Available online at www.sciencedirect.com
ScienceDirect
Gondwana Research xx (2006) xxx–xxx
www.elsevier.com/locate/gr

World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life

Jianghai Li [a], Timothy M. Kusky [b,*]

[a] Department of Geology, Peking University, Beijing China
[b] Department of Earth and Atmospheric Sciences, St. Louis University, St. Louis, Missouri, USA

Received 5 April 2006; received in revised form 24 October 2006; accepted 31 October 2006

Abstract

Black smoker chimneys and biological vent communities have been identified at many sites on the deep seafloor, particularly along oceanic spreading centers. We report the largest and oldest known, microbe-rich sub-meter-sized black smoker chimneys and mounds from a 1.43 billion-year old sulfide deposit in a continental graben in northern China. These chimneys are especially well preserved, with characteristic morphology, internal textures and internal cylindrical mineralogical zonation. Four main types of chimneys are distinguished on textural and mineralogical criteria, exhibiting either Zn–Fe-sulfide or Pb–Zn–Fe-sulfide internal cylindrical mineralogical zones. The chimneys mark vent sites in submarine grabens indicating focused flow-venting processes. The fossil chimneys have mineralogical and geological evolutionary features similar to their counterparts on the modern seafloor and other submarine hydrothermal vents. Black smoker vent fluids and seafloor tectonism played important roles for formation of the massive sulfide deposits in the Mesoproterozoic.

We also report the first known, remarkably diverse assemblage of fossil microbialites from around and inside Precambrian vent chimneys, demonstrating that Proterozoic life flourished around submarine hot vents and deep within the chimney vent passages. Filamentous, spherical, rod, and coccus-shaped fossil microbes are preserved preferentially on sulfide precipitates. Based on the depth and setting of the fossil biota, the organisms that produced the microbialites were likely sulfate-reducing chemosynthetic and thermophyllic microbes. Textural and mineralogical evidence shows that biomineralization processes enhanced chimney growth and sulfide precipitation.

Close association of microorganisms with sulfide chimneys in modern deep-sea hydrothermal vents and younger ophiolites has sparked speculation about whether life may have originated at similar vents. However, little is known about fossil equivalents of vent microfossils and black smoker chimneys from Earth's early evolution. The fossilized microorganisms from the Gaobanhe black smoker chimney sulfide deposits include thread-like filaments with branching and twisted forms and preserved organic carbon, representing fossilized remnants of microbial mats metabolized at high temperatures characteristic of venting fluids. The preservation of fossil microorganisms provides evidence that microbial populations were closely associated with black smoker chimneys in Earth's early history. The microbial population clearly constitutes the site for mediating mineral formation. These ancient microbial fossils lead to a much better understanding of early life on the deep seafloor. The discovery of the Mesoproterozoic microfossils within black-smoker hydrothermal chimneys indicates that hydrothermal activity around sea-floor vents supported dense microbial communities, and supports speculation that vent sites may have hosted the origin of life.
© 2006 International Association for Gondwana Research. Published by Elsevier B.V. All rights reserved.

Keywords: Precambrian; China; Microbialite; Black smoker chimney; Origin of life

1. Introduction and geological setting

Active submarine hydrothermal vent systems and black smoker chimneys have been the subject of multidisciplinary research since their discovery in the 1970's (Hekinian et al., 1980; RISE Project Group, 1980; Rona and Scott, 1993, Scott, 2002). Deep-sea hydrothermal vents host the most primitive thermophyllic, chemosynthetic, sulfate-reducing organisms known, believed to be the closest relatives of the oldest life on Earth, with similar vents having possibly provided nutrients and protected environments for the first organisms (Jannasch,

* Corresponding author.
E-mail address: tkusky@gmail.com (T.M. Kusky).

1342-937X/$ - see front matter © 2006 International Association for Gondwana Research. Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.gr.2006.10.024

ARTICLE IN PRESS

1985; Travis, 1993; Farmer, 2000; Davies, 2001). It is therefore of special interest to identify ancient Precambrian fossil chimneys in the geological record and compare them with modern analogs. Although fragments of sulfide chimneys have been identified in several ancient deposits (Scott, 1981; Oudin and Constantinou, 1985), remarkably few intact chimneys larger than 1 cm in height are preserved because of their tendency to collapse on the seafloor and become incorporated in hydrothermally and structurally reworked sulfide mounds (Hannington and Scott, 1988). Therefore, little is known about ancient chimneys and their role in the origin and development of life throughout geological history. Here we report well-preserved chimneys and fragments up to half a meter long from Precambrian sulfide deposits in North China. Microbialites grew around and inside these chimneys, posing new exciting questions for research on mineralization and ancient biological activities under extreme conditions.

The fossil chimneys and microbialites are identified 150 km east of Beijing (Figs. 1 and 2), in the Mesoproterozoic Gaobanhe Massive sulfide, a polymetal deposit displaying an upward zonation from pyrite to Zn–Pb-sulfides, formed in a fault-controlled graben (Kusky and Li, 2003). Mineralization is dated at 1.425 Ga by the galena isochron method and 1.487 Ga by a Pb–Pb whole-rock isochron (Feng and Zhang, 1985; Bai, 1993). Chimneys grew from and project out of mounds of sulfide talus and breccia that are cut by abundant sphalerite veinlets. Fragments of pyrite conduits and chimneys are common within sulfide mounds, which probably formed through collapse of larger chimneys. Smaller chimneys are commonly buried with intact morphology, whereas large chimneys are fragmented within massive sulfides.

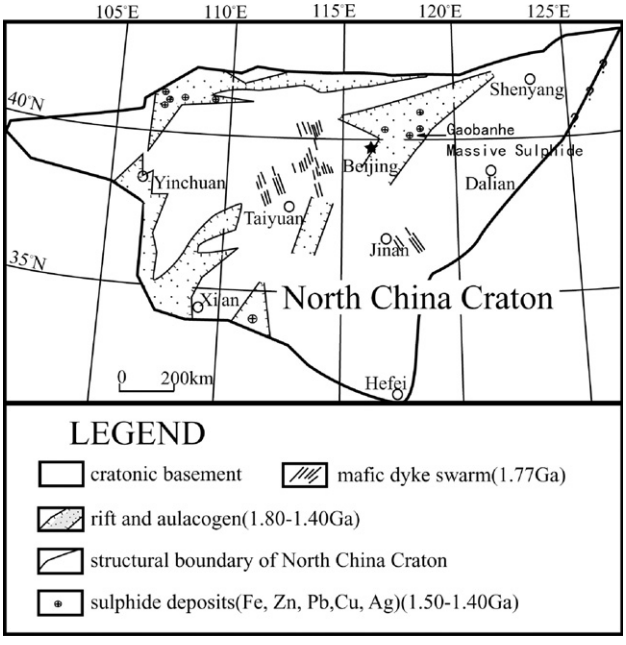


Fig. 1. Tectonic map of North China Craton in the early Mesoproterozoic (1.85–1.40 Ga) showing distribution of sulfide deposits and location of Gaobanhe fossil chimneys.

2. Description of fossil black smoker chimneys

2.1. Morphological classification and internal mineralogical zonation

We classify the chimneys of Gaobanhe into four morphological types with different geological associations. These include large columnar chimneys (Fig. 3a, b), conical chimneys (Fig. 3c, d), small columnar chimneys (Fig. 3e), and round to bulbous blister-like chimneys (Fig. 4). Many of the chimneys are built on larger associated mound structures. Pb–Zn–Fe-sulfide mineralogical zonation tends to be found in conical and columnar chimneys, whereas chimneys with simple Zn–Fe-sulfide mineralogical zonation tend to be smaller mini-cones, located on the margins of larger chimneys, and merge with broader porous mound structures.

Large columnar chimneys include fragments 5–50 cm in diameter, with unknown original heights (Fig. 3a, b). Vertical pipes a few tens of centimeters high and 30 cm in diameter are also recognized. Most large chimneys are preserved as collapsed flat-lying fragments within thicker sulfide ores and friable fine-grained black sediments. They exhibit concentric mineralogical and textural zonation, and some chimneys consist of several coalesced conduits (Fig. 3f, g, h). Thus, some large chimneys may have grown from small vents through sustained hydrothermal activity. Many have an outer chimney wall of massive pyrite intergrown with marcasite, forming compact alternating layers of pyrite, mud, and carbonate, each 5–20 mm thick, associated with microbialites (see below). Dendritic crystals are distributed along the outer parts, indicating rapid crystallization due to rapid cooling under unstable conditions. The dendritic pyrite may be related to mixing and quenching of high-temperature fluid with cold seawater. Early formed marcasite is recognized within the sphalerite matrix. Some cavaties are filled by radiating aggregates of barite and silica, whereas other voids are filled by galena and colloform pyrite aggregates (Fig. 3e, f). Tightly clustered tabular voids are very common within outer walls, explained by replacement of sulfates by sulfides.

