How were collisional collapse products of oceanic limestone mingled with trench-fill sediments? —Tsukumi Limestone in Chichibu terrane, southwest Japan*—

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Abstract

The lithology, distribution, and inter-relationship of the scaly mudstone, alternation of sandstone and mudstone, and basaltic volcanoclastic rocks interleaved in the Tsukumi Limestone of Carboniferous to Triassic collisional collapse products in the Chichibu terrane of eastern Kyushu were described. The discussion chiefly concerns the emplacement mechanism of the Tsukumi Limestone.

The scaly mudstone, alternation of sandstone and mudstone, and basaltic volcanoclastic rocks occur as structural wedges complexly interposed in the Tsukumi Limestone. It comprises an aggregate of complexly wedge-bounded blocks of collisional collapse products that include the broken limestone, limestone breccia with a carbonate matrix, and limestone breccia with an argillaceous matrix, accompanied by redeposited limestone debris. The unfaulted, lithologically sharp, irregularly distorted contact with those wedges is due to submarine slide events of the collisional collapse products onto unconsolidated terrigenous sediments and volcanoclastic sediments. The latter is considered to be redeposited collapse products of the basaltic pedestal of the Tsukumi buildup into the former. The limestone breccia with an argillaceous matrix was formed by gravitational displacement of the collisional collapse products onto the argillaceous sediments, resulting in their sedimentary mixing. The limestone debris and limy sandstone in the scaly mudstone are redeposited sediments derived from the limestone breccia with an argillaceous matrix by debris flows and turbidity flows. These redeposited carbonates originally passed laterally into one another and form the depositional progression along with the limestone breccia with an argillaceous matrix. The gravitational displacement of the collisional collapse products were closely related to their trenchward-movement.

Following the early Early Jurassic initiation of the normal fault-induced, large-scale collisional collapse of the Tsukumi buildup in an outer trench-slope, the displacement of the collisional collapse products and their mixing with the trench-fill sediments most probably took place during late Early to early Middle Jurassic time.

Key words : Tsukumi Limestone, Chichibu terrane, emplacement of oceanic limestone, depositional progression, collisional collapse

Introduction

Pre-Jurassic terranes of accretionary complexes in Japan are characterized by the occurrence of oceanic

rocks forming a lithologically heterogeneous aggregate along with terrigenous rocks. The oceanic rocks and terrigenous rocks, totally differing in the depositional setting from each other, occur complexly juxtaposed with each other.

The oceanic rocks are diverse in rock-types and are of various ages. Carboniferous–Permian shallow-

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Fig. 1. Index map showing study area, Tsukumi, eastern Kyushu, and illustrating approximate location of representative Carboniferous-Permian limestone exposures in Chichibu terrane of eastern Kyushu. Equivalent to Tsukumi Limestone are exposed at Furen Cave, Mitate, Toroku, and Kamura lying in axial zone of Chichibu terrane. Triassic carbonates are known to occur at Tsukumi and Kamura. Compiled from quadrangle maps by Saito et al. (1958), Sakai et al. (1993), Teraoka et al. (1992), and Kambe and Teraoka (1968).

marine carbonates and deep-water chert and related siliceous rocks and Carboniferous basaltic rocks are representative in the Permian terrane (Akiyoshi terrane: Kanmera et al., 1990). Carboniferous-Permian shallow-marine carbonates, Carboniferous to Jurassic deep-water chert and related siliceous rocks, and Permian basaltic rocks are significant constituents of the oceanic rocks in the Jurassic terranes (e.g., Mino terrane: Mizutani, 1990). Among these oceanic rocks common to both the Permian and Jurassic terranes and most voluminous are the Carboniferous-Permian carbonates. They often occur underlain by basaltic volcanic rocks and are exposed in close association with coeval deep-marine siliceous rocks. The intimate lithologic association of shallow-marine carbonates, deep-marine siliceous rocks, and basaltic rocks is interpreted to represent primarily laterally continuous sediments on and around a seamount (e.g., Sano and Kanmera, 1988; Sano, 1989; Jones et al., 1993). The paleogeographic interpretation of these oceanic rocks means that the Japanese pre-Jurassic terranes include accreted remnants of seamounts and associated sediments (Isozaki et al., 1990), which have been complexly mingled with terrigenous rocks.

In spite of the paleogeographic reconstruction of the oceanic rocks, it remains uncertain that how they were displaced into and mingled with trench-fill terrigenous sediments, prior to their incorporation into an accretionary prism. Most critical to be questioned is the structural relationship of the oceanic rocks to the adjoining terrigenous rocks. As well, it is also needed to discuss the timing when the oceanic rocks were encountered and mingled with the terrigenous sediments. The timing of the emplacement of the oceanic rocks can be best approximated by the age of the adjoining terrigenous rocks.

To illustrate the emplacement and mixing processes of oceanic rocks with trench-fill terrigenous sediments, chosen for study are the Carboniferous-Permian Tsukumi Limestone (Sano and Tamada, 1994) and adjoining non-carbonate rocks of the scaly mudstone, alternation of sandstone and mudstone, and basaltic volcanoclastic rocks in the Chichibu terrane of eastern Kyushu (Fig. 1). The field examination has been done in excellent exposures of the two working quarries, Suishozan Quarry and Ganji Quarry, both in the eastern part of the Tsukumi Limestone (Fig. 2). Its relationship to the adjoining non-carbonate rocks was carefully examined through the mapping on a scale of 1 : 500 along the quarry-benches.

The results permit us to draw a conclusion that the Tsukumi Limestone essentially comprises an aggregate of various-sized and shaped masses of internally disrupted, collisional collapse products of carbonates, which were gravitationally displaced down onto trench-fill sediments most probably as submarine slides and debris flows. Parts of the displaced collisional collapse products were redeposited and mingled with trench-fill sediments. Following the initiation of the collisional collapse of the Tsukumi buildup and its basaltic pedestal in early Early Jurassic time, the displacement and mixing of their collisional collapse products with the trench-fill sediments most dominantly took place during late Early to early Middle Jurassic time.

The description and discussion of this paper are closely related to those of the recent paper by the authors (Sano and Tamada, 1994). The terminology for collisional collapse products of carbonates basically follows Sano and Kanmera (1991a) with a minor emendation by Kanmera and Sano (1991).

Fig. 2. Simplified geologic map of Tsukumi area, eastern Kyushu. Chiefly from Sano and Tamada (1994) and partly after Kambe and Teraoka (1968).

