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# Petrography of the Cretaceous Sandstones in the Monobegawa Valley, Shikoku

By

**Takami Miyamoto and Isao Nakai**

*with* 7 *Tables and* 11 *Figures*

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Abstract: The Cretaceous System of the Monobegawa valley, Kochi Prefecture, Shikoku, is distributed in a narrow belt within the Paleozoic Chichibu terrain, forming a synclinorium. On the basis of a major cycle of sedimentation, it is divided into the Ryoseki (Kochian), Yunoki (Aritan), Hibihara-Hagino (Miyakoan), Nagase (Gyliakian) and Kajisako (Urakawan) Formations in ascending order. The stratigraphy is described in this paper in some detail, and besides the sandstone petrography is carried out to comprehend the mode of the Cretaceous sedimentation definitely.

The Cretaceous sandstones mostly show a moderately sorted, normally to positively skewed and meso- to lepto-kurtic type in textural pattern. Besides, most of them are characterized by the feldspathic and lithic wackes and several specimens belong to the feldspathic arenite, based on Okada's (1971) classification scheme. Judging from the gross lithological features, the Cretaceous sandstones of this basin are referred to a variety of the arenite-wacke associations defined by Krumbein and Sloss (1963), although resembling the greywackes texturally.

The contents in the major and accessory minerals of sandstones and the pebbles of conglomerates suggest that the provenance was composed mainly of older sedimentary, basic volcanic, granitic and metamorphic rocks and they functionated throughout the Cretaceous Period. However, based on the stratigraphical changes of mineralogical composition, which are confirmed by the statistical test, it is concluded that some transition of the provenance took place through the five cycles of sedimentation; the role of the granitic rocks as the source became increased gradually from the Ryoseki through the Yunoki to the Hibihara Formation in the Lower Cretaceous, and then decreased again in the Nagase and Kajisako Formations in the Upper Cretaceous. The mode of this vicissitude seems to be well reflected on the volumetrical change of the feldspar content.

From the comparison between the Monobegawa basin and other basins in the Chichibu terrain such as Katsuuragawa and Yatsushiro, it is clarified that there is a close similarity in characteristics of the sandstones and modes of the sedimentation as well as in gross litho- and bio-facies, if excepting minor differences.

Contents

Takami MIYAMOTO and Isao NAKAI

## I. INTRODUCTION

The Cretaceous System in the Chichibu terrain, which has been considered to have been formed on an unstable shelf of the Paleozoic terrain and in a basin transitional to the Cretaceous Shimanto geosynclinal trough, is narrowly distributed in many scattered areas of the Outer Zone of Southwest Japan. The Monobegawa valley in Kochi Prefecture, Shikoku, is a representative one, where the Cretaceous strata form a synclinorium embraced mostly with the Upper Paleozoic Chichibu Supergroup. Up to date, many researches on the Cretaceous System of this basin have been concentrated on the stratigraphy and paleontology. As far as the stratigraphy is concerned, there have been excellent works by YEHARA (1926), YABE (1927), HIRATA (1940), KURATA et al. (1941), KOBAYASHI et al. (1945) and KATTO and SUYARI (1956).

At the suggestion of Prof. Akira HASE, we have reexamined the stratigraphy critically on the basis of those previous studies, and furthermore focussed our eyes on the petrography of the sandstones to make the geologic history clearer, because the sandstone properties are considered to be fairly affected by the mode of sedimentation and tectonism. The sandstones were analyzed on the properties of size parameters, major mineral constituents and heavy mineral assemblages as quantitatively as possible.

The primary purpose of this paper is to give the detailed description of the sandstone petrography in addition to the Cretaceous stratigraphy. Some comments on the vicissitude of tectonism and sedimentation through the Cretaceous Period are given on the basis of the sandstone properties in addition to the other available data. Statistical emphasis is laid on the quantitative changes of the sandstone properties, as done by one of us (NAKAI, 1971). Moreover, comparison between the present basin and other ones of the Katsuuragawa valley in Tokushima Prefecture of Shikoku and the Yatsushiro area in Kumamoto Prefecture of Kyushu are made from the petrographical point of view to scrutinize the characteristics of the Cretaceous sedimentation throughout the Chichibu terrain.

We wish to express our sincere appreciation to Prof. Akira HASE of Hiroshima University, who continuously gave us valuable advice and criticism during this work and besides critically read the typescript of this paper. Thanks are also due to Associate Prof. Mitsuo NAKANO and Dr. Yuji OKIMURA of the same university for their encouragement and kind help in identifying our fossils. We are much indebted to Mr. Hideo TAKAHASHI, who helped us in preparing numerous thin sections of sandstones and conglomerates.

The field work was in part financially supported by the Grant in Aid for Science Research from the Ministry of Education. The practice of the tedious calculation in statistical analysis was carried out with the computer of TOSBAC-3400 in the Computer Center of Hiroshima University.

## II. CRETACEOUS STRATIGRAPHY

### A. GENERAL REMARKS

The investigated area, the eastern part of the Monobegawa valley, has been geotectonically divided into two major terrains, namely, the Chichibu and Shimanto terrains, by the Butsuzo tectonic line which is a high-angled thrust with a general trend of ENE-WSW and dipping northward. In the Chichibu terrain, besides, three faults of the Gozaishoyama thrust line, the Kajisakogawa tectonic line and the Fuigoshi tectonic line from north to south run nearly parallel with the Butsuzo line; the latter two faults subdivide the Chichibu terrain into the Northern, Central and Southern Zones (KATTO and SUYARI, 1956).

The Northern Zone of the Chichibu terrain is composed of the Paleozoic Chichibu Supergroup and the Lower Cretaceous Formations, which are faulted against each other by the Gozaishoyama thrust. The former is subdivided into the Shirakidani Group at least partly of the Upper Permian (the *Yabeina* Zone) and the Upper Carboniferous Shogase Group, both of which consist of chert, altered basic volcanics, slate, sandstone and lenticular limestone. The Lower Cretaceous strata are grouped into the Ryoseki, Yunoki and Hibihara Formations in ascending order on the basis of the cycle of sedimentation. They form usually a synclinorium with a general trend of ENE–WSW and overturned northward, but in some places show an embayed structure like the "Yakyo bending" in the Ryoseki basin (KOBAYASHI, 1941).

The Central Zone is occupied by the Lower Cretaceous Hagino Formation (equivalent of the Hibihara Formation) and the Upper Cretaceous Nagase and Kajisako Formations. The Upper Cretaceous shows a synclinorium and is in a fault contact with the Lower Cretaceous.

The Southern Zone consists of the Paleozoic Kokuzosan Group, the Jurasso-Triassic Odochi Group and the Upper Jurassic Torinosu Group. The first is composed of limestone, chert and sandstone and is at least in part correlated to the Upper Permian by the occurrence of *Yabeina* sp. and *Kahlerina* sp.; the second is composed of limestone, chert, altered basic volcanics, sandstone and shale; the third is characterized with black shale and limestone of the "Torinosu type". They are demarcated by faults from each other.

The geologic map and sections of the surveyed area are illustrated in Fig. 1–A and –B, and a generalized stratigraphical columnar section of the Cretaceous System is shown in Fig. 2. Detailed stratigraphic description of the Cretaceous formations will be given in ascending order in the following section.

### B. CRETACEOUS FORMATIONS

#### 1. *Ryoseki Formation*

The Ryoseki Formation occupies the northern marginal belt of the surveyed area. The beds are overturned almost completely, dipping northwards with a moderate angle. The general trend is nearly ENE–WSW, but in some places (for example, near Yunoki and Oyashiki) a bending structure convex to the west is observed, which may suggest an original embayment. It is considered that the Ryoseki Formation originally overlay the Paleozoic Chichibu rocks with a remarkable unconformity, although the present relation between them is in a high-angled thrust on the north.

Fairly good exposures of this formation are in the vicinity of Yunoki and Kawanouchi (Fig. 3–8 and –13), where it is about 500 meters in thickness and subdivided into the Lower and Upper Members.

Lower Member (about 300 meters in thickness): The lower half of this member is made up of thick beds of poorly sorted conglomerate, which contains mainly angular to subrounded cobbles and pebbles of chert and subordinately those of sandstone, shale, altered basic volcanics and limestone, with a quite little of granitic rocks. The succeeding

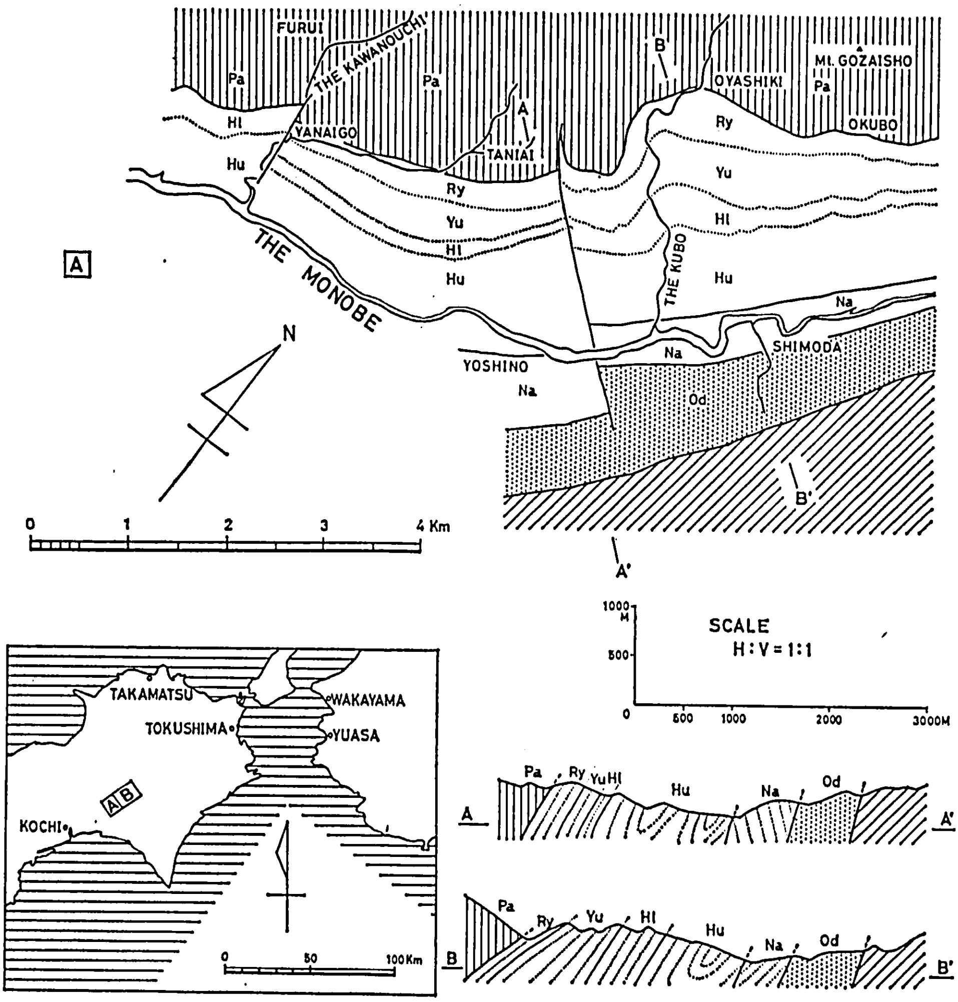


FIG. 1. Geological map and sections of the Monobegawa valley, showing the localities of the sandstone specimens.
A: The western part of the surveyed area.

upper half, as far as the available data are concerned, seems to be composed chiefly of coarse- to medium-grained sandstone and black shale with some intercalations of conglomerate and coaly shale, although its precise lithological succession could not be obtained because of a scarcity of good displays.

Upper Member (about 200 meters in thickness): The lower part, about 100 meters in thickness, of this member is composed of ill-sorted pebbly conglomerate and coarse-grained sandstone. There is almost no difference in the contents of the conglomerate in comparison with the Lower Member. The succeeding upper part consists of rhythmical alternations of black shale and fine- to medium-grained sandstone, containing *Protocyprina naumanni* (NEUMAYR), indeterminable gastropods and terrestrial plants such as *Onichi-*

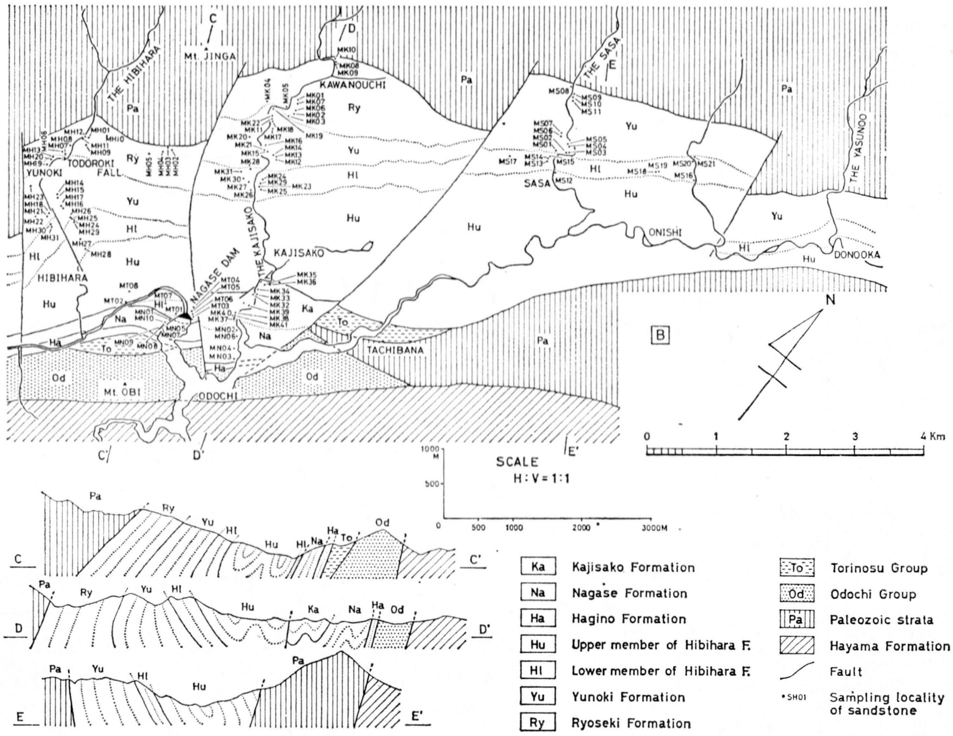


FIG. 1. (Continued). B: The eastern part of the surveyed area.

*opsis* sp., *Nilssonia* sp., *Podozamites* sp., etc.

In the western part of the mapped area the total thickness is decreased (about 150 meters), and the whole succession is represented mainly by poorly sorted conglomerate with some thin intercalations of medium-grained sandstone and black shale. The conglomerate is characterized by reddish coloration, the contents of which are not different from what are described above.

