Cambrian–Silurian contact

In the cliff exposures both along the northern side of the valley 'East Elv' and on the eastern coast of Citronen Fjord (see Fig. 1), a variably rusty-weathering carbonate conglomerate occurs at the poorly exposed contact between Cambrian and Silurian strata. This is interpreted as a deformed stratigraphic equivalent of the Hangingwall debris flow (Unit 9). The matrix of this conglomerate is locally siliceous and individual clasts are commonly elongated and cigar-shaped and in many respects the conglomerate simulates the conglomerates of Unit 2 (the Cigar debris flow of Cambrian age, see Figs 7, 8).

However, the general chararacteristics of this deformed conglomerate favour a genetic relationship with the actual contact zone which is thus interpreted as a regional low-angle thrust fault. Whatever the precise geometry of this dislocation, it appears from regional comparisons that it represents the absence of an appreciable thickness of Cambro-Ordovician strata. This presumably includes the entire Vølvedal Group (if deposited in this part of the basin) and the entire Amundsen Land Group. The outcrop of Cambrian strata in the north-eastern part of the map area is limited to the south by a steeply-inclined NW–SE-trending thrust fault (Fig. 5).

Basic dyke

Basic dykes of several directions cut the Lower Palaeozoic strata of Johannes V. Jensen Land and the Frederick E. Hyde Fjord region (Soper *et al.* 1982; Henriksen 1992). Some N- to NW-trending dykes are shown in Figure 22. These dykes are regarded as late Phanerozoic (Cretaceous–Tertiary) in age and may reflect extensional events during Late Cretaceous rifting and the formation of the Eurasia basin to the east (cf. Surlyk 1991).

One NW-trending, fine- to medium-grained dolerite dyke is exposed along the south shore of Frederick E. Hyde Fjord just west of Citronen Fjord and shown in the north-western corner of the location and geological maps (Figs 3, 5). It is exposed within a very thick limestone conglomerate and at the contact with overlying and partly intercalated sandstone turbidite beds that are referred to Units 11 and 12 (Upper debris flow and Sandstone turbidites, see Fig. 7). The stratigraphic block of thick debris flows and sandstone turbidites in which the dyke occurs is underlain by black mudstones and siltstones that are referred to Unit 8 (Footwall shale). The major break thus indicated between these two successions is inferred to be a low-lying thrust fault (Fig. 5). The contact between the dyke and this thrust fault is not exposed.

Stratigraphy of the Citronen Fjord area

On the basis of field observations and drill core logging, the main characteristics of the twelve lithostratigraphic units recognized are summarized here in chronostratigraphic order. The stratigraphic contacts between the units are conformable unless otherwise stated. A schematic stratigraphic section, which also shows the positions of the three main levels of mineralization, is shown in Figure 7.

Buen Formation

The three oldest units of the succession mapped at Citronen Fjord are referred to the Buen Formation of Cambrian age (Jepsen 1971; see discussion under 'Lithostratigraphic correlation', p. 22). A discontinuous carbonate debris flow unit separates darker coloured, upper and lower siltstone units (Fig. 1).

Unit 1: Green siltstone

The dominant lithology of this basal unit is fine-grained, thick-bedded to massive, greenish grey siltstone. The unit shows thickness variation that may be in part tectonic. Thus, in the north near Frederick E. Hyde Fjord a vertical thickness of at least 300 m is present while the unit appears to thin to less than 100 m of true thickness to the south along Citronen Fjord. However, the base of the unit is not exposed, neither has it been

