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# Multiple origins for flat-pebble limestones and sedimentary environments of the Upper Cambrian Gushan Formation at Tangwangzhai in Shandong Province *

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**Abstract** The Upper Cambrian Gushan Formation in North China Platform is characterized by abundant deposition of flat-pebble limestones (flat-pebble conglomerates). The flat-pebble limestone refers to the so-called edgewise-limestone. Based on the systematic investigation of the sedimentology of the Gushan Formation at the Tangwangzhai Section, Shandong Province, 8 rock types, namely calcareous shale, nodular micritic limestone, muddy banded micritic limestone, thin-bedded micritic limestone, bioturbated micritic limestone, skeletal wackestone-packstone, oolitic grainstone, and flat-pebble limestone, have been recognized in this formation, and have been grouped into 3 rock associations, which were deposited in the shaly basin, deep subtidal zone and shallow subtidal zone. The characteristics of pebbles and matrix and sedimentary successions indicate different provenances for the pebbles and matrix, and suggest that flat-pebble limestones in the Gushan Formation were originated from multiple sedimentary environments. Flat-pebble limestones in the Gushan Formation are grouped into 4 types according to their origins. 1) Both pebbles and matrix were probably formed *in situ* or transported only for a short distance; 2) Both pebbles and matrix were eroded and transported for a long distance from nearshore regions or experienced a sea-level rising process; 3) Matrix might be transported from nearshore regions, and mixed with pebbles and lime mud formed *in situ*; 4) Pebbles might be eroded and transported from micritic limestone on far offshore regions, and mixed together with matrix *in situ*, such as lime mud and skeletal grains.

**Key words** multiple origins for flat-pebble limestone, sedimentary environments, Gushan Formation, Upper Cambrian, Shandong Province

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# 山东省唐王寨上寒武统崮山组沉积环境及竹叶状灰岩的多成因分析

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**摘 要** 华北地台上寒武统崮山组出现了大量的竹叶状灰岩。通过对山东唐王寨剖面崮山组的系统研究，识别出页岩、疙瘩状泥晶灰岩、泥质条带泥晶灰岩、薄层状泥晶灰岩、生物扰动泥晶灰岩、颗粒质（生物碎屑）泥岩—泥质颗粒岩、含交错层理鲕粒灰岩及竹叶状灰岩8种岩石类型，这些岩石类型组成了页岩盆地、深潮下带及浅潮下带岩石组合。竹叶状灰岩中砾屑和基质的特征及其沉积序列，表明砾屑和基质的来源多样并且在不同的沉积环境中其成因具有多样性。据此总结出崮山组竹叶状灰岩具有4种可能的成因类型：1）竹叶状灰岩中砾屑和基质可能均为原地形成或者仅有短距离的搬运过程；2）竹叶状灰岩中砾屑和基质可能均为近岸形成并经历了长距离的搬运过程，或者竹叶状灰岩的沉积环境经历了海平面的突然升高；3）竹叶状灰岩中基质可能来源于近岸未固结的鲕粒和生物碎屑及原地的灰泥，与原地破碎生成的砾屑和灰泥等混合沉积；4）竹叶状灰岩中砾屑可能来源于远岸的固结的泥晶灰岩，并经搬运作用与原地未固结的灰泥及骨架颗粒等基质混合沉积。

**关键词** 竹叶状灰岩的多成因 沉积环境 崮山组 上寒武统 山东省

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## 1 Introduction

Flat-pebble limestones are globally distributed within the Precambrian to the Lower Paleozoic carbonate-rich successions (Myrow *et al.*, 2004). For decades, many studies have been targeted on their origins attributed to either storm origin (Henkel, 1970; Prior and Coleman, 1982; Clukey *et al.*, 1985; Prior *et al.*, 1989) or seismic origin (Pope *et al.*, 1997; Obermeier, 1998; Obermeier and Poud, 1999). Recently, Myrow *et al.*, (2004) proposed that the stages of development of the flat-pebble limestone should have been much more complicated, and constructed a model to interpret the formation of flat-pebble limestones along a wave/storm-dominated carbonate shoreline. Modern vertically imbricated flat-pebble limestones were also attributed as a modern analogue of flat-pebble limestones in ancient sediments (Dionne, 1971; Sanderson and Donovan, 1974). In North China, flat-pebble limestones occur abundantly in the Upper Cambrian Gushan Formation, and have been extensively studied (Wang, 1981; Meng *et al.*, 1986; Zhang and Wan, 1990). Wang (1981) proposed a seismic origin whereas Meng *et al.*, (1986) concluded that this kind of deposit was formed by storms. Zhang and Wan (1990) pointed out that the broken limestones could be rounded by mechanical abrasion and more importantly by chemical dissolution.

Still, views on the origin for flat-pebble limestones remain controversial. Furthermore, most studies on flat-pebble limestones are mainly based on their sedimentary structures as well as environmental interpretation of the adjacent facies. Detailed analyses of the relationship between pebbles and matrix and the depositional processes of flat-pebble limestones in China remain elusive. In this paper, we present the results of a systematic analysis of the sedimentology of the Gushan Formation at the Tangwanzhai Section, Shandong Province, which is the typical section of the Gushan Formation in North China. Particular emphasis was focused on the depositional mechanics and processes of the flat-pebble limestones on the basis of the provenances of and the relationship between the pebbles and the surrounding matrix.

## 2 Geological and stratigraphic setting

The studied section is located at the Tangwangzhai hill, east to the Gushan Town in southwestern Jinan, the capital of Shandong Province (Fig. 1). During the Cambrian, this area, similar to other areas in North China, was dominated by shallow-marine fine-grained clastics and carbonates (named as, in ascending order, the Zhushadong, Mantou, Zhangxia, Gushan and Changshan formations). The Gushan Formation at its type locality, Tangwangzhai, is characterized by abundant shales and flat-pebble limestones with the conformable bottom and top boundaries, and is subdivided into 3 parts. The lower part consists of 30 m thick shale, the couplet of shale and nodular micritic limestone, and thin-bedded flat-pebble limestones. The middle part is about 15 m thick, and is characterized by thin-bedded micritic limestone with abundant flat-pebble limestones. The upper part is about 25 m thick, and begins with the couplet of shale and nodular micritic limestone, overlain by thin-bedded micritic limestone, homogeneous skeletal wackestone-packstone, oolitic limestone, and abundant flat-pebble limestone layers (Zhang *et al.*, 1996).

