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Cement generations and diagenetic history of the upper Ordovician Cliefden Caves Limestone Group of New South Wales, Australia

By

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with 7 Text-figures

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Abstract: Diagenetic features of the upper Ordovician (Caradocian) Cliefden Caves Limestone Group (N. S. W., Australia) were studied by the cathodoluminescence (CL) method, and their relation with depositional environments was discussed. The Cliefden Caves Limestone Group was deposited on a shallow marine carbonate platform developed on a volcanic island. The limestone succession reveals intertidal-subtidal lithofacies and consists of the Fossil Hill, Belubula, and Vandon Limestones, in ascending order. The Fossil Hill Limestone mostly consists of bedded limestone rich in brachiopods and sedentary organisms. The Belubula Limestone is a typical Middle-Upper Ordovician peritidal succession with syn-depositional dolomite and silicified fossil grains. The Vandon Limestone consists of fossiliferous stratified limestone occasionally containing red brown argillaceous limestone beds.

The Cliefden Caves Limestone Group was subjected to various diagenetic processes. The investigation of CL is the best or only method to differentiate the diagenetic products. There are at least three cementation stages and a dissolution stage. The cements of the first stage are mainly dull fine-grained (10-30 μm) calcite crystals fringing inter- and intra-granular porosity, which typically indicate a marine phreatic environment. In some specimens of the Belubula Limestone, cement of the first generation exhibits meniscus fabrics suggesting precipitation in a marine vadose environment. The dissolution formed both molds of aragonitic skeletal grains and fabric-unrelated void spaces which can exceed several cm in diameter. Lack of the first generation cement within the dissolution voids indicates that the dissolution postdated the marine cementation. After the dissolution stage, the second cementation precipitated granular calcite crystals composed of non-luminescence, dull, and bright zones in the peripheral order. The relative thickness of non-luminescence and bright zones probably related with a redox condition during their diagenesis. The last generation of cements formed in a deep burial environment, is normally dull and filled almost all remained porosity. This diagenetic history fits to the change of depositional environment which may have been controlled by both of local and global environmental settings.

Contents

I. Introduction

The cathodoluminescence (CL) method uses the phenomenon of luminescing material under electron bombardment. Luminosity is clearly related to the concentration of certain elements and ions within a host material. Although the method has been used for various geological minerals (Nickel, 1978; Marshall, 1988), a large part of studies applies to carbonate minerals.

One advantage of using the CL method to carbonate minerals is to erase the effect of neomorphism which generally destroys the initial boundaries between crystals having different minor-elements compositions. The relation between the CL luminosity and minor elements of carbonate minerals has been studied (Frank *et al.*, 1982; Fairchild, 1983). The positive relation was found between the intensity of luminescence and Mn^{2+} content in the host carbonate minerals. On the other hand, the most important inhibitor of luminescence is Fe^{2+}. Contents of both Mn^{2+} and Fe^{2+} have a strong relationship with radox condition of pore fluid (Grover and Read, 1983; Walkden and Davies, 1983; Barnaby and Rimstidt, 1989). Oxidized fluid normally precipitates carbonate minerals with low Mn and high Fe contents. Whereas, reduced fluid in restricted condition forms crystals rich in Mn^{2+}. Therefore, CL can be used not only for recognition of original crystal fabrics, but also to reconstruct a radox condition of pore fluid.

The Cliefden Caves Limestone Group is distributed in one of the Upper Ordovician (Caradocian) limestone succession of the central New South Wales, Australia. The limestones exhibit various sedimentary structures including nodular stratification, microbial laminations, burrows, and irregular discontinuous surfaces. The algal-dominated biofacies, together with the sedimentary structures, indicate that the limestone sequence was mostly deposited in a shallow-marine environment. Diagenetic features of the limestones are also various. Besides cementation and dissolution features, hematite concentration and dolomite are commonly occur.

This study investigates the CL of diagenetic features found in the upper Ordovician Cliefden Caves Limestone Group of the Licking Hole Creek area in New South Wales, Australia and their relation with depositional processes will be discussed.