The core part of the chimneys are mainly composed of pyrite and the axial conduits are lined with euhedral sphalerite and pyrite (Fig. 3b, e, f, g, h). Central channelways are highly vesicular with irregular voids, infilled by crystalline galena. They branch downwards, and are interconnected gradually into complicated networks of channelways among breccias. Extensive and interconnecting voids in the lower core part of the chimneys become narrow and intricate tubes in the upper parts of the chimney where they are lined with rims of idiomorphic pyrite and quartz, or infilled with galena and carbonate. Relict marcasite included within pyrite can be recognized; colloform pyrites are also very common, locally replaced with spheroidal sphalerite. The colloform pyrites are in many places also overprinted by conduit-type euhedral pyrite crystals.

On the outer rim of the core zone, bladed crystals of pyrite pseudomorphs after barite are very common, plus dendritic pyrite crystals are also intergrown with galena (Fig. 3f). Euhedral crystals of sphalerite fill many voids. Fluid inclusion

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

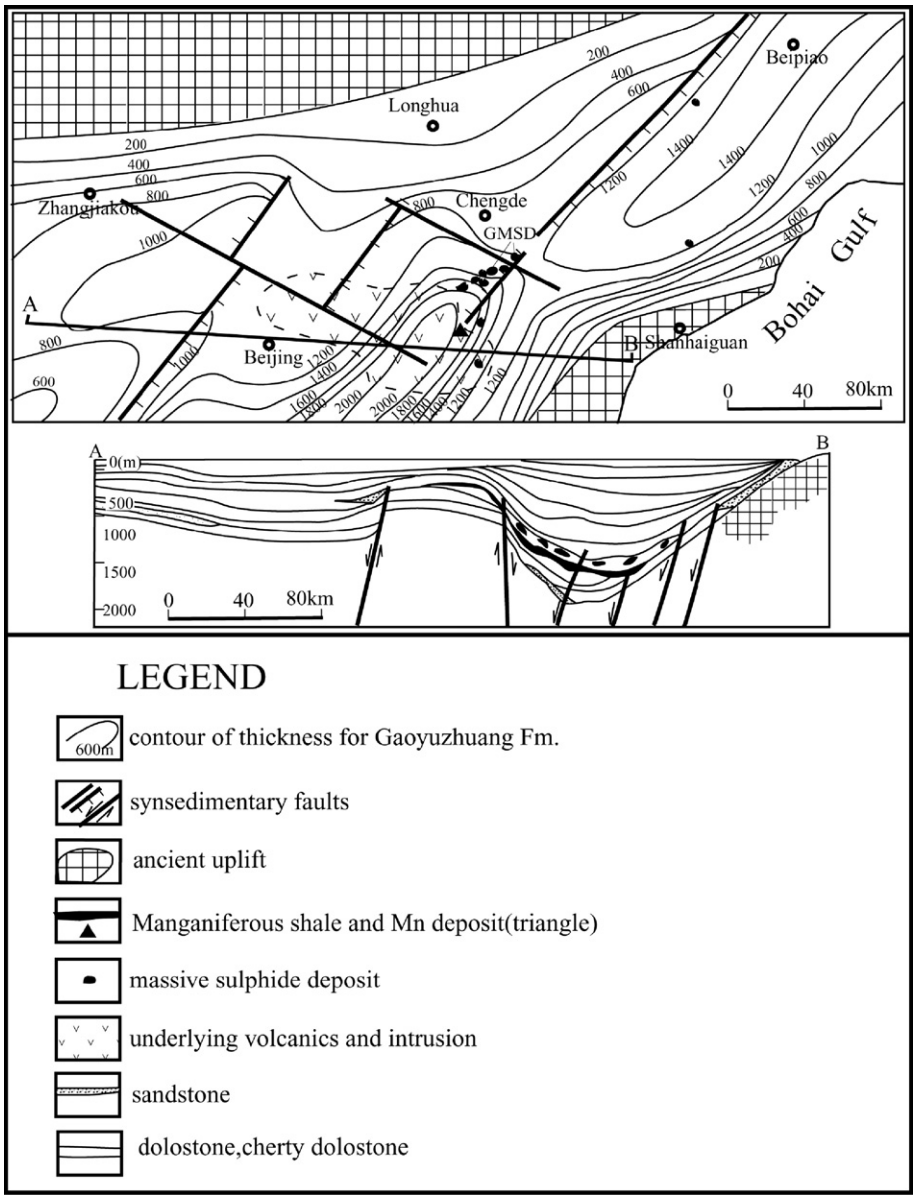


Fig. 2. Map showing the location of the Gabohane Massive Sulfide Deposit, and the tectonic and sedimentary evolution of Gaoyuzhung formation (1.50–1.40 Ga), Changcheng Group (a). Schematic cross-section for Gaoyuzhuang Formation (b).

evidence from quartz and galena–sphalerite record homogenization temperatures of 150° and 290–360 °C respectively (Feng and Zhang, 1985; Xia et al., 1999).

Conical chimneys with well-preserved orifices and axial conduits are the most common chimney type recognized (Fig. 3c, d). Smooth outer surfaces are made from colloform pyrite and marcasite, whereas delicate radiating crystalline pyrite and sphalerite decorate narrow axial channel networks filled with carbonate and silica in chimney cores. Low-velocity circulating fluids permitted inward crystallization (e.g., Fouquet et al., 1993; Binns and Scott, 1993). Coalesced conical chimneys are commonly buried or wrapped within layered Fe-sulfide ores, and underlain by sulfide mounds. Individual chimneys are 3–15 cm high and 3–10 cm in diameter at their base.

Lenticular layers consisting of pyrite pellets and fine-grained sphalerite occur around the summit of the vents of some conical chimneys. The pyrite pellets are clustered together in layers or scattered within a matrix of sphalerite. On top of chimneys, pyrite pellets are locally replaced by sphalerite. Pyritic pellets show distinct concentric layering, or radiating aggregates, with recrystallization in their cores. Two or three pellets may coalesce together. Some pellet trains can be traced to the interior of axial conduits and extend into depressions between chimneys.

The formation of pyrite pellets requires buoyancy to have free space for growth (Vearncombe et al., 1995). Pellets commonly occur above the exit of the chimneys, suggesting that they were discharged from vents. The ascending and turbulent flow of fluids rising from the vents at high velocity led to pellets being suspended and grown in the buoyantly rising black smoker fluids. The focused discharge was responsible for the local high rate of flow. The pyritic pellets deposited on the chimneys were gradually recrystallized toward the base of the