Geologic outline

The Tsukumi Limestone has a regional trend of northeast-southwest and its structural thickness attains 2 km in our study area (Fig. 2). The regional mapping (Kambe and Teraoka, 1968; Teraoka et al., 1992; Sakai et al., 1993) reveals that the Tsukumi Limestone can be traced for 20 km in the axial part of the Chichibu terrane of eastern Kyushu and its equivalent rocks crop out at Kamura in the Takachiho area, approximately 60 km southwest of our study area (Fig. 1; Saito et al., 1958; Kanmera and Nakazawa, 1973).

Sano and Tamada (1994) recently redesignated the Tsukumi Limestone as a tectonostratigraphic unit composed of middle Upper Carboniferous to upper Upper Permian shallow-marine carbonates and minor Lower Triassic carbonate clasts and tectonically intercalated in the Jurassic chaotic mud-dominated two rock-units of the Chichibu terrane in eastern Kyushu (Figs. 1, 2). The Carboniferous and Permian carbonates were previously designated as a coherent stratigraphic unit together with noncarbonate rocks, chiefly of the scaly mudstone, alternation of sandstone and mudstone, and basaltic volcanoclastic rocks, which crop out interleaved with the carbonates (e.g., Fujii, 1954; Asano and Tanaka, 1961; Yokoyama, 1965). Sano and Tamada (1994), however, tectonostratigraphically separated these non-carbonate rocks from the Tsukumi Limestone.

Worthy to note is that the Triassic carbonates, though less extensive, occur in close association with the Tsukumi Limestone and its equivalents (Working Group on the Permian-Triassic Systems, 1975). The Lower Triassic Gobangadake Formation chiefly of the dolomitic limestone (Kambe, 1963) is underlain by the Tsukumi Limestone in our study area (Fig. 2; Kambe

and Teraoka, 1968), and the Triassic Kamura Formation in the Takachiho area (Fig. 1; Saito et al., 1958; Kambe, 1963) rests upon the upper Permian Mitai Formation characterized by the dolomitic limestone (Kanmera and Nakazawa, 1973; Working Group on the Permian-Triassic Systems, 1975) with a disconformity (Watanabe et al., 1979).

As outlined in Sano and Tamada (1994), the mud-dominated rock-units adjoining to the Tsukumi Limestone are labeled as olistostromes, the Ozono Formation on the south and the Okugawachi Formations on the north, both redesignated by Teraoka et al. (1992) in the southwestern extent. The Tsukumi Limestone is in fault contact with the two rock-units. They are characterized by the occurrence of various-sized and shaped, isolated, laterally discrete blocks of chert and related siliceous rocks, basaltic rocks, and minor limestone, all chaotically set in the scaly mudstone and disrupted alternation of sandstone and mudstone. The Ozono and Okugawachi Formations are in the western extent correlated to the upper Lower to lower Middle Jurassic and the upper Lower Jurassic by means of radiolarian fossils, respectively (Teraoka et al., 1992).

Sano and Tamada (1994) described internal textural destruction fabrics of the Tsukumi Limestone and therein identified the three kinds of carbonate rocks, broken limestone, limestone breccia with a carbonate matrix, and limestone breccia with an argillaceous matrix. Broken limestone is characterized by the mechanical, almost in-site, internal, textural destruction of sedimentary and early diagenetic fabrics and primary constituents of carbonates. These authors reveal the prevalence of the internal textural destruction fabrics in the broken limestone throughout the entire extent of the Tsukumi Limestone. The two types of limestone breccia are characterized by the

Fig. 3. Geologic map and profiles of Suishozan Quarry, after Sano and Tamada (1994). Note abrupt thinning and thickening of structural wedges interposed in limestone. See Fig. 2 for mapped area. See Fig. 5 of Sano and Tamada (1994) for ages of limestone.

polymictic association, high angularity, disorganized fabric, and unsorted size of carbonate clasts.

The three kinds of carbonates were thoroughly dated by means of fusulines (Sano and Tamada, 1994). Their examination reveals that the broken limestone includes the upper Middle Carboniferous to upper Upper Permian eleven stages. The point to be made here is the structural heterogeneity of the broken limestone, recorded as the disorderly occurrence of biostratigraphically continuous stages. The minimal age of the two types of limestone breccia is best given by the rare Lower Triassic limestone clasts (Sano and Tamada, 1994), while the Permian carbonate clasts are much predominant.

The Tsukumi Limestone is reconstructed as a shallow-marine carbonate buildup most likely resting upon a basaltic pedestal in an open-ocean setting, including a seamount (Sano and Tamada, 1994). The fusuline fossils record the carbonate sedimentation ranging from late Middle Carboniferous time to late Late Permian time. The contamination of the Lower Triassic limestone clasts leads these authors to a consideration that the Carboniferous to Permian carbonate sedimentation further survived into Triassic time on the buildup. Though the uncertainty still exists, the Tsukumi buildup is better defined as a shallow-marine carbonate mass, in which the sedimentation extended from late Middle Carboniferous time to Triassic time.

Sano and Tamada (1994) consider the broken limestone and the two types of limestone breccia of the

Tsukumi Limestone to be comparable with the collisional collapse products described in the Akiyoshi Limestone Group by Sano and Kanmera (1991b, c). The Tsukumi Limestone is labeled as an aggregate of collisional collapse products of the shallow-marine carbonates instead of as an orderly stratigraphic succession.

Structural wedges of terrigenous and basaltic volcanoclastic rocks

To know the primary relationship between the Tsukumi Limestone and the adjoining non-carbonate rocks, we mapped their distribution in the two quarries (Figs. 3, 4) and carefully examined the contact (Fig. 5). Our examination shows that three kinds of non-carbonate rocks, the scaly mudstone, alternation of sandstone and mudstone, and basaltic volcanoclastic rocks, occur as laterally discrete, structural wedges complexly interposed in the Tsukumi Limestone instead of as stratigraphic intercalations. The whole of the Tsukumi Limestone is in other words expressed as an aggregate of various-sized, wedge-bounded blocks of the collisional collapse products.

Rocks occurring as the structural wedges are in order of abundance the scaly mudstone, alternation of sandstone and mudstone, and basaltic volcanoclastic rocks (Figs. 3, 4). Small amounts of the chert and related siliceous rocks occur as disrupted, isolated, small-sized blocks set in the wedges of scaly mudstone. The radiolarian fossils detected from a siliceous mudstone block (loc. GB 536 in Fig. 2) are

Fig. 4. Geologic sketch map of southern and western parts of Ganji Quarry, after Sano and Tamada (1994). Note tectonic thinning-out of almost north-south trending structural wedge of scaly mudstone at northern end of Q-bench. Mapped area in Fig. 2. Symbols as in Fig. 3. Ages of limestone are in Figs. 6 and 7 of Sano and Tamada (1994).

characteristic of the middle Lower Jurassic (Sinemurian) *Parahsuum simplum* Assemblage Zone of Yao et al. (1982).