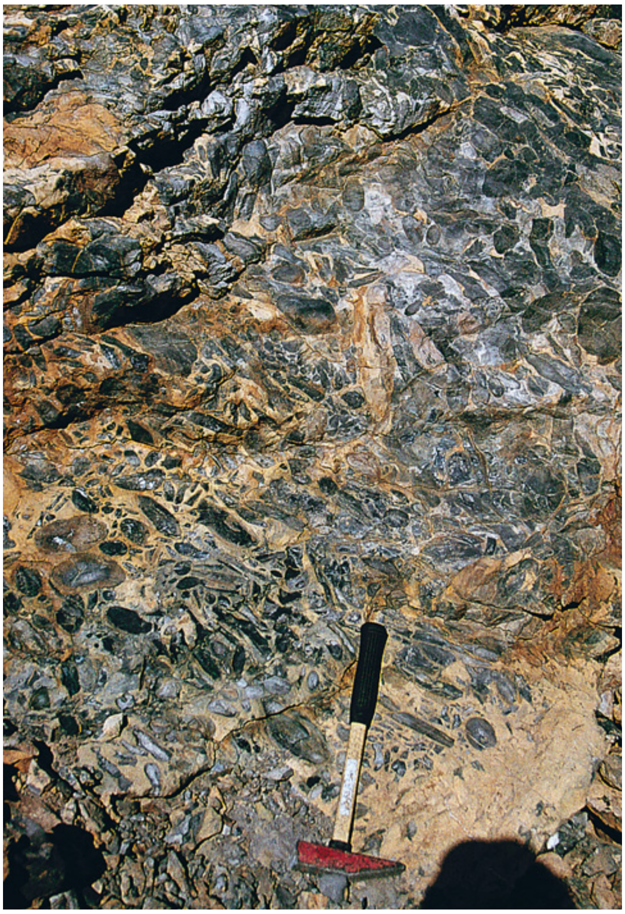


Fig. 8. Cigar debris flow (Unit 2) of presumed Early Cambrian age showing rounded, elongated clasts of dark carbonate in a quartzitic matrix. This is the oldest debris flow unit in the Citronen Fjord area. The hammer is 40 cm long. 'East Elv'; for location, see Fig. 3.

reached by drilling, and thus true thicknesses are unknown. The age of the unit is uncertain since no fossils have been collected.

Unit 2: Cigar debris flow

This, the oldest debris flow mapped, is a pale weathering unit composed of elongated clasts of carbonate and calcareous mudstone in quartzitic matrix; hence the informal name Cigar debris flow (Fig. 8). The unit, which in places has a basal metre-thick layer of massive dolomite, is discontinuous, varying in thickness up to 15 m. Where the debris flow is absent (or not exposed), the stratigraphic division of the siltstones occurring on either side into Units 1 and 3 is difficult and subject to interpretation. No fossils are known.

Unit 3: Black siltstone

This upper argillaceous unit is composed of black, rather monotonous, carbonaceous, planar-laminated and thin-bedded siltstone, which is locally phyllitic. Disseminated pyrite is common. Exposures of siltstones interbedded with black and dark grey cherts are common at the surface in the far north-eastern corner of the map area. The unit has a maximum thickness of 100 m and it thins markedly along the inferred thrust fault contact with the overlying Silurian (Units 9 and 10) where it is locally absent (Figs 5, 6).

The siltstones include a poorly exposed trilobite-rich horizon from which *Olenellus svalbardensis* Kielan, known from elsewhere in Peary Land, has been identified (J. Bergström, personal communication 1997; Blaker & Peel 1997) indicating an Early Cambrian age (Fig. 9).

Amundsen Land Group

In the Citronen Fjord area, the Amundsen Land Group (Friderichsen *et al.* 1982) is composed of dark, recessive, argillaceous strata with intermittent pale weathering, resistant, resedimented carbonate debris flows. Five mapping units are recognized with the two argillaceous units hosting the Citronen Fjord massive sulphides.

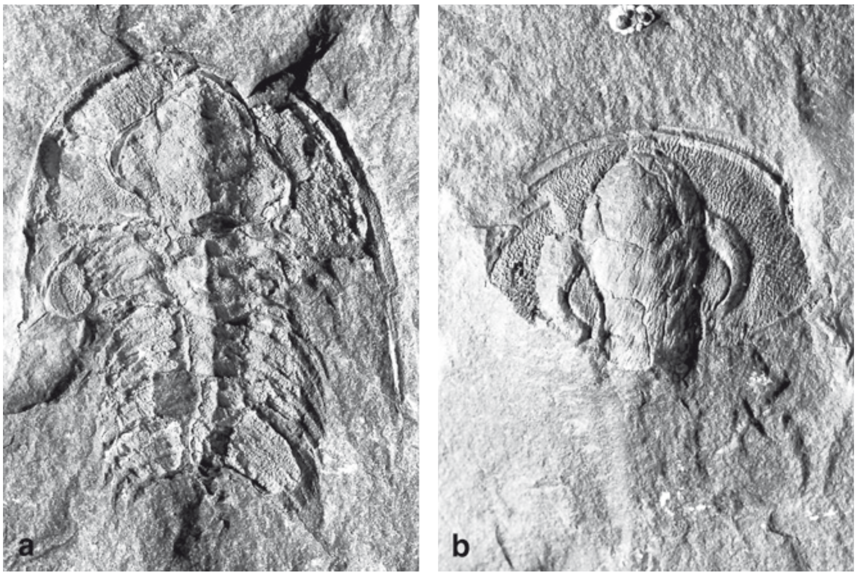
Unit 4: Lower mudstone

The Lower mudstone is dominated by dark grey interbedded dolomitic siltstone and graphitic mudstone, with common intercalations of arenite. The unit is similar to Unit 6 but lenses and 'eyes' of chert formed by the *in situ* replacement of siltstone and mudstone are common. Minor disseminated pyrite is present. No surface exposures are known. This unit is the lowermost unit intersected in drill holes and thus true thickness is unknown.