The Gushan Formation yields abundant trilobites, such as, *Damesella*, *Blackwelderia*, *Drepanura*, *Stephanocare*, *Diceratocephalus*, *Liostracina*, *Chuangia*,

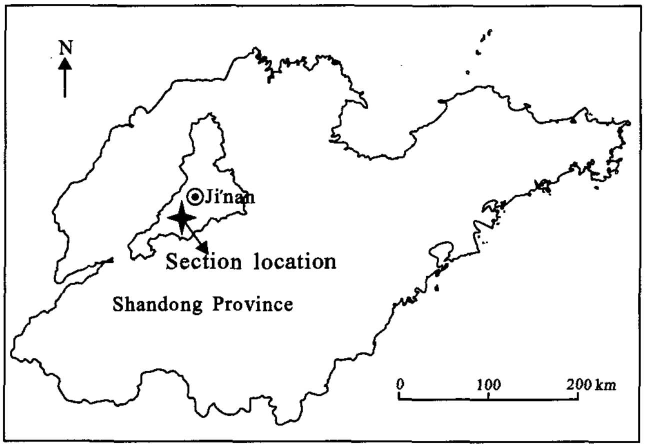


Fig. 1 Location of the Tangwangzhai Section in Gushan Town of Jinan, Shandong Province
图1 山东省济南市崮山镇唐王寨剖面位置

*Changshania*, *Irvingella* and some agnostoids. It also contains some echinoderm stems. Based on the trilobite assemblages, the Gushan Formation ranges from the Middle Cambrian Gushanian Stage to the Early Changshanian Stage of the Late Cambrian (Zhang *et al.*, 1996).

## 3 Rock description

Sedimentary structures and textures are relatively well preserved in the Gushan Formation at the Tangwangzhai Section. Sedimentary characteristics, including grain size, sedimentary structures, and bed geometry were carefully logged in centimeter scale, and fossil occurrences recorded along the sequence (Fig. 2 - 1, 2 - 2). Thin sections were cut for 70 rock specimens collected from the Gushan Formation to examine primary sedimentary structures and secondary diagenetic features under a microscope. Consequently, 8 rock types have been recognized and are described as below.

### 3.1 Calcareous shale

Calcareous shale is dominated by calcareous shale with purple (60% in all), green, yellow and brown colors. The colors of the outcrop shale commonly change randomly, such as from yellow to green, green to purple and so on. The thickness of individual shale layers is variable and the thickest layer is up to 2 m. There are some millimeter-sized trilobite individuals occasionally occurring in the purple shale.

### 3.2 Nodular micritic limestone

This kind of rock comprises an alternation of calcareous shale and nodular micritic limestone, and is 0.3 ~ 2 m thick. Micritic limestone nodules are gray in color, tabular and oval in shape, and 3 ~ 10 cm in size. Homogeneous structure is common, and sporadic parallel laminations also exist (Fig. 3 - 6). The degree of bioturbation is low and burrows are few.

### 3.3 Muddy banded micritic limestone

This type of rock comprises an alternation of light gray lime mudstone and argillaceous limestone, and is 0.2 ~ 0.6 m thick. Limestone layers, about 0.5 to 4 cm thick, are continuous (planar-bedding) or discontinuous (nodular-bedding) in shape and homogeneous or laminated (Fig. 3 - 1). Argillaceous limestone layers are brown in color, and are commonly dolomitized (Fig. 3 - 7).

### 3.4 Thin-bedded micritic limestone

This type of rock is purple to gray in color, 5 ~ 20 cm thick, and homogeneous or parallel to crudely wavy cross-laminated (Fig. 3 - 2). Skeletal fragments are rare. This rock often occurs in the association with the calcareous shale and occasionally associates with flat-pebble limestones.

### 3.5 Bioturbated micritic limestone

This rock shows abundant burrows (Fig. 3 - 3) with individual layer 5 ~ 10 cm thick. Most burrows, commonly 1 ~ 2 cm in diameter, are selectively dolomitized. Horizontal or sub-horizontal burrows show irregular shapes, and are replaced by argillaceous or iron minerals (Fig. 3 - 8).

### 3.6 Skeletal wackestone-packstone

This type of rock is dark gray on fresh surface, but purple after weathering, and is 0.15 ~ 0.6 m in thickness and massive in structure. It contains abundant trilobite fragments, and has planar and sharp top and bottom boundaries (Fig. 3 - 4).

### 3.7 Oolitic grainstone

This type of rock is dark gray in fresh exposure, but dark brown after weathering (Fig. 3 - 5), and is less than 0.6 m in thickness. Ooids, about 0.5 ~ 1 mm in diameter, are commonly spherical with a radial structure (Fig. 4 - 1). Different colors of ooids show cross laminaes (Fig. 3 - 5). This rock has a sharp top and irregular base, and occurs with the disorganized flat-pebble limestones.

### 3.8 Flat-pebble limestone

Based on the texture and characteristics of the pebbles and matrix, the flat-pebble limestones in the Gushan Formation can be divided into 5 types, as de-