This formation represents non-marine facies as a whole and, judging from the stratigraphical position, biofacies and lithofacies, seems to be equivalent to the so-called "Ryoseki Group" in the Chichibu terrain, which has been roughly correlated to the Kochian in Japanese standard.

2. *Yunoki Formation*

On the north side of a synclinorium the Yunoki Formation is distributed somewhat widely, overlying the Ryoseki Formation and arranged nearly parallel with it. The beds are overturned and steeply dip to the north in general, but in the Kajisako area a gradual change from overturned beds through vertical to right-side-up ones is observable. In the Sasa area the northern margin is in a fault contact with the Paleozoic rocks and the beds dip steeply to the south. On the south side, however, only the upper part of this formation is narrowly exposed near the Nagase Dam, being faulted against the Upper Cretaceous Nagase Formation along its southernmost margin.

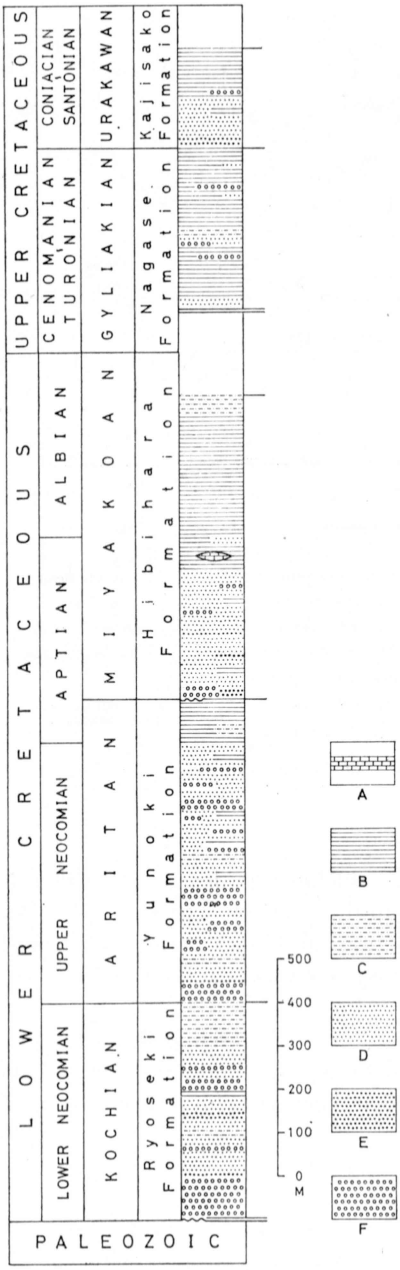


FIG. 2. Generalized stratigraphical columnar section of the Cretaceous strata in the Monobegawa valley. A: Limestone, B: Shale, C: Siltstone to very fine-grained sandstone, D: Medium-grained sandstone, E: Coarse-grained sandstone, F: Conglomerate.

Representative displays of this formation are shown in the south of Yunoki (Fig. 3–8) and along the Kajisako River (Fig. 3–13), where the thickness is estimated at about 700 meters.

The lower part, about 450 meters in thickness, consists of conglomerate and sandstone with some thin intercalations of black shale. The conglomerate is poorly sorted, composed of rounded to subrounded pebbles of chert, altered basic volcanics, shale, sandstone and granitic rocks. It is generally blueish in colour, but in the south of Oyashiki the conglomerate and conglomeratic sandstone are characterized by red coloration as well as those of the Ryoseki Formation. The sandstone is massive, dark greyish blue in colour and coarse- to medium-grained in size.

The succeeding upper part, about 250 meters in thickness, is made up of medium- to fine-grained sandstone and black shale with a few thin intercalations of conglomerate. From the sandstone near the locality of MK13, several specimens of *Pterotrigonia pocilliformis* (YOKOYAMA) were obtained.

In addition to the above pelecypod, the following fossils have been reported by KATTO and SUYARI (1956) and others; *Costcyrena radiostriata* (YABE and NAGAO), *Ostrea* sp., *Nanonavis* (s.s.) sp. aff. *N. yokoyamai* (YABE and NAGAO), *Ptycomya* sp. aff. *P. densicostata* NAGAO, etc. Therefore, the Yunoki Formation represents a shallower marine facies at least in part, and seems to be equivalent to the "Lower Monobegawa Group" or the second cycle of the Cretaceous sedimentation in the Chichibu terrain, which has been correlated to the Aritan in Japanese standard, from the stratigraphical point of view.

3. *Hibihara and Hagino Formations*

The third cycle of the Cretaceous sedimentation in this basin is represented by two formations, namely, the Hibihara and the Hagino; the former is developed in the Northern Zone of the Chichibu terrain and the latter in the Central Zone, as stated previously.

(a) Hibihara Formation

The Hibihara Formation occupies the central zone of the mapped area widely, forming an asymmetrical synclinorium in the Kajisako area, an isoclinal synclinorium overturned to the north in the Oyashiki and Yunoki areas and a syncline overturned to the south in the Sasa area, as shown in the geological sections (Fig. 1). On the north this formation overlies the Yunoki Formation conformably, while on the south it is demarcated from the Upper Cretaceous Nagase Formation or the Pre-Cretaceous strata by the fault, the Fuigoshi tectonic line, which divides the Chichibu terrain into the Northern and Central Zones. At the Nagase Dam, however, the Hibihara Formation overlies the Yunoki Formation with an unconformity.

Typical exposures are observed along the Hibihara River (Fig. 3–8), where the thickness is estimated at more than 600 meters. The formation is subdivided into the Lower and Upper Members on the basis of the lithofacies.

Lower Member (100 to 400 meters in thickness): The basal part of this member consists of conglomerate or very coarse-grained sandstone, and the succeeding main part is made up almost of massive, dark-grey, medium-grained sandstone, intercalated sometimes with conglomerate, black shale and coaly shale. The conglomerate of the basal and intercalated parts is much poorly sorted, composed mainly of rounded to subrounded pebbles (rarely with cobbles) of chert, sandstone, shale, altered basic volcanics and granitic rocks; the last ones are more abundant in this formation than in the other Cretaceous formations.

Upper Member (200 to 500 meters in thickness): The Upper Member consists mainly of monotonous, black shale, with a few intercalations of fine-grained sandstone in the main part and of thinly alternating sandstone and shale in the uppermost part. Besides, the lenses of sandy limestone are observed in the lowermost part of this member, from which *Orbitolina* sp., *Petrophyton* sp. and *Belemnites* sp. have been reported by YABE (1927), HUJITA (1943) and EGUCHI (1944). The limestone is of biosparite, containing terrigeneous grains (quartz, feldspar, chert, etc.) and intraclasts in addition to numerous skeletals.

Although we obtained only fragmentary ammonoids and bivalves from the Upper Member, the following fossils have hitherto been known from the formation; *Pterotrigonia hokkaidoana* (YEHARA), *P. pocilliformis* (YOKOYAMA), *Nipponitrigonia kikuchiana* (YOKOYAMA), *Zamiophyllum* sp., *Cladophlebis* sp., etc.

Judging from the litho- and bio-facies, it seems that the Lower Member was formed under deltaic to littoral environments and the Upper Member under a neritic one. On the ground of its stratigraphical position, the Hibihara Formation is likely to represent the "Upper Monobegawa Group", which is correlated to the Miyakoan in Japanese standard.

(b) Hagino Formation

The Hagino Formation is narrowly distributed in the southern zone of the surveyed area, being faulted against the Upper Cretaceous Nagase Formation on the north and against the Jurassic Torinosu Group or the Jurasso-Triassic Odochi Group on the south. The beds are right-side-up and dip northwards steeply, with a general trend of ENE–WSW.

The typical exposures are in the Hagino area, about 14 km. to the west of the surveyed area. Although the available data are insufficient here, this formation seems to be made up mainly of black shale with a few intercalations of fine- to medium-grained sandstone. The estimated thickness is of 50 to 100 meters. Several specimens of a trigonian fossil, *Pterotrigonia pocilliformis* (YOKOYAMA) were obtained from the fine-grained sandstone near Odochi.

In the Hagino area, many marine fossils of bivalves and ammonoids have been reported by KATTO and SUYARI (1956), AMANO (1957), NAKANO (1960) and HAYAMI (1965a, b, 1966). On the basis of them, the Hagino Formation seems to be equivalent to the Hibihara Formation at least in part.

4. *Nagase Formation*

The Nagase Formation occupies the southern narrow zone in the western half of the present area, with a general trend of ENE–WSW. In the vicinity of Odochi the beds form a synclinorium, overlain by the Kajisako Formation conformably on the north and faulted against the Hagino Formation on the south, while in the other areas they are right-side-up and dip to the north with an angle of about 50 degrees, being demarcated by fault from the Lower Cretaceous Hibihara Formation on the north and from the Jurassic Torinosu and Jurasso-Triassic Odochi Groups on the south.

Representative displays are in the south of the Nagase Dam (Fig. 3–12) and in the north of Odochi (Fig. 3–15). The thickness is estimated at less than 400 meters.

This formation is monotonously made up of black mudstone or silty shale, but sometimes intercalated by a few thin beds of conglomerate and coarse-grained sandstone in the lower part. The conglomerate is more or less well-sorted, composed of subrounded pebbles (a few cm. in size) of chert, sandstone, shale and altered basic volcanics. Granitic pebbles are also contained, but their content is much lower in comparison with the case of the Hibihara Formation. Poorly preserved and fragmentary ammonoids, inocerami and other pelecypods were obtained near the Nagase Dam.

Although the Nagase Formation is hardly distinguishable from the Lower Cretaceous Hibihara Formation, if only judged from the lithofacies, the following fossils indicating the Upper Cretaceous have been reported by MATSUMOTO (1954), KATTO and SUYARI (1956), OZAKI and KATTO (1956) and NAKANO (1960); *Acanthotrigonia pustulosa* (NAGAO), *A.* sp. cf. *A. dilapsa* (YEHARA), *Mantelliceras* sp., *Anagaudryceras* sp. cf. *A. sacya* (FORBES), *Acanthoceras rhotomagenese* (DEFRANCE), *Pachydesmoceras denisonianus* (STOLICZKA), *Cymatoceras yabei* OZAKI and KATTO, etc. On the basis of them, this is correlated to Cenomanian to Turonian in age. Therefore, it represents the fourth cycle of the Cretaceous sedimentation in the Chichibu terrain, that is the "Lower Sotoizumi Group" corresponding to the Gyliakian in Japanese sense.

5. *Kajisako Formation*

The Kajisako Formation is narrowly exposed only in the southern zone of the Kajisako area, forming a synclinorium with a general trend of ENE–WSW. On the south the beds dip to the north with an angle of about 60 degrees and the basal part is in conformable contact with the Nagase Formation, while on the north the dip is about 40 degrees to the south and the lower part is demarcated from the Lower Cretaceous Hibihara Formation by a fault, the Kajisakogawa tectonic line. A minor anticline is observed in the central part of the synclinorium, as shown in the geological section (Fig. 1).

Good displays are shown along the Kajisako River in the north of Odochi (Fig. 3–15 and –16), where the thickness is estimated at about 230 meters.

This formation begins with dark greyish green and coarse- to medium-grained sandstone in the basal part (about 80 meters in thickness), gradually changes to black and fine-grained sandstone with a few thin intercalations of greenish acidic tuff or tuffaceous sandstone in the middle part (about 70 meters in thickness), and finally ends with black sandy shale with intercalated thin layers of fine-grained sandstone in the upper part (about 80 meters in thickness). We obtained *Inoceramus* sp. cf. *I. uwajimensis* YEHARA, *Ostrea* sp. and indeterminable pelecypods.

In addition to our fossils, inocerami such as *Inoceramus japonicus* NAGAO and MATSUMOTO and *I.* sp. cf. *I. naumanni* YOKOYAMA and other marine fossils have been reported by KATTO and SUYARI (1956). On the basis of them, therefore, this formation is correlated to Coniacian to Santonian in age, and represents a part of the "Upper Sotoizumi Group", the fifth cycle of the Cretaceous sedimentation in the Chichibu terrain, which corresponds to the Urakawan in Japanese standard.

## III. PETROGRAPHY OF SANDSTONES

### A. GENERAL REMARKS

In order to ensure the geographical and stratigraphical coverage effectively, as many as possible sandstone specimens were collected from each formation, except for the Hagino Formation, along the main routes of the Monobegawa valley. The geographical and stratigraphical localities of the examined sandstones are shown in Figs. 1 and 3, respectively. The specimens analyzed petrographically herein are 111 in number through the whole successions; 22 in the Ryoseki, 34 in the Yunoki, 35 in the Hibihara, 10 in the Nagase and 10 in the Kajisako Formation.

The sandstones were analyzed in respect of grain size, major mineral constituents and accessory mineral assemblages, and their analytical methods were followed according to one of us (NAKAI, 1971) as a general rule. After measuring the maximum length of quartz grains, more than 300 in number per thin-section, the size parameters were calculated graphically on the probability paper, without using FRIEDMAN's (1962) conversion graph. The composition of major minerals was evaluated on the data which were obtained from the same thin-sections as used in the size analysis by counting more than 1000 points with a Swift point-counter. The heavy minerals were dealt with in several specimens semiquantitatively, after extracted by a orthodox method.

### B. GRAIN-SIZE PARAMETERS

In the grain-size analysis the examination was made into median (Md; phi value at 50 per cent), mean (Mz), index of sorting (So), skewness (Sk) and kurtosis (Ku) on the probability paper, of which the four parameters except for the first one were calculated by the formulae of FOLK and WARD (1957). Their values and evaluations in each specimen are given in Table 1. Besides, the frequency of the textural types based on FOLK and WARD's denotation in each formation is given in Table 2.