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

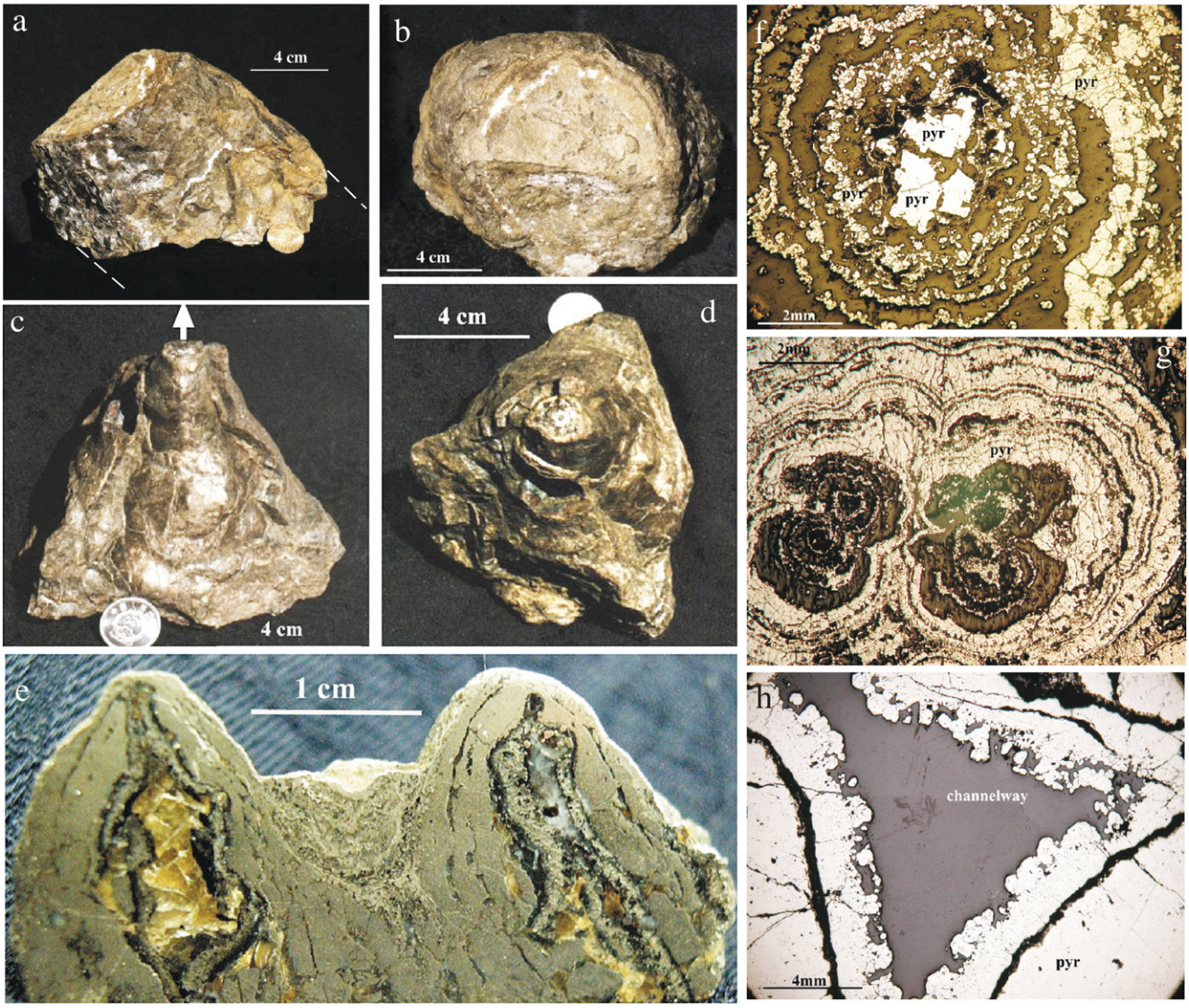


Fig. 3. Photographs showing typical columnar and conical chimneys. (a) Side view of a fragment of columnar chimney. (b) Top view of chimney in Fig. 2a, with concentric mineral zonation. (c) Lateral view of conical chimney with pinnacle. (d) Top view of conical chimney showing the central orifice preserved, same chimney as Fig. 2C. (e) A couple of relict chimneys with spire structures wrapped in sulfide ore. Vertical section of chimneys shows internal geometry, mineral zonation and central conduit. The central channel is lined with pyrite and filled by coarse-grained sphalerite and carbonate. (f) Cross-section of round chimney showing concentric zonation of textures and outer wall with rings of pyrite, and large euhedral pyrite in core. (g) Horizontal polished section through two merged conduits of conical chimney. (h) Detail of open channelway between pyrite grains.

accumulation, and their diameter increased. We suggest that the hydrothermal venting fluid provided the heat and chemicals for the recrystallization and growth.

Mud and carbonate sediments thicken in the depressions around chimneys, and typically exhibit slump folds on the flanks of the depressions. The interlayered pyrite pellets diminish in abundance away from summits of vents, supporting the idea that pellets were derived from venting of the chimneys.

Small columnar chimneys (2–5 cm high; 0.5–1 cm wide) with well-preserved central conduits (Fig. 3e) form clusters at the top of sulfide mounds and gradually merge upwards into conical or columnar chimneys with larger diameters. Fine-grained pyrite particles and debris were deposited in V-shaped depressions between chimneys; hydrothermal precipitates become narrow downward, controlled by the morphology of closely-spaced chimneys. Many of the small columnar sulfide chimneys show at least six concentric mineral zones, including an outer zone of pyrite particles, two zones of compact microcrystalline pyrite, a zone of coarse-grained euhedral to subhedral pyrite, and a central rod of coarse-grained sphalerite with galena and carbonate fillings (Fig. 3e). Delicate primary banding and colloform textures are preserved. Relatively tight inner conduits mark the location of former fluid channelways through the sulfide chimney (Fig. 3e), and the coarse-grained sphalerite and pyrite indicate a temperature increase and replacement in central parts of the conduits.

The porous outer walls of the small columnar chimneys consist of fine-grained to microcrystalline pyrite and minor relict marcasite; some voids were infilled with euhedral pyrite, and many are encrusted by microbialites (see below). The inner

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

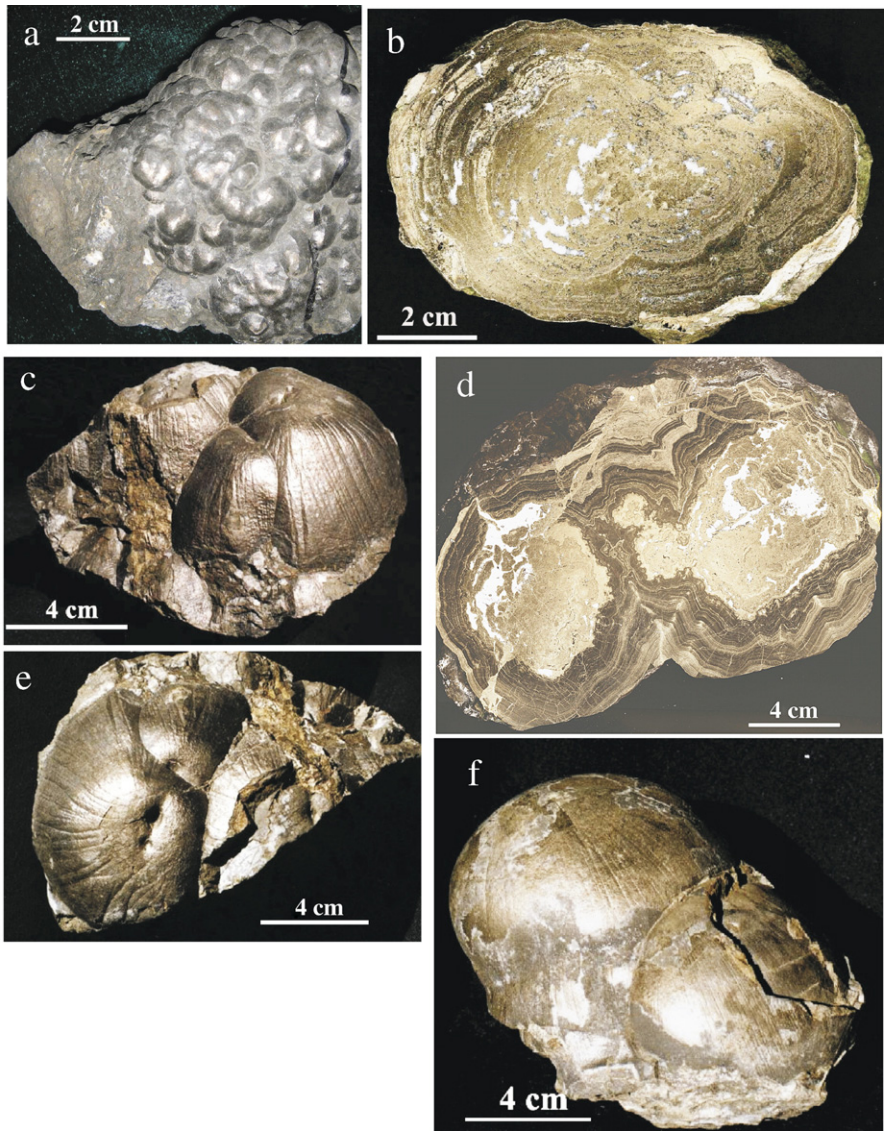


Fig. 4. Photographs of round chimneys. (a) Round chimneys preserved in sulfide ore bed. (b) Horizontal polished section through round chimney showing mineral zonation and carbonate-filled channelways in core. (c) Conical chimneys with coalesced structure; two individual conduits with central orifices can be recognized. (d) Horizontal polished section through two coalesced round chimneys, showing well-delineated core part and outer wall. (e) Top view of bulbous chimney in Fig. 3b, with well-developed orifice. (f) Lateral view of bulbous chimney with radial grooves.

sides of pyritic walls are very smooth and cohesive. In contrast, the outermost skin of chimneys exhibits a porous framework; they were built up and thickened by exterior precipitation of fine-grained pyrite at the interface between chimneys and seawater. Dendritic pyrite is very common in the chimney walls, with the presence of voids among fine-grained pyrite. The cavities are commonly lined with crystalline sphalerite, euhedral to subhedral pyrite, or filled with carbonate.

Near the center of the chimney, sphalerite and coarsely crystalline pyrite dominates the mineralogy and textures, with carbonate filling the pore spaces. Locally, the veinlets of sphalerite extend from the core and may cut across or seal outer walls of porous pyrite. Therefore, the circulation of hydrothermal fluids was responsible for recrystallization within conduits.

The typical morphology of a chimney and vertical axial conduit with mineral lining indicate that focused flow was responsible for its formation. The initial growth of the chimney is through fluid discharge and precipitation around vent sites, followed by circulation within axial channelways and thickening of the inner walls of the chimney. Late fluids were insulated in the conduits. The hydrothermal circulation resulted in the extensive recrystallization and replacement of core parts of chimneys.

Under high magnification in the microscope, some vertical narrow fissures are recognized with the summit of one chimney, which extend into and connected with the interior of the central conduit. On both sides of the fissures, they are rimed with crystalline pyrite, representing the original orifice of the chimney. They provided paths for and focused venting of hydrothermal fluid to the seafloor. As a result, the hydrothermal fluid was insulated within the chimney from the outside, to keep sharp redox and temperature gradients

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

ARTICLE IN PRESS

within the chimney wall. So, the core parts of chimneys were characterized by the crystallization and replacement of sulfides.