Unit 5: Lower debris flow

Like Unit 4, stratigraphically below it, this unit is not known from surface exposures. It is a clast-supported carbonate debris, strongly dolomitized and occasionally silicified. Minor pyrite is present in the matrix, especially in the upper part of the unit. Clast size indi-

Fig. 9. *Olenellus svalbardensis* Kielan, 1960. Dark siltstone of Unit 3 (Buen Formation); magnification: **a**, × 1.2; **b**, × 1.5. Depository: Geological Museum, Copenhagen; **a**, MGUH 24.554; **b**, MGUH 24.555. Photos: Peter Moors.



cates sorting. The average thickness of the unit based on drill hole data is 45 m.

Unit 6: Middle mudstone

This is a dark unit composed of a rhythmic layering of black graphitic, dolomitic and/or calcitic mudstone and dark grey siltstone, variously calcareous arenite, minor carbonate debris flows with fine- to medium-grained massive pyrite beds. Soft-sediment deformation and dehydration textures are characteristic features. The upper part of the unit is commonly brecciated due to depositional erosion by the overlying debris flow (Unit 7). The Middle mudstone unit varies from about 15 m to 85 m; the average thickness from drill cores is 50 m. This unit is the host rock of Level 3 sulphide mineralization (Fig. 7).

Unit 7: Middle debris flow

This is a matrix- and clast-supported calcareous and dolomitic limestone conglomerate unit showing sorted clast size especially in the uppermost part. Preferred orientation of clasts (imbricate structure) occurs locally. The clasts are generally fossiliferous with crinoids, reef corals and occasionally brachiopods being the main forms; the matrix is argillaceous. The conglomerate is locally altered by a penetrative process of dolomitization with associated gradational replacement of matrix and clasts by pyrite and occasionally base metal sulphides (sphalerite and minor galena; see section 'Post-sedimentary mineralization', p. 30). The lower part of the debris flow generally contains angular clasts of laminated massive sulphides, i.e. ripped up from the underlying Level 3 sulphide sheet by depositional erosion.

The thickness of this unit varies between a minimum of 2 m and a maximum of 104 m and is typically inversely proportional to the amount of the underlying massive sulphides (Level 3). The average thickness measured from drill holes is 50 m.

The Middle debris flow shows lateral variations in lithology. Thus in the southern outcrops along 'Citronen Elv' and immediately west of the Discovery area, and also near the west shore of Citronen Fjord, the largely monomictic conglomerate shows rusty weathering and is strongly pyritic. Towards Frederick E. Hyde Fjord, it abruptly changes character into a strongly pyritic, polymictic debris flow containing abundant, huge ('house-size') boulders of dolomite with common intercalations and enclosures of siliceous arenite, black mudstones and massive, fine-grained pyrite. Drill cores and rock exposures in the West gossan area indicate abundant and extensive slump and tectonic breccias, resulting in a stratigraphic–tectonic pattern not seen elsewhere in the Citronen Fjord area.

These rock types occur in the vicinity of the regional Harder Fjord Fault Zone (Fig. 3), that supposedly has been active during long periods. The highly disturbed character of the rock formations in this northern area could well be due to this major dislocation (see section 'Structural geology', pp. 32–33).