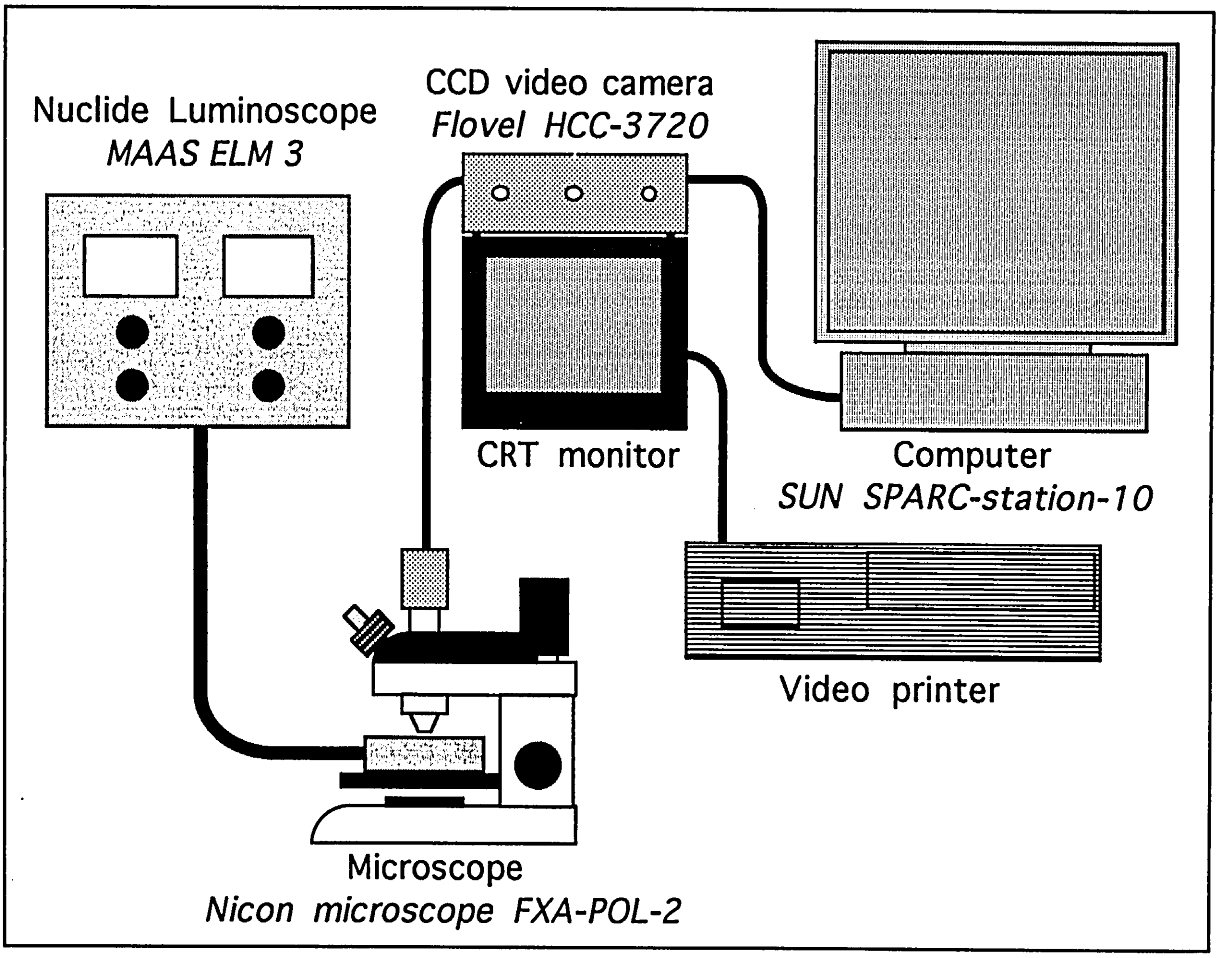

Fig. 1. The cathodoluminescence system in Department of Earth and Planetary Systems Science, Hiroshima University.

Acknowledgment

This is the first research using the cathodoluminescence system which has been introduced in Department of Earth and Planetary Systems Science, Hiroshima University since spring of 1994. We deeply thank to all the stuffs involved in organizing the introducing the facilities. We would also like to thank Drs. Berry D. Webby and Ian G. Percival for the field guidance and permission to use facilities in the University of Sydney. Mr. Hugh and Mrs. Judy McLaren who live in the property of 'Liscombe Pools', kindly provided a part of their accommodation. Kano received the Foreign Research Grant from the Ministry of Education for traveling to Australia.

II. Methods

Field work was carried for three weeks by the first three authors for mapping the geology and constructing the stratigraphy. Approximately 300 rock specimens were collected. Thin sections of each specimen were made in both of Sydney and Hiroshima Universities.

The thin sections were polished and investigated by optical microscope and cathodoluminescence (CL}. The CL equipment of the Hiroshima University consists of a Nuclide Luminoscope MAAS ELM 3 mounted on a Nikon microscope FXA-POL-2. The operating conditions for CL were 12 kV gun potential and 0.8 mA beam current. The CL light can be observed through the microscope and as a view taken by a CCD video camera Flovel HCC-3720. However, the CL view by using the CCD camera alone is often too dark and in low contrast to define different diagenetic properties. Therefore, a video signal of the CL view was sent to computer SUN SPARC-station-10 which is capable to strengthen a slight difference in lightness and colour between different diagenetic properties.

The CL system of the Hiroshima University is shown in Fig. 1.

III. Geological setting of the studied area

The studied area (Licking Hole Creek area) is located east of the Sugar Loaf Road 10 km north of Woodstock in the central-eastern New South Wales State, Australia (Fig. 2). The area is separated by a property boundary between the 'Liscombe Pools' and 'Bingara'. Localities are easy to access from the paddock gates along the Sugar Loaf Road.

The Cliefden Caves Limestone Group is distributed in an area of 1.0 (E-W) x 2.5 (N-S) km^2. Although macrofossils, such as brachiopods, tabulates, and rugose corals, had been reported from the beginning of the century, the first stratigraphic work was done by Percival (1976). He called the limestone succession as the Cliefden Caves Limestone and divided it into 'big shell', 'thin bedded', 'middle member', ' grey', and 'island' units. He estimated the thickness of the limestone 363 m, and also noted occurrence of various faunas and discusses depositional environment of the limestone sequence. However, the work of Percival (1976) left a problem in its informal stratigraphic nomenclature of the 'units'.

The type locality of the Cliefden Caves Limestone Group studied by Webby and Packham (1982) is located several kilometers northeast of the Licking Hole Creek area. The group shows a slight difference in lithology and thickness, however is almost regarded as an equivalent limestone sequence of the Licking Hole Creek area. The work of Webby and Packham (1982) proposed the stratigraphic division and defined three formations, the Fossil Hill, Belubula, and Vandon Limestones, in the ascending order.

The geology of the Licking Hole Creek area consists of the Paleozoic sedimentary rocks deposited on a platform based on the Walli Andesite (Fig. 3). The age of the andesite is unknown, however the geochemical composition suggests that the Walli Andesite might have had an island-arc origin (Cas *et al.*, 1980). A large part of the Paleozoic sedimentary rocks of the area is composed of the upper Ordovician Cliefden Caves Limestone Group followed by the Malongolli Formation. The latter is mostly composed of sandstone and mudstone including limestone layers. Graptolites (Moors, 1970) and trilobites (Webby, 1974) are found from mudstone, and siliceous sponges occur in the limestone blocks (Rigby and Webby, 1988). The relation between the Cliefden Caves Limestone Group and Malongulli Formation is problematic,

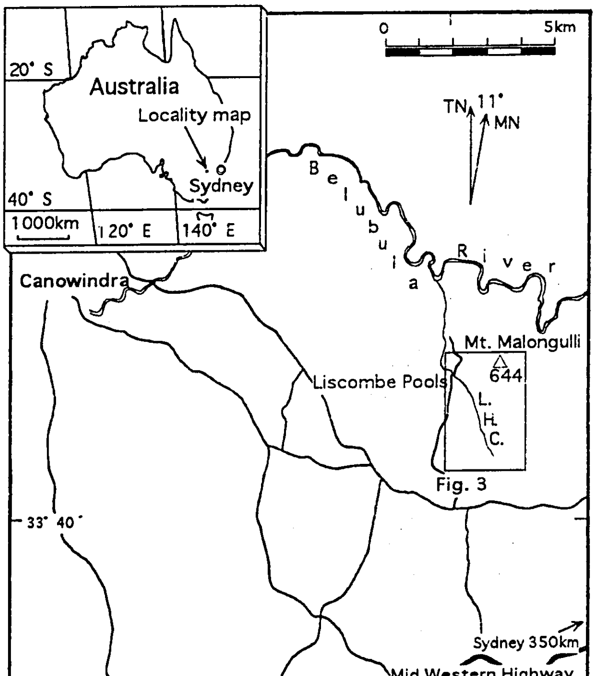

Fig. 2. Map showing the location of the Licking Hole Creek area (L. H. C.), New South Wales, Australia.

