BIOPETROLOGY

Research Report

Earliest calcified green algae from the 520 Ma old Cambrian dolostones in Xinjiang, China

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Abstract

The oldest known calcified green algae are the dasycladalean *Vermiporella* from the Middle Ordovician of North American and Scotland. Though several dasycladalean-like fossils were reported from the Cambrian, their affinity of green algae is not confirmed. Here we reported abundant small calcified fossils from the 520 Ma old dolostones of early Cambrian stage 3 in the Tarim Basin, NW China, which possess all critical characteristics of typical calcified dasycladaleans, such as a central cavity, numerous lateral pores and a microstructure of granular calcite. They are similar to *Vermiporella* in morphology and size, and to the extant calcified dasycladalean *Bornetella* in growth form, with a subspherical, mushroom-like, rod-shaped, or clavate thallus, and which should be assigned to a new genus, *Tarimporella* gen. nov. Discovery of these fossils reveal the morphology and internal structures of the ancestral calcified green algae, and represent an important evolutionary event following the rise and fall of small shelly fossils in the early time of the Cambrian.

Key words: **dasyclad, calcified green algae, early Cambrian, Tarim Basin**.

1 Introduction

Green algae, a group of algae always in a bright green color and resembling higher plants in having chloroplasts and being able to produce the same starch through photosynthesis, are in various microscopic or macroscopic irregular, filamentous, or plant-like forms, and are generally regarded as the ancestors of all present-day green plants. Paleontologists are seeking the earliest fossils of calcified green algae, the ancestors of modern green plants. Generally, only calcified green algae tend to preserve as fossils, and non-calcified types do not leave fossils except for preservation in special environ-

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ments. Calcified green algae refer to those having the capability of secreting a calcareous coating on the outer side of the mucilaginous envelope (Wray, 1977; Liu, 1990). After the soft parts are decayed out, the calcified parts are preserved in deposits as fossils. All Modern calcified green algae belong to two groups, Codiales and Dasycladales. The thalli of the former are composed of filaments that stretch parallel to the thalli in the axial part and turn perpendicular to the surface in the surface part. The thalli of the latter group are composed of a main axis and numerous lateral branchlets that are commonly perpendicular to the main axis.

The earliest non-calcified fossils resembling green algal Dasycladales occur in the upper Precambrian Sparagmite group in Southern Norway (Spjeldnaes, 1963), and are similar to calcified Dasycladales *Vermiporella* in shape and size, even though accurate age of the surrounding rock is unknown. Zhang (1979) reported a possible Dasycladales fossil from the chert layer of the 1450 to 1550 Ma old Wumishan Formation in northern China, which consists of main axis and lateral branchlets, though it is of lower preservation quality and uncertain systematic position. Xiao et al. (2002) reported well-preserved carbonaceous fossils from the terminal Proterozoic in South China, which are very similar to modern green algal Dasycladales in clavate shape, though their assignment to Dasycladales is uncertain because of their flat and open instead of rounded and close terminal ends. The earliest certain green algal fossils with good preservation are from Middle and Late Ordovician (Young et al., 2007; Lamsdell et al., 2017; LoDuca, 2018).

Though it is questionable, the oldest report of Dasycladales are the *Cambroporella* (Korde, 1950) and *Kordesphecia* (Peel, 2014) from the Early Cambrian. Some authors regarded *Cambroporella* as a green algal Dasycladales (Bassoullet et al., 1979), but most authors suspect its placement in this group (Berger and Kaever, 1992; Zhuravlev et al., 1993; Riding, 1991, 2001). Since *Cambroporella* has a double-walled calcareous coat, a feature that has not been observed in other Dasycladales, Elias (1954) and Berger and Kaever (1992) believed that it was more similar to bryozoans than Dasycladales. For the same reason, we reject this genus a calcified dasycladales. The holotype of *Kordesphecia nyeboensis have* lateral pores being rhombic in cross section, a feature that has not been observed in any modern and fossil dasycladales. Thus its affinity of Dasycladales can't be confirmed.

Up to now, the indubitable calcareous Dasycladales fossils are the *Vermiporella* and *Kazakhstanelia* from the Middle Ordovician (Roux, 1991). Here we report typical calcified green algal Dasycladales fossils from the Early Cambrian of the Tarim basin, Xinjiang, China.

