Diagenesis of arc-derived sandstones of Cretaceous formations in the Queen Charlotte Islands, British Columbia, Canada(MEMORIAL VOLUME TO THE LATE PROFESSOR TERUHIKO SAMESHIMA)

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Diagenesis of arc-derived sandstones of Cretaceous formations in the Queen Charlotte Islands, British Columbia, Canada

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Abstract Diagenesis of sediments derived from a magmatic arc provenance may greatly differ from that of sediments derived from an intracratonic- or foreland-type provenance. Sediments from the magmatic arc are compositionally immature and rich in volcanic and sedimentary rock fragments. Sandstone samples of mid- to Upper Cretaceous formations in the Queen Charlotte Islands, British Columbia, Canada, contain either large amounts of pseudomatrix or authigenic cements. An inverse relationship between the content of pseudomatrix and that of authigenic cements suggests that ductile deformation of soft rock fragments has reduced much of the original porosity and has preceded the formation of authigenic cement. The described inverse relationship clearly contradicts the recent report of diagenesis of sandstones rich in volcanic rock fragments (Hawlader 1990).

Key words: diagenesis, porosity, pseudomatrix, authigenic cements, arc-derived sandstones, Queen Charlotte Islands, Cretaceous

INTRODUCTION

Clastic sediments deposited in sedimentary basins along convergent plate margins generally form quartz-poor, and feldspar- and lithic fragments-rich sandstones. Some types of lithic fragments, such as volcanic and soft sedimentary rock fragments in these sediments, are very susceptible to rapid diagenetic alteration. Processes of cementation and compaction of such sediments greatly differ from those of quartz-rich and lithic fragments-poor sediments derived from intracratonic provenances, and they also differ from those of quartz-rich, feldspar- and volcanic rock fragments-poor sediments sourced from foreland-type provenance (Dickinson & Suczek 1979). Thus the course of diagenesis is profoundly controlled by the preburial tectonic setting of sedimentary basins and by the lithology of source rocks (Nagtegaal 1978; Hayes 1979; McBride 1989).

Although studies on sandstone diagenesis in the foreland belt and in the passive plate margin have been frequently carried out (e.g., Loucks *et al.* 1984; Land *et al.* 1987), fewer reports on sandstone diagenesis undergone in the convergent plate margin have appeared to date (e.g., Galloway 1979). This paper will describe and discuss about sandstone diagenesis of mid- to Upper Cretaceous formations in the Queen Charlotte Islands, British Columbia, Canada. The discussion will be focused particularly on processes of mechanical compaction and authigenic cementation of arc-derived sandstones, which originally had large amounts of lithic fragments.

GEOLOGICAL SETTING

The mid- to Upper Cretaceous Queen Charlotte Group is distributed in the central part of the Queen Charlotte Islands. The group consists of the Haida (Albian to Turonian), Honna (Turonian to Coniacian) and Skidegate (Late Cenomanian to Coniacian) Formations (Haggart 1986) (Fig. 1). The biostratigraphic relationship between the Skidegate Formation and the other two formations, however, has not been thoroughly clarified yet. The Haida and Honna Formations are well exposed in coastal areas, only gently deformed and amenable to sedimentological studies. These

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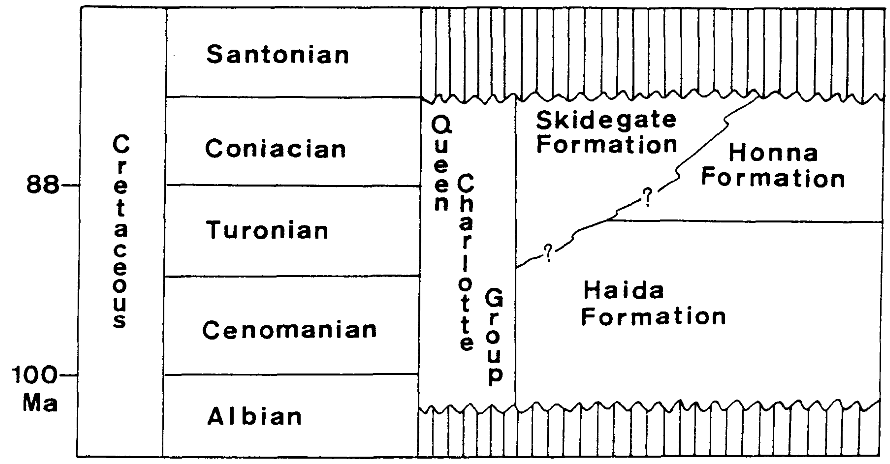

Fig. 1 Stratigraphic column of the Queen Charlotte Group. Modified after Haggart (1986).

formations make two contrasting marine sedimentary facies: the Haida Formation consists of the lower sandstone predominant and upper shaly members, whereas the Honna Formation comprises thick conglomerates intercalated with thin sandstone beds (Fig. 2). Total thickness of the Haida Formation is regionally uniform, about 1,300 to 1,400 m, whereas the overlying Honna Formation has a variable thickness, ranging from 400 to 2,400 m (Yagishita 1985).