The sandstones treated herein show a similar range of the mean size in each formation, that is, from 1.5 to 3.3 phi in general. Its sample average is 2.17 phi in the Ryoseki Formation, 2.31 phi in the Yunoki, 2.37 phi in the Hibihara, 2.07 phi in the Nagase and

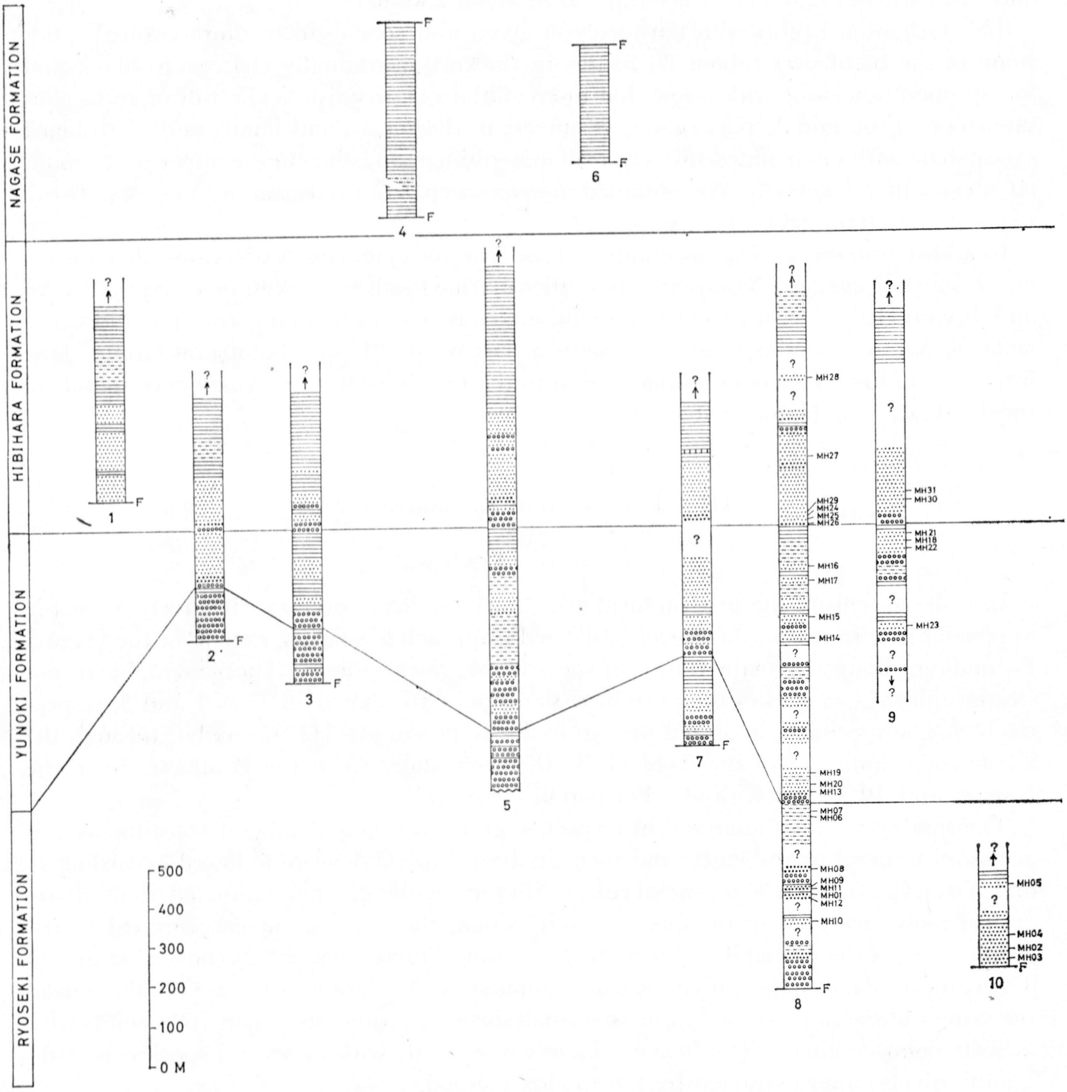


FIG. 3. Stratigraphical columnar section showing the sampling localities of the examined sandstones. 1: South of Frui, 2: South of Yanagawa, 3: Taniai, 4: Yoshino, 5: South of Oyashiki, 6: Shimoda, 7: Okubo, 8: Yunoki-Hibihara, 9: West of Hibihara, 10: South of Jingasan.

2.43 phi in the Kajisako. The index of sorting ranges approximately from 0.4 to 1.3 phi in each formation, and its sample average is nearly 0.7 phi in every one. As known from Table 2, the majority, more or less 80 per cent, of the sandstones in each formation belong to a moderately sorted type. As for the parameter of skewness, each sample of the Ryoseki, Yunoki, and Hibihara Formations takes the average value of about 0.15, and the rest two take that of about 0.12. It is shown in Table 2 that a relatively large

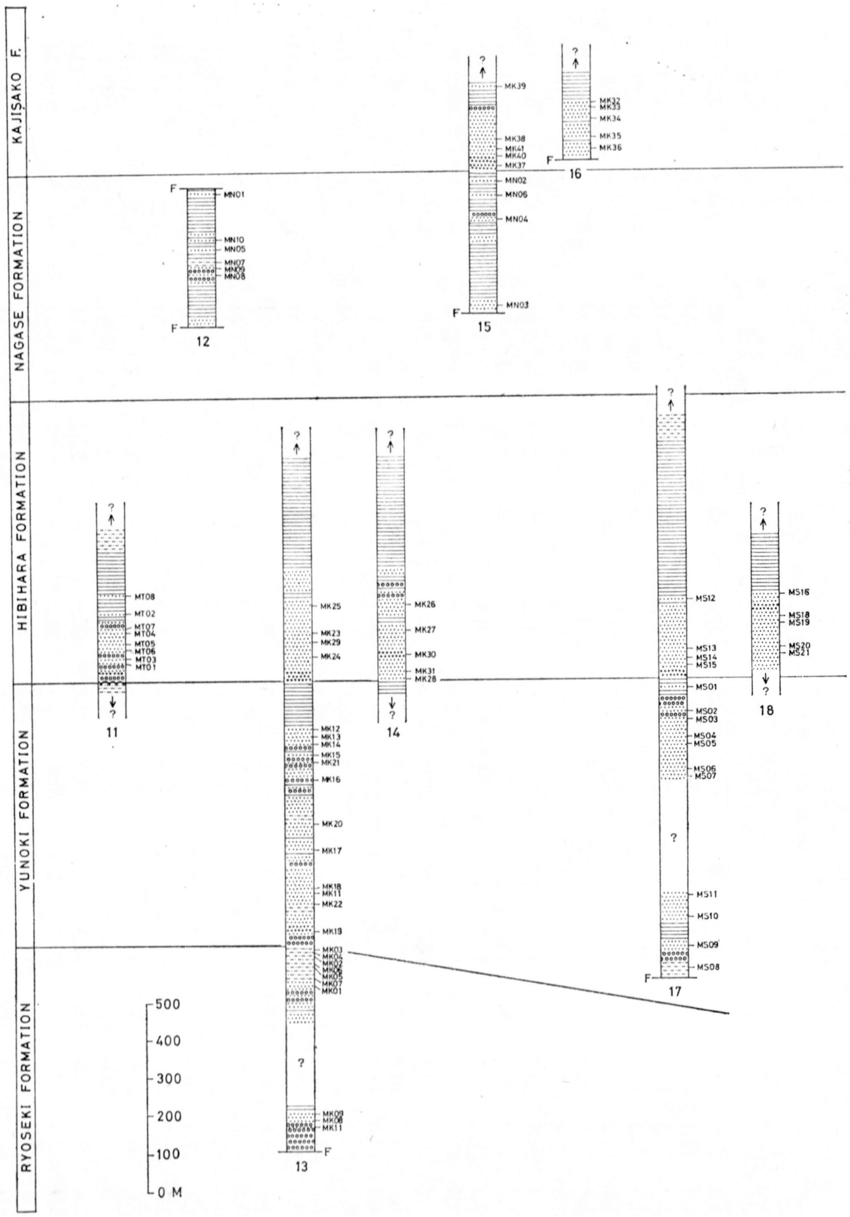


FIG. 3. (Continued). 11: Nagase Dam, 12: South of Nagase Dam, 13: Kajisakogawa, 14: Western Side of Kajisakogawa, 15: North of Odochi (Southern Wing), 16: Ibid. (Northern Wing), 17: Doiban, 18: North of Onishi.

number of specimens belong to a positively skewed or a symmetrical type, although several sandstones of a very positively skewed type and a negatively skewed one occur. As concerns the parameter of kurtosis, the sample average is about 1.05 in every formation, and most of the examined specimens belong to a mesokurtic or a leptokurtic

TABLE 1. QUANTITATIVE DATA ON MAJOR MINERAL COMPONENTS AND SIZE PARAMETERS IN EACH SANDSTONE SPECIMEN

| Formation | Specimen | Major Mineral Components (in %) | | | | | | | | | | Size Parameters | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Quartz | | | Feldspar | | | Rock Fragments | | | Matrix | Median (phi) | Mean (phi) | Sorting Index (phi) | Skewness | Kurtosis |
| | | Q1 | Q2 | T | Or | Pl | T | Ch | Ot | T | | | | | | |
| Ryoseki Formation | MK01 | 8.8 | 4.8 | 13.6 | 18.7 | 12.0 | 30.8 | 3.5 | 12.8 | 16.3 | 39.4 | 3.25 | 3.25 | 0.58(M) | 0.00(S) | 0.87(P) |
| | MK02 | 14.1 | 4.3 | 18.4 | 15.4 | 7.5 | 22.9 | 11.5 | 6.2 | 17.7 | 41.0 | 1.97 | 2.01 | 0.61(M) | 0.18(P) | 1.10(M) |
| | MK03 | 11.1 | 5.4 | 16.5 | 17.8 | 8.1 | 26.0 | 19.4 | 7.7 | 27.1 | 30.5 | 1.56 | 1.62 | 0.54(M) | 0.26(P) | 1.03(M) |
| | MK04 | 16.8 | 12.5 | 29.3 | 14.0 | 21.1 | 35.1 | 4.8 | 11.6 | 16.5 | 19.1 | 1.63 | 1.63 | 0.61(M) | 0.05(S) | 1.01(M) |
| | MK05 | 10.1 | 1.1 | 11.2 | 8.9 | 7.5 | 16.4 | 0.8 | 5.0 | 5.7 | 66.6 | 3.20 | 3.22 | 0.68(M) | 0.07(S) | 0.90(P) |
| | MK06 | 22.4 | 5.8 | 28.1 | 11.1 | 4.3 | 15.4 | 17.6 | 7.4 | 25.0 | 31.4 | 2.20 | 2.30 | 0.62(M) | 0.20(P) | 1.08(M) |
| | MK07 | 13.5 | 3.8 | 17.3 | 17.3 | 10.6 | 28.0 | 12.1 | 12.9 | 25.0 | 29.8 | 2.46 | 2.50 | 0.64(M) | 0.19(P) | 1.08(M) |
| | MK08 | 10.6 | 8.7 | 19.3 | 9.3 | 5.5 | 14.8 | 26.4 | 5.3 | 31.6 | 34.2 | 2.80 | 2.93 | 0.75(M) | 0.22(P) | 0.99(M) |
| | MK09 | 6.2 | 7.7 | 13.9 | 6.9 | 6.2 | 13.1 | 28.4 | 16.9 | 45.3 | 27.7 | 2.12 | 2.20 | 0.78(M) | 0.18(P) | 1.11(M) |
| | MK10 | 7.8 | 9.5 | 17.3 | 11.6 | 8.1 | 19.7 | 17.1 | 14.1 | 31.3 | 31.6 | 2.72 | 2.76 | 0.70(M) | 0.15(P) | 1.02(M) |
| | MH01 | 6.9 | 10.5 | 17.3 | 9.4 | 7.1 | 16.5 | 7.8 | 37.2 | 45.0 | 21.2 | 1.38 | 1.42 | 0.52(M) | 0.17(P) | 0.88(P) |
| | MH02 | 13.6 | 6.9 | 20.5 | 9.7 | 8.9 | 18.5 | 9.1 | 27.0 | 36.2 | 24.8 | 1.67 | 1.83 | 1.05(P) | 0.19(P) | 0.94(M) |
| | MH03 | 11.3 | 7.4 | 18.7 | 10.9 | 8.9 | 19.8 | 8.0 | 27.2 | 35.2 | 26.4 | 1.42 | 1.62 | 0.97(M) | 0.32(VP) | 1.09(M) |
| | MH04 | 12.2 | 4.9 | 17.0 | 19.2 | 4.1 | 23.3 | 6.4 | 22.8 | 29.2 | 30.4 | 1.84 | 1.96 | 0.73(M) | 0.33(VP) | 1.14(L) |
| | MH05 | 13.3 | 7.5 | 20.8 | 13.6 | 7.3 | 20.9 | 4.7 | 22.2 | 26.9 | 31.4 | 1.96 | 2.02 | 0.72(M) | 0.19(P) | 1.33(L) |
| | MH06 | 17.7 | 7.1 | 24.8 | 15.4 | 12.1 | 27.4 | 6.9 | 8.3 | 15.1 | 32.7 | 3.02 | 3.05 | 0.43(W) | 0.09(S) | 1.04(M) |
| | MH07 | 19.8 | 9.5 | 29.3 | 17.4 | 6.6 | 24.0 | 4.0 | 18.5 | 22.4 | 24.3 | 2.21 | 2.26 | 0.77(M) | 0.11(P) | 0.93(M) |
| | MH08 | 18.7 | 7.4 | 26.1 | 8.7 | 11.4 | 20.0 | 13.0 | 10.3 | 23.3 | 30.6 | 1.88 | 1.89 | 0.74(M) | 0.03(S) | 1.05(M) |
| | MH09 | 8.5 | 10.2 | 18.7 | 22.0 | 4.8 | 26.8 | 8.8 | 17.5 | 26.3 | 28.2 | 2.47 | 2.46 | 0.55(M) | −0.05(S) | 1.16(L) |
| | MH10 | 7.4 | 9.5 | 16.9 | 16.8 | 9.3 | 26.1 | 10.3 | 24.5 | 34.9 | 22.1 | 1.67 | 1.72 | 0.69(M) | 0.20(P) | 1.23(L) |
| | MH11 | 11.3 | 11.4 | 22.6 | 8.9 | 9.8 | 18.7 | 10.6 | 20.5 | 31.1 | 27.5 | 1.64 | 1.65 | 0.71(M) | 0.11(P) | 1.11(L) |
| | MH12 | 5.2 | 7.5 | 12.7 | 9.1 | 3.9 | 13.0 | 11.6 | 40.9 | 52.4 | 22.0 | 1.42 | 1.51 | 0.62(M) | 0.22(P) | 1.04(M) |
| | MH13 | 20.7 | 15.6 | 36.3 | 14.6 | 17.8 | 32.4 | 1.7 | 5.4 | 7.1 | 24.2 | 2.32 | 2.43 | 0.63(M) | 0.33(VP) | 1.13(L) |
| | MH14 | 12.5 | 3.3 | 15.8 | 13.6 | 15.3 | 28.9 | 3.5 | 24.7 | 28.1 | 27.2 | 2.42 | 2.42 | 0.59(M) | 0.08(S) | 1.42(L) |
| | MH15 | 14.6 | 2.1 | 16.7 | 16.4 | 15.5 | 31.9 | 2.5 | 19.9 | 22.4 | 28.9 | 2.91 | 2.95 | 0.74(M) | 0.06(S) | 0.95(M) |
| | MH16 | 11.2 | 8.9 | 20.0 | 19.1 | 10.6 | 29.7 | 6.4 | 20.0 | 26.4 | 23.9 | 2.07 | 2.11 | 0.96(M) | 0.09(S) | 0.97(M) |
| | MH17 | 8.9 | 6.8 | 15.7 | 20.4 | 11.0 | 31.4 | 5.2 | 19.2 | 24.3 | 28.6 | 2.60 | 2.64 | 0.55(M) | 0.17(P) | 1.06(M) |
| | MH18 | 20.3 | 4.0 | 24.2 | 23.9 | 21.5 | 45.4 | 0.5 | 11.6 | 12.1 | 18.3 | 2.32 | 2.31 | 0.60(M) | −0.03(S) | 1.17(L) |
| | MH19 | 16.7 | 8.0 | 24.7 | 28.4 | 9.8 | 38.2 | 4.5 | 11.0 | 15.4 | 21.7 | 2.18 | 2.18 | 0.49(W) | −0.02(S) | 1.25(L) |
| | MH20 | 19.0 | 10.6 | 29.6 | 27.0 | 10.4 | 37.5 | 3.6 | 14.6 | 18.2 | 14.7 | 1.82 | 1.89 | 0.50(W) | 0.22(P) | 0.93(M) |