In addition, radially oriented microfractures are concentrated on the top zones of orifices, and propagated outward. They are commonly confined within separate zones of chimneys, rarely extending directly into overlying precipitated layers above chimneys. They branch upwards, or became infilled by carbonate or sphalerite, suggesting that they formed when the chimneys grew. The development of microfractures around the tops of chimneys can be explained as thermal fracturing and hydraulic forces exerted by active hydrothermal fluids (Haymon, 1983).

Depressions surrounding the small and large conical chimneys are typically filled with pyrite breccias with a sphalerite matrix, overlain by carbonate–mud intercalated with sphalerite and pyrite laminae. Pyrite breccias commonly coat or underlie the lower part of chimney walls. In the outer wall of the chimneys, radiating and tabular pyrite crystals intergrown with barite are preserved, and are interpreted to result from pyrite replacing sulfates. The debris among chimneys is derived from collapse or venting of sulfide chimneys, as some fragments of the chimneys can be recognized in the clasts. So, chimneys have grown on the base of sulfide breccias.

Laminated accumulations are found along fringe areas, and these gradually overlap the summit of the chimney upwards (Fig. 3c, e). Therefore, the presence of laminar beds records the initiation, development and extinction of the chimney, and final burial of chimney.

Bulbous to round chimneys with very smooth outer walls (Fig. 4) surround and underlie areas with columnar or conical chimneys, but are shorter than other chimneys. Round chimney cores exhibit high initial porosity, representing blisters of fluid that diffused to the surface. The tops of round chimneys are generally closed, smooth round domes along which lower-amplitude domes form blisters, while others have well-developed orifices (Fig. 4c, e). The outer wall forms a thicker laminated layer of colloform marcasite and pyrite, likely derived from venting and settling of sulfide particles from adjacent high-standing chimneys and their own diffusive flow. Cores are characterized by the development of channelways and voids, lined by euhedral radiating and bladed pyrite on the margins, with sphalerite and galena filling central voids. The voids are interconnected, with irregular shapes and blurred outer boundaries (Fig. 4b, d).

The size, height, and shape of chimneys grade from large columnar chimneys in the center of mounds to lower-relief conical or columnar chimneys and finally round chimneys, with many minor chimneys, at the margins. Larger chimneys are only recognized from thicker ores; thus, variations in chimney morphology partly reflect differences in maturity. Large columnar chimneys form through the coalescence of smaller chimneys, recording extended periods or multiple episodes of focused hydrothermal venting. Conical and round chimneys with porous cores represent complex interconnecting channelways that result from slow rates of hydrothermal flow, permitting growth and recrystallization in their cores.

2.2. Mound structures

Some chimneys can be vertically traced into brecciated sulfide mounds, within which various channelway networks and voids were utilized by at least two phases of hydrothermal fluids. Channelways are well preserved in a fine-grained pyritic matrix. Their porous core zones are filled with radiating pyrite or lined with euhedral crystals of pyrite and sphalerite. The voids are interconnected, with irregular shapes and blurred outer boundaries.

Channelway fillings are very irregular and narrow. They are defined and lined by euhedral radiating and bladed pyrite on the margins, with sphalerite and galena filling central voids. The pyrite fillings around channelways were recrystallized to form coarse and compact masses of crystals. They record the accumulation of sulfide particles from venting, followed by recrystallization.

The early fined-grained matrix was formed by rapid accumulation associated with focused flow, with formation of early chimneys. Later in the evolution of the mound, with blocking and collapse of early chimneys, new channelways formed through intense diffusive flow within the sulfide mounds, representing continuing thermal activity with recrystallization among chimneys.

3. Fossil vent microbial communities

3.1. Seafloor and subseafloor biota in the Precambrian

The discovery of deep-sea hydrothermal vents opens new areas for research on chemosynthetic bacteria, which are the primary producers of the hydrothermal ecosystem fueled by geothermal energy (Jannasch and Mottl, 1985; Rona et al., 1986; Prieur, 1997; Summit and Baross, 2001). The discovery of thriving biologic communities that ultimately derive their energy by chemically breaking down sulfur compounds has sparked speculation as to whether hydrothermal vents on the sea floor may have been the site of the origin of early life. Such speculation is supported by observations that the most primitive life forms on Earth, and closest living forms to the common ancestors of all life flourish at these sites, and that these organisms are chemosynthetic and thermophyllic. The microbial ecology of deep-sea hydrothermal vents may hold the key to understanding the very origin of life (De Ronde and Ebbesen, 1996; Russell and Hall, 1997; Mojzsis and Harrison, 2000; Reysenbach and Cady, 2001; Maruyama et al., 2002). Thus, the documentation of fossil black smoker chimneys and related microfossils are crucibles to probe the origin of life.

Previous studies were mainly limited to the surface of modern hydrothermal vent systems, while the subsurface habitats of hydrothermal vents have rarely been investigated (Kimura et al., 2003). Recent studies at modern vents on the seafloor indicate that microbes also inhabit the interiors of chimney structures, and are found to be very abundant inside the vents. Clouds of microbial material have been observed streaming out of vents during the early stages of vent eruptions (Haymon et al., 1993). Thus, microorganisms hosted by sulfide

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

chimneys on the seafloor suggest the existence of a subvent biosphere (Takai et al., 2001). Although modern vents are typically teeming with bacteria, the geological record of microfossils directly associated with sulfide chimneys is very sparse. Only a few examples of microfossils from hydrothermal sulfides are reported (Juniper and Fouquet, 1988; Little et al., 1999a,b; Halbach et al., 2002). Therefore, our understanding of microfossils from vent chimneys is actually quite limited. It is not clear if fossil equivalents have been preserved with ancient black smoker chimneys from the early evolution of Earth. Thus, research on Precambrian fossil black smoker chimneys may provide important constraints for elucidation of the characteristics of microbial communities that developed under extreme conditions during the early history of the Earth. Fossil black smoker chimneys are also very important to document the relation between microbial activity and mineralization (Russell and Hall, 1997; Zierenberg et al., 2000).

3.2. Macroscopic description of microbialites from Gaobanhe

Sulfide microbialites around the Gaobanhe chimneys include finely layered dome-shaped structures, morphologically similar to carbonate stromatolites (Fig. 5), except these are composed of sulfide minerals interlayered with organic carbon. They represent fossilized remains of microbial communities that lived around the hydrothermal vents 1.43 billion years ago. The sulfide microbialites are made of concentric cm-scale botryoids and columns of pyrite. Circular domains on horizontal sections through the sulfide microbialites (Fig. 5b) include vents, precipitated layers, and biological remains including cross-sections through domal laminae. Concentric growth laminae are preserved in organic remains, forming repetitive alternating dark colored carbon-rich layers and bright pyrite layers. Pyrite crystals precipitated within the lamina are enclosed in the cores of columnar laminae.

In vertical sections (Fig. 5c) microbialites are 5–10 cm thick, and composed of bright exhalative pyrite bands interlayered on a sub-mm scale with dark-colored aphanitic pyrite laminae rich in organic material and carbon (Fig. 5c). Individual columns are 1–2 cm high and 3 mm–1 cm in diameter. They are interpreted as remnants of microbial mats. The microbial laminates are overlain by several cm-thick laminated pyrite (Fig. 5d). Vertical sections of sulfide microbialites show characteristic thickening-upward cylindrical cm-scale cone-shapes and round, convex-upwards, wavy to crinkly laminations (Fig. 5c, d). Laminae are generally planar at the base of the column, but bend down abruptly near the upper column margins, forming a wall of support. Some columns branch and merge together. Most cones have an axial zone, suggesting that cone growth was controlled by upward mobility and intertwining of microbial filaments.

Branching sulfide columnar supports and filmy laminae in the sulfide microbialites create a complex framework with abundant voids representing fluid-filled channel structures. Channel walls are lined with coarse-grained pyrite, sphalerite,