Sediments of both the formations were derived from the east (Yorath & Chase 1981; Yagishita 1983, 1984, 1989) and deposited along a half-graben trough formed by vertical movement of the Rennell Sound Fault (Yagishita 1983). Despite the contrasting sedimentary facies between the two formations, sedimentation is interpreted to have been continuous (Yagishita 1984; Haggart 1990). Shallow, nearshore marine sediments displaying a transgressive cyclic sedimentation pattern characterize the early stage of the Haida Formation. The sequence from the shaly upper member of the Haida Formation to the basal conglomerate of the Honna Formation is thought to have been made by a rapid change of depositional environment from a broad basin plain to the gravelly fan deposits of the Honna Formation. The abrupt appearance of gravelly fan deposits was probably due to the rapid uplift in the source area (Yagishita 1983) or to the rapid sea-level fall in the Turonian (Haggart 1990).

PETROGRAPHY OF SANDSTONE

Procedure: Modal and textural analyses were carried out on 100 thin-sections taken from both the Haida and Honna Formations. All thin-sections were stained with sodium-cobaltinitrite to distinguish K-feldspar from plagioclase and quartz. They were also impregnated with blue-colored epoxy to highlight the porosity. Classification of detrital grains for modal analyses was based on the method of Dickinson's school (e.g., Graham *et al.* 1976) and was detailed in the writer's previous paper (Yagishita 1985).

Many sandstone samples were found to have well-developed authigenic cements or to exhibit replacement by diagenetic minerals such as carbonates, clays and opaque minerals. Most of these thin-sections were reexamined with reflected light to identify the opaque minerals, and 30 samples that had authigenic clay minerals were examined in a scanning electron microscope (SEM).

Clast types: Sandstone samples from both the Haida and Honna Formations have framework modes that plot in the central part of QFL (quartz-feldspar-lithic fragments) diagrams (Fig. 3). Because the matrix content is quite low (mostly less than 5 %, Table 1), sandstones of both the formations are classified as either lithic or feldspathic arenite. Although the matrix content is very low, large amounts of pseudomatrix are conspicuous in sandstones of both the formations (Plate 1F, 1G). In response to overburden pressure, the pseudomatrix has been formed by squashing and twisting of labile grains, such as shale, siltstone and schist rock fragments, between harder framework constituents. For purpose of modal analyses these constituents have been allocated as detrital grains and not as matrix. Criteria for this allocation was outlined by Dickinson (1970). Although the total amount of lithic fragments is almost equal between the Haida and Honna Formations (QFL diagrams of Fig. 3), volcanic rock fragments (VRFs) are much more dominant in Honda sandstones than sedimentary rock fragments which characterize Haida sandstones (Fig. 3 and Table 1).