The wedges of scaly mudstone are widespread in the Tsukumi Limestone we mapped (Figs. 3, 4). The scaly mudstone is dark gray, sandy, and contains crude sandy laminae and thin, parallel-laminated and graded beds of limy sandstone and siliciclastic sandstone. Granule- to cobble-sized, occasionally boulder-sized, rounded limestone debris are also embedded, locally crowded and locally dispersed. Where the limestone debris are highly crowded, the rock is better described as limestone conglomerate having an argillaceous matrix. As well blocks of chert and related siliceous rocks, isolated blocks of limestone, ranging in size from several tens of centimeters to several tens of meters or more occur embedded in scaly mudstone (Fig. 3). The limestone blocks and debris at a few localities contain the Scythian bivalves (Sano and Tamada, 1994). The scaly mudstone is pervasively and penetratively cleaved, often tightly folded, and intensely sheared by a number of faults (Fig. 6-1). The scaly mudstone at the only locality (loc. GB 355 in Fig. 4) yields radiolarian fossils predominantly of the genus *Hsuum*, indicative of an imprecise late Early to Middle Jurassic age.

The alternation of sandstone and mudstone crops out only in the Suishozan Quarry (Fig. 3). Thickness of the sandstone beds in a couplet ranges from several centimeters to a few tens of centimeters, locally attaining several tens of centimeters. The sandstone beds are usually graded, accompanied by sandy-laminated mudstone beds, most commonly several centimeters thick. The sandstone is medium- to coarse-grained, poorly sorted, quartz-feldspathic, and contains abundant rip-up clasts of mudstone. The alternation of sandstone and mudstone are stratally disrupted and intensely folded.

The wedges of the basaltic volcanoclastic rocks typically crop out interposed in the broken limestone of the Carboniferous stages (See Fig. 6 of Sano and Tamada, 1994). The basaltic volcanoclastic rocks are usually dark reddish, locally dark greenish, composed of fine to medium sand-grained basaltic detritus and minor basaltic rock-fragments, and contain the rare blocks of vesiculated basalt lavas and hyaloclastites as well the sporadic limestone blocks. The rocks are fissile and strongly sheared.

The structural wedges occur not only in our mapped areas (Figs. 3, 4), but also in the entire extent of the Tsukumi Limestone (Fujii, 1954; Kambe and Teraoka, 1968; Asano and Tanaka, 1961; Yokoyama,

Fig. 5. Route-map and field-sketch showing complicated distribution of scaly mudstone wedges interposed in broken limestone and limestone breccia of two types along D-bench, southern part of Ganji Quarry. See Fig. 4 for location of mapped part of D-bench. Symbols as in Fig. 3. Abbreviations, Art, M1, M2, and M3, represent Artinskian, lower Maokouan, middle Maokouan, and upper Maokouan Stages. See also Fig. 6 of Sano and Tamada (1994) for ages of limestone along D-bench.

1965). The wedges tend to occur more frequently along the southern and northern margins of the Tsukumi Limestone than in its central part (Figs. 3, 4). As best seen along its southern margin (Fig. 5), a number of the wedges of the scaly mudstone crop out interconnected with one another to form a complicated web-like network. Worthy to note is that the marginal parts are composed predominantly of the limestone breccia with an argillaceous matrix, instead of the broken limestone and the limestone breccia with a carbonate matrix.

Much of the wedges structurally trends northeast-southwest, subparallel with the regional trend of the Tsukumi Limestone, which is best represented by the directions of the fault surfaces against the Ozono and Okugawachi Formations (Figs. 2, 3, 4). Our careful mapping, however, revealed that a few of the wedges change their structural trends on a mappable scale. The large-scale wedge of the scaly mudstone in the western part of the Ganji Quarry, for example, crops out with a structural trend of nearly north-south, where it thins out, which turns northeast-southwest, where it thickens (Figs. 2, 4). The change of the trend of the wedges is often discernible also on an outcrop scale (Fig. 5).

The wedges are laterally discrete (Figs. 5, 6-2) and have a wide range of structural thickness, from several tens of meters or more (Figs. 3, 4, 6-3), through several meters (Fig. 6-5), down to a few tens of centimeters or much less (Figs. 6-4, 7-1, -3). The wedges are laterally and vertically thickening and thinning abruptly on a mappable scale (Figs. 3, 4) and on an outcrop scale (Figs. 5, 6-4, -5, 7-3, -4). The abrupt change is best exemplified by the scaly mudstone wedge in the southwestern part of the Suishozan Quarry, which drastically changes its structural thickness from approximately 100m down to several meters for a few hundreds of meters (Figs. 3, 6-5).

Commonly seen is that one wedge structurally thins out and is entirely replaced by a fault (Figs. 3, 5, 6-2), along which another wedge unexpectedly crops out.

These three kinds of non-carbonate rocks lithologically pass laterally into one another. The alternation of sandstone and mudstone laterally changes into the scaly mudstone that contains a small amount of thin graded beds of quartz-feldspathic sandstone (Fig. 3). Though not enough is known about the sedimentary facies, the scaly mudstone and the alternation of sandstone and mudstone are most properly interpreted to have accumulated as a distal facies of trench-fill turbidites. Worthy to note is the rare lateral lithologic gradation from the scaly mudstone to the basaltic volcanoclastic rocks. The lithologic gradation is represented by a transition zone comprising a mixture of argillaceous materials and basaltic volcanoclastic detritus, including altered plagioclase, chlorite minerals (Fig. 7-5). The transition zone is most commonly a few of centimeters thick, rarely exceeding several centimeters, and is complexly injected by both of the scaly mudstone and basaltic volcanoclastic rocks. All these properties of the lithologic transition zone mean the redeposition of fine-grained basaltic volcanoclastic materials onto and the intermixing with argillaceous sediments under an unconsolidated condition.

With an emphasis upon the lithologic affinity, following the obvious lateral continuation of the large-sized wedge in the western Ganji Quarry to the Ozono Formation on the south of the Tsukumi Limestone (Figs. 2, 4), we consider much of the structural wedges in the Tsukumi Limestone to be the equivalents of the Ozono Formation. A few of the wedges of the alternation of sandstone and mudstone in the Suishozan Quarry (Fig. 3) have a lithologic similarity to that of the Okugawachi Formation.