TABLE 1. (Continued)

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Yunoki Formation | MH21 | 20.7 | 4.4 | 25.1 | 23.3 | 19.3 | 42.6 | 0.2 | 14.4 | 14.7 | 17.6 | 2.68 | 2.68 | 0.51(M) | −0.01(S) | 1.05(M) |
| | MH22 | 20.0 | 3.4 | 23.4 | 22.0 | 18.2 | 40.1 | 0.7 | 15.4 | 16.1 | 20.3 | 2.53 | 2.57 | 0.37(W) | 0.18(P) | 0.91(M) |
| | MH23 | 10.1 | 9.8 | 19.9 | 11.5 | 6.2 | 17.8 | 17.3 | 16.4 | 33.6 | 28.8 | 2.77 | 2.84 | 0.64(M) | 0.13(P) | 0.85(P) |
| | MK11 | 17.7 | 8.8 | 26.6 | 19.1 | 15.6 | 34.7 | 5.8 | 14.6 | 20.4 | 18.4 | 2.41 | 2.44 | 0.54(M) | 0.14(P) | 1.28(L) |
| | MK12 | 14.0 | 4.6 | 18.5 | 27.9 | 18.2 | 46.1 | 3.6 | 7.4 | 11.0 | 24.4 | 2.28 | 2.31 | 0.51(M) | 0.20(P) | 1.34(L) |
| | MK13 | 18.6 | 10.0 | 28.6 | 19.4 | 17.5 | 36.9 | 2.8 | 10.6 | 13.3 | 21.2 | 2.59 | 2.65 | 0.53(M) | 0.19(P) | 1.31(L) |
| | MK14 | 20.1 | 8.1 | 28.2 | 37.5 | 7.5 | 45.0 | 2.8 | 10.5 | 13.3 | 13.6 | 2.82 | 2.86 | 0.54(M) | 0.10(P) | 0.98(M) |
| | MK15 | 12.4 | 7.5 | 19.9 | 24.9 | 10.4 | 35.3 | 5.9 | 21.4 | 27.3 | 17.5 | 1.83 | 2.00 | 0.84(M) | 0.27(P) | 1.01(M) |
| | MK16 | 8.2 | 5.7 | 13.9 | 20.3 | 16.1 | 36.4 | 6.8 | 19.4 | 26.2 | 23.5 | 1.64 | 1.65 | 0.75(M) | 0.12(P) | 1.08(M) |
| | MK17 | 12.7 | 4.1 | 16.8 | 15.1 | 14.1 | 29.2 | 8.7 | 21.9 | 30.5 | 23.5 | 1.47 | 1.67 | 0.95(M) | 0.33(VP) | 1.01(M) |
| | MK18 | 13.1 | 3.5 | 16.6 | 15.3 | 14.5 | 29.8 | 3.9 | 24.6 | 28.5 | 25.1 | 1.65 | 1.85 | 0.90(M) | 0.31(VP) | 0.81(P) |
| | MK19 | 23.7 | 3.0 | 26.6 | 20.0 | 11.5 | 31.5 | 4.3 | 11.0 | 15.2 | 26.6 | 2.62 | 2.65 | 0.51(M) | 0.19(P) | 1.09(M) |
| | MK20 | 8.3 | 5.9 | 14.2 | 6.2 | 16.4 | 22.6 | 19.8 | 15.9 | 35.7 | 27.5 | 1.95 | 2.14 | 1.01(P) | 0.24(P) | 0.84(P) |
| | MK21 | 16.7 | 4.8 | 21.5 | 19.9 | 14.0 | 33.9 | 3.2 | 13.6 | 16.8 | 27.8 | 2.42 | 2.51 | 0.65(M) | 0.12(P) | 1.04(M) |
| | MK22 | 7.2 | 2.7 | 9.9 | 17.7 | 15.9 | 33.6 | 5.2 | 21.3 | 26.5 | 30.0 | 1.84 | 1.98 | 1.03(P) | 0.18(P) | 0.77(P) |
| | MS01 | 16.2 | 4.4 | 20.6 | 15.5 | 10.4 | 25.9 | 1.8 | 24.5 | 26.4 | 27.1 | 2.52 | 2.56 | 0.56(M) | 0.11(P) | 0.98(M) |
| | MS02 | 13.4 | 5.1 | 18.5 | 20.2 | 14.2 | 34.4 | 6.8 | 18.9 | 25.7 | 21.4 | 2.32 | 2.38 | 0.64(M) | 0.10(P) | 0.95(M) |
| | MS03 | 19.1 | 6.5 | 25.6 | 21.5 | 12.3 | 33.8 | 3.7 | 16.2 | 19.9 | 20.7 | 2.26 | 2.32 | 0.66(M) | 0.13(P) | 1.12(L) |
| | MS04 | 15.3 | 9.5 | 24.7 | 11.8 | 11.4 | 23.2 | 8.7 | 17.5 | 26.2 | 25.8 | 1.88 | 2.00 | 0.95(M) | 0.21(P) | 0.91(M) |
| | MS05 | 17.8 | 2.3 | 20.2 | 15.9 | 12.3 | 28.2 | 3.6 | 20.3 | 23.9 | 27.8 | 2.56 | 2.61 | 0.54(M) | 0.18(P) | 1.31(L) |
| | MS06 | 17.6 | 4.1 | 21.7 | 17.0 | 15.0 | 32.1 | 1.4 | 15.7 | 17.1 | 29.1 | 2.86 | 2.89 | 0.51(M) | 0.10(P) | 0.99(M) |
| | MS07 | 15.9 | 3.3 | 19.2 | 19.6 | 10.9 | 30.4 | 4.0 | 23.0 | 27.0 | 23.4 | 2.61 | 2.60 | 0.54(M) | 0.06(S) | 1.27(L) |
| | MS08 | 20.8 | 4.3 | 25.1 | 18.3 | 17.6 | 36.0 | 1.2 | 13.1 | 14.2 | 24.7 | 2.36 | 2.40 | 0.56(M) | 0.10(S) | 1.11(L) |
| | MS09 | 25.3 | 17.6 | 42.9 | 10.5 | 6.3 | 16.8 | 6.7 | 15.4 | 22.1 | 18.2 | 1.72 | 1.73 | 0.60(M) | 0.10(P) | 0.97(M) |
| | MS10 | 16.2 | 12.5 | 28.7 | 14.7 | 10.9 | 25.7 | 6.3 | 18.0 | 24.3 | 21.4 | 1.76 | 1.75 | 0.56(M) | 0.07(S) | 0.99(M) |
| | MS11 | 16.2 | 5.5 | 21.7 | 11.5 | 13.9 | 25.4 | 9.8 | 21.9 | 31.6 | 21.2 | 1.42 | 1.49 | 0.63(M) | 0.26(P) | 1.18(L) |
| | MH24 | 9.0 | 2.7 | 11.8 | 26.7 | 13.7 | 40.4 | 3.6 | 21.7 | 25.3 | 22.5 | 2.31 | 2.37 | 1.12(P) | 0.09(S) | 0.97(M) |
| | MH25 | 7.4 | 3.8 | 11.2 | 20.0 | 17.0 | 36.9 | 6.3 | 19.3 | 25.6 | 26.2 | 2.78 | 2.51 | 1.27(P) | −0.26(N) | 0.81(P) |
| | MH26 | 8.0 | 3.8 | 11.8 | 20.5 | 17.6 | 38.1 | 3.9 | 16.4 | 20.3 | 29.8 | 2.14 | 2.23 | 1.12(P) | 0.12(P) | 0.76(P) |
| | MH27 | 6.8 | 3.7 | 10.5 | 19.4 | 19.6 | 39.0 | 2.9 | 20.0 | 22.8 | 27.7 | 2.10 | 2.21 | 1.06(P) | 0.14(P) | 0.84(P) |
| | MH28 | 9.8 | 3.2 | 12.9 | 21.7 | 16.9 | 38.6 | 1.6 | 17.4 | 19.0 | 29.4 | 3.22 | 3.27 | 0.74(M) | 0.05(S) | 1.00(M) |
| | MH29 | 8.1 | 3.3 | 11.3 | 28.0 | 21.8 | 49.8 | 4.1 | 10.2 | 14.3 | 24.6 | 2.45 | 2.56 | 0.88(M) | 0.17(P) | 0.92(M) |
| | MH30 | 11.4 | 4.4 | 15.8 | 15.3 | 18.7 | 34.0 | 3.2 | 17.5 | 20.7 | 29.5 | 2.80 | 2.84 | 0.55(M) | 0.14(P) | 1.07(M) |
| | MH31 | 9.5 | 7.5 | 17.1 | 16.8 | 21.1 | 37.9 | 7.3 | 12.1 | 19.4 | 25.7 | 2.66 | 2.68 | 0.54(M) | 0.11(P) | 1.10(M) |
| | MK23 | 11.4 | 4.3 | 15.7 | 27.5 | 21.9 | 49.5 | 6.1 | 14.8 | 20.9 | 14.0 | 2.36 | 2.37 | 0.43(W) | 0.11(P) | 1.16(L) |

TABLE 1. (Continued)

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hibihara Formation | MK24 | 21.2 | 4.8 | 25.9 | 32.9 | 22.3 | 55.3 | 3.0 | 4.5 | 7.5 | 11.3 | 2.43 | 2.46 | 0.46(W) | 0.14(P) | 1.08(M) |
| | MK25 | 14.6 | 4.2 | 18.8 | 32.4 | 22.5 | 54.9 | 1.2 | 6.3 | 7.5 | 18.8 | 2.50 | 2.53 | 0.35(W) | 0.14(P) | 1.02(M) |
| | MK26 | 16.3 | 5.3 | 21.7 | 15.6 | 19.0 | 34.6 | 5.7 | 16.4 | 22.1 | 21.6 | 2.30 | 2.35 | 0.52(M) | 0.25(P) | 1.46(L) |
| | MK27 | 13.8 | 5.6 | 19.4 | 21.9 | 21.0 | 42.9 | 1.3 | 13.4 | 14.6 | 23.1 | 2.26 | 2.22 | 0.85(M) | 0.01(S) | 1.15(L) |
| | MK28 | 15.6 | 9.5 | 25.1 | 22.8 | 19.0 | 41.9 | 0.8 | 12.7 | 13.4 | 19.6 | 2.48 | 2.53 | 0.42(W) | 0.22(P) | 1.12(L) |
| | MK29 | 19.8 | 5.1 | 24.9 | 23.4 | 21.5 | 44.8 | 1.3 | 11.0 | 12.3 | 17.9 | 2.37 | 2.40 | 0.41(W) | 0.15(P) | 1.05(M) |
| | MK30 | 11.9 | 3.8 | 15.7 | 19.8 | 16.3 | 36.1 | 2.9 | 19.0 | 21.9 | 26.3 | 2.34 | 2.37 | 0.74(M) | 0.03(S) | 1.02(M) |
| | MK31 | 8.8 | 5.0 | 13.8 | 23.5 | 17.7 | 41.2 | 3.5 | 17.0 | 20.5 | 24.6 | 2.93 | 2.88 | 0.58(M) | −0.06(S) | 1.11(L) |
| | MS12 | 15.8 | 4.0 | 19.8 | 18.9 | 22.8 | 41.7 | 2.3 | 16.7 | 19.0 | 19.6 | 2.00 | 2.00 | 0.81(M) | 0.04(S) | 1.17(L) |
| | MS13 | 14.5 | 9.9 | 24.4 | 20.6 | 15.2 | 35.8 | 3.5 | 19.9 | 23.4 | 16.4 | 1.77 | 1.91 | 0.88(M) | 0.25(P) | 1.09(M) |
| | MS14 | 11.4 | 3.8 | 15.1 | 16.2 | 19.5 | 35.7 | 2.4 | 19.6 | 22.0 | 27.2 | 2.69 | 2.73 | 0.79(M) | 0.09(S) | 0.87(P) |
| | MS15 | 18.6 | 5.1 | 23.7 | 17.9 | 21.0 | 38.9 | 1.8 | 18.9 | 20.6 | 16.8 | 2.27 | 2.33 | 0.60(M) | 0.11(P) | 1.20(L) |
| | MS16 | 7.4 | 6.3 | 13.7 | 12.3 | 18.3 | 30.6 | 7.5 | 29.2 | 36.7 | 19.0 | 1.78 | 1.85 | 1.05(P) | 0.13(P) | 0.91(M) |
| | MS17 | 13.3 | 7.0 | 20.3 | 6.1 | 10.2 | 16.3 | 13.6 | 19.8 | 33.4 | 30.0 | 2.07 | 2.21 | 1.12(P) | 0.22(P) | 0.86(P) |
| | MS18 | 17.1 | 2.3 | 19.4 | 18.7 | 23.0 | 41.7 | 1.2 | 10.8 | 11.9 | 26.9 | 2.81 | 2.81 | 0.44(W) | 0.07(S) | 1.18(L) |
| | MS19 | 17.2 | 3.9 | 21.1 | 26.6 | 19.0 | 45.7 | 0.3 | 11.3 | 11.5 | 21.7 | 2.65 | 2.66 | 0.54(M) | 0.10(P) | 1.09(M) |
| | MS20 | 13.8 | 1.8 | 15.6 | 22.6 | 15.1 | 37.6 | 2.6 | 16.7 | 19.3 | 27.4 | 2.27 | 2.52 | 0.80(M) | 0.40(VP) | 0.91(M) |
| | MS21 | 14.5 | 4.7 | 19.2 | 22.9 | 13.2 | 36.1 | 2.7 | 17.5 | 20.3 | 24.5 | 2.46 | 2.55 | 0.69(M) | 0.20(P) | 1.18(L) |
| | MT01 | 10.6 | 8.4 | 19.0 | 25.1 | 18.5 | 43.6 | 5.0 | 10.2 | 15.2 | 22.2 | 1.82 | 1.84 | 0.64(M) | 0.06(S) | 0.97(M) |
| | MT02 | 11.7 | 4.8 | 16.5 | 15.2 | 22.3 | 37.5 | 2.5 | 13.6 | 16.1 | 30.0 | 2.14 | 2.14 | 0.76(M) | 0.06(S) | 1.07(M) |
| | MT03 | 6.1 | 11.5 | 17.5 | 19.5 | 20.4 | 39.9 | 5.2 | 10.0 | 15.2 | 27.4 | 2.23 | 2.27 | 0.57(M) | 0.17(P) | 1.18(L) |
| | MT04 | 8.7 | 11.6 | 20.3 | 23.0 | 14.5 | 37.5 | 10.2 | 12.2 | 22.4 | 19.9 | 1.90 | 1.89 | 0.63(M) | −0.02(S) | 1.04(M) |
| | MT05 | 15.4 | 8.1 | 23.5 | 16.2 | 22.5 | 38.7 | 6.5 | 14.7 | 21.2 | 16.7 | 1.98 | 1.98 | 0.66(M) | 0.02(S) | 1.12(L) |
| | MT06 | 11.7 | 9.6 | 21.3 | 19.9 | 15.6 | 35.5 | 3.1 | 16.6 | 19.6 | 23.5 | 2.27 | 2.37 | 0.67(M) | 0.29(P) | 1.16(L) |
| | MT07 | 8.0 | 8.4 | 16.4 | 16.9 | 22.2 | 39.0 | 3.4 | 17.4 | 20.7 | 23.9 | 1.96 | 1.86 | 0.69(M) | −0.11(N) | 1.07(M) |
| | MT08 | 16.9 | 5.5 | 22.4 | 19.6 | 24.8 | 44.4 | 1.7 | 8.1 | 9.9 | 23.4 | 2.07 | 2.13 | 1.06(P) | 0.08(S) | 0.84(P) |
| Nagase F. | MN01 | 15.0 | 11.8 | 26.8 | 13.6 | 8.6 | 22.2 | 4.4 | 12.9 | 17.3 | 33.7 | 2.03 | 2.07 | 0.48(W) | 0.19(P) | 1.22(L) |
| | MN02 | 7.8 | 2.8 | 10.6 | 20.0 | 18.0 | 38.0 | 10.2 | 4.3 | 14.5 | 36.9 | 1.97 | 2.03 | 0.48(W) | 0.15(P) | 1.12(L) |
| | MN03 | 18.0 | 7.2 | 25.3 | 11.4 | 17.9 | 29.3 | 7.8 | 8.2 | 16.0 | 29.4 | 3.21 | 3.24 | 0.52(M) | 0.12(P) | 1.18(L) |
| | MN04 | 22.0 | 26.4 | 48.4 | 12.6 | 16.6 | 29.3 | 3.8 | 6.7 | 10.5 | 11.8 | 0.53 | 0.60 | 0.74(M) | 0.22(P) | 1.14(L) |
| | MN05 | 13.8 | 10.2 | 24.1 | 24.8 | 11.0 | 35.8 | 6.0 | 8.3 | 14.2 | 25.9 | 1.70 | 1.72 | 0.82(M) | 0.06(S) | 0.99(M) |
| | MN06 | 11.6 | 6.2 | 17.8 | 16.1 | 15.0 | 31.1 | 3.6 | 13.3 | 16.9 | 34.2 | 2.55 | 2.70 | 0.68(M) | 0.36(VP) | 1.12(L) |
| | MN07 | 9.7 | 8.0 | 17.7 | 13.7 | 13.1 | 26.7 | 8.6 | 19.6 | 28.2 | 27.4 | 1.81 | 1.80 | 0.94(M) | 0.00(S) | 0.92(M) |