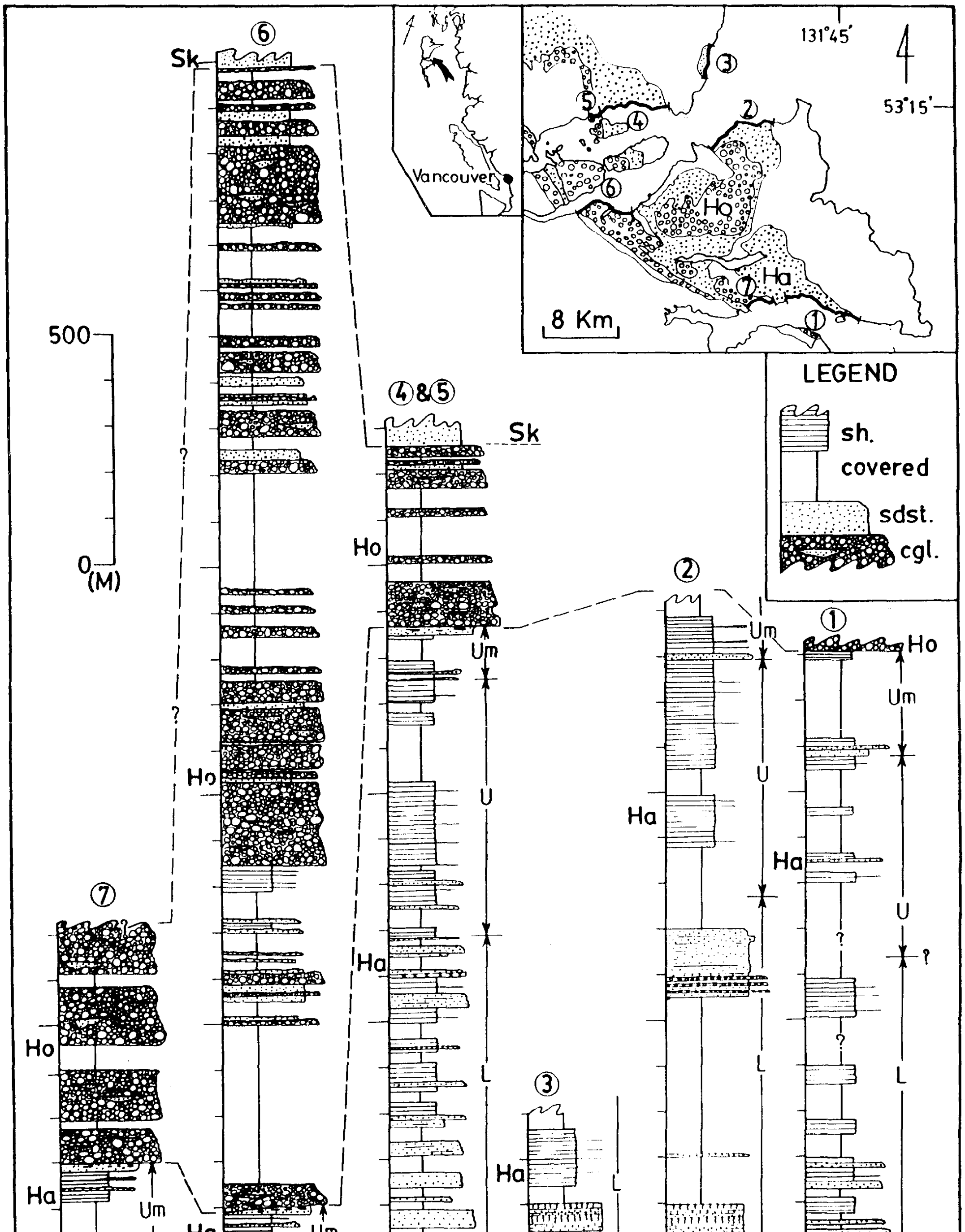

Fig. 2 Lithological sections of the Haida and Honna Formations in the central part of the Queen Charlotte Islands. The sections displayed were measured by the writer and partly supplemented by information from Sutherland-Brown (1968). Ha: the Haida Formation (L: lower member, U: upper member, Um: upper most submember), Ho: the Honna Formation, Sk: the Skidegate Formation, B: basement (modified after Yagishita 1985).

Table 1 Average composition of modal analyses of the Haida and Honna sandstones of mean grain diameter between 1.0-3.0 ϕ.

	Q	F	L			Oth	Mx	Repl	Cement				Pr
			Ls	Lm	Vrf				Ch	Zl	Ca	Misc	
Haida Fm. (n = 34)	31.3	26.8	9.8	3.1	6.0	5.6	1.9	8.3	5.5	0.6	0.6	0.3	0.5
Honna Fm. (n = 46)	22.3	34.1	3.6	2.8	17.5	4.1	2.4	5.6	5.1	0.7	0.6	0.8	0.8

Q: total quartz grain, F: total feldspar grain, L: lithic fragments (Ls: sedimentary, Lm: metamorphic, Vrf: volcanic), Oth: others including biotite, opaques etc., Mx: matrix, Repl: replacement by calcite, chlorite etc., Cement (Ch: chlorite, Zl: zeolite, Ca: calcite, Misc: smectite, hematite etc.), Pr: visual porosity, n = number of samples.

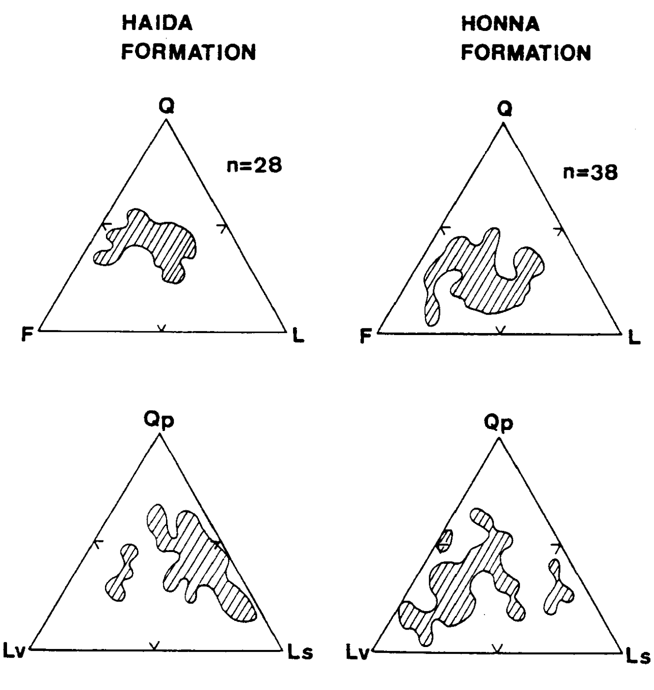

Fig. 3 Q-F-L and Qp-Lv-Ls diagrams of sandstones from the Haida and Honna Formations. Mean diameter of sandstone samples ranges from 1.0 to 3.0 phi. Samples having more than 20% replacement of detrital grains by calcite, chlorite and other diagenetic minerals are omitted from these diagrams. For the individual plot of each sandstone sample, readers are referred to the writer's earlier paper (Yagishita 1985).
Qp: polycrystalline quartz including aphanitic quartzose grains such as chert,
Lv: volcanic rock fragments,
Ls: sedimentary rock fragments.

DIAGENESIS

Authigenic cements: Four types of authigenic cement are present in sandstones of the Haida and Honna Formations; they are chlorite, zeolite, calcite and smectite. Silica cements (quartz overgrowth) are very rare in sandstones of the both formations.