Fig. 6. Outcrop views of scaly mudstone and its relationship to limestone. All localities are indicated in Fig. 3.

1. Typical outcrop view of intensely sheared scaly mudstone with disrupted thin beds of sandstone. Note hammer denoted as H for scale. Loc. TK 501.
2. Perspective view of steeply dipping, vertically discrete, thinning and thickening, irregularly branching structural wedges of scaly mudstone (W, C) in broken limestone (L). Nearly north-south trending benches in western part of Suishozan Quarry. Structural wedges of scaly mudstone (C) are at Loc. TK 358. Automobile at center bottom for scale.
3. Irregularly curved and distorted, but lithologically sharp, unfaulted boundary between large-sized mass chiefly of broken limestone (L) and scaly mudstone (M). Loc. TK 502. Almost along A-A' profile in Fig. 3. Width of view is approximately 40 m.
4. Close-up view of structural wedges of scaly mudstone indicated as C in Fig. 6-2. Irregularly distorted and curved, lithologically sharp boundaries (P) between broken limestone and scaly mudstone wedges containing isolated limestone blocks have been partly disrupted by faults (F), by which scaly mudstone wedges have been thinning out. Loc. TK 358.
5. Partly faulted (F), irregularly curved and distorted boundaries between structural wedge of scaly mudstone (M) interposed and two masses mainly of broken limestone (L). Note drastic change of direction of unfaulted boundary surface, traced from A, through B and C, to D. W=Laterally discrete, thin wedges of scaly mudstone, wholly surrounded by broken limestone. Persons for scale at lower right. Loc. TK 17.

Relationships of collisional collapse products to terrigenous rocks

The field examination revealed that the Tsukumi collisional collapse products (Sano and Tamada 1994) were gravitationally displaced as various-sized and shaped blocks and settled down onto unconsolidated terrigenous and volcanoclastic sediments. Through the careful observation of unfaulted boundaries, we recognized two modes of primary contact. One is represented by the lithologically sharp boundary between the collisional collapse products and the terrigenous and volcanoclastic rocks, and the other is characterized by the lithologic gradation best described by a gradual increase in proportion of the argillaceous matrix of the limestone breccia laterally toward the scaly mudstone containing crowded limestone debris. The former is best thought to be due to submarine slides and falls of the blocks of the collisional collapse products and is tentatively termed a *block-in-wet sediment contact*. The latter mode of contact reflects the sedimentary mixing of the collisional collapse products with the terrigenous sediments. These primary boundaries, however, have been often obliterated and complicated by later faults.

Block-in-wet sediment contact between collisional collapse products and terrigenous and volcanoclastic rocks

The broken limestone and the two types of limestone breccia are bounded by the structural wedges of the scaly mudstone, alternation of sandstone and mudstone, and basaltic volcanoclastic rocks, where unfaulted, with irregularly knobby and uneven, curved, and distorted boundary surfaces (Figs. 6-3, -4, -5, 7-3, -4). These limestones have been often mud-injected along the boundary (Fig. 7-1, -2). Where the broken limestone and the limestone breccia with a carbonate matrix are bounded by these terrigenous and volcanoclastic rocks, their boundaries are apparent and lithologically well defined. No contamination of terrigenous nor volcanoclastic grains is discerned in the broken limestone and the limestone breccia with a carbonate matrix and no any kinds of lithologic changes have been recognized across their boundaries. The precise boundary, however, between the limestone breccia with an argillaceous matrix and the scaly mudstone is, if not all, difficult to trace in an outcrop, for the limestone breccia with an argillaceous matrix adjoining to the scaly mudstone is often rich in the matrix. To be stressed is that no wedges of the basaltic volcanoclastic rocks occur adjoining to the limestone breccia with an argillaceous matrix. The basaltic volcanoclastic rocks most frequently occur interposed in the broken limestone of the Carboniferous stages and at a few localities in the limestone breccia with a carbonate matrix.

Unexpected and highly irregular changes of the

attitude of the boundary surfaces are commonly seen on an outcrop scale (Figs. 6-3, 7-3, -4). One obviously continuous boundary surface, for instance, abruptly changes its inclination from 0° to 90° within a short interval. The outcrop-scale irregular distortion of the boundary surfaces reflects in the mappable-scale change of the structural trend of the wedges (Figs. 3, 4). The irregularity of the distortion of the boundary surfaces on various scales can not be explained by any types of the folding. In spite of the later structural modification, the irregular distortion of the boundary surfaces is best considered to record the complicated primary geometry of the various-sized blocks of the collisional collapse products.

All the properties of those unfaulted boundary surfaces mean that the collisional collapse products of the broken limestone and the two types of the limestone breccia are exotic to the terrigenous and volcanoclastic sediments. The block-in-wet sediment contact is best considered to have resulted from the gravitational emplacement of the collisional collapse products onto terrigenous and volcanoclastic sediments under an unconsolidated condition. The emplacement mechanisms are most probably presumed to have been submarine slides and falls.

As well the scaly mudstone and alternation of sandstone and mudstone, the basaltic volcanoclastic rocks are considered to have acted as a sediment enclosing the slide blocks of the collisional collapse products mostly of the broken limestone. To be restated is the lithologic gradation from the basaltic volcanoclastic rocks to the scaly mudstone, accompanied by an intermixing zone, in a structural wedge. The basaltic volcanoclastic rocks have no marked difference in the distribution pattern, the structural relationship to the collisional collapse products, and the deformation style from the terrigenous rocks except that the basaltic volcanoclastic rocks contain no blocks of the limestone breccia with an argillaceous matrix and no wedges of the basaltic volcanoclastic rocks occur adjoining to the limestone breccia with an argillaceous matrix.

Depositional progression of redeposited carbonates

Differing from the broken limestone and the limestone breccia with a carbonate matrix, of which close genetic relation has been demonstrated by Sano and Tamada (1994), the limestone breccia with an argillaceous matrix is thought to have originally passed laterally into redeposited carbonates of various types in the terrigenous rocks. The redeposited carbonates include granule- to cobble-sized limestone debris and limy sandstone, all embedded chiefly in the wedges of the scaly mudstone and alternation of sandstone and mudstone. With an emphasis upon the reworked nature of limestone breccia with an argillaceous matrix (Sano and Tamada, 1994), we postulate the depositional progression from the limestone breccia

Fig. 7. Relationship of limestone to scaly mudstone and basaltic volcanoclastic rocks and their intermixing.