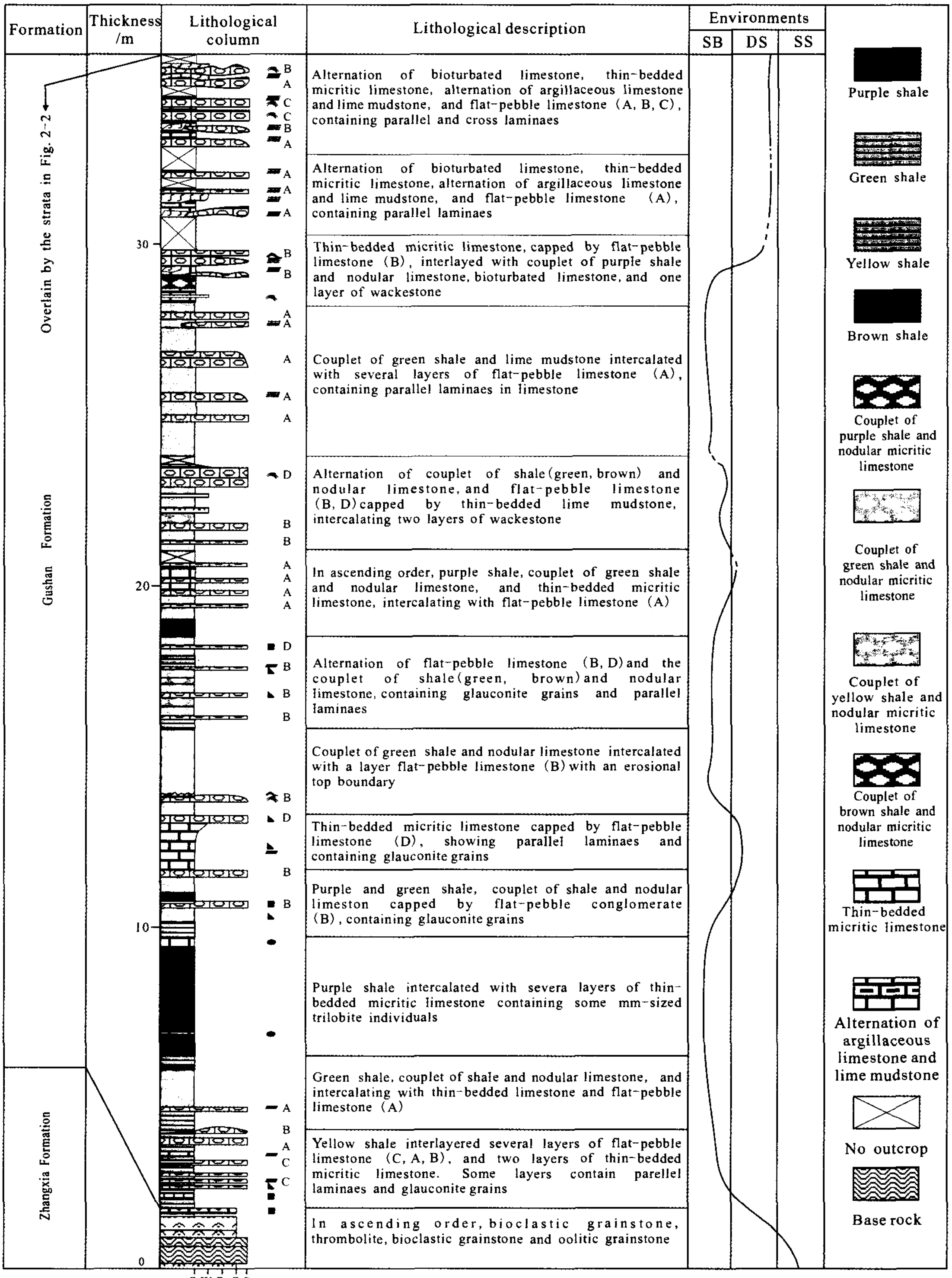


Fig. 2-1 Stratigraphic column of the Gushan Formation at Tangwangzhai Section

图 2-1 唐王寨剖面崮山组地层柱状图

S—shale, micritic limestone; W—wackestone; P—packstone; G—grainstone; C—flat-pebble limestone; SB—shaly basin; DS—deep subtidal zone; SS—shallow subtidal zone. A, B, C, D, E are the five types of flat-pebble limestone described in section 3.8

tailed below.

**Type A. Flat-pebble limestone of micritic limestone pebbles with lime mud matrix:** Pebbles are disorganized limestone that partly show inverse

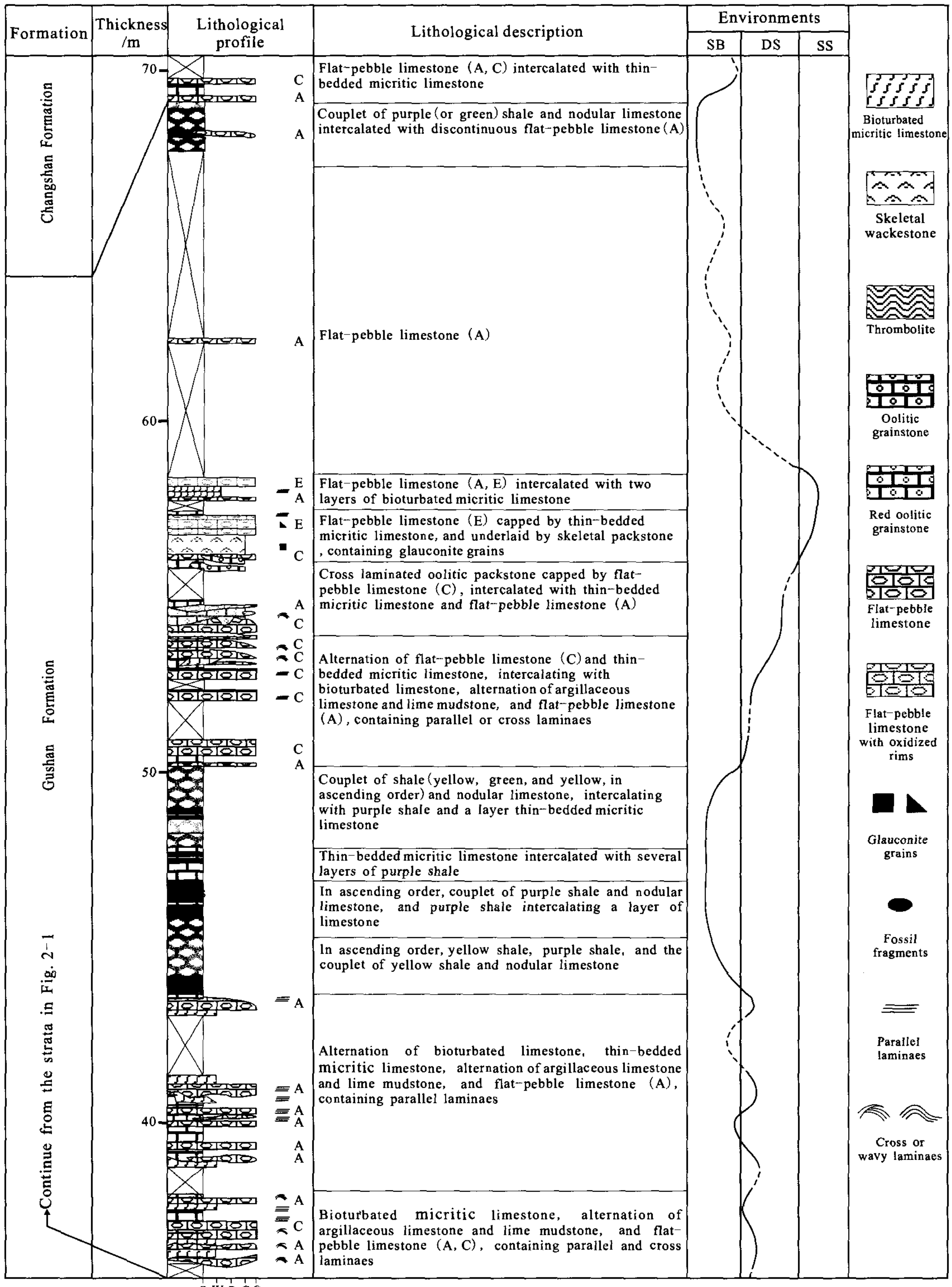


Fig. 2-2 Stratigraphic column of the Gushan Formation at Tangwangzhai Section

图2-2 唐王寨剖面崮山组地层柱状图

S—shale, micritic limestone; W—wackestone; P—packstone; G—grainstone; C—flat-pebble limestone; SB—shaly basin; DS—deep subtidal zone; SS—shallow subtidal zone. A, B, C, D, E are the five types of flat-pebble limestones described in section 3.8

grain size grading (Fig. 4-2). Pebbles are well rounded, but poorly sorted. Some pebbles connect with each other and show crudely parallel laminaes. The matrix is composed of lime mud and clays, in