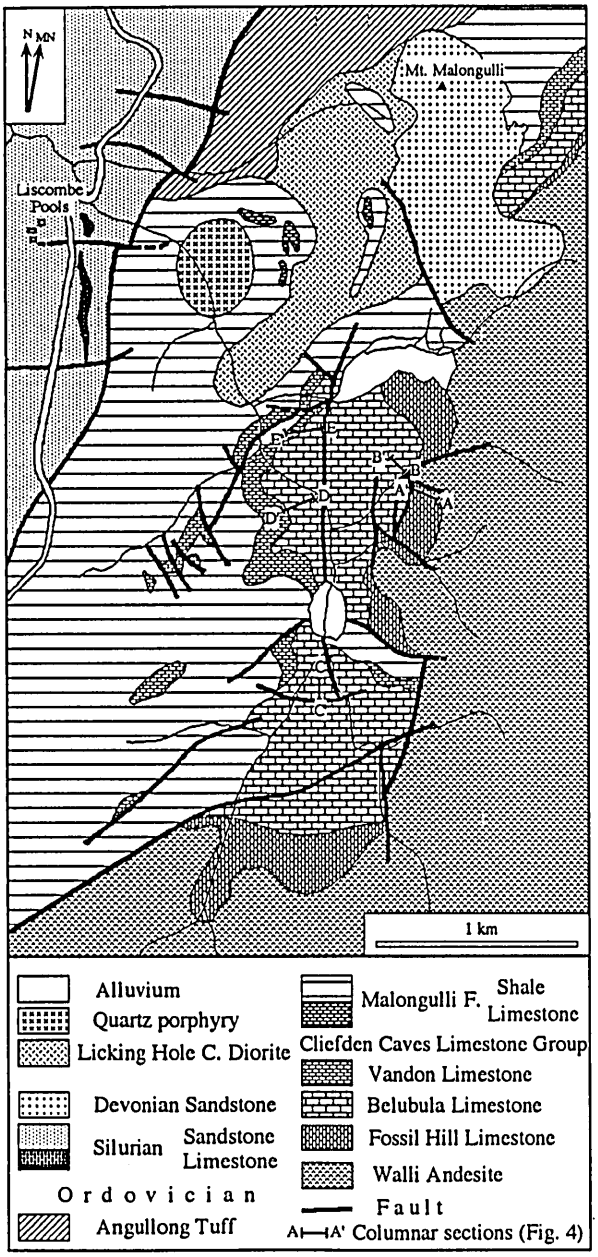

Fig. 3. Geological map of the Licking Hole Creek area. Relationships between different geological units refer to the text. Localities of the columnar sections (Fig. 4) are shown.

although an unconformity has been suggested by Webby and Packham (1982). The unconformity is also supported by the distributing pattern of the two units in Licking Hole Creek area, however the low angle fault contact cannot be refuted. The Silurian shale and sandstone including autochtonous limestone beds (Millambri Formation; Percival, 1976) occurs in the western part of the area in a probable fault contact with the Malongulli Formation. A Devonian sandstone, in the northern part of the area, covers on the older rocks with an uncomformable contact. The Devonian sandstone may have fluvial to brackish water origin, but its sedimentology and stratigraphic position is poorly defined. The younger volcanics (quartz porphyry and Licking Hole Creek Diorite) also occur (Fig. 3).

IV. Cliefden Caves Limestone Group

Because the stratigraphic units used by Percival (1976) do not sounds formal, we basically follow the stratigraphic definition of Webby and Packham (1982). Therefore, the limestone succession is treated as a group and divided into three formations; Fossil Hill, Belubula, and Vandon Limestones. Stratigraphic columns are shown in Fig. 4. Facies of the three formations are described below.

A. Fossil Hill Limestone

The Fossil Hill Limestone forms the lowermost of the Cliefden Caves Limestone Group. The maximum thickness of this formation is at least 25 m (Fig. 4) however the thickness varies within the studied area. In the southern part of the area, this formation is almost thinning out.

The lower part (17 m) of this formation mostly consists of bedded limestones (thickness of a single bed is 10-30 cm) of various lithology characterized by a sufficient content of terrigenous material. Some beds abound with large brachiopod (*Eodinobolus* sp.) shells were noted by Webby and Percival (1983) as *in-situ* shell beds representing a comparable paleoecology with recent oyster banks. This part is equivalent to Percival's (1976) 'big shell unit'. Large (up to 50 cm in diameter) skeletons of tabulates (*Tetradium cribriforme* is the most common species) and stromatoporoids are found in the lower part of the formation. Oncoids are common. Reddish brown argillaceous limestone containing trilobite skeletons occurs in several horizons.

The upper part (8 m in thickness) of the Fossil Hill Limestone is composed of relatively thin (20-40 cm) limestone beds, and has been previously called as the 'thin bedded unit' by Percival (1976). The most profound characteristics of the upper part are silicified skeletons (probably originated from sponges) and dolomitized burrows (Figs. 5-c, d) found on bedding planes.

In thin sections, the limestones of this formation commonly exhibit wackestone to grainstone textures. The limestone beds contains various fossil grains and peloids. Dominant fossil components of the lower part are calcareous algae, molluscs, trilobites, and echinoderms whereas the upper part abounds with sponge spicules and molluscs. The limestone normally contains 2-10 % (one specimen contains 30%) of insoluble residue. Hematite is more common in the lower part. Dolomite increases in the upper part.