1. Thin structural wedge of scaly mudstone separating two masses of broken limestone from each other. Note small-scale injection of scaly mudstone, denoted as A, B, and C. Loc. OG 109 in Fig. 4.
2. Close-up view of injection of scaly mudstone, denoted as C in Fig. 7-1.
3. Irregular-shaped, structural wedge of basaltic volcanoclastic rocks (V) interposed in broken limestone (L). Note abrupt thinning-out of wedge, denoted as T, bounded by limestone with lithologically sharp, irregularly curved and distorted, unfaulted boundary. B=small limestone block in basaltic volcanoclastic rocks. F=distinct fault surface. Loc. GB 287 in Fig. 4.
4. Limestone block (B) wholly encircled by basaltic volcanoclastic rocks (V) of structural wedge in broken limestone (L). Loc. GB 341 in Fig. 4.
5. Polished slab showing intermixing of scaly mudstone (A) and fine-grained basaltic volcanoclastic rocks (V), accompanied by lithologically transition zone (M) characterized by great admixture of basaltic materials into argillaceous materials. Polished slab. Scale bar=1 cm. Loc. TK 248 in Fig. 3.

with an argillaceous matrix (Fig. 8-1, -2; Plate I), through the limestone debris crowded and scattered in scaly mudstone (Fig. 8-3, -4; Plate II-1, -2, -3), to the limy sandstone (Plate II-4, -5). Though often tectonically disrupted and obliterated, the depositional progression of these redeposited carbonates is important for the discussion as to the mixing process of the collisional collapse products with

terrigenous sediments.

The limestone breccia with an argillaceous matrix is most typically poor and in part totally lacks in the matrix (Plate I-1, -2; Sano and Tamada, 1994). The carbonate clasts are in a stylolite contact, where the matrix is totally absent, or extremely sparse (Fig. 8-1). Although diagenetically rounded in part, the clasts are highly angular. Such a matrix-poor variety

Fig. 8. Polished slabs of limestone breccia with argillaceous matrix and redeposited limestone. All scale bars represent 1 cm.

1. Limestone breccia with sparse matrix of argillaceous materials. All polymictic limestone clasts are bounded by one another with stylolite sutures (S) along which argillaceous materials occur concentrated. Characteristic fusulines in middle Maokouan, upper Maokouan, and Wuchiapingian Stages are contained in limestone clasts. Loc. GB 353 in Fig. 4.
2. Limestone conglomerate containing angular to subangular clasts of limestone, dolomite (D), and mudstone, all chaotically set in argillaceous matrix. Loc. TK 164 in Fig. 3.
3. Dense-crowded, crudely oriented and graded, subrounded clasts in limestone conglomerate having rare mudstone chips (M). Loc. GB 349 in Fig. 4.
4. Crudely laminated and densely crowded, subrounded, granule- to small pebble-sized limestone clasts and mudstone clasts (M) in limestone conglomerate with argillaceous matrix. Loc. GB 663 in Fig. 4.

occurs in close proximity to the the limestone breccia with a carbonate matrix. Laterally toward a scaly mudstone wedge, however, the proportion of an argillaceous matrix gradually increases (Plate I-3). Even apparently subrounded carbonate clasts and subrounded to subangular, silt- to sand-sized clastic quartz grains are contained (Plate I-4), where the argillaceous matrix occurs extensive. Additionally, the granule- to pebble-sized carbonate clasts tend to dominate over the cobble-sized ones, where the clast angularity is low and the rocks are rich in the matrix (Fig. 8-1, -2). As demonstrated by Sano and Tamada (1994), the lithologic affinity means that the carbonate clasts in the limestone breccia with an argillaceous matrix were supplied from the limestone breccia with a carbonate matrix. All the sedimentological properties with no doubt indicate the reworked nature of the limestone breccia with an argillaceous matrix and the sedimentary mixing of the collisional collapse products with argillaceous sediments. The limestone breccia with an argillaceous matrix is, therefore,

better defined as a chaotic aggregate of carbonate clasts reworked from the collisional collapse products and deposited on the argillaceous sediments. The reworking is thought to have uninterruptedly followed upon the collisional collapse. The matrix-poor and matrix-rich varieties laterally pass into each other and most properly reflect the proximity to the provenance (Fig. 9). The rock-fabric of the limestone breccia with an argillaceous matrix means that its carbonate clasts were transported by debris flows.

The limestone debris set in scaly mudstone in places occur crowded to form a rock referable to as limestone conglomerate and in places occur scattered. In both the cases, the granule- to cobble-sized debris are much predominant and minor boulder-sized ones are contaminated. All the rock-types of the debris can be identified in the limestone breccia with an argillaceous matrix. The rare dolomite debris are contained.

The limestone conglomerate occurs as laterally discrete, lenticular intercalations in the scaly mudstone. The rocks appear to be almost indistinguishable from

Fig. 9. Schematic profile showing emplacement of collisional collapse products with idealized illustrations of microscopic fabrics of limestone breccia with argillaceous matrix, limestone conglomerate, and limy sandstone. Slide contact of collisional collapse products and isolated occurrence of limestone block are also schematically illustrated on outcrop-scale.

the matrix-rich variety of limestone breccia with an argillaceous matrix (Plate II-1, 2). These two similar-looking rocks are, however, discriminated from each other by the difference in roundness and fabric of the clasts as well by the clast association. Much of the debris in limestone conglomerate is subrounded (Plate II-1), apparently water-worn, and is supported by a poorly sorted argillaceous matrix having a great admixture of minute carbonate particles (Plate II-2) and silt-sized clastic quartz grains (Plate II-3). Although the limestone debris are usually chaotically set in the matrix (Fig. 8-2), the indistinctly oriented clast-fabric occurs in places where small-sized debris are predominate (Fig. 8-4). Along with the limestone debris of various types, a considerable amount of mudstone clasts (Fig. 8-3, -4; Plate II-3) and a very small amount of radiolarian chert clasts (Plate II-3) are contaminated in the limestone conglomerate. Much of the mudstone and chert clasts is subangular to subrounded, but some of the mudstone clasts are labeled as rip-up clasts having elongated, lenticular shapes with sharp edges (Fig. 8-3; Plate II-2). The limestone breccia with an argillaceous matrix contains a very few amount of mudstone clasts and is devoid of chert clasts.

Where the limestone debris are scattered in the scaly mudstone, the rock is better described as pebbly mudstone. The limestone debris are in the granule to cobble size and rounded to subrounded. Although they are usually disseminated chaotically in the scaly mudstone, their longer axis are in places crudely oriented.