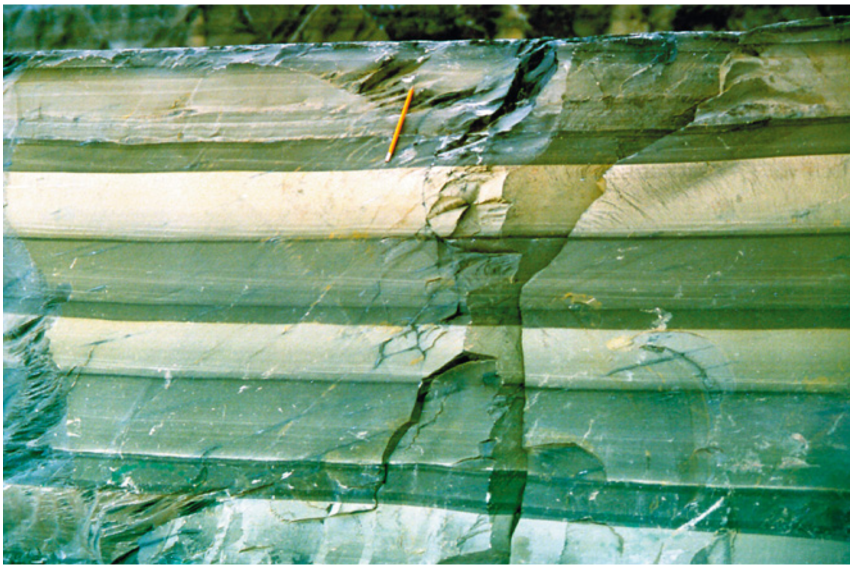


Fig. 10. 'Tiger striped' calcareous siltstone of Unit 10. The pen is 14 cm long. Esrum Elv, near the type locality of the Citronens Fjord Member; for location, see Fig. 3.

Unit 8: Footwall shale

This unit received its informal name 'Footwall shale' in 1993 after the discovery of outcropping massive sulphides in the inland gossan area, south-east of Citronen Fjord. Here, the unit forms the footwall of the stratiform (Level 1) sulphide sheet while the hangingwall is formed by an extensive carbonate debris flow, which for that reason was field-dubbed 'Hangingwall debris flow' (Unit 9; see Figs 5, 7).

The main lithology of the unit is black graphitic mudstone with dark grey, weakly calcareous siltstone. Intercalations of calcarenite and thin carbonate debris flows are common. Soft sediment deformation structures occur but are not characteristic. The unit is very similar to the calcareous siltstone of Unit 10 both in drill core appearance and outcrop, except that sedimentary features like ripple marks and cross-laminations are lacking. Scattered and disseminated pyrite occur throughout. The unit thickens rapidly to the north-west of Esrum Elv where there is an increase in the number of intercalated limestone debris flows. The drill-core thickness of the unit varies between 45 and about 100 m with an average of 55 m.

This unit hosts the upper levels of sulphide mineralization, viz. Levels 1 and 2 (Fig. 7).

Fig. 11. Sharp contact between the Upper debris flow (Unit 11) and the underlying calcareous siltstones of Unit 10 showing slight encroachment of the siltstone by the debris flow. The pen is 14 cm long. Esrum Elv, near the type locality of the Citronens Fjord Member; for location, see Fig. 3.

Fig. 12. Strongly-developed bottom structures, interpreted as flute casts, in upright folded sandstone turbidite beds of Unit 12 – the basal part of the Merqujôq Formation of Hurst & Surlyk (1982). Hammer in centre as scale. South of Esrum area; for location, see Fig. 3.

Peary Land Group (Merqujôq Formation)

The Peary Land Group (Hurst 1980) represents the uppermost strata of the Lower Palaeozoic succession in the Citronen Fjord area, being overlain by Quaternary and Recent deposits. Four mapping units are recognized, all of which are referred to the Merqujôq Formation of Hurst & Surlyk (1982).

Unit 9: Hangingwall debris flow

This is a clast-supported limestone conglomerate; the clasts are size sorted, especially in the upper part, and they occasionally show a preferred orientation. The carbonate clasts are fossiliferous with crinoids and reef corals common; a coral-crinoid-brachiopod fauna is regarded by Bjerreskov & Poulsen (1973) to be of Llandovery age. The conglomerate generally has a brown to rusty appearance (Fig. 4). Pyrite is a common constituent within the matrix; in places pyrite occupies the entire matrix, with occasional traces of sphalerite and galena. The thickness of the unit varies from a few metres to 90 m; the average thickness from drill cores is about 55 m. In general, the unit has a sharp lower contact with the argillaceous rocks of Unit 8.

The Hangingwall debris flow unit equates with the lower and thicker of the two carbonate conglomerate units in the Citronens Fjord Member of Hurst & Surlyk (1982; Fig. 4) that has a thickness of about 80 m at the type locality.

Unit 10: Calcareous siltstone

This unit is generally of rather monotonous lithology composed of dark grey, thin-bedded calcareous siltstone and muddy carbonate turbidites. Some types show a discrete banding of darker and paler silt beds (Fig. 10). A common, well-preserved sedimentary feature is cross-lamination (starved ripples). Graptolites, common at certain intervals, indicate a Late Llandovery age for Unit 10 that corresponds to the age of the Citronens Fjord Member established by Hurst & Surlyk (1982).