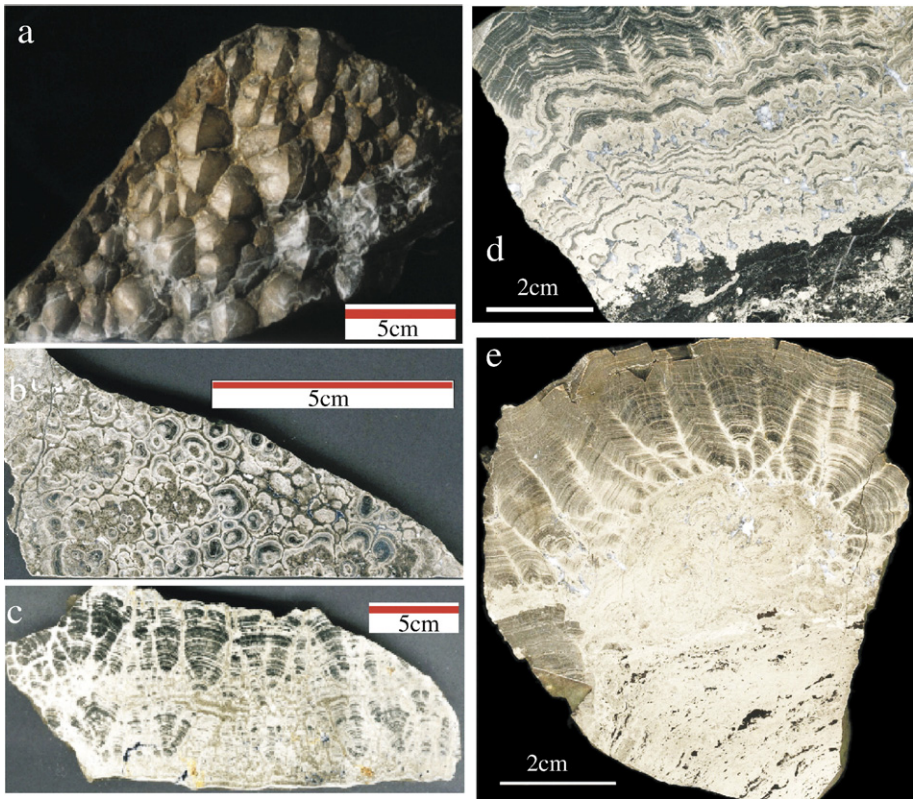


Fig. 5. Photographs of pyrite microbialites. (a) Top view of the sulfide microbialite, encrusted with elongate dome structures. (b) Vertical section showing pyritized lamination, concentric lines, and circular growth laminae. (c) Finely repetitive lamination and microstructure alternating with dark colored and bright pyrite layers. (d) Finely laminated microbial mat. (e) Sulfide microbialites that grew around pyrite breccia, showing pyrite in intercolumn areas.

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

ARTICLE IN PRESS

galena, and calcite. These minerals show concentric banding representing continued growth in the channels, indicative of mineral precipitation within the fluid conduit. Radially-oriented filamentous structures are common ornaments on the interior parts of channels. These mineral-filled channels show that the microbialites grew over an exhalative center and may have used vent fluids and dissolved metals for nutrients. The microbialites are attached directly on pyrite surfaces, suggesting that the fossilized organisms may have been sulfate-reducing, chemosynthetic, and thermophyllic.

The combined detrital and precipitated layers within the sulfide, such as laminae and pyrite crystals, demonstrates that the sulfide microbialites did not from through diagenetic thermal sulfide replacement of carbonate, but represent original exhalative and microbial structures. The columnar laminations are due to variations in the grain size of pyrite and compositional variations, indicative of a biological origin. Microscopic fossilized relict filamentous structures with pyrite are recognized, which may include preserved organic material produced by bacterial mats. Scanning Electron Microscopy (SEM) has revealed the presence of possible microbial microstructures within dark colored laminae (Fig. 6a–d). Clusters of well-preserved microbial spheres (Fig. 6e–f) are intimately interspersed within the filamentous remnants, recording former microbial activity associated with vent fluids. Elongate filaments are also well preserved (Fig. 6). Other possible traces of bacterial structures preserved with the sulfide microbialites include dense alternating laminae, single framboidal pyrite crystals, clusters of framboidal pyrite, and radiating and round aggregates of pyrite. Framboidal pyrite is commonly associated with bacteria in anoxic water sedimentary settings. Within the framboidal pyrite and radiating aggregates of pyrite, dense-concentrations of filamentous and laminated pyrite occurs on their crystal surfaces. Clearly, organic structures from a microbial community formed at the same time that the sulfide ore was precipitated. Large cavities are commonly associated with mat growth or decay of organic matter.

3.3. Microscopic, BSE and Raman spectroscopic analysis of fossilized microorganisms

All samples described here were collected from typical chimney-like structures of the Gaobanhe sulfide mining area (Xia et al., 1999; Kusky and Li, 2003). Petrography and SEM were used to determine textures and components of chimneys and their microfossils. Mineralogy was determined with electron microprobe and Laser–Raman spectroscopy.

Various traces of microfossils can be identified on a variety of scales ranging from hand specimen to thin section. Around sulfide chimneys, rich laminated sulfide microbiolites are distributed in original growth relationships, suggesting a genetic relationship between hot vent fluids and growth of the microbes. We concentrate our observations in the interior and outer walls of the chimney. Reflected light microscopy supports the existence of possible microfossils inside the chimneys and their upper sulfide layers (Fig. 7). Various morphological features are interpreted as micro-organic fossils. A wide variety of mat structures are preserved as mineral fabrics within iron sulfides, such as filaments and radiating aggregates of pyrites. The dense filamentous microbes with coated pyrite crystals become entombed within pores of chimneys (Figs. 7 and 8).

Fossil microbes have been found inside the chimneys, closely associated with voids in the outer wall and conduits in the chimney cores. These conduits may be traced to sulfide veinlets in the host rock, and are therefore interpreted as small microchannels initially connected with deep fluid channels. The conduits and voids are commonly rimmed by idiomorphic pyrite, filled with pyrite, sphalerite, galena and carbonate minerals, representing fluid-filled channel structures. The voids are filled with bladed and blocky calcite and pyrite. Within the porous sulfide of the chimneys, dense-concentrations of filamentous and laminated pyrite occurs on mineral surfaces, and typically project into the interior of the minor conduits. (Figs. 7 and 8).

Filamentous microtextures are very common, in which groups of filaments plug the pores and cavities within sulfide chimney, or are dispersed in the sulfide matrix of the chimney. The filaments form clusters and bundles of very similar size to form spongy textures. The presence of organic carbon in the filaments, surrounded by rims of pyrite, was confirmed by Laser–Raman spectroscopy (Fig. 9). A number of morphological features and components are interpreted as possible microfossils. High densities of microbial imprints and remnants of microbial filaments occur in the pores of iron sulfides, and as radial and bundle-like fibrous fabrics with fine-grained pyrite. Dense filaments often form coiled or irregular twisted morphologies. The filaments branch and twist in different directions, preserved by pseudomorphic replacement and overgrowths by iron-sulfide minerals (Figs. 7 and 8). Individual filaments may be straight, sinuous, curved or looped in form, very similar to fossillized microbial strands or filamentous archaea. As analysed by electron microprobe and Laser Raman spectroscopy, they are coated with fine-grained arsenopyrite aggregates, silica and dolomite, with late-stage subhedral to euhedral pyrite crystals formed among the filaments (Figs. 7 and 8). The filaments are also characterized by relatively high contents of organic matter, which may be produced by mats of microbial organisms. With the plugging up of vent conduits and pores by fossilized filaments and sulfide precipitation, the porosity in the core parts of chimneys decreased to form crystalline sulfide.

Thread-like filaments and irregular dendritic forms within pyritic sulfides are also very common, especially in other parts of the chimney. The filaments can be continuously traced from pores to the adjacent pyrite matrix, where they become degraded bundles within sulfides. They are interpreted to result from microbial community growth with venting (e.g., Rasmussen, 2000; Reysenbach and Cady, 2001; Takai et al., 2001).

At high magnifications small, branching filamentous structures coated with pyrite and carbonates are recognized, generally less than 30 μm in size, but ranging in length from a few micrometers to tens of microns (Figs. 7 and 8). They have straight to curvilinear and circular branching and twisting forms. Filamentous fabrics typically contain embedded pyrite