2 Stratigraphy and methods

The studied materials are collected from two Lower Cambrian sections at Penglaiba and Shiairike, Aksu, Tarim Basin, Xinjiang, China (Fig. 1A). The two sections are divided into three formations in ascending order, the Yuertusi, Xiaoerbulake, and Wusonggeer. The Xiaoerbulake Formation in the two sections is composed of thrombolitic dolostone in its lower part and dolograinstone in its middle part, and stromatolitic dolostone in its upper part. Calcified green algal fossils are from the dolograinstone.

The trilobite *Shizhudiscus* (=*Tsunyidiscus*) *sugaitensis* occurs in the lower part of the formation, indicating an age of Cambrian basal Stage 3 (Zhang, 1981; Lin et al., 2004; Peng et al., 2012). *Tianshanocephalus tianshanensis* and *Kepingaspis kepingensis* from the middle part of this formation are correlated with the *Ushbaspis* of South China, indicating an age of basal upper Stage 3 (Peng,

2009; Peng et al., 2012). *Paokannia* sp. is present in the upper part of the formation, indicating an age of middle upper Stage 3 (Peng et al., 2012). The calcified green algal fossils are found in the middle parts of the formation of the two sections, and have an age of middle Stage 3 of Cambrian Series 2 (upper part of Atdabanian).

Samples were collected from the two sections at the intervals of 1 m. Thin sections of 5x7 cm size and 0.04 mm thickness were made and examined. Abundant microscopic rounded fossils are found in 32 thin sections, and comprise the grains of the dolomitic grainstone and dolomitic packstone. Due to the strong dolomitization, the original structures of the fossils have been mostly destroyed, features characteristic of Dasycladales are present in some of the fossils.

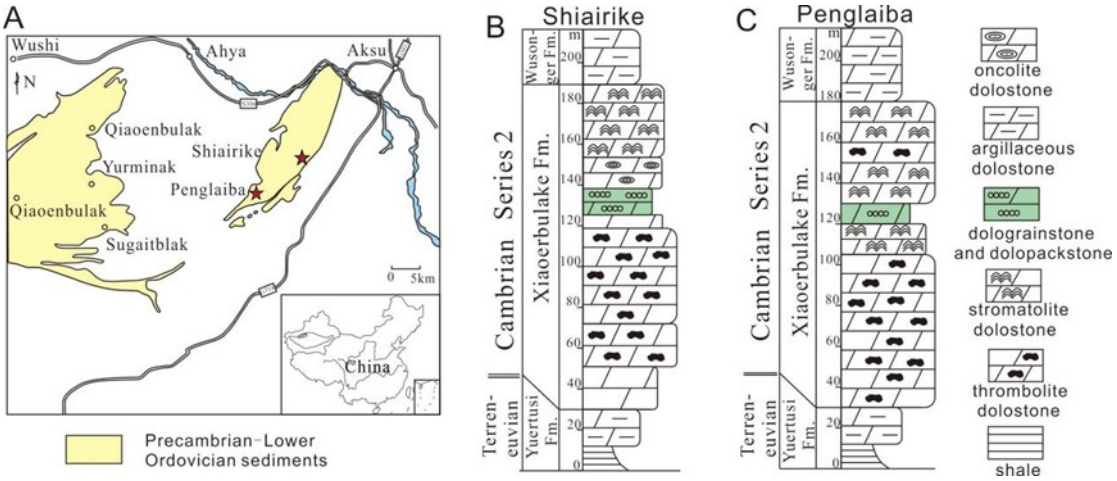

Fig. 1 Location (A) of the two sections yielding the earliest calcified green algal fossils, Shiairike (B) and Penglaiba (C), in the Tarim Basin, Xinjiang, China. Shiairike is after Yu et al.(2016). Penglaiba is after Yang et al. (2015).

3 Earliest Calcified green algal fossils from Tarim

Most of the fossils are rounded in thin sections, with some in triangular or elliptical shapes (Fig.2 A-D). The rounded sections are the random cuts of spherical fossils, or cross sections of columnar fossils, whereas the elongate sections the longitudinal sections of columnar fossils, and the triangular sections the vertical sections of mushroom-like fossils. Simple statistic shows that the spherical and ellipsoidal sections account for 90% and 80% of the fossils, and columnar and mushroom-like for 10% and 20%, respectively. Thus most of the fossils are spherical, with some in columnar and mushroom-like in forms. The three forms, spherical, columnar, and mushroom-like, are all present in modern and fossil Dasycladales (Berger and Kaever, 1992).