1) Chlorite cement: The dominant authigenic clay mineral encountered in this study is green to yellow-green chlorite. This authigenic cement is present entirely in the both Haida and Honna sandstones (Fig. 4). Most of this chlorite occurs as a pore-lining clay coating form, or as well crystallized flakes that are oriented perpendicular to the silicate or volcanic rock fragment substrate (i.e., radiating chlorite, McDonald 1979) (Plate 1A and 1 B). In most samples, the radiating chlorite completely fills intergranular spaces. However, in some cases, other authigenic constituents, such as zeolite, fill the interior of pores (Plate 1D). The chlorite cement is clear and transparent, and the absence of other detrital materials and impurities clearly differentiates it from the detrital matrix.

All cements observed with SEM were confirmed with SEM X-ray spectra. According to SEM observations made by Wilson & Pittman (1977), there are four types of authigenic chlorite cement; plate-type, rosette-type, honeycomb-type and cabbage-head-type, in order of decreasing iron concentration. The most common type in both the Haida and Honna sandstones is the plate-type chlorite cement (Plate 2A and 2B), followed by a mixed rosett and plate type. Although the chlorite cement is easily recognized in the well-sorted Haida

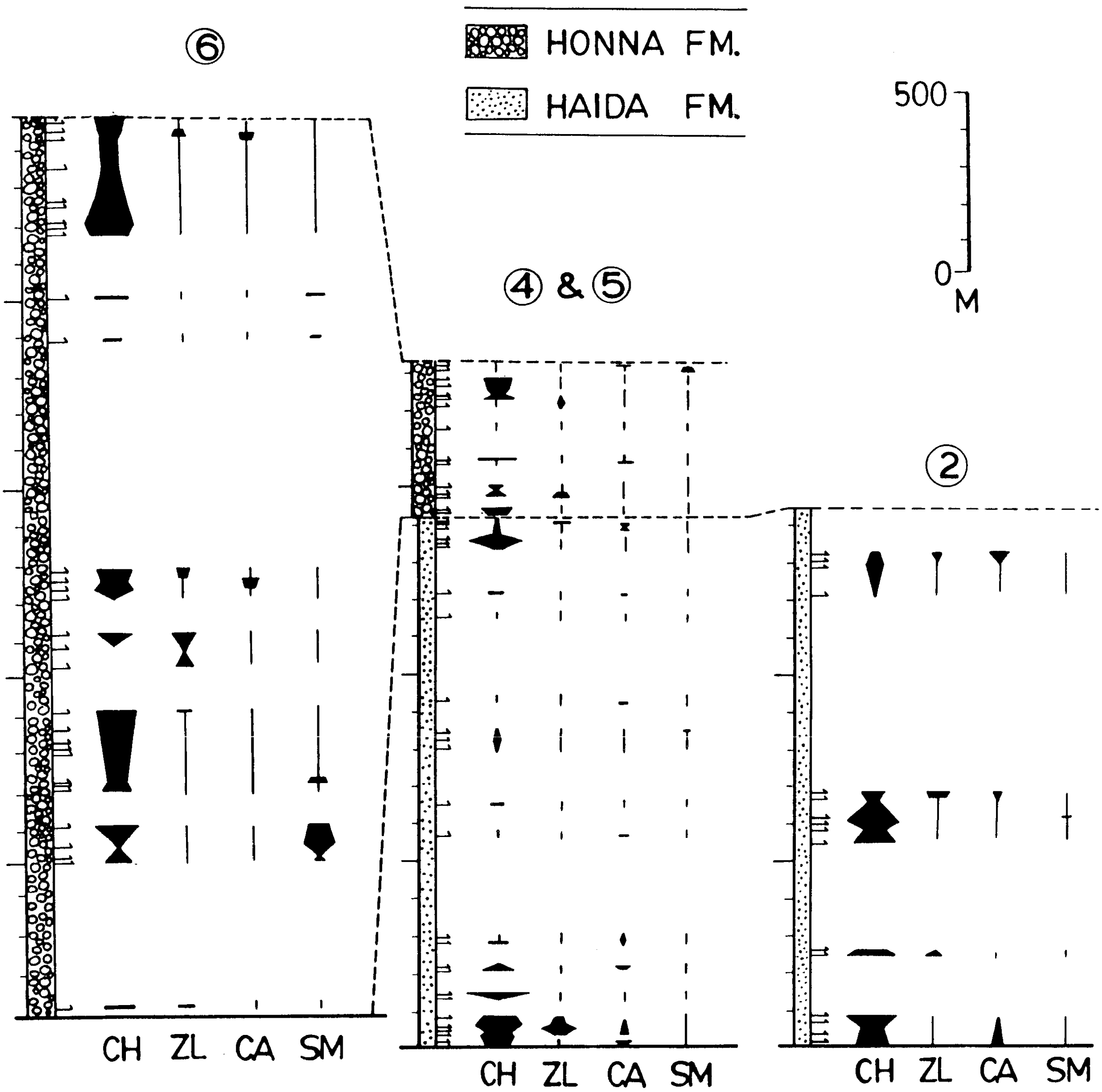

Fig. 4 Stratigraphic distribution of four representative authigenic cements; chlorite (CH), zeolite (ZL), calcite (CA) and smectite (SM) cements. Chlorite cement is the most common authigenic cement, but the cement does not show any systematic paragenesis with other cements. Numbers 2, 4, 5 and 6, correspond to those numbers of stratigraphic columnar sections shown in Fig. 2. Arrows in the columnar sections show the stratigraphic positions of the individual thin-sections observed.

sandstone beds, it is much less in those sandstone beds which have large amounts of pseudomatrix. The average amount of authigenic chlorite cement in the Haida Formation is 5.5 vol. %, whereas in the Honna Formation it is about 5.1 vol. %.