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

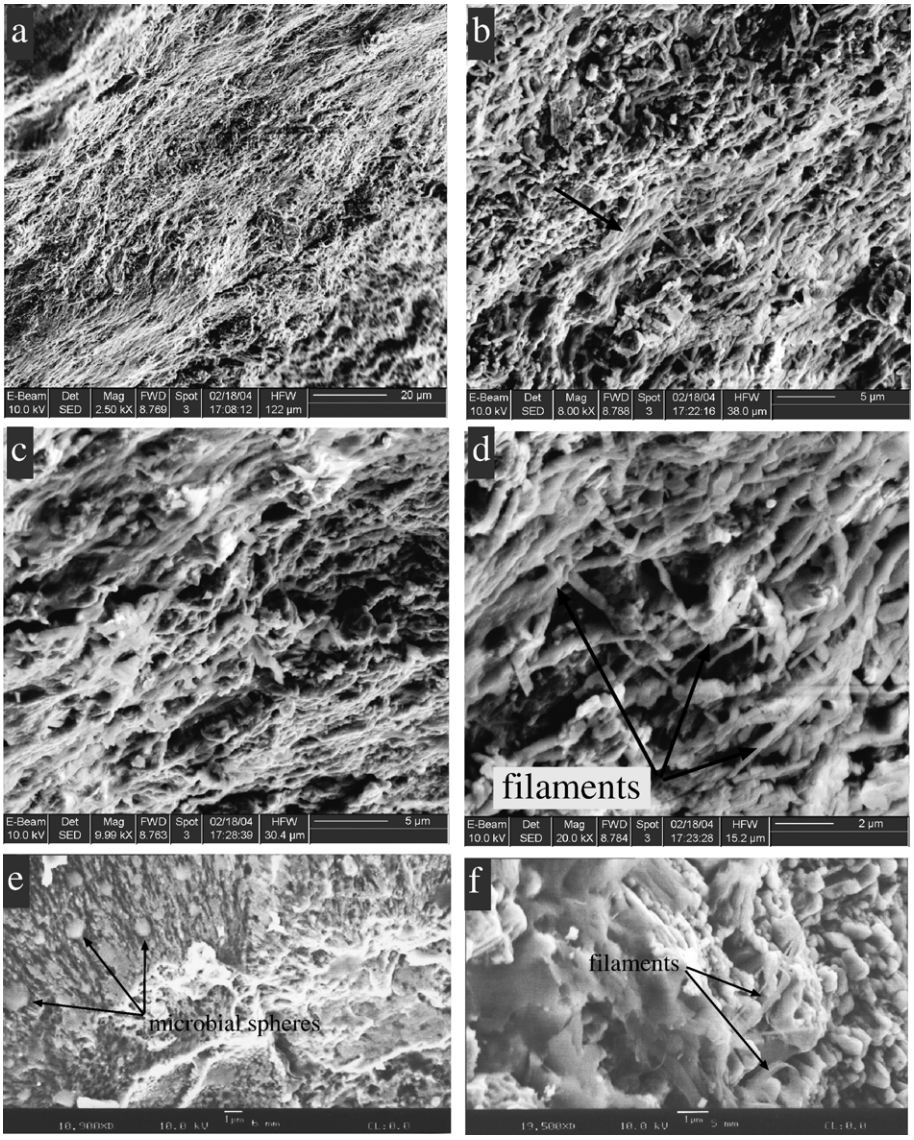


Fig. 6. (a–d). Scanning electron microscope images illustrating variations in filament morphology within sulfide chimneys of North China. The filaments form clusters and bundles of very similar size, with common twisting and branching morphologies. (e). SEM photomicrograph of clusters of fossil bacterial spheres intimately interspersed within the filamentous remnants of exopolymer matrix. (f) SEM photomicrograph of thread-like fossil filaments in Fe-sulfide.

minerals. Organic matter is generally associated with the microbial fossil organisms. Electric probe and Laser–Raman spectrum analysis reveal the outer surfaces of the filament to be composed of silica, iron oxide and pyrite (Li, Kusky and Chen, in prep.). They are encrusted with iron sulfides or replaced by carbonate.

The conduits presumably served as a channel for fluids and transported microorganisms to and from the subsurface environment. Clearly, organic structures from a microbial community formed at the same time that the sulfide ore was precipitated. They represent fossilized microorganisms formerly colonized inside the black smoker chimney, similar to those on the modern seafloor. They may be ejected to the sea floor from the subterranean environment when venting of the smoker proceeded. They may have used the vent fluids and dissolved metals for nutrients. Thus, it is inferred that the microbes grew over an exhalative center.

Samples were taken from both freshly fractured internal surfaces and polished thin sections of sulfide chimneys. Samples were observed under a high resolution Scanning Electron Microscope (Strata DB235 FIB of FEI company), with an operating voltage of 5 or 15 kV. Filamentous microtextures are clearly delineated by detailed SEM investigation. SEM has also revealed the presence of abundant filamentous microbes associated with sulfide microfossils within chimneys (Fig. 8). Most microorganisms display filamentous morphologies, although we have observed rod- and coccus-shaped members. Filaments exhibit curved, straight, single and branching morphologies. They commonly coalesce in discrete patches. Some of the clusters of microfossil-like features might be colonies, all have similar sizes and morphologies, and form carpets of fossilized cells. Morphologically, the filamentous bacteria appear identical or comparable to those described from modern and ancient hydrothermal sites (Juniper and Fouquet, 1988; Binns et al.,

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

1993; Hein et al., 1999; Little et al., 1999a,b; Rasmussen, 2000; Halbach et al., 2002). Some mats display a ropy structure (e.g. Fig. 8b), showing that they were once soft, organic material.

Well-preserved microbial fossils are now embedded in complex filamentous networks of pyrite and silica, or attached to surfaces of pyritic precipitates. Some filaments are replaced by pyrite forming replicas of cells. They have appearances typical of filamentous and rod-like microbes.

Bundles of well-preserved filamentous remnants are intimately interspersed within fine-grained pyrite and poorly crystalline spheres (Fig. 8), recording former microbial activity directly associated with hydrothermal venting fluids within chimneys. Fossil cells are mostly filamentous, ranging from 0.5 to 2.0 μm in diameter and up to tens of microns long. The vast majority of cells have dimensions of about 20–50 μm. The variation in microfossil size may be related to biomineralization and encrustation during their preservation (Reysenbach and Cady, 2001), as indicated by observations of modern hydrothermal vents. Thread-like filaments are commonly twisted or coiled, resembling modern vent bacterial biofilms with comparable sizes and morphologies (Binns et al., 1993; Hein et al., 1999). Dense microbial communities may have been supported by ancient hydrothermal venting.

Microscopic examinations and Raman spectroscopy clearly show that the observed filaments have organic carbon and are biogenic in origin, retaining intact morphologies that record rapid preservation by mineralization around sea-floor hydrothermal vent settings. Preliminary research suggests that bacterial mats are encrusted and replaced by metal sulfide minerals and silica. Encrustation of individual cells and filaments within the mats indicate that bacterial filaments act as nucleation sites for precipitation of sulfide. Biofilms appear to excrete a conditioning polymer around them, which serves as templates or nucleation surfaces for mineral precipitation and trapping (Konhauser, 1998; Reysenbach and Cady, 2001). Thus, microbial populations played a role in mineral precipitation, and they clearly constitute sites for mediating mineral formation around black smoker chimneys.

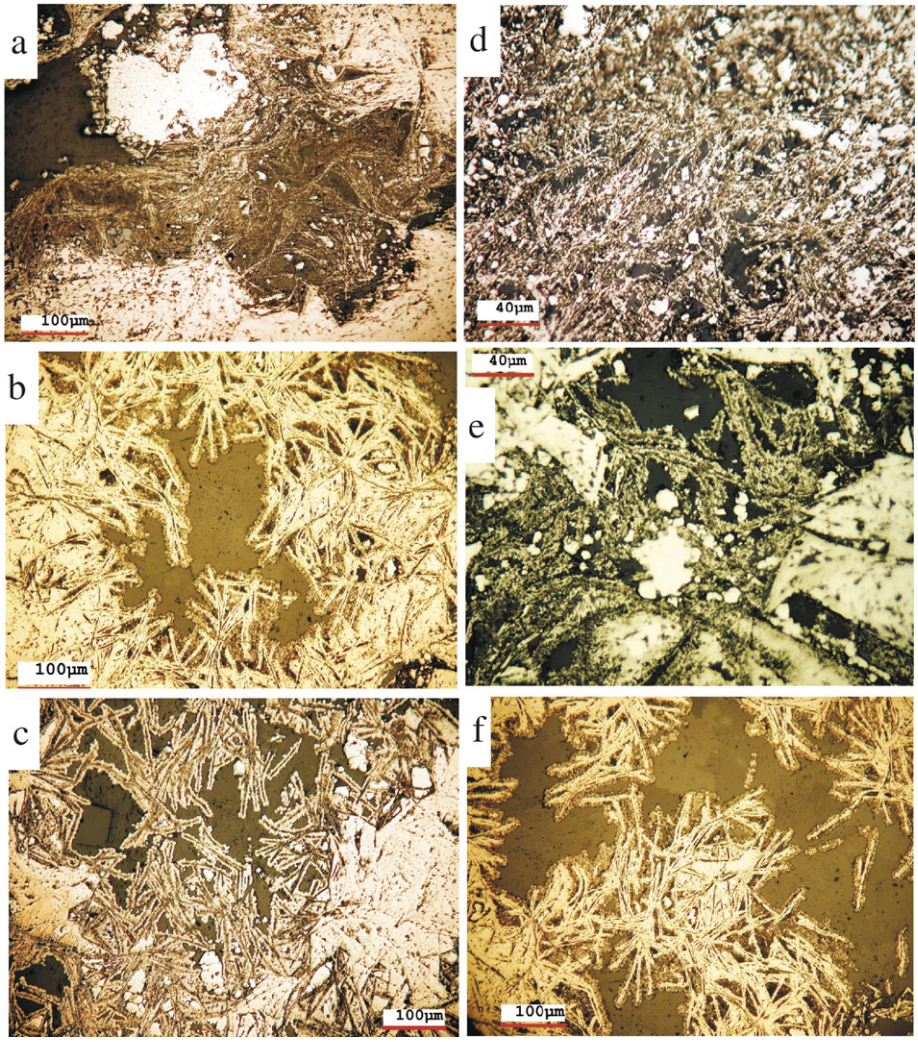


Fig. 7. Digital optical photomicrographs showing filamentous microbial fossils in petrographic thin sections of Mesoproterozoic sulfide chimneys. Filamentous fabrics entombed within pores of chimney (a, b, c, d, e). Dense-concentrations of filamentous fabrics often project into the interior of the minor conduits (b, c, d, e, f, g). The voids are commonly rimmed by idiomorphic pyrite, and filled with carbonate (h, i, j, k). The branching filamentous structures are with coated pyrite crystals, silica and carbonate (l).