Laterally discrete beds of limy sandstone sporadically occur intercalated in the scaly mudstone and alternation of sandstone and mudstone. The limy sandstone is usually medium- to coarse-grained, locally granule-grained, and consists predominantly of carbonate detritus and subordinately of quartz grains and lithic fragments of mudstone (Plate II-4). All these particles are subangular to subrounded, poorly sorted, and exhibit an arenitic texture having a sparse matrix of mixture of terrigenous mud and lime-silt. The beds are commonly 5 to 8 cm thick, and usually parallel-laminated and graded (Plate II-5). The wet-sediment deformation, including a syndimentary fault (Plate II-5), is occasionally seen.

To be discussed here is the isolated limestone blocks set in the scaly mudstone, alternation of sandstone and mudstone, and basaltic volcanoclastic rocks (Figs. 3, 7-3, -4). The blocks widely vary in size, ranging

from a several tens of centimeters to several tens of meters, occasionally up to 100 m, and are pod- to lenticular-shaped. They are bounded with lithologically well-defined, irregularly knobby surfaces by the surrounding terrigenous and volcanoclastic rocks, which are often dotted by the pebble- to cobble-sized redeposited limestone debris. The blocks are at many localities composed of the broken limestone and limestone breccia with a carbonate matrix, but the rare blocks of limestone breccia with an argillaceous matrix crop out in places where embedded in the scaly mudstone. With an emphasis upon the isolated occurrence and the intimate association with the redeposited limestone debris, we consider the limestone blocks to have been dislodged from the slide masses of the collisional collapse products and settled down onto unconsolidated terrigenous and volcanoclastic sediments.

The sedimentological properties of the limestone breccia with an argillaceous matrix, the limestone debris crowded and scattered in the scaly mudstone, and the limy sandstone mean the sedimentary mixing and redeposition of the collisional collapse products due to sediment-gravity flows. The limestone debris embedded in the scaly mudstone are thought to have been redeposited by debris flows. The graded structure of the limy sandstone implies the redeposition of granule- to sand-sized carbonate particles by turbidity flows. The clast-association of these redeposited carbonates in the scaly mudstone means the apparent derivation of their carbonate clasts from the limestone breccia with an argillaceous matrix. All these redeposited carbonates are considered to have been originally graded laterally into one another, forming a depositional progression (Fig. 9). Their lithologic gradation is best recorded as a decrease in the clast-size and also inferred by an increase in amount of an argillaceous matrix and a decrease in angularity of the clasts. The abundance of clastic quartz grains in the argillaceous matrix also appear to be related to this lithologic gradation. According to the downslope evolution model for the mass transportation mechanism (Davies, 1977; Nardin et al., 1979), the limestone debris crowded in the scaly mudstone are interpreted to be a proximal facies, which originally passed laterally into a distal facies of the limy sandstone, through the limestone debris scattered in scaly mudstone. The limestone breccia with an argillaceous matrix, labeled as matrix-poor debris flow deposits, is assigned to have acted as a provenance of the limestone debris of the redeposited carbonates in the scaly mudstone.

The depositional progression of the Tsukumi redeposited carbonates is comparable with that of the Akiyoshi Limestone Group described by Sano and Kanmera (1991c). The Tsukumi and Akiyoshi collisional collapse products were gravitationally dis-

placed down onto and mingled with trench-fill sediments (Fig. 9: See also Fig. 4 of Sano and Kanmera, 1991d).

Collisional and accretionary process of Tsukumi Limestone

Timing of collisional collapse

As discussed by Sano and Tamada (1994), the prevalence of the internal destruction fabrics in the Tsukumi Limestone and its structural heterogeneity are most satisfactorily explained by the working hypothesis proposed by Sano and Kanmera (1991d), in which a large-scale collisional collapse of the Akiyoshi reef complex induced by the normal faulting along an outer trench-slope is emphasized. The Tsukumi buildup is considered to have been involved in the collisional collapse process analogous to that of the Akiyoshi reef complex experienced (See Fig. 4 of Sano and Kanmera, 1991d). The Tsukumi Limestone is the second example of accreted shallow-marine carbonates, of which collisional process could be explained by the normal fault-induced, large-scale collisional collapse.

To be discussed is the timing when the collisional collapse of the Tsukumi buildup took place. The timing is best constrained by both the youngest age of all the collisional collapse products and by the age of the adjoining terrigenous rocks. The former is related to the timing when the carbonate sedimentation on a buildup was terminated, and the latter could approximate the timing when the collisional collapse products were encountered and mingled with the terrigenous sediments. The smaller the time-interval between the former and the latter is, the more precisely the timing of the collisional collapse is given. The collisional collapse of the Akiyoshi reef complex, for example, is considered to have happened during latest Middle to earliest Late Permian time on the basis of the upper Middle Permian fusulines in the limestone breccia and by the upper Middle to lower Upper Permian radiolarian fossils from the adjoining scaly mudstone (Sano and Kanmera, 1991d).

In the case of the Tsukumi Limestone, the Scythian bivalves in the isolated limestone blocks and scattered limestone debris in the scaly mudstone, so far as examined, give the youngest age of the Tsukumi collisional collapse products. The contamination of the Lower Triassic limestone implies that the carbonate sedimentation on the Tsukumi buildup extended into Early Triassic time. Sano and Tamada (1994), however, postulated the further survival of the carbonate sedimentation into Middle and Late Triassic time, on the basis of the stratigraphy ranging from the upper Upper Permian into the Upper Triassic (upper Norian), through the Lower and Middle Triassic (Watanabe et al., 1979), in the southwestern equivalent of the Tsukumi Limestone (Kamura area in Fig. 1). Accord-

ing to this postulation, the Tsukumi buildup could be better defined as a long-lived oceanic buildup during late Middle Carboniferous to Late Triassic time, although the stratigraphic continuity from the Tsukumi Limestone to the overlying Lower Triassic Gobangadake Formation (Kambe, 1963; Kambe and Teraoka, 1968) is suspectable; the mudstone intercalation at the bottom of the Gobangadake Formation described by these authors has a possibility to be a structural wedge of scaly mudstone, as pointed out by Sano and Tamada (1994). The terrigenous rocks, on the other hand, are most properly correlated to the upper Lower to lower Middle Jurassic by the radiolarian fossils from the scaly mudstone wedge in the western Ganji Quarry (GB 355 in Fig. 4). Teraoka et al. (1992) and Sakai et al. (1993) also reported the upper Lower to lower Middle Jurassic radiolarians from the mudstone around the Furen Cave in the southwestern extent (Fig. 1). The Tsukumi collisional collapse products are considered to have been encountered and then mingled with the trench-fill terrigenous sediments presumably during late Early to early Middle Jurassic time. With an emphasis upon these time-constraints, we postulate that the collisional collapse of the Tsukumi buildup was initiated in early Early Jurassic time; a short interval between the late Late Triassic termination of the carbonate sedimentation and the late Early Jurassic encounter of the collisional collapse products with the trench-fill sediments. The duration of the collisional collapse is presumed to have ranged up probably into late Early Jurassic time, or later, during which the formation of the collisional collapse products and their emplacement simultaneously took place.