B. Belubula Limestone

This Formation is characterized by bedded limestones exhibiting dolomitization and silicification features. Thickness of the formation is approximately

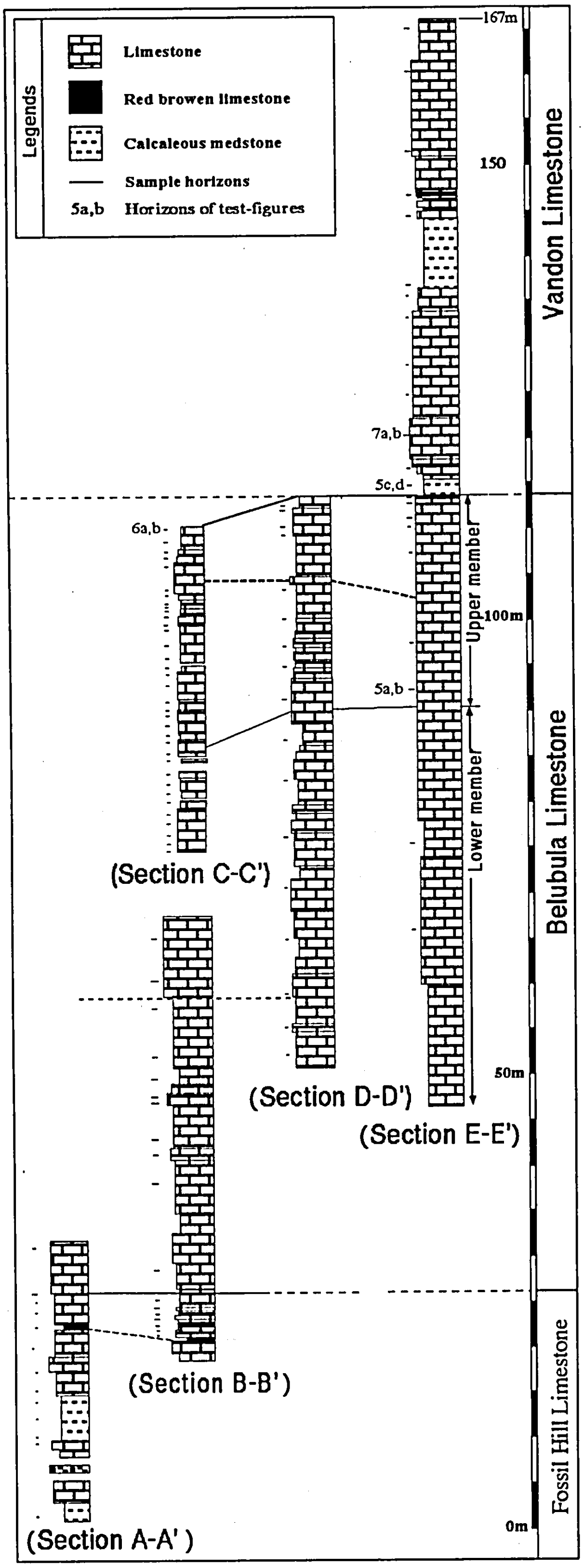

Fig. 4. Columnar sections of the Cliefden Caves Limestone Group of the Licking Hole Creek area. The localities of the sections are shown in Fig. 3. The stratigraphic horizons of the specimens of the microscopic and CL photographs (Figs. 5-7) are shown.

87.5 m that occupies more than half of the total thickness of the Cliefden Caves Limestone Group. The Belubula Limestone can be divided into two members (Fig. 4) which differs in sedimentological charac-teristics each other.

The lower member consists of thicker (mostly 50-120 cm) bedded limestone, and all together makes 65 m in thickness. On the outcrops large fossils are rare although calcareous algae can be found in some cases. Dolomititized burrows are common, but silicified sponges become less. A 10 cm thick red-coloured limestone bed occurs at 30 m from the base of the Belubula Limestone. In thin sections, most of the limestones of this member exhibit lime-mudstone to wackestone textures, abounding with calcareous algae and sponge spicules. The biofacies of the lowermost specimen is dominated by calcareous algae. Then, the lower limestones are rich in sponge spicules, and the upper limestones abound with calcareous algae. Insoluble recidue is less than 10 %.

The 22.5 m thick upper member appears similar in lithology to the lower member. However, the most important difference is that the upper member contains brachiopod (*Eodinobolus* sp.) shell beds which have been identified as 'E-horizon" by Percival (1976). Thus, the boundary between the lower and upper members is defined by the base of the first shell bed. The upper member also includes a 1.5 m thick biostrome formed by stromatoporoids (*Labechiella* and *Clathrodictyon* are common genera) and heriolitids. The growth form of the stromatoporoids is mostly domical. In thin sections, the limestones mostly exhibit wackestone to lime-mudstone textures although a specimen from the biostrome consists of peloidal grainstone. Molluscs, calcareous algae, and echinoderms are the most important fossil components. Dolomitized burrows are still found in the upper member. Intraclast occurs in several horizons. About 10 % insoluble residue is contained.

C. Vandon Limestone

This formation consists of thin (5-50 cm) bedded limestones. The total thickness is 52.5 m. There are three different types of limestones, and they are here temporary called as red, greyish yellow, and dark grey limestones.

The red limestones are found in three different horizons, and the base of the lowermost bed defines the boundary between the Belubula and Vandon Limestones (Fig. 4). They are normally thin (up to 20 cm), and exhibit various textures (from packstone to grainstone). In thin sections, the red limestone beds normally contain intraclasts. This and hematite-originated red colour indicate that the beds might have been associated with subaerial exposure. They contain around 15 % percent of insoluble residue.

The greyish yellow limestones occur at the separated two horizons (Fig. 4). They are thin (10-20 cm) bedded and normally contain molluscs, echinoderms, and trilobites. In thin section, they are grainstone fabrics, especially specimens of the lower horizons (Fig. 4) show well-winnowed peloidal lithofacies.

The dark grey limestones are, on outcrops, similar in lithology to the Belubula Limestone however they are poor in dolomitized burrows. A single bed is thicker (30-50 cm). Calcareous algae, molluscs, and echinoderms are the most common fossil components. However, some horizons exhibit concentration of ostracodes. They are mostly bioclastic wackestone or peloidal grainstone.

Birdseye structures are found in a greyish yellow and dark grey limestones of the lower horizons of the Vandon Limestone.

V. Diagenetic features in CL

The Cliefden Caves Limestone Group has been subjected several different diagenesis; cementation, dissolution, and dolomitization. At least three different cement generations can be identified in a CL view. Veins were formed during or after the diagenesis. Here, we describe these diagenetic characteristics in the order of formation.