2) **Zeolite cement**: Zeolite cement and its replacement are common in both the formations (Fig. 4). With SEM X-ray spectra, most of the zeolite cements were identified as laumontite, and one exception was recognized as mordenite. Optical characteristics of zeolite cement are a pale-color under crossed-nicols together with the low index of refraction (Plate 1C and 1D). Some zeolite cements which fill the interior of pores are separated from detrital grains by authigenic chlorite coatings (Plate 1D). Replacement of plagioclase by laumontite is common, as shown by partial or entire destruction of twin lamellae (Yagishita 1985).

3) **Calcite cement**: Pore-filling calcite cement, including both sparry and micritic types, is less common than chlorite and zeolite cements in both the formations and is less prominent in the Honna Formation than in the Haida Formation. In some thin-

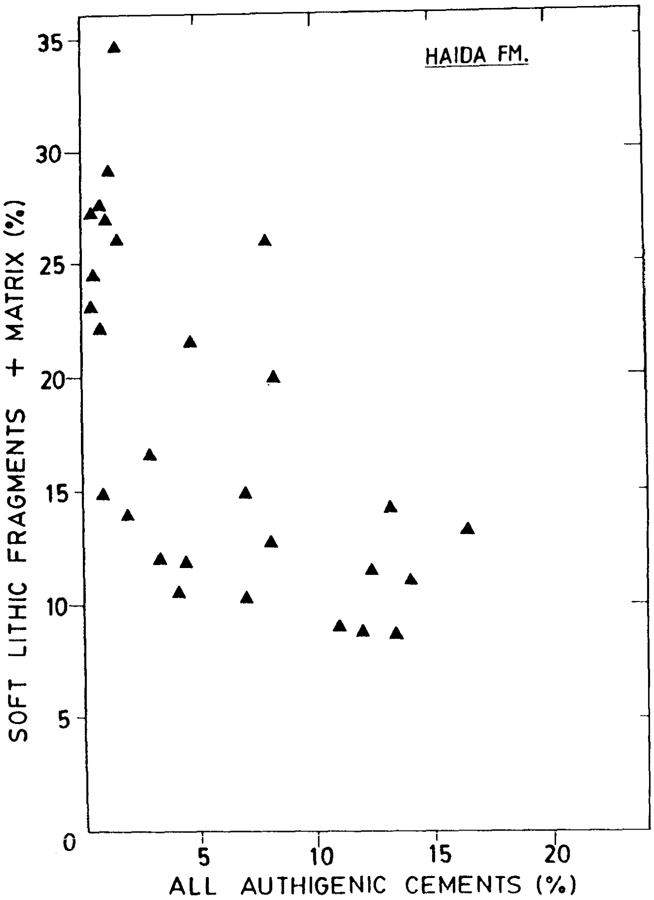

Fig. 5 Amount of soft rock fragments plus matrix (detrital matrix) versus amount of all authigenic intergranular cements of the Haida sandstone samples. Compositional data having more than 15% replacement of detrital grains by calcite and chlorite and other diagenetic minerals were excluded. The soft rock fragments include detrital grains of shale, siltstone, schist and biotite. Authigenic cements are chlorite, zeolite, calcite and smectite. Mean diameter of sandstone samples ranges from 1.0 to 3.0 phi.

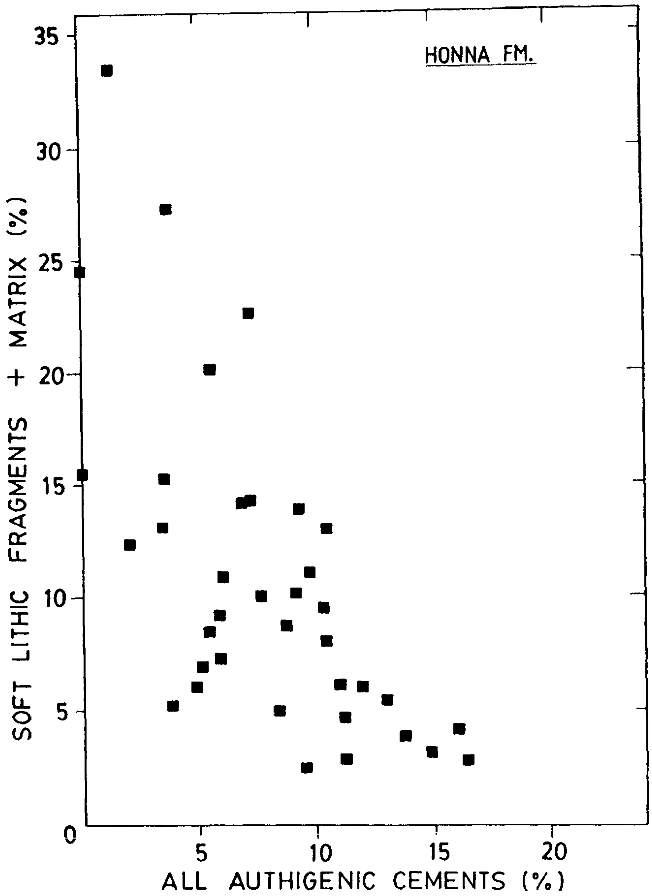

Fig. 6 Amount of soft rock fragments plus matrix (detrital matrix) versus amount of all authigenic intergranular cements of the Honna sandstone samples. Sampling data are based on the same conditions.

sections the calcite cements are separated from the detrital grains by coatings of authigenic chlorite.