A common form in modern and fossil calcified green algal Dasycladales is bead-like, consisting of spherical segments linked by non-calcified connections. After death and decay of the connections, the spherical segments lie scattered on the seafloor. Due to the presence of two non-calcified ends for each segment, sections passing the vertical axis of a segment should be hallow and hemispherical in form. Since there are no hemispherical sections in the thin sections, no beaded types are present.

Measurement shows that the fossils from the Shiairike section range 0.2 to 0.8 mm in diameter. The spherical and ellipsoidal fossils range 0.2 to 0.7 mm in diameter, usually 0.3 to 0.5 mm, and those

in other forms range 0.4 to 0.8 mm in diameter, generally 0.4 to 0.6 mm. The fossils from the Penglaiba section range 0. 2 to 0.7 mm in size. The spherical and ellipsoidal fossils range 0.2 to 0.7 mm in diameter, usually 0.3 to 0.5 mm, and those in other forms range 0.3 to 0.5 mm in diameter.

The diagnostic feature of the fossils is the presence of a central cavity that is generally filled by dolomite cement, enclosed by a thick "wall". There are numerous thin pores penetrating the "walls" (Fig. 2B, D) and being generally perpendicular to the outer surface of the fossils. Though the pores in most of the "walls" have been destroyed by diagenesis, some are left.

The wall pores range from 0.04 to 0.07 mm in length and 0.004-0.006 mm in width in the fossils from the Shiairike section, and 0.04 to 0.12 mm in length and 0.004-0.006 mm in width in the fossils from the Penglaiba section. The ratio of the diameter of the central cavity to the outer diameter of the fossils is 0.5 to 0.9 for the fossils from the Shiairike section, and 0.5 to 0.8 for the fossils from the Penglaiba section.

Even though the rock is dolomitic, the wall, the interior of the fossils and the matrix between the fossils show different fabrics. The interior of the fossils is filled by coarse blocky dolomite, the wall composed of fine dolomites, and the matrix is micritic. Thus, the dolomitization is of mimic type, which alters the mineral composition but keep fabric. Since the walls are not micritic, it is inferred that the wall is originally composed of coarser minerals, such as granular calcite. It is inferred that the interior is originally empty, and was filled by dolomite cement during late dolomitization.

Thalli of modern green algal Dasycladales consist of a main axis and the numerous lateral branchlets that arise from and are perpendicular or oblique to the main axis (Berger and Kaever, 1992). The branchlets are branched or non-branched, generally rod-like, and are in different arrangements, numbers, and forms. Calcifications occur in some modern Dasycladales, by precipitating a coating of needle-like aragonite (<5μm) on the surfaces of the main axis and branchlets. Under normal conditions, the thalli will decay out after death, leaving the central cavity by the main axis and the lateral pores by the branchlets. Both the central cavity and branchlets are enveloped by the calcareous coating, and only the coating can be preserved as fossils.

Almost all coating fossils in the Paleozoic, Mesozoic, and Cenozoic are composed of granular calcite (Kirkland and Chapman, 1990; Mu, 1991; Wu, 1991a, b; Bucur, 1999; Riding and Fan, 2001; Senowbari-Daryan et al., 2011; Liu et al., 2012; Bucur et al., 2016). This is because the aragonite is

Table 1 Measurements (D=the outside diameter of the fossil; d= the inside diameter; L=the length of the wall pores; W=the width of the wall pores) of the calcified green algal fossils from the Cambrian Shiairike and Penglaiba sections and those of the Ordovician *Vermiporella* from the Tazhong area of the Tarim Basin

Fossils	Shape	D (μm)	D (μm)	d/D	L (μm)	W (μm)
Cambrian Shiairike	spherical, ellipsoidal or tubular	200-800	120-680	0.5-0.85	40-70	4-6
Cambrian Penglaiba	spherical, ellipsoidal or tubular	200-740	100-620	0.5-0.83	40-120	4-6
Ordovician *Vermiporella*	curved tubular	320-870	200-640	0.5-0.83	40-140	10-20