TABLE 1. (Continued)

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MN08 | 14.7 | 7.5 | 22.2 | 18.5 | 7.2 | 25.8 | 6.0 | 16.4 | 22.4 | 29.6 | 2.02 | 2.04 | 0.67(M) | 0.08(S) | 1.05(M) |
| | MN09 | 15.1 | 10.2 | 25.3 | 10.1 | 12.0 | 22.1 | 3.3 | 21.8 | 25.1 | 27.5 | 1.93 | 1.88 | 0.70(M) | −0.01(S) | 1.24(L) |
| | MN10 | 12.2 | 6.6 | 18.8 | 9.7 | 17.7 | 27.5 | 2.5 | 15.5 | 18.1 | 35.7 | 2.48 | 2.61 | 0.66(M) | 0.37(VP) | 1.17(L) |
| Kajisako F. | MK32 | 9.1 | 8.7 | 17.8 | 32.0 | 19.6 | 51.6 | 3.6 | 6.1 | 9.7 | 21.0 | 2.41 | 2.45 | 0.45(W) | 0.17(P) | 1.08(M) |
| | MK33 | 11.9 | 6.7 | 18.6 | 14.5 | 19.3 | 33.9 | 7.1 | 16.9 | 24.0 | 23.6 | 2.77 | 2.72 | 0.69(M) | −0.12(N) | 0.99(M) |
| | MK34 | 13.4 | 4.7 | 18.0 | 15.8 | 16.5 | 32.2 | 8.9 | 7.8 | 16.8 | 33.0 | 2.21 | 2.28 | 0.77(M) | 0.15(P) | 1.10(M) |
| | MK35 | 5.4 | 3.2 | 8.6 | 6.9 | 15.5 | 22.4 | 3.9 | 19.1 | 23.0 | 46.0 | 2.13 | 2.21 | 0.65(M) | 0.20(P) | 1.41(L) |
| | MK36 | 6.7 | 11.6 | 18.3 | 16.5 | 18.5 | 35.0 | 8.9 | 11.8 | 20.7 | 26.0 | 1.97 | 1.94 | 0.81(M) | −0.02(S) | 0.88(P) |
| | MK37 | 13.4 | 6.5 | 19.8 | 15.1 | 12.6 | 27.7 | 9.9 | 9.1 | 19.0 | 33.5 | 1.91 | 1.98 | 0.69(M) | 0.20(P) | 1.13(L) |
| | MK38 | 8.9 | 6.7 | 15.6 | 17.4 | 12.6 | 29.9 | 6.3 | 8.4 | 14.7 | 39.8 | 2.70 | 2.85 | 0.84(M) | 0.26(P) | 0.90(P) |
| | MK39 | 7.4 | 14.9 | 22.3 | 13.1 | 16.0 | 29.1 | 2.8 | 7.4 | 10.2 | 38.5 | 2.60 | 2.62 | 0.48(W) | 0.10(P) | 1.14(L) |
| | MK40 | 15.2 | 5.3 | 20.5 | 20.2 | 8.4 | 28.7 | 4.3 | 15.6 | 19.9 | 30.8 | 2.76 | 2.69 | 0.78(M) | −0.11(N) | 0.89(P) |
| | MK41 | 12.1 | 5.5 | 17.6 | 19.5 | 10.0 | 29.4 | 5.2 | 12.7 | 17.9 | 35.0 | 2.55 | 2.58 | 0.53(M) | 0.17(P) | 1.02(M) |

Q1: non-undulose quartz, Q2: undulose quartz, T: total, Or: orthoclase, Pl: plagioclase, Ch: chert, Ot: others, Sorting Index by W: well sorted, M: moderately sorted, P: poorly sorted, Skewness by N: negative, S: symmetrical, P: positive, VP: very positive, Kurtosis by P: platykurtic, M: mesokurtic, L: leptokurtic.

TABLE 2. NUMBER FREQUENCY OF TEXTURAL TYPES IN EACH FORMATION

| | Sorting Index | | | Skewness | | | | Kurtosis | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | W | M | P | N | S | P | VP | P | M | L |
| Ryoseki | 1 | 20 | 1 | | 6 | 14 | 2 | 3 | 14 | 5 |
| Yunoki | 3 | 29 | 2 | | 9 | 22 | 3 | 4 | 18 | 12 |
| Hibihara | 6 | 22 | 7 | 2 | 13 | 19 | 1 | 6 | 17 | 12 |
| Nagase | 2 | 8 | | | 4 | 4 | 2 | | 3 | 7 |
| Kajisako | 2 | 8 | | 2 | 1 | 7 | | 3 | 4 | 3 |

Symbols are identical with those of Table 1.

type. Thus, there is no remarkable difference among the five samples in relative frequency of the textural types based on the size parameters.

It has been insisted that the scatter diagrams between the parameters (FOLK and WARD, 1957; FRIEDMAN, 1961; MOIOLA and WEISER, 1968; etc.) and CM pattern (PASSEGA, 1957) are very useful for understanding the geological significance and grasping the information on depositional environment from the grain-size analysis. We tried to make a close inspection on them. On the scatter diagrams, however, the present five samples did not show any clear trends in all combinations of the parameters and could not be differentiated from each other. On the CM pattern, they were not restricted in any certain characteristic pattern which has been suggested by PASSEGA (1957) and there was no appreciable from each other.

If it should be accepted that the size parameters of sandstone reflect somewhat sensitively the depositional processes and environments, it may be concluded in the present case that a certain formation is composed of various sandstones which were formed under various depositional conditions, but then that the samples of the five formations were formed under similar depositional conditions on the whole.

### B. MAJOR CONSTITUENTS

#### 1. *Descriptive Remarks*

The major minerals of sandstone are classified into quartz (non-undulose quartz and undulose quartz), feldspar (orthoclase and plagioclase), rock fragments (chert and others) and matrix. The quantitative data of the mineralogical composition in each specimen are tabulated in Table 1.

Quartz: The content of detrital quartz grains ranges from 8.6 to 48.4 per cent, occupying on the average 19.6, 22.4, 18.1, 23.7 and 23.4 per cent of the whole composition in the sample of the Ryoseki, the Yunoki, the Hibihara, the Nagase and the Kajisako, respectively. Although the quartz grains had been genetically classified into several types by some authors, the classification seems to be very doubtful and is very arduous to perform explicitly and quantitatively. In this paper, therefore, they are simply subdivided into non-undulose and undulose one, which may correspond to "igneous" and "metamorphic quartz" of OKADA (1960, 1961), respectively. The former has commonly inclusions of empty vacuoles or bubbles and of minerals such as zircon, mica, tourmaline, etc., and is larger in content than the latter in any sample. Quartz grains are generally subrounded in shape and belong to the C-type of PETTIJOHN's (1957) chart. Secondary growth is rarely detected.

Feldspar: Among the major minerals the detrital grains of feldspar are the most abundant on the average in any sample of the five formations, occupying 21.7, 32.4, 39.8, 28.8 and 32.0 per cent of all constituents in each of the Ryoseki, the Yunoki, the Hibihara, the Nagase and the Kajisako, respectively. Its amount ranges from 13.0 to 55.3 per cent. The grains are herein classified into orthoclase and plagioclase. Although microcline, perthite and myrmekite occur a little, the former two are counted in orthoclase and the latter one in plagioclase. The content of orthoclase is slightly larger than that of plagioclase. Grains of plagioclase are frequently corroded with calcite. Feldspar is more angular in shape and more cloudy in appearance than quartz in general.

Rock Fragments: The other framework elements except for the grains of quartz and feldspar are counted in a category of rock fragments, which are quantitatively analyzed

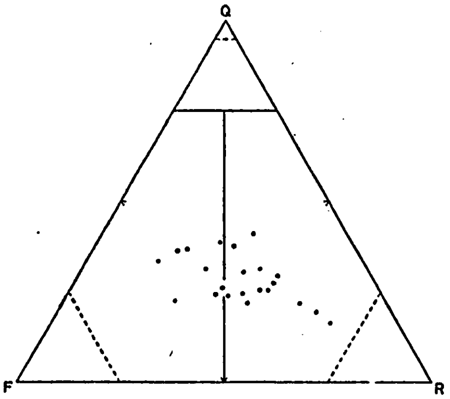


FIG. 4. Compositional diagram of sandstones from the Ryoseki Formation. Dot shows the wacke, and cross shows the arenite. Q: quartz, F: feldspar, R: rock fragments.

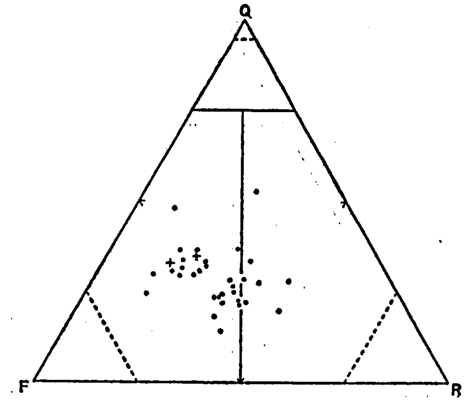


FIG. 5. Compositional diagram of sandstones from the Yunoki Formation. Symbols are identical with those of Fig. 4.

to be subdivided into chert and others. Their amount ranges from 5.7 to 52.4 per cent, occupying on the average 28.2, 21.8, 19.0, 18.3 and 17.6 per cent of all elements in the sample of the Ryoseki, the Yunoki, the Hibihara, the Nagase and the Kajisako, respectively. The detrital grains of chert are composed of microcrystalline quartz and are more rounded in shape than those of quartz. The other rock fragments consist of mudstone and volcanics with hyalopilitic or intersertal texture. Unquestionable metamorphic rocks are not found out in rock fragments, but the grains of quartz-aggregate showing a schist-like texture are sporadically met with.

Matrix: Most of the analyzed sandstones have a high content of matrix, that is, more than 20 per cent. It occupies on the average 30.6, 23.4, 23.1, 29.2 and 32.7 per cent of the whole components in the sample of the Ryoseki, the Yunoki, the Hibihara, the Nagase and the Kajisako, respectively. Matrix is made up of secondary clay minerals, detrital grains smaller than 6 phi and carbonate cement. The last one reaches more than 20 per cent in a few specimens.

2. *Classification of Sandstone*

Recently OKADA (1968a, b) has given the excellent review on the classification problem of sandstone and he (1971) has finally proposed a new classification scheme. The sandstone examined herein are plotted on OKADA's triangular diagram, as shown in Figs. 4 to 8, after each component of quartz, feldspar and rock fragments was recalculated in the proportion to the total framework elements from Table 1. As known from the figures, the sandstones are all restricted within the feldspathic and lithic fields, and the majority in each sample belong to the wacke type with more than 15 per cent matrix content.