A. Stage 1 cement

Stage 1 cement consists of small (10-30 μm) crystals fringing intra- and intergranular porosity (Fig. 6-b). This is the first diagenetic feature and found most of the specimens of the Cliefden Caves Limestone Group. CL of the stage 1 cement is mostly dull (Fig. 6-b) however some specimens (Fig. 7-b) exhibit small dull crystals followed bright fringes. In specimens of the Belubula Limestone, the first generation of cements forms a larger dull crystals bridging in the pore space between grain components (Fig. 5-a, b). Generally the porosity of fine-grained peloidal grainstone is almost filled up with the stage 1 cement. However, in coarser-grained lithologies, the stage 1 cement normally fills 10-50 % of porosity.

B. Dissolution

Dissolution of the Cliefden Caves Limestone Group selectively affected molluscan and calcareous algal skeletons which might originally have had aragonitic mineralogy (Figs. 5-a and 7-a). However less frequently, micritic sediment of the 'host' rock is also dissolved (Fig. 7-a). Brachiopods which retain an original calcite mineralogy, generally preserve their internal skeletal structure. Fig. 7-a shows two dissolution void spaces formed within a calcareous algal grain. The void space was later filled by cement, however stage 1 cement does not exist in the dissolution voids (Fig. 7-b).

C. Stage 2 cement

The stage 2 cement consists of rhombic or granular crystals which often follows the stage 1 cement (Figs. 6-b, 7-b) and appears as the first generation within dissolution voids (Fig. 7-b). The most common type of the stage 2 cement appears crystals showing an increase in the luminosity, which normally consists of the non-luminescent to dark dull base followed by a dull part and the bright margin. Some crystals lack the non-luminescent basal part. A variation was found in the relative thickness between dull and bright zones. However, other types of the stage 2 cement having a multiple zoning of CL colour or a dolomitic zone in the very marginal part of the crystals. Variation in CL fabrics of the stage 2 cement might have some relation with stratigraphic horizons, however further investigation is necessary to establish the relationship. The stage 2 cement filled 5-50 % of porosity.

D. Stage 3 cement

The stage 3 cement is always an overgrowth from the margins of the stage 2 cement and filled remained porosity. CL of the stage 3 cement mostly dull-bright with slight zonation in colour. In a void within an ostracodes skeleton of Fig. 7-b, the zoning of the stage 3 cement outlines the configuration of the stage 2 cement. Sector zonings (Reeder and Paquette, 1989; Raven and Dickson, 1989) of an unknown origin are often found in the stage 3 cement.

E. Dolomite

Dolomite occurring within the sediment in burrows is most common in the Belubula Limestone. Configuration of the dolomite rhombs is much more easily recognized in a CL view (Fig. 5-d) than in a normal microscopic view (Fig. 5-c). The dolomite rhombs normally consist of dull center and bright margin.

F. Veins

Veins are common in the limestone specimens of the Cliefden Caves Limestone Group. They were formed in several different periods. All the veins truncate stages 1 cement. The first generation of the veins predates the stage 2 cement, and shows an open space filled mostly by non-luminescent to dull CL calcite crystals with bright margins. The veins might have been formed during a period between the stage 2 and 3 cementations (Fig. 6-b). However, veins of very bright CL shown in Fig. 6-b, can be a calcite fill within a fracture at the crystal boundary between the stage 2 and 3 cements.

VI. Discussion

A. Depositional environments of the Cliefden Caves Limestone Group

Geochemical composition of the Walli Andesite indicates an island-arc setting (Cas *et al.*, 1980) that is coincides tectonic setting of the Lechlan Fold Belt (Cas, 1983). Initiation of the late Ordovician carbonate deposition may have been associated with the ceasing of the andestic volcanism and the following subsidence of a volcanic island. The three