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

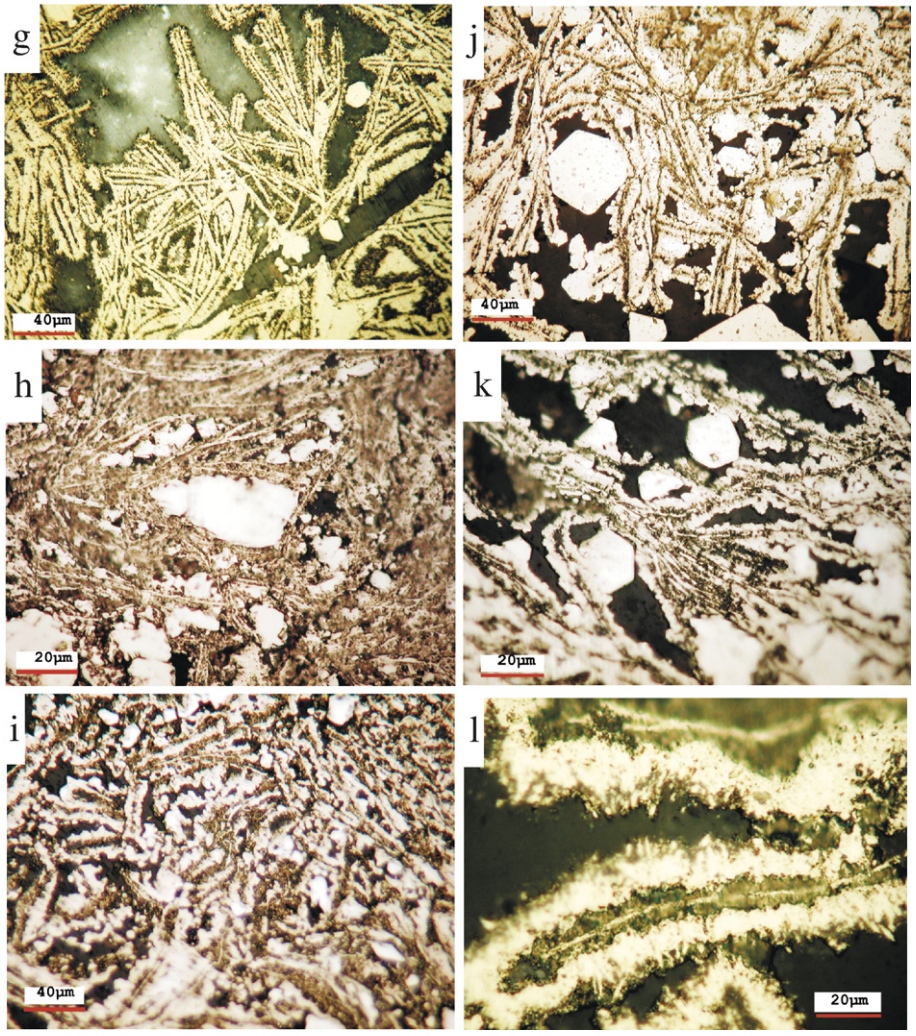


Fig. 7 (*continued*).

3.4. Discussion of sea floor and sub-sea floor biota in the Precambrian

We have documented the presence of microbial remains within Precambrian sea-floor black smoker chimneys of north China, including microfossil morphologies and organic carbon. Furthermore, we have shown that these early primitive organisms influenced and left a biological imprint on sulfide mineralization, including a high content of organic carbon within related sulfides. This is the first reported occurrence of microfossils inside ancient sulfide chimneys. Recognition of filamentous microbes is an important step to document the nature of microbial activity and processes associated with the development of life and mineralization around deep-sea chimneys.

As indicated by petrological and SEM observations, fossilized microbial filaments and exopolymers are well preserved both within the porous structures and matrix, the interior of sulfide chimneys, and the surface layer at the top part of the chimney. The observations reported here provide the first evidence that microbial organisms inhabited the environment within ancient hydrothermal vents in deep water basins of Mesoproterozoic grabens, and that the organisms are morphologically quite similar to filamentous thermophiles at modern hydrothermal vents (Reysenbach and Cady, 2001). These fossils provide crucial clues for the existence of a subvent biosphere in the early evolution of the Earth. From observations of these microbial fossils and comparison with modern analogs on the sea floor, we may achieve a better understanding of microbial ecology of ancient sulfide chimneys.

As mineralizing environments, hydrothermal systems have the potential to preserve evidence of biogenic activity including microfossils within sulfide chimneys. The dense microbial mats formerly colonized in the chimney structures may be preserved by rapid overgrowths or replacement of filaments by iron-sulfides.

Thick dense layers of filamentous bacteria grow on the sediment surface near hydrothermal vents in modern subaquatic environments, such as in the Manus Basin, Lake Bakail, the East Pacific Rise, Atlantic ridge, and central India Ocean (Jannasch et al., 1989; Delaney et al., 1992; Fortin et al., 1998; Kelley et al., 2001; Kimura et al., 2003). The bacteria grow in

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

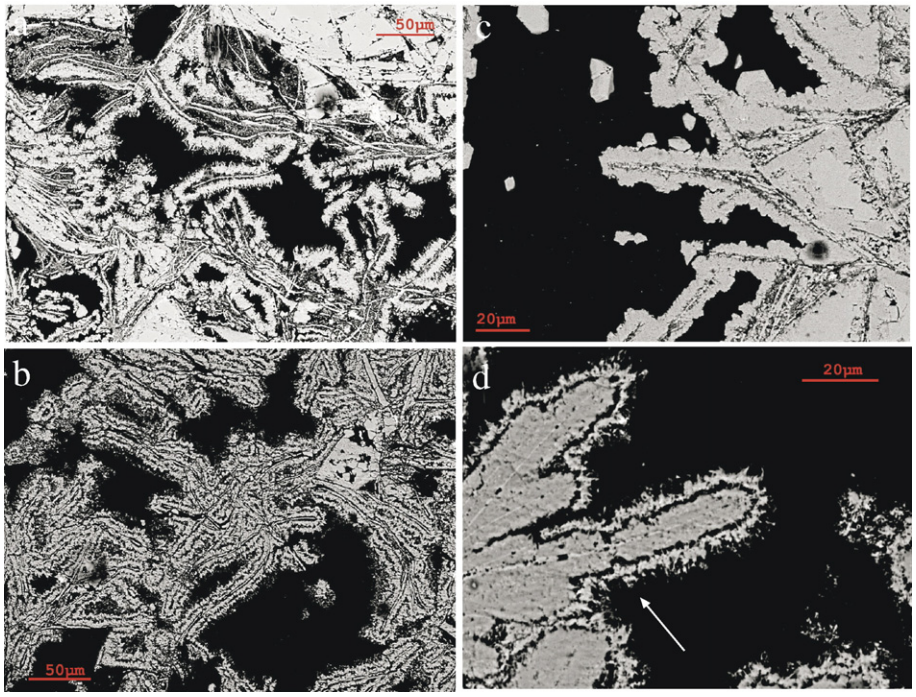


Fig. 8. Backscattered images of filamentous microbial fossils in sulfide chimney, showing internal texture of filamentous fabrics. The filaments were formed by fossilization of microbes. a and b show curved, twisted, and branching filaments, c and d show details of biomineralized filaments including possible cell division (d).

thick mats that cover all hard surfaces around the vents, and even grow in pores below the rocky surface (Verati et al., 1999; Summit and Baross, 2001). Moreover, clouds of bacteria and bacterial matter are blasted into the ocean from modern hydrothermal vents, which are teeming with sulfide-oxidizing bacteria. Potential habitats for bacterial growth are the external surfaces and porous structures of the hydrothermal chimneys (Verati et al., 1999). The dense filamentous microbial layers hosted in the pores of chimneys are closely associated with venting fluids, which are very similar to those of modern chimney complexes (Takai et al., 2001). Similar bacterial filaments in chert have been reported from VMS (3.26 Ga old) in the Pilbara craton, in the Zambalas ophiolite in the Philippines, the Californian Coastal Range, Troodos ophiolite in Cyprus, and the Franciscan complex (Juniper and Fouquet, 1988; Little et al., 1999b; Rasmussen, 2000).

When the Gaobanhe sulfide deposit formed in the graben, the water depth is estimated to have been more than 800 m (indicated by calculation and measurement on fluid inclusions, see Feng and Zhang, 1985). Thus, hydrothermal microbial communities flourished far below the level of light penetration where sulfide precipitates through hydrothermal venting. It supports the idea developed from observations on modern hydrothermal venting on the sea floor, that vent bacteria rely on chemosynthesis to get the energy required to fix carbon dioxide and produce organic matter by the oxidation of hydrothermal sulfide (H_2S) or reduced minerals in hydrothermal deposits (Felbeck, 1981; Prieur et al., 1995; Edward et al., 2003).