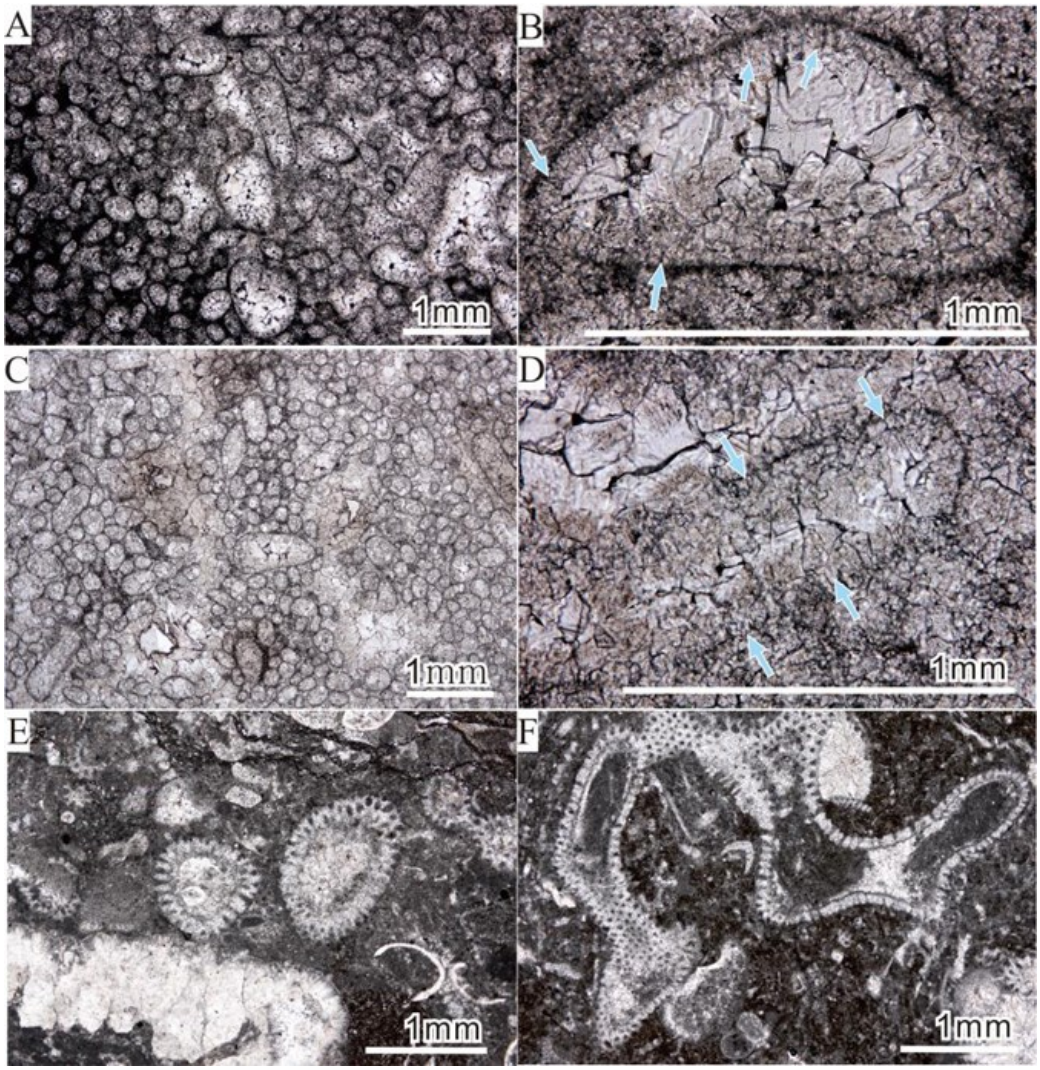

Fig. 2 Calcified green algal fossils from the Cambrian Series 2 Stage 3 of the Tarim Basin, Xinjiang, China, with a wall enclosing a central cavity and numerous pores (pointed by arrows) penetrating the wall. (A) from the Shiairike section; (B) a mushroom-like fossil from the Shiairike section. (C) from the Penglaiba section; (D) a columnar fossil from the Penglaiba section. (E) *Vermiporella*, cross section, from Well 822 at the Tazhong area of the Tarim Basin. (F) *Vermiporella*, longitudinal section.

unstable, and generally turns to granular calcite during later diagenesis.