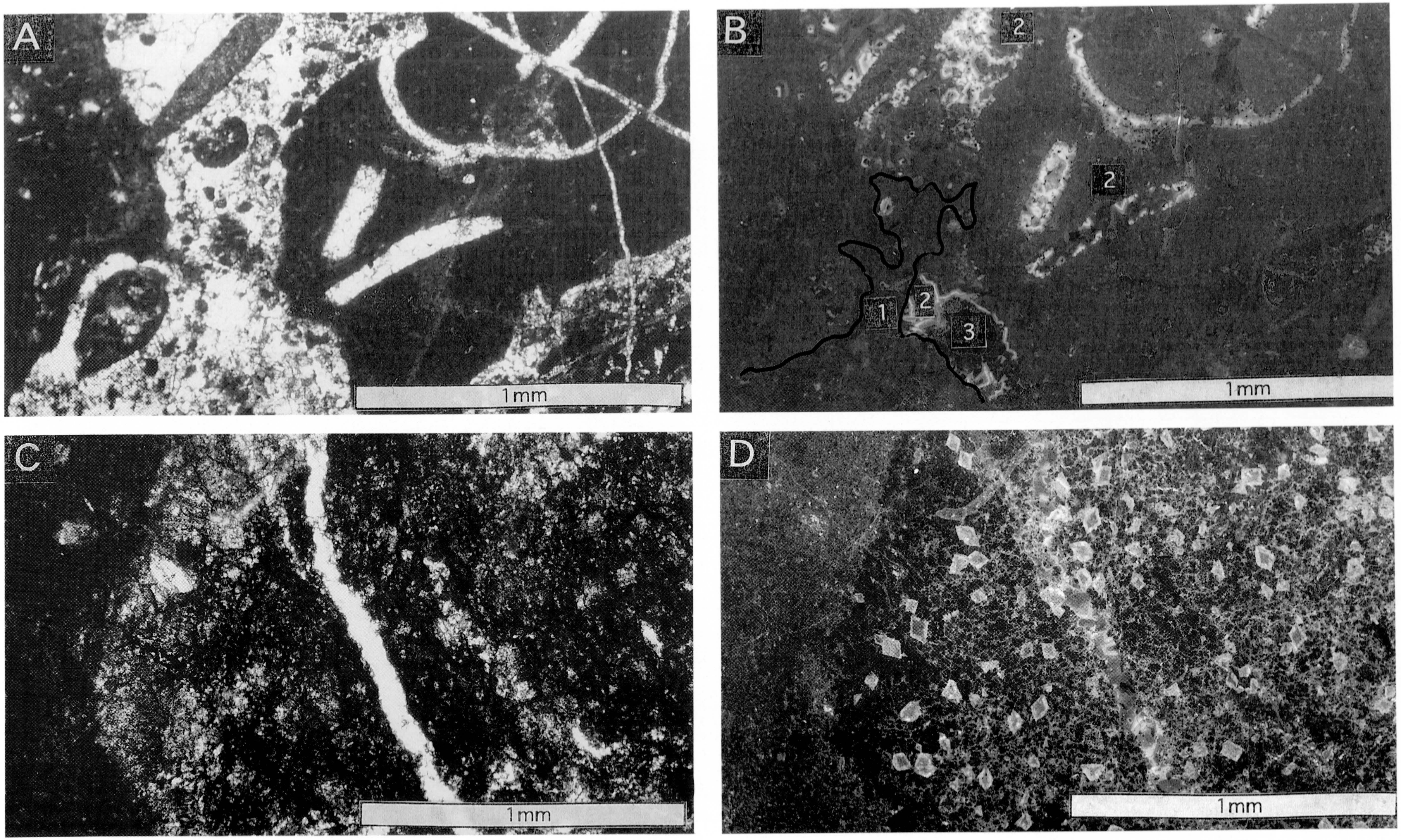

Fig. 5. Diagenetic features of the Cliefden Cave Limestone Group of Section E-E'. a) Intergranular porosity of the upper member of the Belubula Limestone (see Fig. 4). b) The CL view of the same area of Fig. 5-a. The porosity is filled with cements of the stages 1, 2 and 3. The stage 1 cement exhibit a meniscus fabrics which might indicate a precipitation under a marine vadose environment. c) A burrow filling including dolomite rhombs of the lowermost of the Vandon Limestone (see Fig. 4). d) The CL view of the same area of Fig. 5-c. The rhombs are much more easier to be recognized.

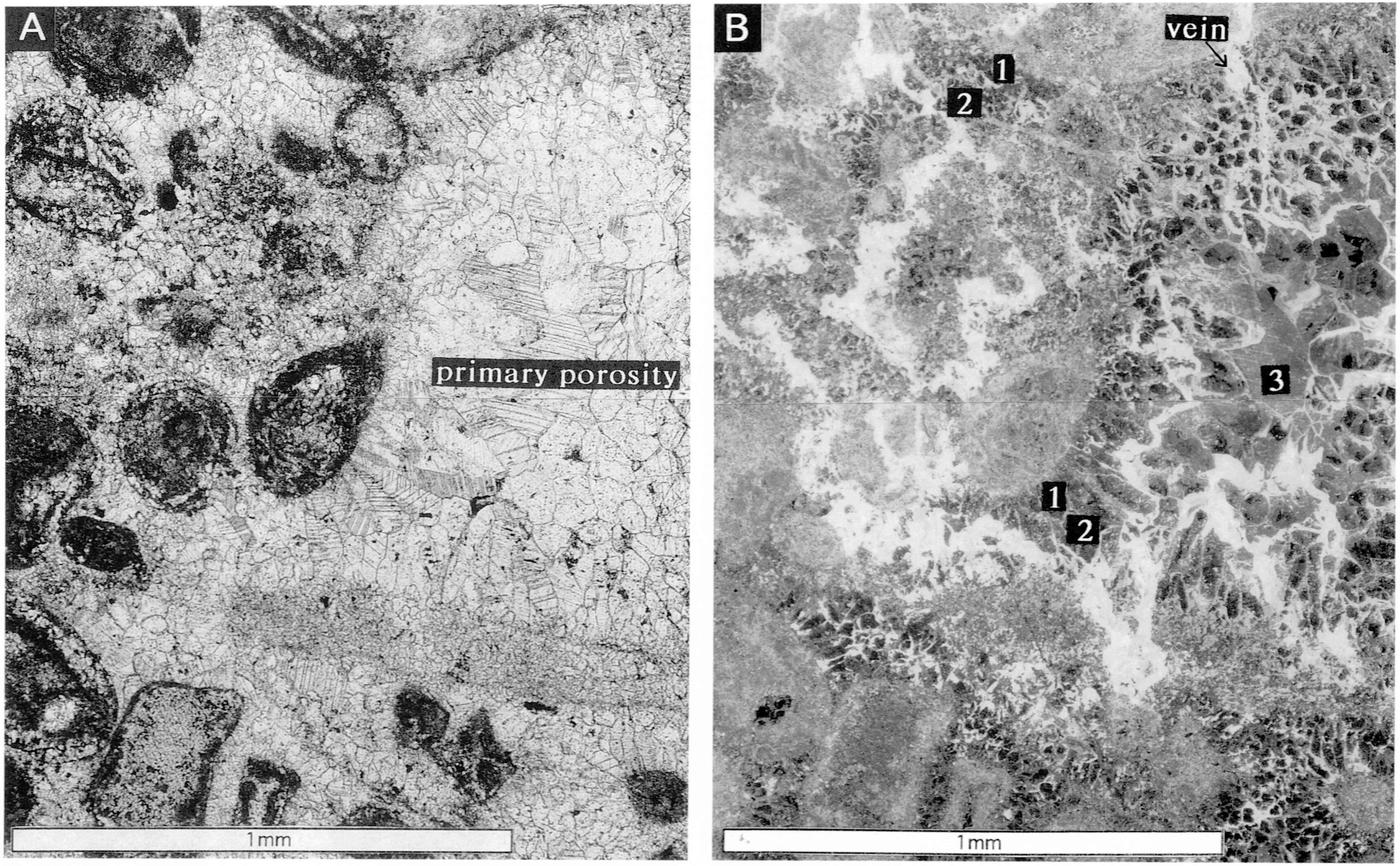

Fig. 6. Bioclastic grainstone of the lower part of the Vandon Limestone of the section E-E' (see Fig. 4). a) The specimen shows a large (more than 1 mm in diameter) primary porosity filled with cement. b) The CL view of the same area of Fig. 7-a. All the three stages of cement are recognized. The veins exhibit a very bright CL.