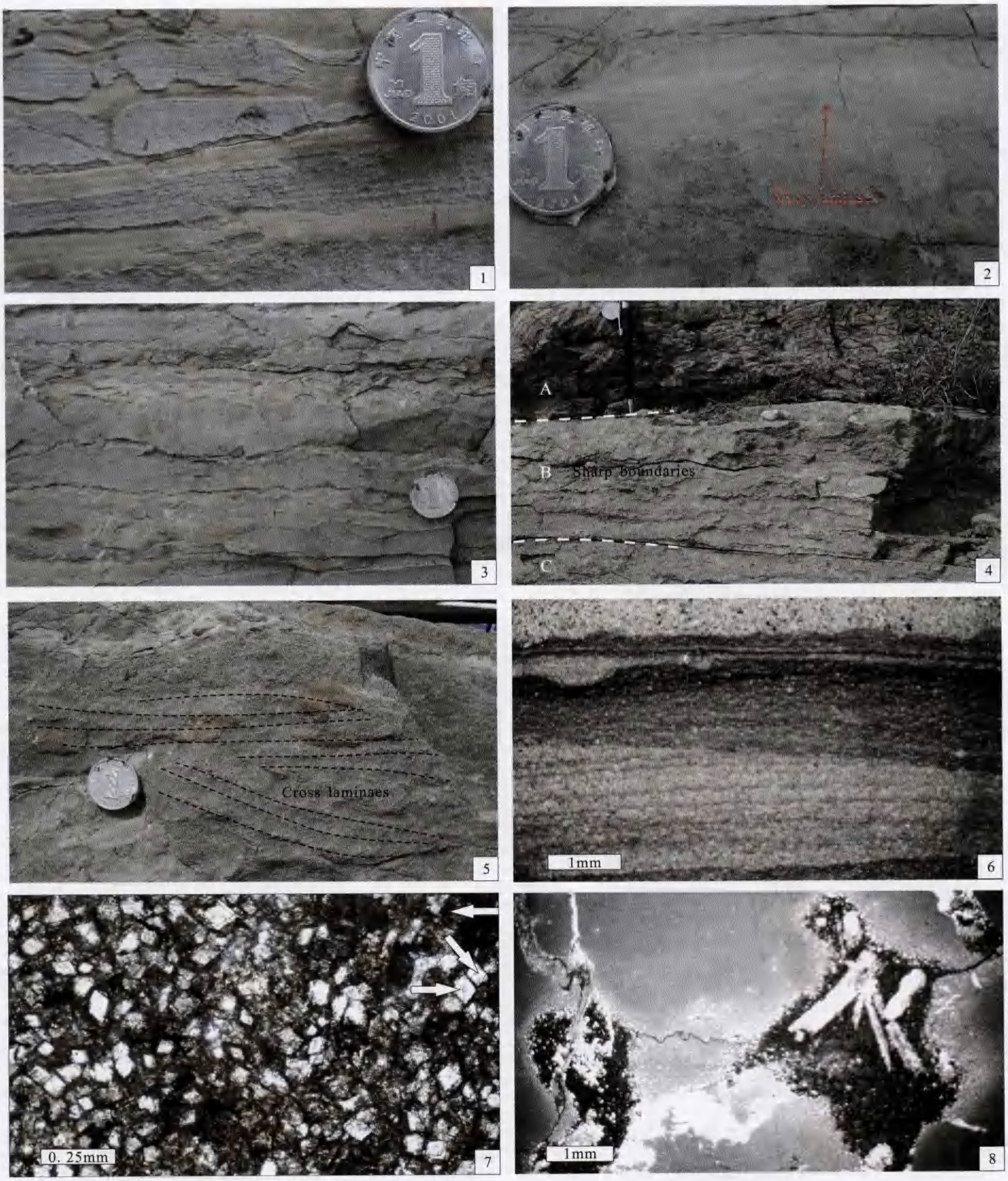


Fig. 3 Rock types of the Gushan Formation and microphotos

图 3 崮山组岩石类型及显微照片

1—Micritic limestone layers show parallel laminaes; 2—Thin-bedded micritic limestone shows wavy laminaes; 3—Limestone beds in bioturbated limestone are tabular and mostly homogeneous in fabric; 4—Flat-pebble limestone beds are tabular and have relatively flat bottom surfaces; Skeletal packstone commonly has a planar top boundary and an irregular base; A—micritic limestone pebbles (with oxidized rims) with lime mud and abundant skeletal fragments matrix; B—Micritic limestone pebbles with lime mud and abundant skeletal fragments or oolitic grain matrix; C—Skeletal packstone; 5—Cross laminated oolitic packstone is dark brown after weathering and with cross laminaes; 6—Micritic limestones in couplet of shale and nodular micritic limestone show parallel laminaes; 7—Rhombohedral dolomite crystals in alternation of argillaceous limestone and lime mudstone, white arrows show rhombohedral dolomite crystals; 8—Burrows show irregular shapes in bioturbated micritic limestone which are replaced by argillaceous or iron minerals; Coin for scale is 1. 9 cm in diameter, and pencil for scale is 14. 5 cm in length