The typical Dasycladales fossils are characterized by a "wall" enclosing a central cavity and numerous lateral pores penetrating the "wall" and perpendicular or oblique to the central cavity. Modern calcified Dasycladales skeletons as well as Dasycladales fossils can be spherical, rod-like, clavate, and catenulate in form, and range from less than 1 mm to more than ten mm in diameter.

Thus, the essential features of Dasycladales fossils include: (1) the construction of a "wall" enclosing a central cavity and numerous lateral pores penetrating the "wall" and connecting with the central cavity, (2) the microstructure of the wall is granular calcite, (3) sizes, and (4) shapes. A typical representative of Dasycladales fossils is *Vermiporella* (Fig. 2E, F), which has been reported from the Ordovician of many areas around the world (Bian and Zhou, 1990; Liu et al., 2012; Zhang et al., 2014).

The Tarim Cambrian fossils possess the above four features. In addition, their measurements in-

cluding the outer diameter of the skeleton, the diameter of the central cavity, the length and width of the lateral pores, as well as the ratio of the central cavity diameter to the skeletal outer diameter are very similar to those of *Vermiporella* (Table 1), and the skeleton may be originally composed of granular calcite. Thus, these fossils are assigned to the calcified green algal Dasycladales.

The Tarim Cambrian fossils differ from *Vermiporella* in their unbranched thalli, and are assigned to a new species of a new genus, *Tarimoporella globia* gen. et sp. nov. It is characterized by a spherical, or columnar or mushroom-like skeleton ranging from 0.2 to 0.8 mm in size, a rounded central cavity ranging from 0.1 to 0.7 mm in diameter, and numerous unbranched, cylindrical lateral pores ranging from 0.04 to 0.12 mm in length and 0.004 to 0.006 mm in width. Modern calcified green algal Dasycladales attach to sea floor with a non-calcified rhizoid. *Tarimoporella globia* gen. et sp. nov. is inferred to live in the same mode (Fig. 3).

Since the previously-reported earliest questionable Codiales fossil, *Palaeoporella*, was from the Late Cambrian, and the earliest unquestionable Codiales fossil, *Dimorphosiphon*, was from the Ordovician, the Dasycladales fossils from the Tarim Cambrian sections are the earliest calcified green algae.

The discovery of these fossils provides valuable information about the morphology and construction of the ancestral calcified green algae, which represent an important evolutionary event following the rise and fall of small shelly fossils in the early time of the Cambrian.