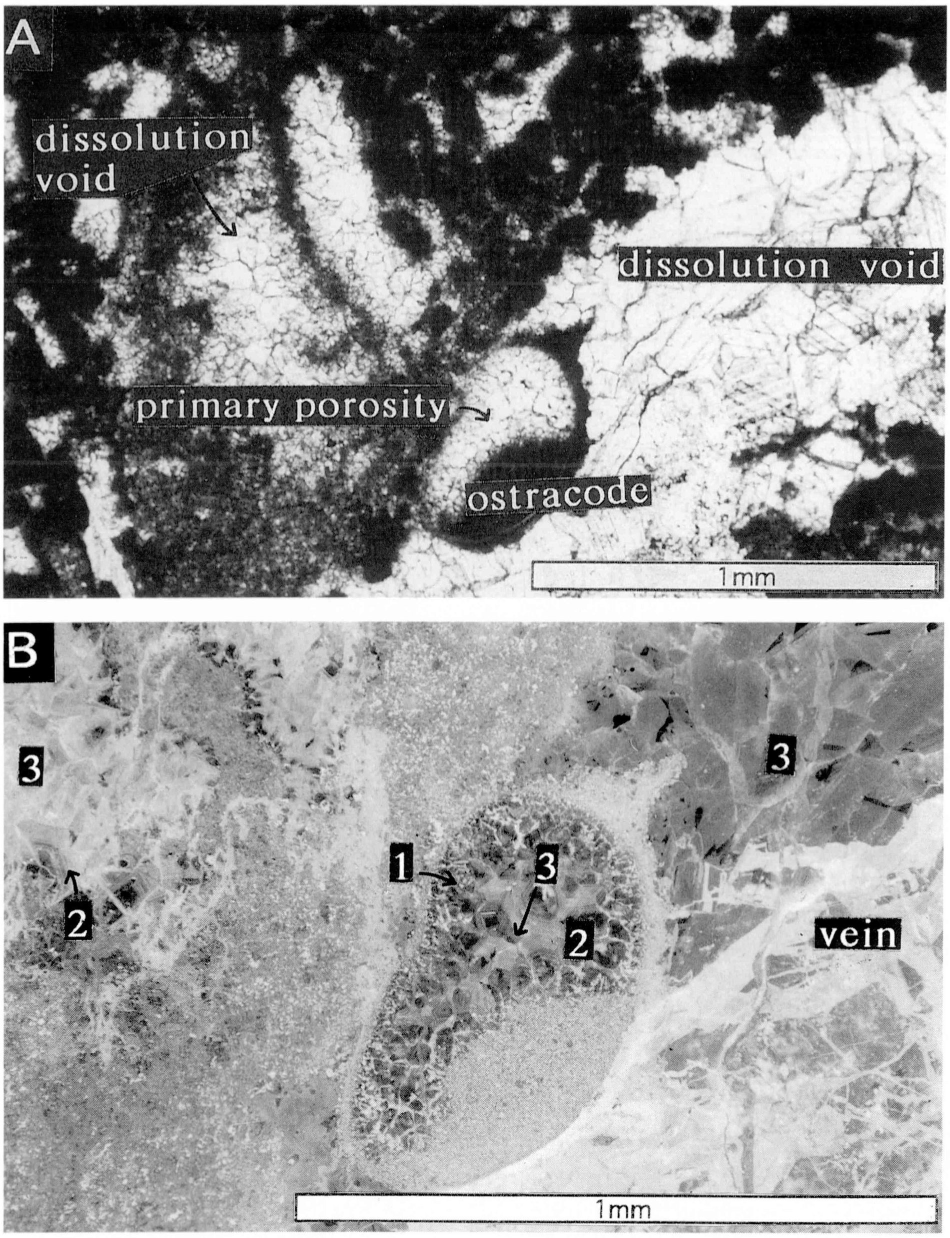

Fig. 7. Diagenetic features of the upper member of the Belubula Limestone of the section C-C' (see Fig. 4). a) Partly dissolved peloidal grainstone. The dissolution truncates the original configuration of peloids. However, an ostracode grain with primary porosity survived the dissolution. b) The CL view of the same specimen of Fig. 6-a (but, magnification is different). The porosity and voids are filled with all three stages of the cements, however the stage 1 cement is only found in the primary porosity within the ostracode skeleton.

formations of the Cliefden Cave Limestone Group, represent different lithological characteristics resulted from the differences in depositional environments.

The Fossil Hill Limestone on-lapped upon the slopes of the platform surrounding an island of the Walli Andesite. The on-lapping mode of sedimentation is indicated by the variation in thickness of the Fossil Hill Limestone within the studied area. Because the platform was partly submerged above the sea-level, terrigenous material was supplies to carbonate sediment. The sea water circulation was relatively well. This probably responds to the grainstone fabrics and richness in sedentary organisms of the Fossil Hill Limestone. However, the oncoids and microbial lamination suggests that a restricted environment was developed in a part of the platform. Sulfur reducing bacteria once formed iron sulfide, however the following sufficient circulation oxidized it to hematite.

The contact between the Fossil Hill and Belubula Limestones appears irregular surfaces stained by hematite. These features might be related with subaerial exposure. If it is the case, sea-level was at least slightly lowered.

The Belubula Limestone shears the depositional and some of diagenetic characteristics with typical Middle-Upper Ordovician limestones deposited on eperic platforms (Rao and Wang, 1990; Montanez and Read, 1992a; Kano *et al.*, 1994; Sun, 1994). Depositional condition of these platforms is now interpreted as a very shallow platform with a huge flat bathymetry, which had been always filled up with sediment. The Belubula Limestone may not be an exception. The previous deposition of the Fossil Hill Limestone may have filled sediment in a shallower portion of the platform and formed a relatively large flat sediment surface. This lateral growth of the flat surface caused the restriction of water circulation. When the sea water was evaporated in such a restricted environment, the sediment was partly subjected to dolomitization and silicification (Osleger and Read, 1991; Montanez and Read, 1992b). However, the cause of a fabric-selecting pattern of the dolomitization and silicification is difficult to be explained.

Many of depositional characteristics of the Vandon Limestone, such as the hematite concentration, peloidal grainstone, and common occurrence of ooids, indicate that the water circulation became well again. As indicated by red brown limestones, the carbonate platform was occasionally exposed above the sea-level. The local tectonic movement may have caused the sea-level fluctuation. However, if a gradual heat loss of the volcanic island rather resulted to a simple subsidence pattern, a larger amplitude of sea-level fluctuation may be only the cause.

B. Interpretation of the diagenetic features

The limestones of the Cliefden Caves Limestone Group has been subjected to various diagenetic processes. The diagenetic properties (Figs. 5-7), especially calcite cements, were often lost their optical fabrics during neomorphism. The neomorphism, however, dose not destroy the distribution of minor elements in calcite. Therefore, investigation using CL is very useful to recognize the original fabrics of the diagenetic properties.