Possible collisional collapse of basaltic pedestal

We recognized many similarities of the Tsukumi Limestone in the internal textural destruction fabrics and also in the relationship to the adjoining terrigenous rocks to the Akiyoshi Limestone Group (Sano and Kanmera, 1991a, b). The difference from the Akiyoshi to be discussed is in that the structural wedges of the basaltic volcanoclastic rocks are interposed in the Tsukumi Limestone. No basaltic volcanoclastic rocks occurring interposed in the Akiyoshi Limestone Group are mapped by Sano and Kanmera (1991a). The Tsukumi basaltic rocks are in a block-in-wet sediment contact with the collisional collapse products usually of the broken limestone and have isolated, various-sized blocks of broken limestone, limestone breccia with a carbonate matrix, basaltic lavas, and hyaloclastites. All these characters are very similar to those of the terrigenous rocks interposed in the Tsukumi Limestone, though the basaltic volcanoclastic rocks contain no blocks of the limestone breccia with an argillaceous matrix and no structural wedges of the basaltic volcanoclastic rocks are interposed in the limestone breccia with an argilla-

ceous matrix. We postulate that the basaltic rocks, inferred to have been initially overlain by the Tsukumi buildup (Sano and Tamada, 1994), were involved in its large-scale collisional collapse and mechanically crushed in the same manner as the overlying carbonates. The fine-grained basaltic volcanoclastic rocks are considered to be a sediment derived from the collisional-collapsed masses of basaltic rocks, reworked, and intermixed with unconsolidated trench-fill argillaceous sediments. The sporadic occurrence of the blocks of basalt lavas and hyaloclastites represents their episodic transportation presumably due to debris flows into the reworked basaltic volcanoclastic sediments.

Our discovery of the structural wedges of the basaltic volcanoclastic rocks in excellent exposures of the quarries suggests that their relationship to the adjoining carbonates is needed to be carefully examined in the field. Without a careful observation, an adjoining occurrence of basaltic rocks to carbonates may be easily misunderstood as their stratigraphic relation. The basic volcanic rocks, for example, which were described to be interbedded with and rest upon the Permian limestone around the Furen Cave, the southwestern continuation of the Tsukumi Limestone (Fig. 1), by Teraoka et al. (1992), are better understood as a structurally interposed wedge through our preliminary field-observation. No lithologic gradation were recognized across the boundary between the basic volcanic rocks and the adjoining limestone in this example. Our suggestion means that the recognition of the lithologic gradation from the basaltic rocks into carbonates would be essentially important to confirm their depositional relationship.

How were collisional collapse products mingled with trench-fill sediments?

The working hypothesis of Sano and Kanmera (1991d) gives us the key to answer the question as to the emplacement mechanism of the Tsukumi collisional collapse products into the trench-fill sediments. The Tsukumi collisional collapse products are considered to have been gravitationally displaced down into a trench area and complexly mingled with trench-fill terrigenous sediments, with which basaltic volcanoclastic materials derived from the collisional collapse products of the volcanic pedestal were locally intermixed.

Where unfaulted, the collisional collapse products are bounded by the scaly mudstone, alternation of sandstone and mudstone, and basaltic volcanoclastic rocks with a lithologically sharp and irregularly distorted surface. The nature of the contacts is due to the displacement of submarine slide blocks of the collisional collapse products and their settling on unconsolidated terrigenous and volcanoclastic sediments. The irregularly distorted boundary surfaces reflect the primarily irregular geometry of the slide

blocks of the collisional collapse products. The slide events are considered to have been closely related to the invasion of the downslope-moving wedge of the collisional collapse products into a trench area (Fig. 9). The successive slides resulted in the aggregation of the collisional collapse products that are complexly separated by the structural wedges.

The limestone breccia with an argillaceous matrix having an obvious reworked nature was created by the chaotic mixing of polymictic carbonate clasts and argillaceous sediments. With an emphasis upon the lithologic affinity of the clasts, the limestone breccia with a carbonate matrix is considered to have been the most potential provenance of the carbonate clasts in the limestone breccia with an argillaceous matrix. Their transportation was due to debris flows triggered by slope-failure on the steep-dipping slope of the downslope-moving wedge of the collisional collapse products (Fig. 9). The matrix-poor, dense-packed, stylolitized clast-fabric is owing to an intense pressure-solution effect.

The limestone debris crowded and scattered in the scaly mudstone and the limy sandstone are labeled as redeposited carbonates that form the depositional progression with the limestone breccia with an argillaceous matrix (Fig. 9). The proximal facies is represented by the limestone debris in the scaly mudstone and the distal facies is recorded as the limy sandstone having the turbidite origin. All the limestone particles in the redeposited sediments were supplied from the limestone breccia with an argillaceous matrix.

It is strongly suggested that terrigenous rocks adjoining to a large-scale accreted body of carbonates are characterized by various types of redeposited carbonates. This character is best exemplified by the Tsunemori Formation that is tectonically overlain by the Akiyoshi Limestone Group and contains the redeposited carbonates (Fujii and Mikami, 1970; Kanmera and Nishi, 1983; Sano and Kanmera, 1991 c). The Uji Formation around the Koyama Limestone (Yokoyama et al., 1979) is also characterized by the frequent intercalation of redeposited carbonates (Sano et al., 1987). The lithologic affinity indicates that the redeposited carbonates of the Tsunemori and Uji Formations were derived from the Akiyoshi Limestone Group and Koyama Limestone, respectively. To be added is that both the Tsunemori and Uji Formations are labeled as chaotic mud-rich units. These lithologic characteristics, already pointed out by Sano and Kanmera (1991 c), means that the redeposition of the carbonates has a close genetic relation to the collisional collapse of a carbonate buildup. The collisional collapse products acted as the provenance of the redeposited carbonates. Their gravity-controlled displacement is considered to have been triggered by slope-failure of a trenchward-moving wedge of the

collisional collapse products.