In the sample of the Ryoseki, about one third specimens (8/22) belong to the feldspathic wacke, and about two thirds (14/22) to the lithic wacke. No sandstone of the arenite type with less than 15 per cent matrix occurs in this formation. The sample of the Yunoki consists mainly of the feldspathic wacke, which occupies more than two thirds of the total

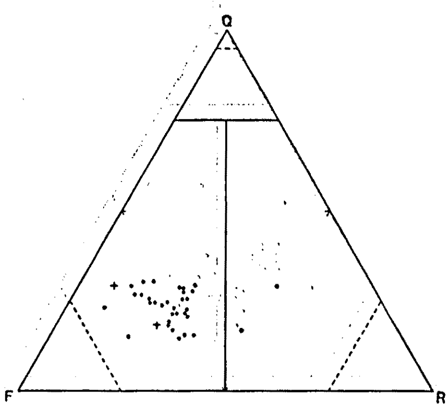


FIG. 6. Compositional diagram of sandstones from the Hibihara Formation. Symbols are identical with those of Fig. 4.

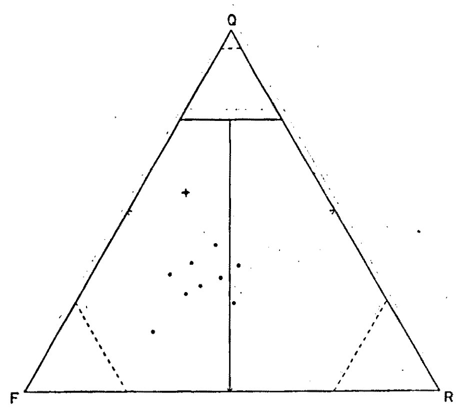


FIG. 7. Compositional diagram of sandstones from the Nagase Formation. Symbols are identical with those of Fig. 4.

specimens (25/34), and secondarily of the lithic wacke (7/34). Only 2 specimens belong to the feldspathic arenite. As to the sample of the Hibihara, most of the examined specimens (31/35) are of the feldspathic wacke, and only 2 specimens are referred to the lithic wacke and to the feldspathic arenite. Concerning the Nagase Formation, about two thirds of the specimens (7/10) are represented by the feldspathic wacke, and 2 specimens fall in the lithic wacke and 1 in the feldspathic arenite. In the sample of the Kajisako, most of the specimens (9/10) belong to the feldspathic wacke and only 1 specimen to the lithic wacke. There is neither feldspathic nor lithic arenite in it.

In addition to OKADA's scheme, furthermore, we tried to classify sandstones numerically by the cluster analysis, following the method which has been suggested by one of us (NAKAI, 1973). The used variables were contents of subdivided components and values of the size-parameters in Table 1. In this analysis, 111 specimens were continuatively clustered within a slight distance coefficient in Euclidean expression, that is, from 0.064 at the first clustering of the two specimens of MH26 and MH27 to 0.319 at the final clustering of the whole ones, without forming discriminative groups. It was not displayed, contrary to our expection, that the sandstones from a certain limited stratigraphical unit might be strongly clustered with each other. This fact may suggest that the samples of the five stratigraphical units have similar and continuous characters on the whole.

### C. HEAVY MINERALS

The heavy mineral analysis was carried out on the several selected specimens in each formation, and the mineral composition was dealt with only semi-quantitatively.

The accessory minerals occupy on the average about 0.54, 1.13, 1.26, 0.40 and 0.42 per cent in weight in the sample of the Ryoseki, the Yunoki, the Hibihara, the Nagase and the Kajisako Formation, respectively. The majority of their grains are composed of opaque minerals in any specimen. The identified heavy minerals of non-opaques consist of epidote group (epidote, clinozoisite, zoisite and piedmontite), garnet, zircon, tourmaline, pyroxene (clinopyroxene and orthopyroxene), amphibole (hornblende and glaucophane), mica (chlorite, biotite and muscovite), rutile, anatase and others.

Among non-opaque minerals, such stable minerals as epidote (excepting piedmontite), garnet and zircon make up most parts of the composition. The grains of tourmaline, clinopyroxene, orthopyroxene, hornblende and mica occur commonly in any specimen, although their content is somewhat low. Rutile and anatase, occupying a few per cent in number, are observable in most specimens. The grains of glaucophane and piedmontite are sporadically detected; the former occurs from the whole stratigraphical units, and the latter is restricted in the samples of the Ryoseki, Yunoki and Hibihara Formations.

The following ideal suites of heavy minerals are approximately constructed according to KRUMBEIN and PETTIJOHN (1938), PETTIJOHN (1957), TICKELL (1965) and others:

Suite I ...... anatase, biotite, hornblende, muscovite, rutile, tourmaline, zircon
Suite II ...... anatase, hornblende, pyroxene, rutile, zircon
Suite III...... anatase, biotite, epidote, garnet, glaucophane, hornblende, muscovite, piedmontite, rutile, tourmaline
Suite IV...... well-rounded, re-worked minerals

These ideal suites may indicate the source rocks of acidic igneous, basic igneous, metamorphic and sedimentary terrains, respectively, although not definitely decided.

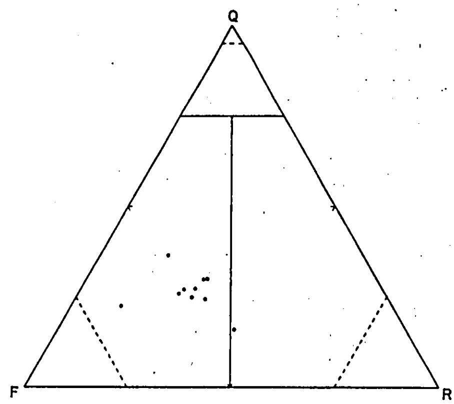


FIG. 8. Compositional diagram of sandstones from the Kajisako Formation. Symbols are identical with those of Fig. 4.

D. STATISTICAL ANALYSIS OF STRATIGRAPHICAL VARIATION

It is very important for the comprehension of the vicissitudes of sedimentation to scrutinize the stratigraphical variation in the population mean of each sandstone property statistically. The mean, confidence interval of the mean, standard deviation and coefficient of variation of each property in the five samples are shown in Table 3. As the objective judgement on the similarity or dissimilarity of properties is not precisely decided from this table, the statistical analysis was carried out to reveal the stratigraphical variation of the estimated population variance and mean of each measured property clearer, following the same method as done by one of us (NAKAI, 1971); Snedecor's variance ratio test as to the difference of the population variance and Student's t-test as to the difference of the population mean were executed.

TABLE 3. MEAN, CONFIDENCE INTERVAL OF THE MEAN, STANDARD DEVIATION AND COEFFICIENT OF VARIATION OF EACH VARIABLE IN THE FIVE SAMPLES

| | Quartz | non-undulose | undulose | Feldspar | orthoclase | plagioclase | Rock Fragments | chert | others | Matrix | Mean-Size | Sorting Index | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ryoseki F. | | | | | | | | | | | | | | |
| Mean | 19.6 | 12.2 | 7.4 | 21.7 | 13.3 | 8.4 | 28.2 | 11.0 | 17.1 | 30.6 | 2.17 | 0.68 | 0.16 | 1.05 |
| CI | 2.3 | 2.0 | 1.2 | 2.6 | 1.9 | 1.6 | 4.8 | 3.1 | 4.4 | 4.3 | 0.25 | 0.06 | 0.04 | 0.05 |
| SD | 5.2 | 4.7 | 2.7 | 5.9 | 4.3 | 3.7 | 10.9 | 7.1 | 10.0 | 9.7 | 0.57 | 0.14 | 0.10 | 0.11 |
| CV | 0.27 | 0.38 | 0.36 | 0.27 | 0.32 | 0.44 | 0.39 | 0.65 | 0.58 | 0.32 | 0.26 | 0.21 | 0.63 | 0.10 |
| Yunoki F. | | | | | | | | | | | | | | |
| Mean | 22.4 | 15.9 | 6.5 | 32.4 | 18.8 | 13.6 | 21.8 | 5.1 | 16.7 | 23.4 | 2.31 | 0.65 | 0.15 | 1.06 |
| CI | 2.3 | 1.6 | 1.3 | 2.5 | 2.1 | 1.3 | 2.5 | 1.5 | 1.7 | 1.5 | 0.14 | 0.06 | 0.03 | 0.06 |
| SD | 6.5 | 4.5 | 3.7 | 7.1 | 6.0 | 3.7 | 7.1 | 4.2 | 4.9 | 4.3 | 0.40 | 0.17 | 0.09 | 0.16 |
| CV | 0.29 | 0.28 | 0.57 | 0.22 | 0.32 | 0.27 | 0.33 | 0.82 | 0.29 | 0.18 | 0.17 | 0.26 | 0.60 | 0.15 |
| Hibihara F. | | | | | | | | | | | | | | |
| Mean | 18.1 | 12.5 | 5.6 | 39.8 | 20.8 | 19.0 | 19.0 | 3.8 | 15.2 | 23.1 | 2.37 | 0.73 | 0.11 | 1.04 |
| CI | 1.5 | 1.4 | 0.9 | 2.3 | 1.8 | 1.1 | 2.1 | 1.0 | 1.7 | 1.7 | 0.11 | 0.08 | 0.04 | 0.05 |
| SD | 4.4 | 4.0 | 2.6 | 6.8 | 5.3 | 3.3 | 6.2 | 2.8 | 4.9 | 4.8 | 0.33 | 0.24 | 0.12 | 0.14 |
| CV | 0.24 | 0.32 | 0.46 | 0.17 | 0.25 | 0.17 | 0.33 | 0.74 | 0.32 | 0.21 | 0.14 | 0.33 | 1.09 | 0.13 |
| Nagase F. | | | | | | | | | | | | | | |
| Mean | 23.7 | 14.0 | 9.7 | 28.8 | 15.1 | 13.7 | 18.3 | 5.6 | 12.7 | 29.2 | 2.07 | 0.67 | 0.15 | 1.12 |
| CI | 7.1 | 2.9 | 4.6 | 3.7 | 3.4 | 2.9 | 3.9 | 1.9 | 4.1 | 5.2 | 0.50 | 0.11 | 0.09 | 0.07 |
| SD | 10.0 | 4.1 | 6.4 | 5.2 | 4.8 | 4.0 | 5.4 | 2.6 | 5.8 | 7.2 | 0.70 | 0.15 | 0.13 | 0.10 |
| CV | 0.42 | 0.29 | 0.66 | 0.18 | 0.32 | 0.29 | 0.30 | 0.46 | 0.46 | 0.25 | 0.34 | 0.22 | 0.87 | 0.09 |
| Kajisako F. | | | | | | | | | | | | | | |
| Mean | 17.7 | 10.4 | 7.4 | 32.0 | 17.1 | 14.9 | 17.6 | 6.1 | 11.5 | 32.7 | 2.43 | 0.67 | 0.10 | 1.05 |
| CI | 2.6 | 2.4 | 2.5 | 5.2 | 4.6 | 2.8 | 3.5 | 1.8 | 3.2 | 5.5 | 0.23 | 0.10 | 0.07 | 0.11 |
| SD | 3.7 | 3.3 | 3.5 | 7.7 | 6.4 | 3.9 | 4.9 | 2.5 | 4.5 | 7.7 | 0.32 | 0.14 | 0.14 | 0.16 |
| CV | 0.21 | 0.32 | 0.47 | 0.23 | 0.37 | 0.26 | 0.28 | 0.31 | 0.39 | 0.24 | 0.13 | 0.21 | 1.40 | 0.15 |

CI: Confidence interval of population mean at 95 per cent confidence coefficient, SD: Standard deviation, CV: Coefficient of variation.

Before entering into the statistical analysis, we must consider the following points duly. The first consideration was, of course, given on the problem of the normality in distribution of each property, because the statistical tests are based on the normal distribution of variables. KRUMBEIN and GRAYBILL (1965) and FUJII (1971) have suggested that percentages of abundant minerals in rocks may be sufficiently approximated to a normal distribution, and besides the result of chi-square test for the normality satisfied us actually. The same test was done as to the size parameters. The second consideration was taken up as to the problem of the relation between the mineral composition and the grain-size. OKADA (1968a) has pointed out that the mineral composition of sandstone is fairly linearly changed in accordance with the decrease or increase of grain-size. However, the linear relation between them was not clearly shown in the present samples, as known from Table 4, except for the relation between the matrix content and the mean-size in the samples of the Ryoseki and Nagase Formations. Furthermore, as the five samples treated herein show similar averages and ranges in the mean-size, there seems to be no necessity for the effect of grain-size upon mineral composition to be taken into consideration.

It is, of course, indispensable to ensure that there is no areal variation in a given sample, for our purpose is to make clear the stratigraphical variation. As an example, the sandstones from the Yunoki Formation were grouped into three subgroups on the basis of their collected routes, namely, the routes along the Hibihara River, along the Kajisako River and along the Sasa River from west to east, which are denoted by the symboles of MH, MK and MS in Table 1, respectively. Table 5 shows the result of the statistical test on the major mineral components and the grain-size parameters. Judging from the result, the statistically significant difference in population mean among the three subgroups is not estimated in nearly all variables, except for total feldspar content between MK and MS. In this way the areal variation in any sample was not almost recognized significantly.

The result of the statistical test on the stratigraphical variation of each observed property is summarized in Table 6. Although the test was performed in all the combinations of the five samples, this table takes up only the combinations of the stratigraphically adjoining samples.

TABLE 4. SIMPLE CORRELATION COEFFICIENTS BETWEEN SIZE PARAMETERS AND MINERAL COMPONENTS

| | Ry | Yu | Hi | Na | Ka | T |
|---|---|---|---|---|---|---|
| Mz-Quartz | −0.16 | −0.01 | −0.23 | −0.62 | 0.16 | −0.24* |
| Mz-Feldspar | 0.10 | 0.25 | 0.15 | −0.01 | 0.04 | 0.21* |
| Mz-Rock Frags. | −0.58* | −0.38* | −0.26 | 0.15 | −0.25 | −0.37* |
| Mz-Matrix | 0.67* | 0.24 | 0.33 | 0.75* | 0.05 | 0.35* |
| So -Quartz | 0.02 | −0.46* | −0.51* | 0.14 | −0.12 | −0.31* |
| So -Feldspar | −0.36 | −0.36* | −0.46* | −0.03 | −0.36 | −0.20* |
| So -Rock Frags. | 0.28 | 0.59* | 0.57* | 0.41 | 0.53 | 0.38* |
| So -Matrix | −0.11 | 0.30 | 0.39* | −0.48 | 0.08 | 0.09 |

Mz: Mean Size, So: Sorting Index, Ry: Sample of the Ryoseki Formation, Yu: Sample of the Yunoki Formation, Hi: Sample of the Hibihara Formation, Na: Sample of the Nagase Formation, Ka: Sample of the Kajisako Formation, T: Total specimens, *: Significant at 5 per cent risk level.

