERNÈGRE V. 2004b. — *Les Ptéraspidiformes (Vertebrata, Heterostraci) de la Formation de Wood Bay (Dévonien inférieur, Spitsberg) : position phylogénétique, implications biostratigraphiques et paléobiogéographiques*. Thèse de doctorat, Muséum national d'Histoire naturelle, Paris, xvi + 328 p.

PERNÈGRE V. 2004c. — Biostratigraphy of Pteraspidiformes (Agnatha, Heterostraci) from the Wood Bay Formation, Lower Devonian, Spitsbergen, *in* YOUNG G. C. (ed.), Lower vertebrates from the Palaeozoic (First International Palaeontological Congress, Sydney, 2002). *Fossils and Strata* 50: 1-7.

PERNÈGRE V. N. 2005. — Description d'une nouvelle espèce et analyse morpho-fonctionnelle du genre *Doryaspis* White (Heterostraci) du Dévonien du Spitsberg. *Geobios* 38 (2): 257-268. http://dx.doi.org/10.1016/j.geobios.2003.10.005

PERNÈGRE V. 2006. — Un nouveau ptéraspidiforme (Vertebrata, Heterostraci) du Dévonien inférieur du Spitsberg : nouvelles données paléo-ontogéniques. *Geodiversitas* 28 (2): 239-248.

PERNÈGRE V. N. & DUPRET V. G. 2004. — Evidence of biostratigraphic correlations within the Wood Bay Formation (Lower Devonian, Spitsbergen). Some paleontological results of the 1969 French expedition with geological implications, *in* LUKSEVICS E. & STINKULIS G. (eds), The Second Gross Symposium "Advances of Palaeoichthyology" (Riga, 2003). *Acta Universitatis Latviensis*, *Earth and Environment Sciences* 679: 148-157.

PERNÈGRE V. N. & ELLIOTT D. K. 2008. — Phylogeny of the Pteraspidiformes (Heterostraci), Silurian-Devonian jawless vertebrates. *Zoologica Scripta* 37 (4): 391-403. http://dx.doi.org/10.1111/j.1463-6409.2008.00333.x

Pernègre V. N. & Goujet D. 2007. — The genus *Gigantaspis* Heintz, 1962 (Vertebrata, Heterostraci) from the Lower Devonian of Spitsbergen. *Palaeontology* 50 (2): 323-346. http://doi.org/10.1111/j.1475-4983.2007.00638.x

Piepjohn K., Brinkmann L., Grewing A. & Kerp H. 2000. — New data on the age of the uppermost ORS and the lowermost post-ORS strata in Dickson Land (Spitsbergen) and implications for the age of the Svalbardian deformation, *in* Friend P. F. & Williams B. P. J. (eds), New Perspectives on the Old Red Sandstone. *Geological Society, London, Special Publication* 180: 603-609.

Schultze H.-P. 1968. — Palaeoniscoidea-Schuppen aus dem Unterdevon Australiens und Kanadas und aus dem Mitteldevon Spitzbergens. *Bulletin of the British Museum of Natural History, Geology* 16: 341-368.

Schweitzer H.-J. 1999. — Die Devonfloren Spitzbergens. *Palaeontographica* B 252 (1-4): 1-122.

Scotese C. R. 2002. — PALEOMAP Project: Plate tectonic maps and continental drift animations. Arlington, Texas. http://www.scotese.com (last access 25/2/2016).

Torsvik T. H. & Cocks L. R. M. 2004. — Earth geography from 400 to 250 Ma: a palaeomagnetic, faunal and facies review. *Journal of the Geological Society, London* 161: 555-572. http://dx.doi.org/10.1144/0016-764903-098

Vogt T. 1929. — Fra en Spitsbergen-ekspedition i 1928. *Årbok Norske Videns-Akademiens, Naturforsker-Videns Klass* 11: 10-12. [In Norwegian]

Žigaitė Z., Karatajūtė-Talimaa V., Goujet D. & Blom H. 2013. — Thelodont scales from the Lower and Middle Devonian Andrée Land Group, Spitsbergen. *Geologiska föreningens i Stockholm förhandlingar* (*GFF*) 135 (1): 57-73.

Žigaitė Z., Blom H., Pérez-Huerta A. & Goujet D. 2014. — Vertebrate microfossils as tools in stratigraphy: a study of the Lower Devonian Andrée Land Group, Spitsbergen, *in* Rocha R., Pais J., Kullberg J. C. & Finney S. (eds), First International Congress on Stratigraphy "At the cutting edge of stratigraphy". Springer, Series "Springer Geology", 1167-1171.

Submitted on 15 January 2015;
accepted on 22 July 2015;
published on 25 March 2016.