Conclusion

According to the working hypothesis of Sano and Kanmera (1991 d), all the results herein described, combined with those of Sano and Tamada (1994), would permit us to draw the following sequence of the collisional collapse-related events of the Tsukumi buildup and its subsequent displacement onto trench-fill sediments. (1) encroachment of the Upper Carboniferous to upper Upper Triassic Tsukumi buildup-capped seamount into a trench area in early Early Jurassic time, (2) split of the buildup and its pedestal by the normal faulting in an outer trench area and initiation of their large-scale collapse owing to normal fault-induced fractures in early Early Jurassic time, (3) internal textural destruction of the collisional-collapsed blocks and formation of the broken limestone, (4) generation of the wedge of the internally disrupted, collisional collapse products and its trenchward-movement, (5) nondepositional intermixing of the collisional collapse products within the wedge, having resulted in formation of the limestone breccia with a carbonate matrix, (6) submarine slide of the collisional collapse products and their gravitational displacement from the wedge due to debris flows, having produced the limestone breccia with an argillaceous matrix through the mixing of the collisional collapse products with trench-fill sediments in late Early Jurassic to early Middle Jurassic time, (7) redeposition of limestone particles from the limestone breccia with an argillaceous matrix, and (8) incorporation of the collapsed products together with the trench-fill sediments into an accretionary prism by the offscraping accretion mechanism. All the collisional collapse-related tectonic and depositional events took place in the short time-interval during early Early to early Middle Jurassic time.

The discovery of the prevailing internal textural destruction fabrics in the Tsukumi Limestone (Sano and Tamada, 1994) means that they are by no means local in the Akiyoshi Limestone Group, where Sano and Kanmera (1991 b, d) first described the widespread internal textural destruction of the limestone. This means a possibility that other accreted oceanic carbonates have been also internally fragmented as the Akiyoshi Limestone Group and the Tsukumi Limestone. More case-studies are needed, through which the internal deformation fabrics of the accreted oceanic carbonates as well their structural relation to the adjoining terrigenous rocks are thoroughly examined.

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* : in Japanese with English abstract ; ** : in Japanese

(地 名・地層名)

Tsukumi	津久見	Warabino	蔵野	Omura	大村
Ganji	願寺	Inukai	犬飼	Mitate	見立
Okugawachi	奥河内	Kabunoki Fault	株ノ木断層	Toroku	土呂久
Yoshiro	与四郎	Suishozan	水晶山	Chinnanzan	鎮南山
Furen Cave	風連鍾乳洞	Ozono	小園	Inazumiyama	稲積山
Kamura	上村	Gobangadake	碁盤ヶ岳	Miemachi	三重町
Takachiho	高千穂				

(要 旨)

Sano, H. and Tamada, E., 1994, How were collisional collapse products of oceanic limestone mingled with trench-fill sediments?—Tsukumi Limestone in Chichibu terrane, southwest Japan. *Jour. Geol. Soc. Japan*, 100, 915-930. (佐野弘好・玉田恵美, 1994, 海洋性石灰岩の衝突性崩壊物はどうにして海溝充填堆積物と混じりあったか? —秩父帯津久見石灰岩の例一. 地質雑, 100, 915-930.)

衝突性崩壊物である津久見石灰岩中には泥質岩, 砂泥互層, 玄武岩質火山碎屑岩からなる楔状岩体が挟まれる。石灰岩とは岩相移化せず, 不規則に湾曲した面で接する。この関係は石灰岩が未固結の陸源碎屑性・火山碎屑性堆積物上に滑動ないし滑落したことを意味する。

石灰岩崩壊物のうち, 泥質基質の角礫岩は泥質岩中の石灰岩礫岩・石灰岩塊・石灰岩砂岩などの重力流堆積物と側方移化の関係にあった。これらの再堆積物中の石灰岩礫は海溝に向かって前進していた石灰岩崩壊物から供給された。

石炭紀中世後期からトリアス紀末に浅海成炭酸塩岩として海山上で形成された津久見石灰岩はその基盤とともに海溝付近で大規模に崩壊した。崩壊物は滑動, 土石流などで海溝充填堆積物上に移動し, 一部は海溝充填堆積物と混じりあい, 再堆積した。大規模崩壊はジュラ紀古前期に始まり, 崩壊物の海溝充填堆積物上への移動・再堆積はジュラ紀古世後期から中世前期に生じた。

Explanation of Plates

Plate I Thin-section photomicrographs of limestone breccia with argillaceous matrix. Plane light. All scale bars represent 1 mm. All sample localities are in Fig. 4.

1. Limestone breccia having very sparse argillaceous matrix (M). Limestone clasts are in stylolite contact with concentration of argillaceous materials, indicated as S. Clasts yield lower Maokouan and middle Maokouan fusulines. Loc. OG 43.
2. Typical dense-packed clast-fabric of limestone breccia with sparse argillaceous matrix, denoted as M, having minute carbonate particles. Local stylolitization of clast-contact is discernible (S). Lower Maokouan and upper Maokouan fusulines-yielding clasts are contained. Loc. OG 85.
3. Limestone breccia rich in argillaceous matrix (M). Note that clast-angularity is lower than that of limestone breccia poor in argillaceous matrix (e.g., Plate I-1, 2). Same locality as that of Plate I-2.
4. Extraordinarily quartz grain (Q)-rich, coarse-grained matrix of limestone breccia. Fusulines characteristic in Middle Maokouan, Upper Maokouan, and Wuchiapingian Stages are detected from limestone clasts. Loc. GB 353.

Plate II Thin-section photomicrographs of redeposited limestone and related sediments. Plane light. All scale bars represent 1 mm.

1. Limestone conglomerate consisting of subangular to subrounded limestone debris of various sizes set in argillaceous matrix (A) containing minute clasts of limestone. Loc. TK 164 in Fig. 3.
2. Apparently water-worn, subrounded limestone debris-bearing limestone conglomerate with poor-sorted, sand-grained carbonate particle-rich argillaceous matrix (A) containing shale chips (C). Note matrix-supported fabric of limestone clasts. Loc. OG 74 in Fig. 4.
3. Granule conglomerate crowded with crudely oriented, subangular to subrounded debris of limestone (L), mudstone (M), radiolarian chert (C), and monocrystalline quartz grains (Q), all supported by one another and set in sparse argillaceous matrix. Loc. GB 663 in Fig. 4.
4. Coarse-grained limy sandstone composed of sand- to granule-sized limestone particles, angular quartz grains, and rip-up-clasts of shale. Loc. OG 81 in Fig. 4.
5. Limy sandstone having graded structure and synsedimentary fault (F). Loc. OG 226 in Fig. 4.