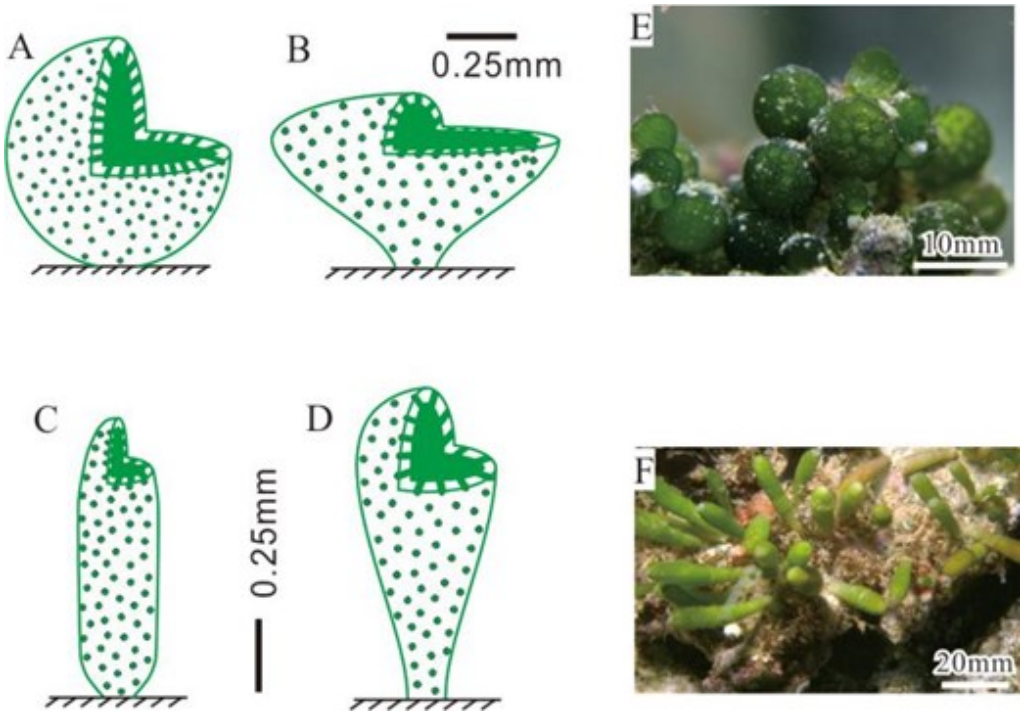

Fig. 3 Reconstruction of growth forms of the earliest calcified green algae, *Tarimoporella globia* gen. et sp. nov., from the Cambrian Series 2 Stage 3 of the Tarim Basin, Xinjiang, NW China. (A) Spherical, (B) mushroom-like; (C) rod-shaped; (D) clavate; (E-F) thalli of modern living dasycladaleans (Guiry and Guiry, 2019) *Bornetella sphaerica* (E) and *Bornetella oligospora* (F).

4 Systematic paleontology

The thin sections described here are housed in the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing.

Division Chlorophyta

Order Dasycladales Pascher, 1931

Family Seletonellaceae (Korde, 1950) Bassoullet et al., 1975

Tribe Dasyporelleae (Pia, 1920) Bassoullet et al., 1979

Genus *Dasyporella* gen. nov.

Type species *Tarimoporella globia* gen. et sp. nov.

Diagnosis: Thalli can be spherical, mushroom-like, rod-shaped, and clavate in shape, small (< 1 mm), with a small (< 0.7 mm), rounded central. There are numerous unbranched cylindrical lateral pores perpendicular to the surface of the thallus, which are very thin (< 0.006 mm in width).

Tarimoporella globia gen. et sp. nov.

(Fig. 2: A, B, C, D)

Description: The skeletons are spherical, columnar, and mushroom-like in shape, range from 0.2 to 0.8 mm in size, have a rounded central cavity ranging from 0.1 to 0.7 mm in diameter. There are numerous unbranched, cylindrical lateral pores penetrating the wall and perpendicular to the surface of the skeletons. The lateral pores range from 0.04 to 0.12 mm in length and 0.004 to 0.006 mm in width.

Occurrence: The Stage 3 of the Cambrian System, at Shiairike and Penglaiba, Aksu, Xinjiang, China.

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Comment by Santanu Banerjee:

The manuscript is significant as it reports as one of the earliest calcareous green algae.

Comment By Hong-Wei Kuang:

This paper describes the fossils that may be the oldest algae fossils. It is a new found on paleontology. The reliability of the new discovery is verified and the growth model is reconstructed. Therefore, it has high scientific value.

Comment By Fritz Neuweiler:

Most importantly, this studies requires the understanding of diagenesis. It is necessary to apply cathodoluminescence microscopy on these samples to make a point between primary ghost structures and products of diagenetic alteration (very evident from normal light micrographs alone).

Comment By Giorgio Bianciardi:

An important contribution in the paleobiological study of a form of life dating back to 500 million years ago.

Comment By Ya-Sheng Wu:

The interpretation as green algae of these structures is an important advance, since they occur in a special geological time, the Cambrian Stage 3, when the CambrianLife'sExplosion occurred. Because they are the main grains of the reservoirs of petroleum in the Tarim Basin, the identification of them is important to the understanding the reservoir strata. Thus, it deserves a quick publication. However, more research is needs, such as observation with a cathodoluminescence microscope.

Comment By Robert Burne:

An important contribution concerning the earliest report of Green Algae.

Innovation scored by: Dong-Jie Tang, Santanu Banerjee, Yue-Feng Shen, Hong-Wei Kuang, Fritz Neuweiler, Hua-Xiao Yan, G. W. Hughes, Giorgio Bianciardi, Robert Burne.

Innovation score (0-5): (5+3+0+3+3+5+5+5+5)/=3.8.

Detailed reviewed by: G. W. Hughes, Boguslaw Kolodziej, Qi-Jian Li.

Revised by: G. W. Hughes, Qi-Jian Li.

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