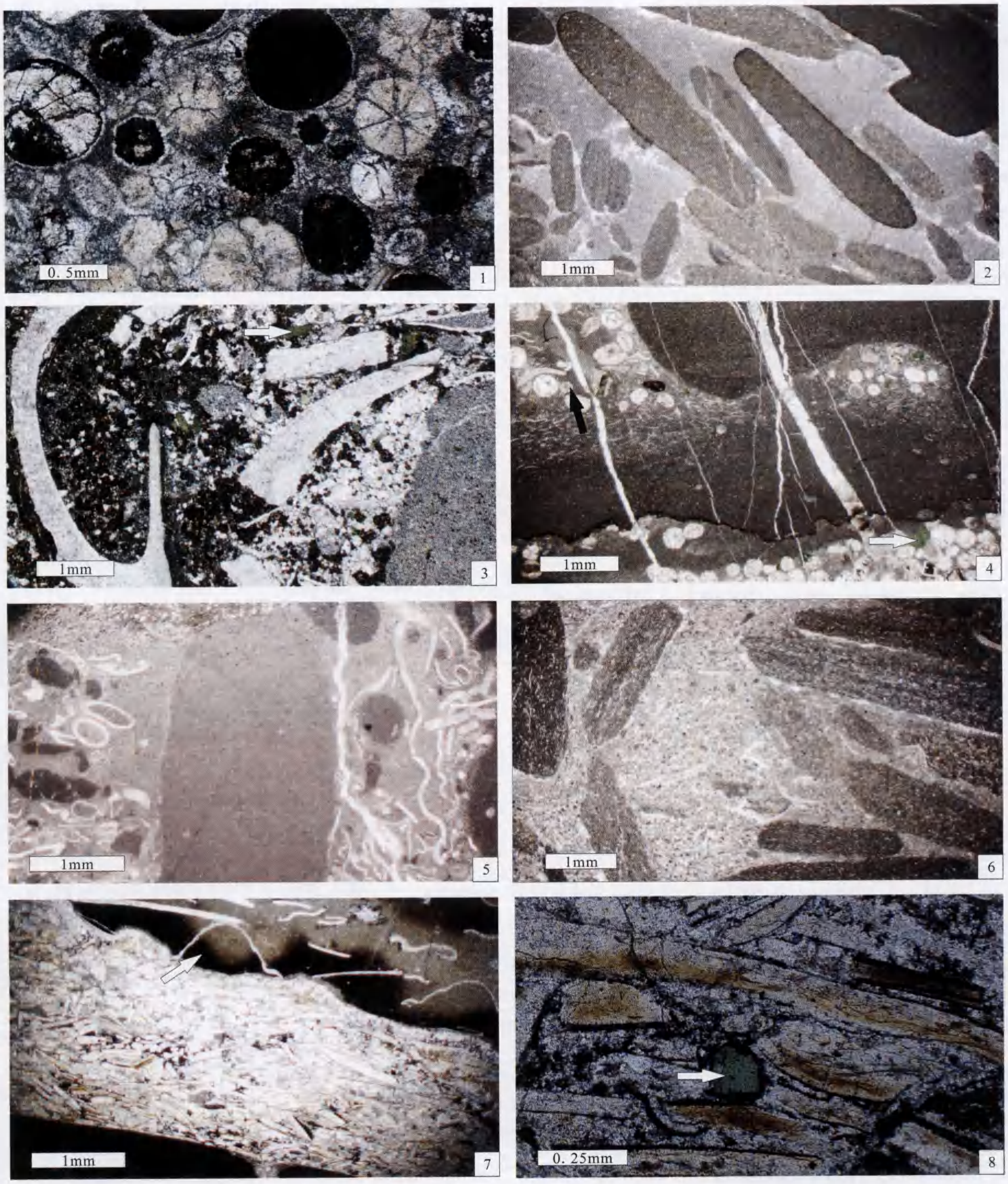


Fig. 4 Microphotos of flat-pebble limestones

图4 竹叶状灰岩的显微照片

1—Spherical ooids are 0. 5 ~ 1 mm in diameter and with radiate structures, white arrows show radiate srtuctures; 2—Micritic limestone pebbles in the flat-pebble limestone of micritic pebbles with lime mud matrix are mostly homogenous, inclined or vertical and show inverse grain size grading; 3—Matrix in some flat-pebble limestone contains trilobite fragments, iron minerals and glauconite grains, the white arrow shows a glauconite grain; 4—Pebbles in some flat-pebble limestones are big, planar and with irregular boundaries; Matrix contains ooids, skeletons and glauconite grains, the black arrow shows ooids and the white arrow shows a glauconite grain; 5—Pebbles in the flat-pebble limestone of micritic pebbles with lime mud and abundant skeletal fragments matrix are vertically oriented and poorly sorted; 6—Wackestone pebbles show parallel or cross laminaes, and partly are nearly vertically oriented; 7—The flat-pebble limestone of micritic limestone pebbles (with oxidized rims) with lime mud and abundant skeletal fragments matrix contains poorly oxygenated fossil fragments, the white arrow shows oxidized rims; 8—Matrix contains iron-rim skeletal fragments and glauconite grains in the flat-pebble limestone of micritic limestone pebbles (with oxidized rims) with lime mud and abundant skeletal fragments matrix, the white arrow shows a glauconite grain place with a few fossil fragments ( <5% ). This type of flat-pebble limestone commonly intercalates with or overlies the couplet of shale and nodular limestone, and sometimes lies above the thin-bedded micritic limestone, alternation of argillaceous limestone and lime mudstone, or bioturbated micritic limestone (Fig. 2 - 1, 2 - 2).

**Type B. Flat-pebble limestone of micritic limestone pebbles with lime mud and a few skeletal fragments matrix:** Pebbles probably come from the fragmented limestone, and are oval in shape. Most pebbles are poorly oriented to the bedding plane, and are 3 ~ 5 cm in length. The matrix is composed of lime mud and trilobite fragments (Fig. 4 - 3), with some containing abundant iron minerals and glauconite grains (Fig. 4 - 3). This type of flat-pebble limestone is commonly located within or above the couplet of shale and nodular micritic limestone, and sometimes lies above bioturbated micritic limestone or skeletal wackestone (Fig. 2 - 1, 2 - 2).

**Type C. Flat-pebble limestone of micritic limestone pebbles with lime mud and abundant skeletal fragments or oolitic grains matrix:** Pebbles of this type are composed of micritic limestone, and as big as 8 cm in length and irregular in shape (Fig. 4 - 4). Unlike Type B, most pebbles of this type are vertically oriented and poorly sorted (Fig. 4 - 5), but may be sub-horizontal in the lower part of an individual layer. The matrix component varies, and may include recrystallized ooids, skeletal fragments, glauconite grains (Fig. 4 - 4) and lime mud. This type of limestone typically appears within or above thin-bedded micritic limestone, alternation of argillaceous limestone and lime mudstone, or bioturbated micritic limestone, and occasionally lies within shale (Fig. 2 - 1, 2 - 2).

**Type D. Flat-pebble limestone of wackestone pebbles with lime mud and a few skeletal fragments matrix:** Pebbles are mainly derived from skeletal wackestones with parallel or cross laminaes (Fig. 4 - 6). Similar to Type C, pebbles in this type are subrounded, moderately-sorted, and partly vertically oriented (Fig. 4 - 6). The matrix is also composed of skeletal fragments and micrite. The boundaries between pebbles and matrix are rather diffuse. This type of limestone is not widely distributed in the Gushan Formation, but occasionally overlies the thin-bedded micritic limestone or the couplet of shale and nodular micritic limestone (Fig. 2 - 1, 2 - 2).

**Type E. Flat-pebble limestone of micritic limestone-wackestone pebbles (with oxidized rims) with lime mud and abundant skeletal fragments matrix:** Pebbles might be derived from micritic limestone or wackestone, and usually have irregular shapes with dark brown oxidized rims (Fig. 4 - 7). Interstitial space between pebbles is filled with skeletal grains and lime mud. Some fossil fragments within matrix also show oxidized rims. This type of limestone is rare in this formation, and sporadically occurs above the skeletal wackestone-packstone or the bioturbated micritic limestone (Fig. 2 - 1, 2 - 2).

## 4 Rock associations and sedimentary environments

The 8 types of rocks described above, can be assembled into 3 rock associations, which were deposited in the shaly basin, deep subtidal zone and shallow subtidal zone (Fig. 2 - 1, 2 - 2). The description and environmental interpretation of these rock associations and their environments are shown as following (Fig. 5).

### 4.1 Shaly basin rock association (SB)

Shaly basin is defined as the area below the storm-wave base that can be occasionally affected by extremely strong storms (Burchette and Wright, 1992). This association consists of, in ascending order, calcareous shale, couplet of shale and nodular micritic limestone, alternation of argillaceous limestone and lime mudstone with a paucity of thin-bedded micritic limestone. The couplet of shale and nodular micritic limestone is the most dominant component in this association. The shaly basin sequence has a high clay content that decreases upwards (Fig. 5). Homogeneous structures are common in this association. 4 types of flat-pebble limestone, including Types A, B, C and D, commonly occur as interlayers in this association.

Fine-grained sediments and well-developed laminaes in shale indicate low-energy depositional conditions (Myrow *et al.*, 2004). Millimeter-sized trilobites might have been pelagic. The siliciclastic mud may have been transported by bottom-hugging nepheloid layers or dilute clouds during the periods of low carbonate production. These rocks were deposited in shaly basin settings below the storm wave base (Osleger and Read, 1991). The purple color indicates occasional oxygen inputs into deep water (Liu, 2006). Discontinuous limestone nodules in the couplet of shale and nodular micritic limestone are related to the early synsedimentary patchy cementation, compaction and pressure solution (Read, 1982). Alternation