The main graptolites identified in our samples are *Monograptus turriculatus, Monograptus* ex. gr. *exiguus, Monograptus* cf. *becki, Monograptus* sp. cf. *contortus, Pristiograptus* sp., *Streptograptus pseudoruncinatus*, and *Rastrites carnicus* n. ssp., indicative of the *M. turriculatus* Zone of early Telychian age (M. Bjerreskov, personal communication 1993). A single graptolite, *Monograptus* aff. *Monograptus anguinuus*, from 30 m below the top of the Citronens Fjord Member – presumably within Unit 10 of this paper – is reported by Hurst & Surlyk (1982) and said to be indicative of the *Monograptus spiralis* Zone.

Scattered pyrite is common, but no massive sulphides have been observed. The unit is hardly distinguishable from Unit 8 (Footwall shale) in both outcrop and drill core, and, although the unit forms a discrete stratigraphic interval between the units of debris flow (Units 9 and 11), calcareous siltstones indistinguishable from Unit 10 lithology, interdigitate with the turbidites of the overlying, and uppermost unit of the succession, viz. Unit 12. The estimated thickness of Unit 10 is between 200 and 450 m.

Unit 11: Upper debris flow

This unit is a clast-supported limestone conglomerate in which clast size varies from centimetre to a couple of metres (see Fig. 26). In general, the rock is poorly sorted; vague preferred orientation of clasts is locally seen. The clasts are fossiliferous with crinoids and reef corals the most common forms. The matrix is argillaceous but it becomes increasingly sandy in northern exposures where the unit thins out and gradually changes into a matrix-supported conglomerate. The Upper debris flow, which is characterized by sharp upper and lower boundaries (Fig. 11), has an average thickness of about 20 m.

The Upper debris flow corresponds with the thin limestone conglomerate beds that occur in the uppermost part of the type section of the Citronens Fjord Member of Hurst & Surlyk (1982, section 33; location in Fig. 3).

Unit 12: Sandstone turbidites

This, the uppermost unit of the exposed succession the map area, is a reddish brown weathering, fine-grained turbiditic sandstone with common intercalations of carbonate and quartz-chert debris flows, and abundant calcareous siltstone. Sedimentary features such as graded bedding, cross-bedding, load casts, and flute marks are common (Fig. 12).

The sandstone turbidites interfinger with the calcareous siltstones of Unit 10 and they are limited upwards by the present erosion surface and surficial deposits. Our estimate of the preserved thickness of Unit 12 in the Citronen Fjord area is about 700 m but a greater thickness may occur to the south.

Lithostratigraphic correlation

In the section above, the twelve informal lithostratigraphic units recognized in the Citronen Fjord area, are described under three formally-named rock units, viz. the Cambrian Buen Formation, the Ordovician Amundsen Land Group and the Silurian Peary Land Group. In addition, the early Silurian part of the succession is correlated at formation level (Merqujôq Formation) while one member – the Citronens Fjord Member – that has its type section at Citronen Fjord (see Fig. 3), is readily applicable to this study (Fig. 7).

However, formal lithostratigraphic subdivision of the Cambro-Ordovician trough sediments in North Greenland has not been made and the formations mentioned in the literature and included on published maps of the Frederick E. Hyde Fjord area have not been formally described (Bengaard & Henriksen 1986a, b; Pedersen & Henriksen 1986; Higgins *et al.* 1991a; Henriksen 1992).

A summary of the lithostratigraphy of the Frederick E. Hyde Fjord area, taken from published sources, is given in Figure 13 but the stratal limits of the seven formations of the Vølvedal and Amundsen Land Groups, and their spatial distribution, remain unpublished. The correlation of the lower eight units mapped by us at Citronen Fjord to named units in the literature is not obviously apparent and therefore in this paper no formal correlation is attempted. However, some comments on the correlation of the informal units with the regional lithostratigraphy are given below as an aid to further mapping and research.

Cambrian

Are the Cambrian strata recognized herein at Citronen Fjord representative of the Buen Formation or the Polkorridoren Group?

The Polkorridoren Group is a monotonous sequence at least 2 km thick of turbiditic sandstones, siltstones and mudstones with a type area to the north-west of Citronen Fjord in Johannes V. Jensen Land (see Fig. 22; Dawes & Soper 1973; Friderichsen *et al.* 1982). The