4) Smectite cement: The occurrence of the smectite cement was identified with SEM X-ray spectra, and the cement occurs as thick crystallized flakes, oriented perpendicular to the rock fragment substrate (Plate lE and Plate 2E and 2F). The cement is less common in the Haida Formation than that in the Honna Formation.

Order of cementation features: In both the Haida and Honna sandstones the following order of cementation is observed; 1) pore-lining chlorite cement coating on detrital framework grains, 2) precipitation of radiating pore-filling chlorite in the interior of pores, or precipitation of zeolite or calcite cement in the center of pores not completely filled by radiating chlorite. The calcite and zeolite cements coexist even in the center of a pore (Plate H). It is hard to detect the timing (order) of smectite cementation. The cement often shows the entire pore-filling without coating by chlorite cement on detrital grain surfaces.

Mechanical compaction and secondary porosity: As described earlier, the matrix content in both the Haida and Honna sandstones is very low. However, large amounts of pseudomatrix are conspicuous in both the formations. An inverse relationship exists between the amount of labile rock fragments (including detrital matrix, which is defined here as a grain finer than 5 phi) and the amount of authigenic cements (Figs. 5 and 6). Although the content of sedimentary rock fragments in the Honna sandstones is less than that in the Haida sandstones, the inverse relationship in the Honna sandstones is clearly discernible as well as in the Haida sandstones.

Despite the existence of large amounts of pseudomatrix or intergranular authigenic cements, dissolution of such intergranular materials and framework grains cannot be seen in both the formations. Namely, the studied sandstones are characterized by the total lack of secondary porosity.

DISCUSSION

Diagenesis begins immediately after deposition. The principal factors determining the diagenetic history for the sediments include time-dependent exposures to varying temperatures, pressures, and pore-fluid chemistry (Galloway 1979). However, preburial conditions, such as textures and mineralogic composition of detritus, also exert a marked influence on the course of diagenesis (Nagtegaal 1978; Benson, 1981; Fontana *et al.* 1986; McBride 1989).

Cementation and compaction are "competing in the race" to obliterate the original interstitial porosity (Hayes 1979). If the abundant soft lithic fragments are present in the original sand-sized sediments, however, the mechanical compaction of the ductile grains may precede cementation, and it drastically reduces the original porosity. This compaction by burial pressure retards circulation of fluids from which interstitial authigenic cements can be precipitated. In the case where ductile grains are not abundant, the porosity loss due to ductile grain deformation is less important than that by geometrical rearrangement of grains (McBride *et al.* 1991). However, the sandstones having such detrital grains are much more susceptible to the porosity-reducing processes, when compared with very mature quartz arenites that may undergo only geometrical rearrangement of detrital frameworks (Nagtegaal 1979). Benson (1981) revealed in his experiments that porosity reduction heavily depends on the content of ductile grains; the more ductile grains, the more porosity loss. The reason for the inverse correlation between the amount of pseudomatrix and that of authigenic cements in the Haida and Honna sandstones (Figs. 5 and 6) obviously lies in the intergranular porosity-reducing process by ductile grains prior to the formation of any significant amount of authigenic cements.

However, Hawlader (1990) has insisted that sandstones rich in VRFs may undergo an early interstitial precipitation of various authigenic minerals at shallow burial depth and that the cementation may retard mechanical compaction of sediments. But the study in this paper obviously reveals that the mechanical compaction preceded the formation of authigenic cementation. Such a diagenetic order is particularly evident even in the Honna sandstones that are very abundant in VRFs.

In addition, the most common cement in the studied sandstones is chlorite, and the cement mostly shows pore-lining coating on grain surfaces or radiating-form filling completely the pores (Plate 1A, 1B). Obviously the chlorite cement is not so competent as the other hard detrital grains such as quartz or feldspar. If the mechanical compaction took place after cementation by chlorite, those original forms of pore-lining or radiating would be totally deformed and squashed. However, this is not the case. From such a diagenetic appearance the writer believes that the mechanical compaction took place prior to the chlorite cementation.

Volcanogenic sandstones are generally characterized by little or no silica cementation (McBride 1989). The alkali cations derived from the dissolution or breakdown of feldspars, mafic minerals and volcanic rock fragments easily combine with dissolved silica, resulting in the formation of authigenic clays and zeolites (Hayes 1979). Moreover, authigenic clays coating detrital grains can retard or inhibit quartz overgrowth by isolating detrital grains from water that may be capable, if any, of precipitating dissolved silica (McBride 1989). Thus, unlike the sandstones derived from the intracontinental provenance, quartz overgrowths are rarely seen in the volcaniclastic sandstones. This is the main reason for the fact that silica cementation was recognized in neither the Haida nor Honna Formation.