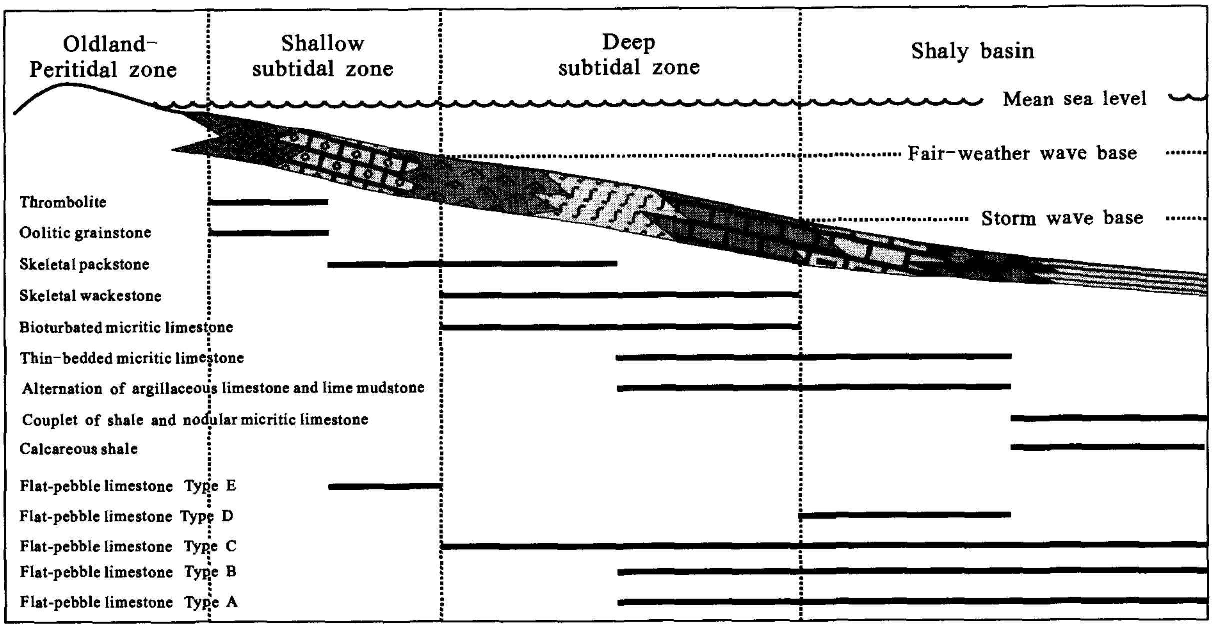


Fig. 5 Sedimentary environments model for flat-pebble limestones distribution (modified from Liu, 2006) Legends are the same as Fig. 2 - 1, Fig. 2 - 2

图5 竹叶状灰岩分布的沉积环境模式（据刘建波，2006，有修改）图例见图2-1，2-2

of argillaceous limestone and lime mudstone shows the variation of carbonate and silicilastic mud during fair-weather phases (Burchette and Wright, 1992), indicating the influence of minor base-level fluctuations (Burchette *et al*., 1990).

Because of their coverage by bioturbated limestone and being interlayered with siliciclastic mudstone and thin-bedded micritic limestone, the alternation of argillaceous limestone and lime mudstone should have been deposited in a deep subtidal environment, deeper than the depositional setting of bioturbated micritic limestone-wackestone (Aigner and Schughart, 1985). Several lines of evidence, including the shale-supported nature, apparent absence of wave and current structures, and the paucity of thin beds of flat-pebble limestone suggest the deposition under a low-energy condition below the storm wave base (Calvet and Tucker, 1988; Reading, 1996; Myrow *et al*., 2004). This rock association occurs at the three intervals of 2 m to 29 m, 43.5 m to 50 m, and 67.5 m to 69 m from the bottom of the Gushan Formation at the Tangwangzhai Section (Fig. 2 - 1, 2 - 2).

## 4.2 Deep subtidal rock association (DS)

This association contains relatively less siliciclastic content than the shaly basin rock association, and consists of, in ascending order, alternation of argillaceous limestone and lime mudstone, thin-bedded micritic limestone, bioturbated micritic limestone and skeletal wackestone. 3 types of flat-pebble limestone, Type A, Type B, Type C also frequently occur in this association. Bioturbated limestone commonly overlies the alternation of argillaceous limestone and lime mudstone (Fig. 3 - 3), and partly laterally or vertically passes into the flat-pebble limestone. Wavy-laminated micritic limestones overlie or are intercalated with flat-pebble limestones.

Wavy laminaes in thin-bedded micritic limestone above or between flat-pebble limestones probably indicate the intermission of storm events that caused the formation of ripples on the irregular or erosional surfaces above flat-pebble limestone beds. Pervasive bioturbation in bioturbated micritic limestone implies that this type of rock was deposited in a well-oxygenated sea floor (Calvet and Tucker, 1988; Osleger and Read, 1991), where the sediments were stirred by intensive activities of the infauna. Lack of a grain-supported texture suggests its low-energy environment. Rhombohedral dolomite crystals in the alternation of argillaceous limestone and lime mudstone, and bioturbated micritic limestone indicates that the presence of argillaceous minerals can make dolomitization easy and common in limestone (Peng and Zhang, 2000).

The absence of shale indicates a reduction of siliciclastic input, which probably improved the carbonate productivity. The presence of parallel laminaes in micritic limestone layers indicates a relatively low-energy environment without strong wave currents (Liu, 2006). In normal marine conditions, burrowed limestone represents subtidal deposition below the fair-weather wave base (Osleger and Read, 1991), and the presence of abundant bioturbation and skeletons reflects good oxygenated conditions on the seafloor (Calvet and Tucker, 1988; Osleger and Read, 1991). However, the wavy laminaes in the thin-bedded limestone represent the intermittent periods between storm events (Wu, 1982). This rock association occurs at the three intervals of 29 m to 43.5 m, 50 m to 54 m, and 58.5 m to 67.5 m from the bottom of the Gushan Formation at the Tangwangzhai Section (Fig. 2-1, 2-2).

### 4.3 Shallow subtidal rock association (SS)

This association occurs above the fair-weather wave base. It is characterized by skeletal wackestone-packstone, oolitic grainstone and the flat-pebble limestone of type E. The skeletal wackestone-packstone commonly has a planar top boundary and an irregular base (Fig. 3-4), and changes into flat-pebble limestone upwards. The oolitic grainstone has a planar top boundary and an irregular base and occurs with flat-pebble limestone beds.

The cross laminaes in oolitic grainstone in this association reflect constant wave agitation above the fair-weather wave base (Wright, 1986). The brown to red color indicates complete weathering under oxic conditions, and the abundant fossil fragments in the skeletal wackestone-packstone indicate the presence of abundant animals. The presence of abundant oxygen and warm environment increases the activities of animals, or the strong wave currents transport fossil fragments to deposit. This rock association occurs at the interval of 54 m to 58.5 m from the bottom of the Gushan Formation at the Tangwangzhai Section (Fig. 2-1, 2-2).

### 4.4 The distribution of 5 types of flat-pebble limestones

Flat-pebble limestone of micritic limestone pebbles with lime mud matrix (Type A) is mainly distributed in the shaly basin to deep subtidal rock associations in the lower and middle parts of the Gushan Formation. Flat-pebble limestone of micritic limestone pebbles with lime mud and a few skeletal fragments matrix (Type B) mainly occurs in the shaly basin rock association in the lower part of the Gushan Formation, and occasionally appears in the deep subtidal rock association in the middle Gushan Formation. Those with lime mud and abundant skeletal fragments or oolitic grains matrix (Type C) primarily occur in the deep subtidal rock association in the upper part of the Gushan Formation, it is also partly distributed in the shaly basin rock association in the lower part of the Gushan Formation, and in the deep subtidal rock association in the mid part of the Gushan Formation. Flat-pebble limestone of wackestone pebbles with lime mud and a few skeletal fragments matrix (Type D) is scarce in this section, just occurring occasionally in the shaly basin rock association in the lower part of the Gushan Formation. Flat-pebble limestone of micritic limestone-wackestone pebbles (with oxidized rims) with lime mud and abundant skeletal fragments matrix (Type E) is only found in the shallow subtidal rock association in the upper part of the Gushan Formation (Fig. 2-1, Fig. 2-2, and Fig. 6).