TABLE 5. STATISTICAL COMPARISON OF SANDSTONE PROPERTIES BETWEEN MAJOR ROUTES IN THE YUNOKI FORMATION

| | MH route - MK route | | | | | MH route - MS route | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Fo | Sig | d | to | Sig | Fo | Sig | d | to | Sig |
| Quartz | 1.01 | NS | 2.8 | 1.07 | NS | 1.20 | NS | 1.5 | 0.54 | NS |
| non-undulose | 1.25 | NS | 1.5 | 0.74 | NS | 2.02 | NS | 1.7 | 1.01 | NS |
| undulose | 2.91 | * | 1.3 | 0.92 | NS | 1.28 | NS | 0.2 | 0.11 | NS |
| Feldspar | 1.42 | NS | 0.4 | 0.14 | NS | 1.82 | NS | 5.8 | 2.01 | NS |
| orthoclase | 1.89 | NS | 0.3 | 0.11 | NS | 2.23 | NS | 4.0 | 1.99 | NS |
| plagioclase | 2.39 | NS | 0.2 | 0.12 | NS | 2.70 | NS | 1.8 | 1.06 | NS |
| Rock Fragments | 1.06 | NS | 2.2 | 0.66 | NS | 2.53 | NS | 3.6 | 1.29 | NS |
| chert | 1.05 | NS | 1.9 | 0.96 | NS | 2.63 | NS | 0.7 | 0.41 | NS |
| others | 1.12 | NS | 0.3 | 0.13 | NS | 2.24 | NS | 2.9 | 1.52 | NS |
| Matrix | 1.08 | NS | 0.2 | 0.10 | NS | 2.09 | NS | 0.6 | 0.33 | NS |
| Sorting Index | 1.79 | NS | 0.13 | 1.72 | NS | 1.60 | NS | 0.02 | 0.27 | NS |
| Skewness | 2.00 | NS | 0.09 | 2.29 | NS | 3.00 | * | 0.02 | 0.52 | NS |
| Kurtosis | 1.24 | NS | 0.02 | 0.21 | NS | 1.61 | NS | 0.01 | 0.12 | NS |

| | MK route - MS route | | | | |
|---|---|---|---|---|---|
| | Fo | Sig | d | to | Sig |
| Quartz | 1.21 | NS | 4.3 | 1.57 | NS |
| non-undulose | 2.53 | NS | 3.2 | 1.77 | NS |
| undulose | 3.74 | * | 1.1 | 0.71 | NS |
| Feldspar | 1.28 | NS | 6.2 | 2.43 | * |
| orthoclase | 4.21 | * | 4.3 | 1.70 | NS |
| plagioclase | 1.13 | NS | 2.0 | 1.58 | NS |
| Rock Fragments | 2.69 | NS | 1.4 | 0.50 | NS |
| chert | 2.52 | NS | 1.2 | 0.73 | NS |
| others | 2.52 | NS | 2.6 | 1.32 | NS |
| Matrix | 1.94 | NS | 0.4 | 0.23 | NS |
| Sorting Index | 2.87 | NS | 0.12 | 1.61 | NS |
| Skewness | 1.50 | NS | 0.07 | 2.36 | NS |
| Kurtosis | 2.00 | NS | 0.02 | 0.35 | NS |

Fo : Observed variance ratio
Sig: Significance
d : Difference of sample means
to : Observed t values
NS: Not significant
* : Significant at 5% risk level

In the combination of the samples of the Ryoseki and the Yunoki, the significant difference in population mean is recognized in the contents of non-undulose quartz, total feldspar, orthoclase, plagioclase, total rock fragments, chert and matrix. It is safely said that the sample of the Ryoseki Formation has a lower content in the former four variables and a higher content in the latter three ones than that of the Yunoki Formation.

The comparison between the samples of the Yunoki and the Hibihara shows the significant difference in population mean in the contents of total quartz, non-undulose quartz, total feldspar and plagioclase. The former two show a higher content and the latter two a lower content in the sample of the Yunoki Formation than in that of the Hibihara.

In the comparison between the population means in the samples of the Hibihara and the Nagase, the significant difference is statistically revealed in the contents of total feldspar, orthoclase, plagioclase and matrix. The sample of the Hibihara Formation shows a higher content in the former three variables and a lower content in matrix than that of the Nagase.

The combination of the samples of the Nagase and the Kajisako reveals the significant difference only in the population mean of non-undulose quartz content, which is higher in the former than in the latter.

Thus, the stratigraphical variation is recognized in the major mineral constituents, but not appreciated in the size parameters at all in any combination of the five samples. Judging from this fact, the change in the mineralogical composition seems to depend on the vicissitudinary provenance through five stratigraphical units, which is to be discussed in detail in the succeeding chapter.

The stratigraphical variation of the mineralogical composition is clearly illustrated in Fig. 9.

## IV. Remarks on Sedimentation

### A. Vicissitude of Sedimentation

1. *Ryoseki Formation*

It is undoubted that the Cretaceous basin of the present area was organized on the Paleozoic Chichibu rocks, which had been formed in an eugeosynclinal trough, the Chichibu geosyncline, during the Paleozoic ages and at least in part uplifted in the Pre-Triassic age already (Ichikawa et al., 1953).

Throughout the Mesozoic this area was under a condition of unstable shelf, where the upheaval (regression) and the subsidence (transgression) took place alternately. Although the Jurassic basin was in a shallow marine environment which was directly connected with an open sea, as represented by a characteristic facies of the "Torinosu-type Limestone", the incipient Cretaceous basin is considered to have been demarcated from an open sea and restricted in a non-marine environment during the sedimentation of the Ryoseki Formation, based on the fossil evidence; the time of emersion was inserted between the Jurrassic and the Cretaceous. This seems to be supported by the occurrence of reddish conglomerate in the basal part of the formation. Kobayashi (1941) has considered that the non-marine environment was retained by a barrier, the "Ryoseki barrier", which may be attributed to the upheaval of the complex rocks along the Kurosegawa tectonic zone (Yamashita, 1957a, b).

The sandstones of this formation have a higher content of rock fragments, as represented by the lithic wacke, and the contents in the rock fragments of sandstones as well as in the pebbles of conglomerates indicate that the clastic detritus may have been derived mainly from the older sedimentary, basic volcanic, granitic and metamorphic rocks. This agrees well with a supposition of the provenance judged from the ideal suites of heavy minerals in sandstone, which were alluded to in the previous chapter. The older sedimentaries and basic volcanics are presumably referred to the rocks of the Pre-Cretaceous strata, mainly of the Paleozoic Chichibu Supergroup which frames the basement of the present basin. Some basic rocks may have been derived from the Mikabu green rocks, although not precisely concluded. As the possible origin of the granitic rocks, the Ryoke igneous com-

TABLE 6. STATISTICAL COMPARISON OF SANDSTONE PROPERTIES BETWEEN THE ADOJOINING FORMATIONS

| | Ryoseki - Yunoki | | | | | Yunoki - Hibihara | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Fo | Sig | d | to | Sig | Fo | Sig | d | to | Sig |
| Quartz | 1.56 | NS | 2.84 | 1.72 | NS | 2.19 | * | 4.33 | 3.22 | ** |
| non-undulose | 1.08 | NS | 3.77 | 3.03 | ** | 1.27 | NS | 3.46 | 3.39 | ** |
| undulose | 1.84 | NS | 1.06 | 1.02 | NS | 2.09 | * | 0.87 | 1.13 | NS |
| Feldspar | 1.43 | NS | 10.75 | 5.92 | *** | 1.06 | NS | 7.33 | 4.38 | *** |
| orthoclase | 1.96 | NS | 5.54 | 3.73 | ** | 1.28 | NS | 1.93 | 1.41 | NS |
| plagioclase | 1.02 | NS | 5.19 | 5.10 | *** | 1.23 | NS | 5.42 | 6.39 | *** |
| Rock Fragments | 2.39 | * | 6.35 | 2.42 | ** | 1.29 | NS | 2.77 | 1.73 | NS |
| chert | 2.86 | ** | 5.95 | 3.56 | ** | 2.27 | * | 1.26 | 1.47 | NS |
| others | 4.08 | ** | 0.39 | 0.17 | NS | 1.02 | NS | 1.51 | 1.28 | NS |
| Matrix | 4.99 | ** | 7.23 | 3.28 | ** | 1.23 | NS | 0.24 | 0.22 | NS |
| Mean-Size | 2.09 | * | 0.14 | 0.97 | NS | 1.42 | NS | 0.06 | 0.67 | NS |
| Sorting Index | 1.58 | NS | 0.03 | 0.73 | NS | 1.93 | * | 0.08 | 1.53 | NS |
| Skewness | 1.13 | NS | 0.01 | 0.32 | NS | 1.75 | NS | 0.04 | 1.62 | NS |
| Kurtosis | 2.17 | * | 0.01 | 0.25 | NS | 1.30 | NS | 0.02 | 0.44 | NS |

| | Hibihara - Nagase | | | | | Nagase - Kajisako | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Fo | Sig | d | to | Sig | Fo | Sig | d | to | Sig |
| Quartz | 5.11 | ** | 5.63 | 1.74 | NS | 7.33 | ** | 5.99 | 1.78 | NS |
| non-undulose | 1.04 | NS | 1.53 | 1.07 | NS | 1.52 | NS | 3.64 | 2.20 | * |
| undulose | 6.21 | ** | 4.07 | 1.97 | NS | 3.33 | * | 2.31 | 1.00 | NS |
| Feldspar | 1.73 | NS | 10.99 | 4.69 | *** | 2.21 | NS | 3.21 | 1.09 | NS |
| orthoclase | 1.23 | NS | 5.70 | 3.03 | ** | 1.77 | NS | 2.05 | 0.81 | NS |
| plagioclase | 1.41 | NS | 5.31 | 4.26 | *** | 1.04 | NS | 1.19 | 0.68 | NS |
| Rock Fragments | 1.32 | NS | 0.72 | 0.33 | NS | 1.23 | NS | 0.73 | 0.32 | NS |
| chert | 1.18 | NS | 1.79 | 1.83 | NS | 1.03 | NS | 0.47 | 0.41 | NS |
| others | 1.40 | NS | 2.53 | 1.39 | NS | 1.66 | NS | 1.21 | 0.52 | NS |
| Matrix | 2.22 | * | 6.09 | 2.52 | * | 1.15 | NS | 3.51 | 1.05 | NS |
| Mean-Size | 4.50 | ** | 0.30 | 1.30 | NS | 4.95 | * | 0.36 | 1.49 | NS |
| Sorting Index | 2.64 | NS | 0.06 | 0.72 | NS | 1.10 | NS | 0.00 | 0.00 | NS |
| Skewness | 1.29 | NS | 0.05 | 1.10 | NS | 1.00 | NS | 0.05 | 0.90 | NS |
| Kurtosis | 2.00 | NS | 0.07 | 1.48 | NS | 2.50 | NS | 0.06 | 1.03 | NS |

**, ***: Significant at 1 per cent and 0.1 per cent risk level, respectively. Other denotations are identical with those of Table 5.

plex, which is situated to the north of the Median tectonic line in the present state, is considered to have played an important role. KANO (1969) has inferred through his close petrologic inspection that the source of the granitic rocks in the Upper Cretaceous conglomerates of the Aritagawa basin in Wakayama Prefecture might be referred to the Ryoke granitic rocks. However, as to the Lower Cretaceous, there is no detailed information. The Mitaki granitic rocks of the Kurosegawa terrain may have partly contributed to the source. As regards the origin of the metamorphic rocks, which is suggested by the characteristic occurrence of glaucophane and piedmontite in the heavy minerals of sandstone, it is considered that the Sambagawa metamorphic rocks which are extensively developed immediately to the north of the Chichibu terrain at present played an important contribution to the detritus, although the precise decision could not be made out.

2. *Yunoki Formation*

Coarse-grained sediments predominate in this formation as well as in the Ryoseki Formation, and a non-marine environment seemed to be retained at least to its basal part, where such deposits as characterized by red coloration are observable at a few localities. It is considered, however, that the environment in the succeeding part was transformed into shallower marine condition from non-marine one, and that the Cretaceous basin became to face to an open-sea in the uppermost part, as judged from the lithofacies and biofacies. Such a transition may have been resulted by a gradual subsidence in the depositional site, because any tectonic difference is not detected between the Ryoseki and Yunoki Formations.

As confirmed by the statistical test, the content of matrix becomes significantly lower in the sample of the present formation than in that of the Ryoseki, though there is no appreciable difference in any size parameter between them. This fact probably indicates that the clastics were deposited under slightly higher energy condition as a whole than in the Ryoseki.

The pebbles of conglomerates and the rock fragments of sandstones in the Yunoki Formation are quite similar in composition to those in the Ryoseki Formation. Judging from the ideally constructed suites of heavy minerals in addition to the contents of pebbles and rock fragments, the source rocks in this stage are probably referred to the same ones as in the sedimentation of the Ryoseki. In comparison with the sandstone sample of the Ryoseki, however, the statistical analysis reveals that the sample of the Yunoki shows a higher content in non-undulose quartz, orthoclase and plagioclase and a lower content in rock fragments (chert). This is reflected on the triangular diagrams (Figs. 4 and 5) roughly and the majority of sandstones from the present formation are represented by the feldspathic wacke type. As there is no distinguishable structural difference between the two formations, this compositional change seems to have been mainly caused by the vicissitude of the backgrounds, but not by an intense tectonism. Judging from the fact that the sandstones of this formation show a significant increase of feldspar content in spite of their formation in a higher energy condition than those of the Ryoseki, it is considered that the granitic rocks became to contribute more greatly as the source, although the main role was also played by the Paleozoic Chichibu terrain.