The small crystal of dull CL fringing walls of porosity indicates that the stage 1 cement with dull CL is most likely formed under a marine phreatic condition. This first generation of cement predates the other diagenetic process including the dissolution (Fig. 7-d). Lack of evident collapse of the dissolution molds indicates that carbonate sediment was lithified by the stage 1 cementation.

The stage 1 cement shown in Fig. 5-b is a large crystal bridging space between two grains. The cement predates the stage 2 cement. Therefore, it was most likely formed in a marine vadose environment (Tucker and Wright, 1990).

Dissolution and the following stage 2 cementation may have processed in meteoric phreatic water. The original carbonate sediment of the Cliefden Caves Limestone Group was mostly composed of a metastable biogenic aragonite and high-Mg calcite. If the metastable carbonate is subjected to a meteoric diagenesis, more soluble aragonitic skeletons normally tend to be dissolved. In the case of the Cliefden Caves Limestone Group, almost all molluscs and a large part of calcareous algae were dissolved in meteoric phreatic water, and thus these skeletons may originally have an aragonite mineralogy.

Meteoric dissolution is often followed by meteoric cementation, because the pore fluid normally increases its saturation state to carbonate minerals by dissolving metastable minerals and possible evaporation during the diagenetic processes (Solomon and Walkden, 1985; Frykman, 1986; Lavoie and Bourque, 1993). The stage 2 cement of the Cliefden Caves Limestone Group was precipitated, after the diagenetic state turned from dissolution to precipitation. The increasing of luminosity of the stage 2 cement during precipitation is common characteristics associated with reduction of the meteoric pore fluid caused by the decreasing of discharge of fluid into the pore system (ten Have and Heijnen, 1985). However, the zonation found in the stage 2 cement of some specimens, suggests that the discharge of fluid might have fluctuated.

An extensive meteoric cementation indicates subaerial exposure of the carbonate platform. Therefore at least, a part of the sediment should have been subjected to a vadose diagenesis. However, no specimen of the Cliefden Caves Limestone Group shows a definite vadose cement, such as one with gravitational fabrics (Freeman, 1971; Kano, 1991).

The stage 3 cement was formed in a deep burial environment because some of veins probably predated the precipitation of the stage 3 cement (Fig. 6-b). Dull CL of deep burial cement is common because the precipitation fluid contains cation originated from pressure solution.

C. Depositional pattern and the Ordovician climatic change

Late Ordovician has been recently regarded as the age of global cooling (Marshall and Middleton, 1990; Wadleigh and Veizer, 1992). From Llanvir (Middle Ordovician) to Caradoc (Late Ordovician). The global sea-level had been relatively stable (Lenz, 1982; Hallam, 1992; Ross and Ross, 1992) because of the 'green house' condition (Frakes *et al.*, 1992), and the shallow eperic platform had received thick peritidal sequence. These sequence is very common among the Ordovician of 0-40 degrees in paleolatitude. A restricted water circulation and evaporative condition caused development of micritic lithofacies and syn-sedimentary dolomite (Rao, 1981; Montanez and Read, 1992a).

Among the Cliefden Cavès Limestone Group, only the Belubula Limestone shears these characteristics of the Ordovician peritidal limestone. The lack of dolomite and silicified skeletons in the lower Fossil Hill Limestone ascribes to the island-arc setting of the Cliefden Caves carbonate platform which has a steeper slope than the eperic platforms. Water circulation during the depositional period of the Fossil Hill Limestone, allowed diverse fauna including various sedentary organisms (Webby, 1992), until the sedimentation had filled up the shallower portion of the platform. Then, the Belubula Limestone, a 'typical' Ordovician carbonate, started to be deposited.

On the other hand, lithological change from the Belubula to Vandon Limestone, may have related with a global climatic change. The global cooling found the boundary between Caradoc and Ashigill (Upper Ordovician) and a strong glaciation in Ashigill have gained a consensus by many of authors (Marshall and Middleton, 1990; Frakes *et al.*, 1992; Wadleigh and Veizer, 1992). However, the exact age of the beginning of cooling and lasting period of the glaciation are still in controversy (Brenchley, *et al.*, 1994). The sea-level fluctuation indicated by the sedimentary and diagenetic features of the Vandon Limestone possibly involved an eustatic change associated with the global cooling. Then, the further sea-level lowering exposed the platform surface, and the carbonate sedimentation was ceased.

Although the global sea-level was low, the continuous subsidence of the andestic volcanic island re-submerged the platform under sea water. Then, the siliciclastic dominated Malongulli Formation was deposited on the erosional surface. Lithofacies change from carbonate and siliciclastics has been observed several Caradoc-Ashigill successions around the world (Wadleigh and Veizer, 1992). Abundance of sponges in the limestone layers indicates a deeper or cooler environment. The cause of the abrupt lithofacies change may have been associated with climatic cooling or the Ashigillian mass extinction. However, the age of the Malongulli Formation has not been poorly defined (late Caradoc or Ashigill?; Webby, 1976). Therefore, the global climatic control cannot be simply applied to the lithofacies change from the Cliefden Caves Limestone Group to the Malongulli Formation.

VII. Conclusions

1) The shallow marine Cliefden Caves Limestone Group is divided into three; Fossil Hill, Belubula, and Vandon Limestones. The Fossil Hill and Vandon Limestone contains various fossil grains, whereas the Belubula Limestone is dominated by molluscs, sponges, and calcareous algae.

2) CL investigation defines three stages of cementation associated with different diagenetic environments; marine phreatic, meteoric phreatic, and deep burial. The extensive meteoric diagenesis (not only cementation but dissolution) suggests that the platform have been exposed above the sea-level.

3) The Fossil Hill Limestone is carbonate sediment on-lapping the platform on an andestic volcanic island. The on-lapping sedimentation formed a relatively flat platform. The Belubula Limestone is a peritidal succession associated with the syn-depositional dolomitization, silicification, and precipitation of marine vadose cement. The Vandon Limestone contains three red brown argillaceous limestones which might have been related to the sea-level lowering.

4) The changes in the lithofacies and diagenetic characteristics is partly explained by local geological settings, however was partly controlled by the Middle-Late Ordovician global climate change, such as the cooling from Caradoc to Ashigill.

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