## 5 Multiple origins for flat-pebble limestones

### 5.1 Multiple provenances for pebbles and matrix

About the mechanical process of the flat-pebble limestone, some people proposed that the strong currents produced by either storm or seismic waves could rework the semi-consolidated limestone into intraclasts (Meng *et al.*, 1986; Myrow *et al.*, 2004). Most researchers hypothesized the provenance for the pebble, which might be broken *in situ* or experience a long-distance transportation. Only a few studies mentioned that the matrix in flat-pebble limestones is mainly lime mud and shale, but did not interpret the provenance for matrix (Kwon *et al.*, 2002). However, the matrix in flat-pebble limestones should not just be deposited *in situ*. It can also be transported from other regions. Some matrix, similar to the contents of syndepositional sedimentary rocks, reflects the depositional background. Others, however, might be transported from onshore or offshore regions. Pebbles, based on the similarity with the syndepositional sedimentary rocks, might be derived from other regions or be produced *in situ*. Clasts, produced by any strong wave currents, became sub-rounded or rounded pebbles after experiencing physical abrasion and chemical dissolution.

### 5.2 Multiple origins for the 5 types of flat-pebble limestones

Using evidence from the relationship between the pebbles and matrix, together with their stratigraphic occurrences, the authors here hypothesize the provenances of the pebbles and matrix, and propose a for-

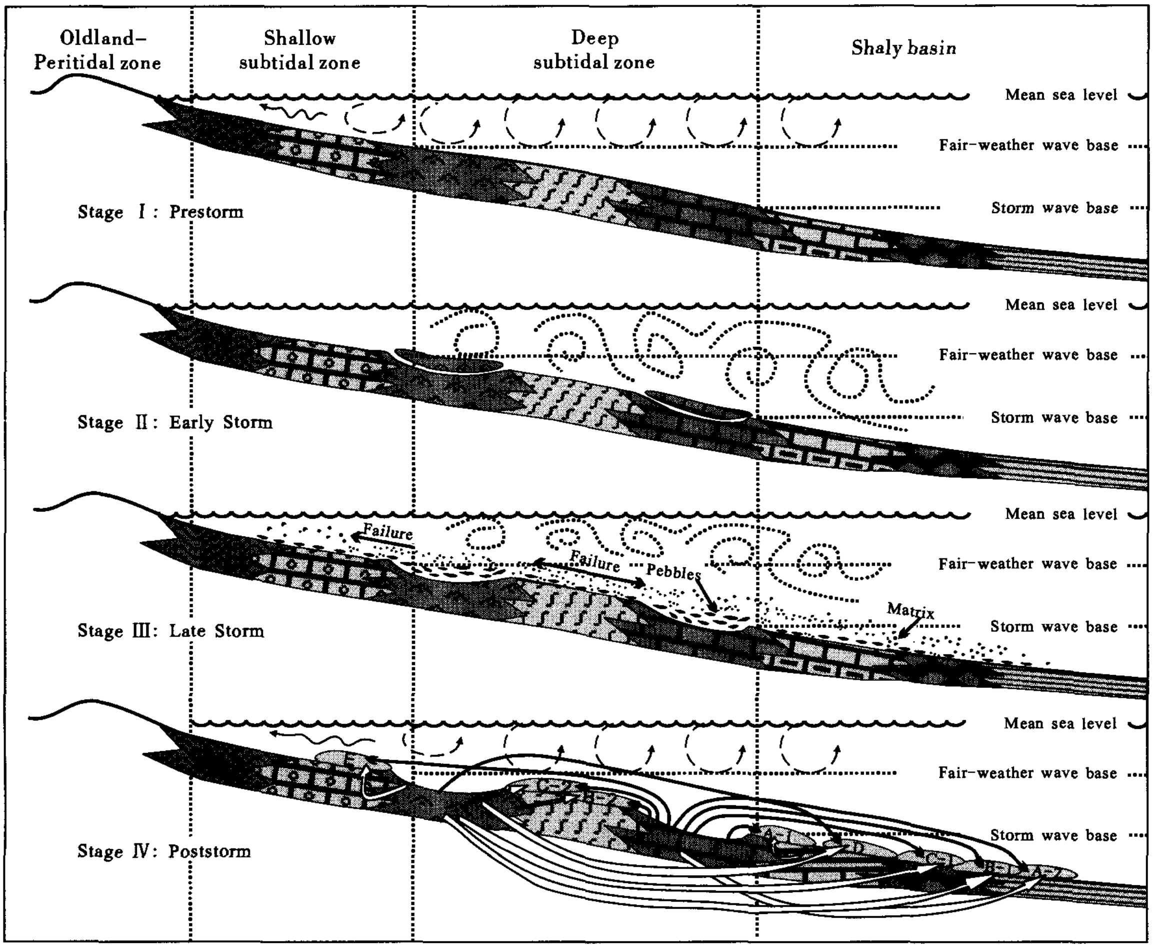


Fig. 6 Model for the formation of flat-pebble limestones (modified from Myrow *et al.*, 2004)

图6 竹叶状灰岩形成模式（据 Myrow 等，2004，有修改）

Black arrow heads stand for the source of pebbles and white ones indicate the source of matrix. Stage Ⅰ-Conditions before storm; Stage Ⅱ-Cyclic waves loading during storm caused failures of limestone which moved along the sea floor; Stage Ⅲ-Limestone blocks broke up into small pebbles through the action of storm waves, while matrix materials were transported along the sea floor; Stage Ⅳ-Different kinds of pebbles and matrix materials combined and deposited in different parts of the sea floor, forming five types of flat-pebble limestones separately. A-E represent different types (Type A-Type E) of flat-pebble limestones of the Gushan Formation

mation model to interpret the multiple origins for the 5 types of flat-pebble limestones (Fig. 6, Table 1).

### 5.2.1 Both pebbles and matrix might be formed *in situ* or be transported only for a short distance (Type A-1)

Flat-pebble limestone of Type A-1 was mainly deposited on the lower part of deep subtidal zone. Pebbles with lime mud fabric might be eroded by strong wave currents from fragmentation or brecciation of consolidated limestone in the alternation of argillaceous limestone and lime mudstone or the thin-bedded limestone. The contact characteristic of some pebbles showed the uncompleted break of the rocks. The most convictive explanation for the lithologic similarity among the pebbles, matrix and the syndepositional sedimentary rocks is that the pebbles in this type might be reworked *in situ*. Disorganized pebbles and their poorly sorted characteristic also show that there is no long-distance transportation to sort pebbles well and make them organized. Processes including physical abrasion and chemical dissolution removed the angular edges of the clasts, forming the well-rounded pebbles. Unconsolidated lime mud was stirred by wave currents, and formed the matrix in the interstitial space between the pebbles (Fig. 6).