Although the breakdown of mafic minerals or volcanic rock fragments (VRFs) is presumably the main cause for producing the authigenic clay or zeolite cements, many thin-sections from both the formations display minor amounts of VRF together with large amounts of chlorite cement. This fact suggests that the migration of pore fluids was not restricted to a limited stratigraphic interval. The best example to show this lack of relationship between the content of VRF and the presence of chlorite cement is the sandstone beds of the Haida Formation at Queen Charlotte-City section (Fig. 7). The well-sorted but almost VRF-free sandstone beds in the lower member of the formation contain large amounts of chlorite cement. There is no VRF-rich sandstone bed above and below, at least over the stratigraphic interval of hundred meters. Judging from the lack of correlation between the amount of chlorite cement and that of VRFs within the same stratigraphic level (Fig. 7), the migration of the pore fluids which carry much of the dissolved mafic ions may have occurred over a wide stratigraphic interval. The limited occurrence of the authigenic chlorite cement in the Haida Formation was controlled by the presence of soft lithic fragments that were squashed and twisted in response to overburden pressure and formed pseudomatrix. Most of the chlorite-rich beds in Figure 7 are well-sorted sandstone beds (sorting ranges from 0.4 to 0.6 in phi scale).

Although the migration of the pore fluid is very discernible, it is hard to detect the origin of the fluid. The upper member of the Haida Formation is predominantly composed of thick shaly sediments. There may be a possibility that the fluid

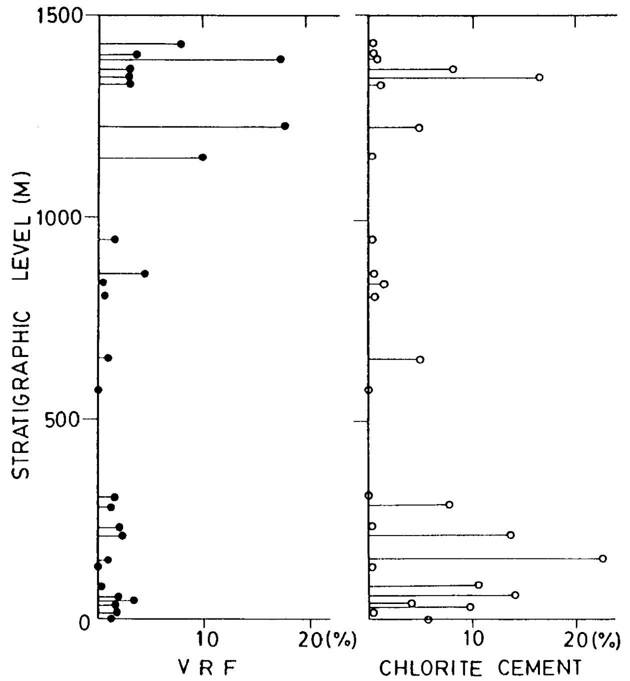

Fig. 7 Amount of VRFs and authigenic chlorite cement in sandstone beds of the Haida Formation (Queen Charlotte-City section, stratigraphic columnar section No. 4 in Fig. 2). Note that the amount of VRFs and that of chlorite cement of each sandstone bed are not correlative.

might have been derived from the compaction of the upper member of the Haida Formation. To determine the origin of the fluid, however, there is a need for more detailed studies, including oxygen isotope data.

CONCLUSIONS

1) Sandstones from the mid- to Upper Cretaceous Haida and Honna Formations are classified as either lithic or feldspathic arenite. Although the matrix content is very low, large amounts of pseudomatrix are conspicuous in both the Haida and Honna sandstones.

2) Sandstones in both the formations display well-developed authigenic cementation. The dominant authigenic clay mineral is chlorite, and the most common type of the cement is the plate-type chlorite.

3) In both the Haida and Honna sandstones the inverse relationship exists between the amount of lithic rock fragments that include pseudomatrix and the amount of authigenic cements. This suggests that ductile deformation of soft rock fragments has reduced much of the original porosity and has preceded the formation of authigenic cements.

4) The main cause for producing the authigenic cementation is probably due to the breakdown of mafic minerals or volcanic rock fargments (VRFs). However, the amount of VRFs and that of the authigenic cements, particularly the chlorite cement, are not correlative in many thin-sections. Such a non-correlative relationship suggests that the migration of pore fluids took place throughout the two formations. However, the origin of the fluids has not been clarified yet.

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Explanation of Plates.

Plate 1. Photomicrographs showing authigenic intergranular cements of the Haida and Honna sandstones.