3. *Hibihara Formation*

The lower half of the Hibihara Formation is composed mainly of sandstone, and its lithological feature suggests that this part was formed under the condition of non-marine to pro-deltaic or littoral environments. Judging from the fact that its basal part covers directly the shale of the Yunoki Formation which seems to have been made up in a phase of marine inundation, a marine regression may have taken place in the interval between

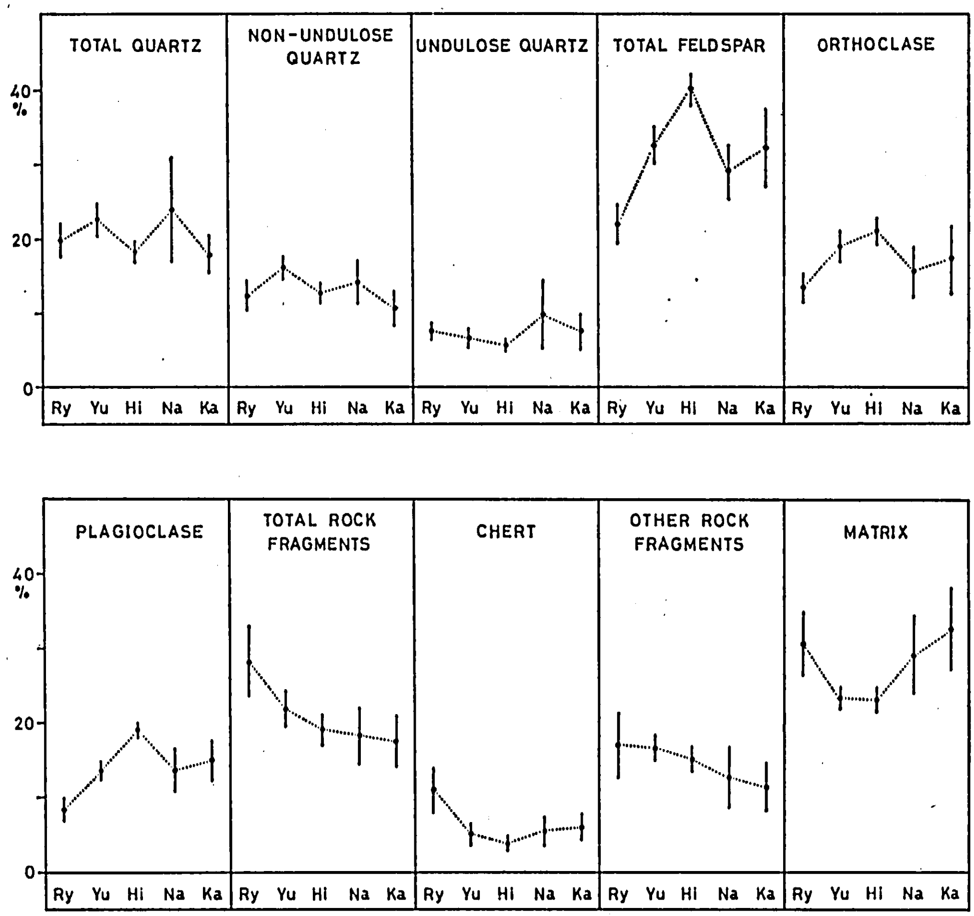


Fig. 9. Stratigraphical variation of the major mineral components in sandstones of the Monobegawa valley. Dot shows the sample mean and solid line shows the confidence interval of the population mean at 95 per cent confidence coefficient. The symbols of Ry, Yu, Hi, Na and Ka show the samples of the Ryoseki, the Yunoki, the Hibihara, the Nagase and the Kajisako Formation, respectively.

them. The general conformability between the Yunoki and Hibihara Formations probably denies an intense tectonic movement in this interval, although an unconformity is observed in some places on the south side of a synclinorium. Since any significant difference in content of matrix and size parameters is not recognized between the sandstone samples of the two formations, as confirmed by the statistical test, the same energy condition is presumed in the deposition of these sandstones in general.

The succeeding upper half of the Hibihara Formation consists almost of fine-grained sediments of mudstone and siltstone, which must have been deposited in the relatively deeper part of neritic sea with somewhat calm currents. As the relation between the lower and upper members of this formation is, of course, of a gradation, the transition of the Cretaceous basin could be referred to the gradual subsidence in the depositional site, or relatively to the gradual progression of marine transgression.

As concerns the provenance, the same backgrounds as in the underlying two formations seem to have been framed up in this stage. The pebbles of conglomerates and the rock fragments of sandstones are composed mainly of the Paleozoic sedimentaries and basic volcanics, and the occurrence of heavy minerals such as glaucophane and piedmontite in sandstones suggests that the metamorphic rocks also took part in the source successively. Judging from the abundant influx of granitic pebbles into conglomerate, besides, it is inferred that the granitic rocks became to contribute to the source more greatly in this stage than in the previous one, though the main background was of the Paleozoic Chichibu terrain.

This vicissitude of the provenance which is presumed on the basis of the contents of conglomerates is well reflected on the compositional change of sandstones (Figs. 5 and 6). Although the majority of the sandstones in the Hibihara and Yunoki Formations are represented by the feldspathic wacke type, the sample of the former shows a higher content of feldspar (plagioclase) and on the contrary a lower content of quartz (non-undulose) in the population mean than that of the latter.

4. *Nagase Formation*

The Nagase Formation is similar in lithology to the upper member of the Hibihara Formation in general, but its lower part is abundant in silty deposits. This may show that the sediments were formed under a shallower part of neritic sea in the present stage in comparison with the preceding one. Besides, the frequent intercalations of coarse-grained sediments are probably attributable to the fluctuation of the Cretaceous basin. The sandstones of this formation are reasonably considered to have been formed under a relatively lower energy condition of currents than those of the lower member of the Hibihara, because the latter ones are presumed to have mainly been placed in a deltaic to littoral environment. This inference may be supported by the significant increase of matrix content in the population mean.

Since the Nagase Formation is demarcated, in the present state, from the Hibihara Formation by a major fault, the Kajisakogawa tectonic line and the information on the structural similarity or dissimilarity of the original state can not be obtained at all, we could not make reference to the tectonism in the interval between the two stages.

The pebbles of conglomerates, the rock fragments of sandstones and the ideal heavy mineral suites indicate the same provenance as in the other formations. In comparison with the sandstone sample of the Hibihara, the present sample shows a significant decrease of feldspar content in the population mean, as confirmed by the statistical test and roughly displayed in Figs. 6 and 7, in spite of its formation under a relatively lower condition of currents in general. This fact intimates that the contribution of the granitic rocks to the source became in some degree decreased in this stage. This is probably supported also by the quantitative decrease of the granitic pebbles in conglomerates.

5. *Kajisako Formation*

The Kajisako Formation shows a semi-cycle of sedimentation, which begins with coarse-grained sediments, gradually changes to finer-grained ones and finally ends with shale. Judging from the lithology and the fossil evidence, this formation seems to have been placed on a littoral environment at the early stage and then gradually on a neritic environment. It is considered that no intense tectonic movement took place in the interval between this stage and the preceding, since the present formation covers the Nagase conformably without showing any appreciable structural difference.

No significant change is recognized in the population means of the matrix content and the size parameters, if comparing the sandstone sample of the Kajisako with that of the Nagase, and therefore the similar energy condition of currents in the depositional site is presumed.

The provenance is considered to have been framed up by the same sources as those of the preceding stages, as judged from the pebbles of conglomerates, the rock fragments

TABLE 7. CORRELATION OF THE CRETACEOUS SYSTEM IN THE THREE BASINS

| Time / Province | Lower Cretaceous | | | | Upper Cretaceous | | |
|---|---|---|---|---|---|---|---|
| | Kochian | Aritan | Miyakoan | | Gyliakian | Urakawan | Hetonaian |
| Yatsushiro | Kawaguchi F. | Hachiryuzan F. | Hinagu F. | Yatsushiro F. | ? Tomochi F. | | |
| Monobegawa | Ryoseki F. | Yunoki F. | Hibihara F. | | Nagase F. | Kajisako F. | |
| Katsuuragawa | Tatsukawa F. | Hanoura F. | Hoji F. | Fujikawa F. | ? Kushibuchi F. | Tatsue F. | |

of sandstones and the heavy mineral suites constructed conceptually. In comparison between the sandstone samples of the Nagase and the Kajisako, the change of the mineral composition is not significantly recognized, except for only the decrease of non-undulose quartz content. It is, therefore, assumed that the vicissitude of the provenance did not occur there. However, some intercalations of acidic tuffaceous clastics suggest that a volcanic activity took place in the background at this stage.

### B. COMPARISON WITH THE OTHER BASINS

As far as the petrographical study on the Cretaceous sandstones in the Chichibu terrain is concerned, there are FUJII's (1956) work in the Yatsushiro area in Kumamoto Prefecture, Kyushu, and NAKAI's (1971) in the Katsuuragawa valley in Tokushima Prefecture, Shikoku. These basins, together with the Monobegawa basin treated herein, have been considered to have been formed under a quite similar tectono-sedimentary environment, that is, on an unstable shelf, based on their lithofacies and biofacies as well as their geologic situations.

The Cretaceous stratigraphy and the correlation of the three basins are summarized in Table 7. As concerns the sandstone petrography of the Katsuuragawa basin, we can not obtain the information on the Upper Cretaceous Kushibuchi and Tatsue Formations.

To compare the results from the sandstone petrography with one another seems to be effective for understanding the characters of the Cretaceous sedimentation in the Chichibu terrain. As the result, the following remarkable features are pointed out.

(1) The majority of sandstones in each basin are characterized by the wacke type with more than 15 per cent matrix content, and the sandstones classified into the arenite type are poor in occurrence. Although similar to the greywackes texturally, the sand-

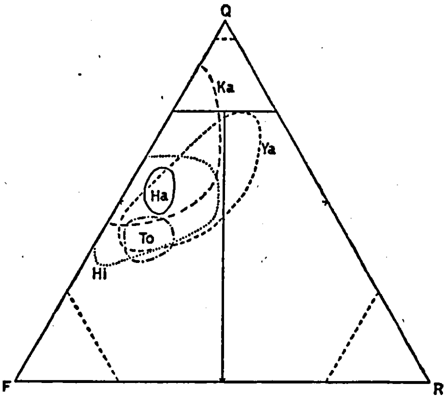


FIG. 10. Compositional diagram of the Cretaceous sandstones in the Yatsushiro area, Kumamoto Prefecture, Kyushu. Ka: Kawaguchi Formation, Ha: Hachiryuzan Formation, Hi: Hinagu Formation, Ya: Yatsushiro Formation, To: Tomochi Formation. Other denotations are identical with those of Fig. 4. (Data from FUJII, 1956).

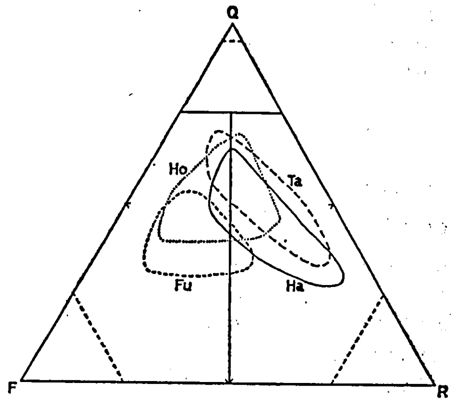


FIG. 11. Compositional diagram of the Lower Cretaceous sandstones in the Katsuuragawa valley, Tokushima Prefecture, Shikoku. Ta: Tatsukawa Formation, Ha: Hanoura Formation, Ho: Hoji Formation, Fu: Fujikawa Formation. Other denotations are identical with those of Fig. 4. (Data from NAKAI, 1971).

stones of the three basins must be referred to a variety of the arenite-wacke associations defined by KRUMBEIN and SLOSS (1963), if based on the lithological features.

(2) The major mineral composition on the average of the whole samples is more or less different among the three basins, as known from Figs. 4 to 8, 10 and 11, although the qualitative difference does not seem to be recognized. However, there seems to be a systematic change in the Lower Cretaceous samples; from the Kochian to the Miyakoan the content of feldspar tends to increase, while the content of quartz inclines to decrease. The relation is reversal in the case between the Hinagu and Yatsushiro Formations in the Yatsushiro basin, but this may possibly depend on the fact that the sandstones of the Yatsushiro Formation were formed under a much higher energy condition.

(3) The heavy minerals are also similar in their quality and even in their relative frequency of quantity among the three basins. However, the grains of kyanite occur restrictedly in the Yatsushiro basin, and besides the occurrence of the grains such as glaucophane and piedmontite is known only in the Monobegawa basin.

(4) The background of three basins is considered to have been made up of the closely similar source rocks, which were of older sedimentaries, basic volcanics, granites and metamorphics. This framework seems to have been maintained throughout the Cretaceous Period. However, through the several major cycles of sedimentation, each of which is represented by the corresponding formation, the contribution of each source rock was probably vicissitudinary in some degree. In the Lower Cretaceous, as a general rule, the three basins are in agreement in the point that the role of the granitic rocks in the provenance became increased in due order from early to late stage, though minor differ-

ences are recognized. In the Upper Cretaceous, besides, the decrease of their role is presumed in the Monobegawa and Yatsushiro basins, though there is no datum in the Katsuuragawa.

## V. CONCLUSION

The Cretaceous System in the Monobegawa valley of Shikoku, which has been considered to have been formed on an unstable shelf of the Paleozoic Chichibu terrain and in a transitional zone to the Shimanto geosynclinal trough, is divided into five formations, namely, the Ryoseki (Kochian), Yunoki (Aritan), Hibihara-Hagino (Miyakoan), Nagase (Gyliakian) and Kajisako (Urakawan) Formations in ascending order. Each of them represents a major cycle of sedimentation.

On the basis of the detailed stratigraphical investigations, our further attention is concentrated on the sandstone petrography in order to understand the Cretaceous sedimentation clearer. The sandstones were analyzed on the properties of size parameters and major and accessory mineral compositions. The results are summarized as follows:

(1) As concerns the textural type, most of the examined specimens are characterized by a moderately sorted, normally to positively skewed and meso- to lepto-kurtic pattern, based on FOLK and WARD's (1957) category. There is not any significant difference in size parameters among the samples of the five formations.

(2) According to OKADA's (1971) classification scheme on the basis of the major mineral composition, the sandstones treated herein are marked by a large number of the feldspathic or lithic wacke and a very small number of the feldspathic arenite, as shown in Figs. 4 to 8. Although bearing a resemblance to greywackes in their texture, they must be referred to a definite type of the arenite-wacke associations which are characteristic in sandstones formed under normal currents, as judged from the lithological features.

(3) The stratigraphical variation of the sandstone properties is revealed in the major mineral composition by the statistical analysis, as shown in Table 6 and Fig. 9. It is concluded that the change of the mineral composition was caused by the transition of the provenance.

(4) From the contents of rock fragments and heavy minerals in sandstones in addition to the contents of pebbles in conglomerates, it is inferred that the source areas were composed of older sedimentary, basic volcanic, granitic and metamorphic rocks. Although not decided explicitly, they may be referred to the Paleozoic Chichibu sedimentaries, the Mikabu green rocks, the Ryoke granitic complex and the Sambagawa crystalline schists, among which the first must have played the most important role.

(5) All these source rocks probably functionated throughout the Cretaceous Period. However, some transitions of the provenance may have taken place through the cycles of sedimentation. The role of the granitic rocks is likely to have become promoted progressively in due order from the Ryoseki through the Yunoki to the Hibihara Formation in the Lower Cretaceous, and then decreased again in the Upper Cretaceous Nagase and Kajisako Formations. This vicissitude is well reflected on the volumetrical change of the feldspar content in sandstones.

(6) The characteristics of the sandstone properties and the vicissitudinary sedimentation in the Cretaceous basin of the Monobegawa valley show a close resemblance to those of the Katsuuragawa valley in Shikoku and of the Yatsushiro area in Kyushu, except

for minor differences. There is, of course, a similarity also in major lithofacies and biofacies.

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Takami MIYAMOTO:
INSTITUTE OF GEOLOGY AND MINERALOGY,
FACULTY OF SCIENCE, HIROSHIMA UNIVERSITY,
HIROSHIMA, 730, JAPAN

Isao NAKAI:
MEIJI CONSULTANTS, CO. LTD.,
TOKYO, 105, JAPAN