### 5.2.2 Both pebbles and matrix might be eroded and transported for a long distance from nearshore regions or might experience a sea-level rising process (Type A-2, Type B-1, Type C-1 and Type D)

Flat-pebble limestones of Type A-2, Type B-1, Type C-1 and Type D were located in the shaly basin zone. Flat-pebble limestones occurred within shale,

**Table 1 The category and multiple origins for flat-pebble limestones**

表 1 竹叶状灰岩的分类及成因

| Rock types | Depositional environments | Components of pebbles | Components of matrix | Origins for flat-pebble limestones |
|---|---|---|---|---|
| Type A | lower part of DS to SB | micritic limestone | lime mud | Both pebbles and matrix might be formed *in situ* or be transported only for a short distance |
| | lower part of SB | micritic limestone | lime mud | Both pebbles and matrix might be eroded and transported for a long distance from nearshore regions or might experience a sea-level rising process |
| Type B | SB | micritic limestone | lime mud, skeletal fragments | |
| | lower part of DS | micritic limestone | lime mud, skeletal fragments | Matrix might be transported from nearshore regions, and mixed with pebbles formed *in situ* |
| Type C | lower part of SB | micritic limestone | lime mud, skeletal fragments, glauconite | Both pebbles and matrix might be eroded and transported for a long distance from nearshore regions or might experience a sea-level rising process |
| | lower part of DS | micritic limestone | lime mud, skeletal fragments | Matrix might be transported from nearshore regions, and mixed with pebbles formed *in situ* |
| Type D | upper part of SB | wackestone | lime mud, skeletal fragments | Both pebbles and matrix might be eroded and transported for a long distance from nearshore regions or might experience a sea-level rising process |
| Type E | lower part of SS | micritic limestone-wackestone | lime mud, skeletal fragments, glauconite | Pebbles might be eroded and transported from offshore regions, and mixed with *in situ* matrix |

and couplet of shale and nodular micritic limestone. The lithologic difference between the flat-pebble limestone and the syndepositional sedimentary rocks shows their different forming environments, which means that both pebbles and matrix came from other places but were not formed *in situ*. Pebbles of these flat-pebble limestones might come from fragmentation or brecciation of consolidated micritic limestone and wackestone in the deep subtidal rock association. Matrix has complex content, such as lime mud, trilobite fragments, glauconite grains and so on, which means that matrix was not just produced *in situ*. Some flat-pebble limestone layers have planar bottom boundaries, which mean the failure came from other places. There are two potential processes for these types of flat-pebble limestones. In the first one, pebbles originally deposited in subtidal settings, were reworked by storm waves, and transported by mass flow downwards to the shaly basin (Fig. 6). Meanwhile, unconsolidated lime mud or skeletal fragments in the deep subtidal zone were also stirred by storm waves and entered into the same mass flow. Finally, the reworked pebbles, skeleton-rich matrix among the mass flow were deposited together in the shaly basin zone, and formed the flat-pebble limestones of Type A-2, Type B-1, Type C-1 and Type D, respectively. The other potential process is that the deep subtidal zone changed into shaly basin after experiencing a sea-level rising process. And the pebbles and matrix were deposited in the same place on the floor but in different depositional environments. There is not enough evidence to support this hypothesis.

### 5.2.3 Matrix might be transported from nearshore regions, and mixed with pebbles formed *in situ* (Type B-2, Type C-2)

These types of flat-pebble limestones occurred with the bioturbated limestone and thin-bedded micritic limestone, and above the alternation of argillaceous limestone and lime mudstone, thus might be deposited in the deep subtidal zone. Pebbles in Type B-2 and Type C-2 are similar in lithology to the syndepositional sedimentary rocks, which are probably induced by pebbles' formation *in situ*. Thus, pebbles probably came from fragmentation or brecciation of consolidated micritic limestone of the thin-bedded micritic limestone *in situ*. Matrix, containing trilobite fragments, glauconite grains and oolitic grains, similar to the former type, probably came from skeleton-rich sediments in the deep subtidal zone. Matrix were transported by storm currents offshore, and deposited together with the pebbles (broken *in situ*) in the deep subtidal zone (Fig. 6).

### 5.2.4 Pebbles might be eroded and transported from offshore regions, and mixed with *in situ* matrix (Type E)

In this origin type, flat-pebble limestones overlied the skeletal wackestone-packstone in the shallow subtidal zone. The tubular nature of flat-pebble limestone of

Type E beds and their relatively flat bottoms (Fig. 3-4) suggest that skeletal wackestone-packstone beds were not eroded, and the lithologic difference between pebbles and the syndepositional sedimentary rocks meant that pebbles were not produced from the background rocks, thus consolidated pebbles were not eroded *in situ*, but transported from other regions (Myrow, *et al.*, 2004). Meanwhile, well-rounded shape of pebbles also reflects a long-distance transportation (Fig. 3-6). Oxidized rims around pebbles (Fig. 4-7) suggest oxidation of the pebbles above the fair-weather wave base. Pebbles were probably derived from the fragmentation or brecciation of consolidated micritic limestone in the deep subtidal rock association. However, the matrix, containing abundant skeletal fragments with poorly oxidized rims (Fig. 4-8), might come from unconsolidated materials which would form the skeletal wackestone-packstone. The matrix, similar to the underlying skeletal wackestone-packstone, reflected the syndepositional environment in the shallow subtidal zone (Fig. 6). Thus, this kind of flat-pebble limestone probably had the forming process following as below. Firstly, pebbles were transported by strong current, and matrix was stirred by storm current. Secondly, offshore pebbles and *in situ* matrix deposited in the shallow subtidal zone together, then formed flat-pebble limestone of micritic limestone-wackestone pebbles (with oxidized rims) with lime mud and abundant skeletal fragments matrix.

## 6 Conclusion

Flat-pebble limestones were distributed abundantly in the Gushan Formation at the Tangwangzhai Section of Shandong Province. Many hypotheses have been offered over the years for the origins for flat-pebble limestones, including the discussion on the provenance of pebbles, the oxidized rims of the pebbles, and the stages of development of such beds. This study analyzed the characteristics of the pebbles and matrix, and emphasized the significance of the matrix. Based on the characteristics and relationship between pebbles and matrix, 5 types of flat-pebble limestone were recognized. Considering the syndepositional sedimentary rocks, the authors have analyzed the provenances of pebbles and matrix, and proposed the multiple origins for flat-pebble limestones: 1) Both pebbles and matrix might be formed *in situ* or be transported only for a short distance (Type A-1); 2) Both pebbles and matrix might be eroded and transported for a long distance from nearshore regions or might experience a sea-level rising process (Type A-2, Type B-1, Type C-1 and Type D); 3) Matrix might be transported from nearshore regions, and mixed with pebbles formed *in situ* (Type B-2, Type C-2); 4) Pebbles might be eroded and transported from offshore regions, and mixed with *in situ* matrix (Type E). Based on the systematic analyses of sedimentology of the Gushan Formation, 8 rock types were also recognized, and were grouped into 3 rock associations, the shaly basin, the deep subtidal and the shallow subtidal rock associations.

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