A. Well developed authigenic chlorite cement (CH). The entire interstitial pore space is filled with the cement. Haida Formation (thin-section No. KY-26). Polarizer only. Bar length 0.1 mm.
B. Well developed chlorite cement (CH). Honna Formation (thin-section No. KY-149T). Polarizer only. Bar length 0.2 mm.
C. Well developed zeolite cement (Z). A high relief detrital epidote (EP) in the lower left. Honna Formation (thin-section No. KY-144). Polarizer only. Bar length 0.2 mm.
D. Zeolite cement (Z) separated from detrital frameworks by authigenic chlorite cement (CH). Haida Formation (thin-section No. KY-05). Polarizer only. Bar length 0.1 mm.
E. Authigenic smectite cement (SM). This photograph displays a typical style of pore-lining cementation. Honna Formation (thin-section No. KY-194). Polarizer only. Bar length 0.1 mm.
F. Shale fragments as pseudomatrix (PS). Haida Formation (thin-section No. KY-28). Polarizer only. Bar length 0.2 mm.
G. Shale fragments as pseudomatrix (PS) and a twisted biotite (BT). Haida Formation (thin-section No. KY-04). Polarizer only. Bar length 0.2 mm.
H. Pore-filling calcite (CA) and zeolite (Z) cements are separated from detrital frameworks by chlorite cement (CH). Haida Formation (thin-section No. KY-05). Crossed nicols. Bar length 0.1 mm.

Plate 1

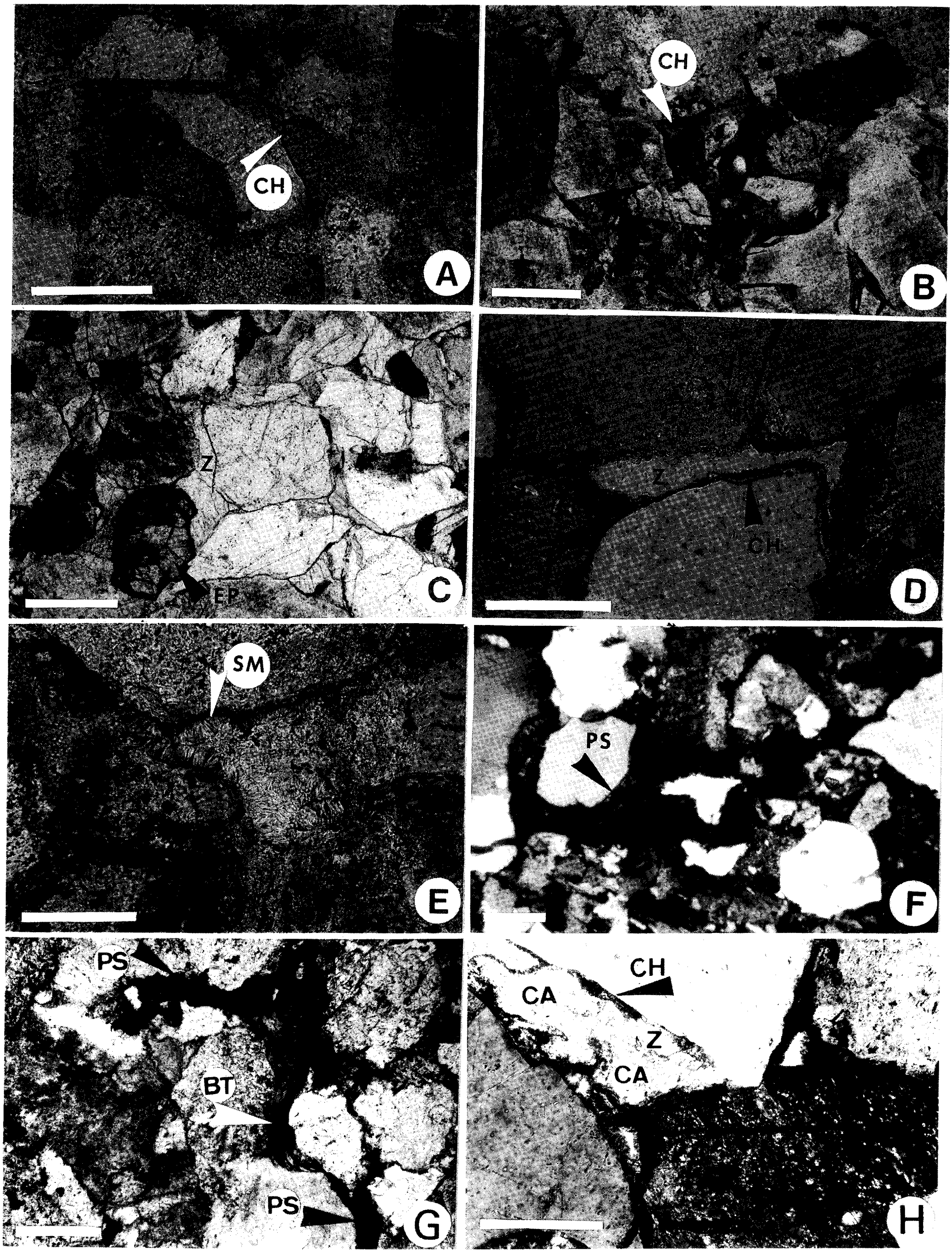

Plate 2 SEM (Scanning electron microscope) photographs of authigenic cements.

A & B. Authigenic intergranular chlorite cement. A, overview. B, detailed figure. The photograph shows a typical plate-type chlorite cement. Honna Formation (sample No. KY-156).

C & D. Authigenic intergranular zeolite cement showing massive pore-filling cementation. C, overview. D, detailed figure. Haida Formation (sample No. KY-20).

E & F. Authigenic smectite and illite-mixed cement. E, overview. F, detailed figure. Honna Formation (sample No. KY-194).

Plate 2