The Gaobanhe bacterial mats are encrusted and replaced by metal sulfide minerals, carbonate and silica in deep sea hydrothermal vent environments, providing important clues about the genetic mechanism of biomineralization. As the vents were forming on the deep sea floor, the microbial mass and colonization processes begin to thrive around and in hydrothermal vents in the Mesoproterozoic. Biofilms often serve as templates for mineral trapping (Fortin et al., 1998; Maginn et al., 2002). With precipitation of minute particles of sulfide from vent fluids, the bacteria are rapidly buried and mineralized. They are trapped within the sticky layer of mucilage that surrounds the bacterial colonies. The growing mat of bacterial filaments clearly constitute sites for mediating mineral formation around and within black smoker chimneys, so as they gradually build the mineralized pyrite aggregate in vents, the filaments are well preserved in the pore area. Similar processes have been documented with modern and ancient thermal spring deposits, and hydrothermal sulfide ore deposits (Juniper and Fouquet, 1988; Zierenberg and Schiffman, 1990; Fortin et al., 1998; Takai et al., 2001). In addition, bacterial mats mediate mineral formation by actively driving the chemical conditions (PH, carbon dioxide production or by expelling sulfide and ferrous iron) of venting fluids. Furthermore, since bacterial cell surfaces expose anionic sites for metal cations, they may act as nucleation sites for mineral formation induced by the numerous sites of charged groups on cell surfaces. As a result, bacteria mediated the precipitation of base metal sulfide (Edward et al., 2003). That is also the reason that the very rich ore bodies are closely associated with sulfide microbialites in Gaobanhe area.

4. Chimney types and their implications for mineralization

As their modern analogue on the seafloor, chimneys of Gaobanhe display delicate concentric mineral and textural

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

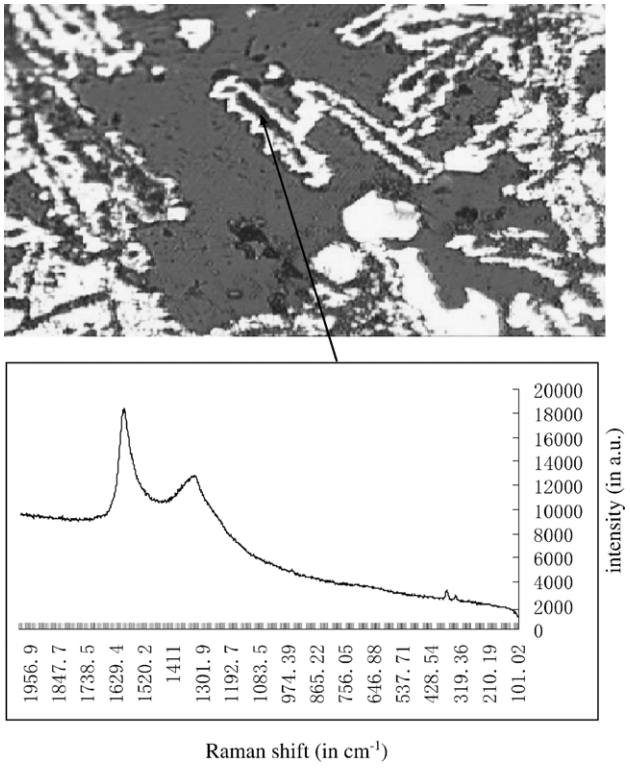


Fig. 9. Backscattered map and Raman spectra across a filamentous microfossil from within a chimney in the Gaobanhe massive sulfide. The spectra (Raman shift, in cm^{-1} on horizontal axis vs. intensity in a.u. on vertical axis) shows the presence of disordered carbon in the microfossil, consistent with an organic origin.

zonations and provide new insights into the development and evolution of early submarine chimneys. They formed in sedimentary sequences, and locally were buried by sulfide or sedimentary laminae, suggesting that the chimney structures were clearly built at the seawater–hydrothermal fluid interface, comparable to those of modern submarine black chimneys (Marchig and Rosch, 1988).

The vent fragments recognized in the North China Craton are relatively small compared with those of modern active chimneys on the seafloor (e.g., Knott et al., 1998). Globally, ancient fossil chimneys within massive sulfide ores of different ages are much smaller than their modern counterparts on the seafloor. This phenomenon may be explained as lower flow rates and temperatures of venting hydrothermal fluids (Banks, 1985). Supporting this idea is the observation that hydrothermal venting in modern continental graben settings including the East African rift, Red Sea and Baikal, typically operates at lower temperature than at mid-ocean ridges (Crane, 1991; Tiercelin et al., 1993).

The change in types of mineral zonation within Gaobanhe chimneys compared to ocean-ridge type black smokers may have been also caused by a decrease of fluid temperature. The central part of chimney in the Gaobanhe is composed of mainly sphalerite, pyrite, galena and silica, suggesting that they formed by relative low-temperature venting within a continental graben. The fact that the sulfide chimneys have very little chalcopyrite, which is a common core component of modern black smoker chimneys from oceanic ridge settings, suggests that lower geothermal gradients produced the Gaobanhe deposits, analogous to other SEDEX-types of deposits. Moreover, barite and anhydrite are rare in chimneys, also supporting the idea that the Gaobanhe chimneys formed from lower temperature venting fluids than those typical on the sea floor ocean ridges.

The sulfide ore bodies formed in the deepest depression controlled by a major normal fault, indicating that the hydrothermal episodes were associated with faulting within the graben; hydrothermal convection was caused by enhanced permeability adjacent to the fracture zone and locally high geothermal gradient of the underlying seafloor (Fig. 10). In addition, numerous fragments of chimneys can be recognized within the sulfide mounds. Sulfide mounds were widely impregnated by sphalerite, which filled and cemented breccias in their cores. Galena fills open spaces within the cores. Chimneys are commonly based on brecciated ore and underwent extensive brecciation associated with local tectonism at the seafloor, with the formation of sulfide mounds. From this evidence, it is inferred that tectonism played an important role for initiation of venting and final formation of sulfide mounds.

The typical morphology of the spires and orifices proves that both the Pb–Zn–Fe and the Zn–Fe chimneys were formed by focused fluid flow. Some Pb–Zn–Fe chimneys are covered by a thin veneer or cluster of pyrite pellets, with steeply-dipping outer walls of sphalerite. Suspended pyrite pellets are widely distributed around these chimneys. This observation can be explained by relatively higher rates of hydrothermal fluid flow responsible for Pb–Zn–Fe chimneys, compared with flow rates of Zn–Fe chimneys on the margins of the mound complexes.

As indicated by analysis of ore sequences, Pb–Zn–Fe chimneys also underlie Zn–Fe chimneys, and they formed in Pb–Zn and Fe–Pb–Zn sulfide ore horizons, respectively. The evolution of hydrothermal fluids recorded by chimney types was responsible for the zonation of the ore bodies. In summary, the chimney studies suggest that the hydrothermal activity is a continuously evolving process resulting in generation of deposits from Zn- to Fe-sulfide end members.

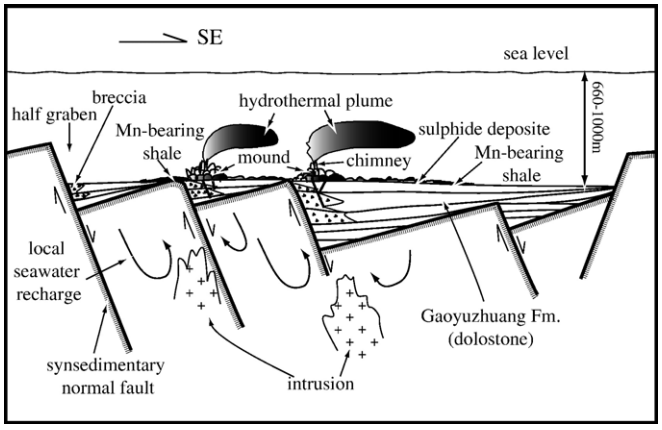


Fig. 10. Schematic model for generation of Gaobanhe vent sulfide complex on the seafloor. Sulfide mounds and chimneys developed adjacent to a normal fault, and convection cell may be driven by a cooling pluton under the surface.

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

ARTICLE IN PRESS

5. Growth and formation of black smoker chimneys

On the basis of observations of mineralogical zonation and primary relations between chimneys and surrounding sulfides and sediments, three schematic stages of growth and formation of black smoker chimneys are proposed here (Fig. 11). These stages are comparable to the development of modern black smokers on the ocean bottom (Fouquet et al., 1993).

During the first stage, the development of chimneys is initiated by precipitation and settling of particles of sulfide and sulfate (barite) above vents, derived from quenching or mixing of hydrothermal fluids with seawater (Rona and Scott, 1993). Numerous baby chimneys preserved around the margins of mounds containing larger cone and columnar chimneys show very irregular and nonchannelized pore structures of diffuse flow (Fig. 11). Thus, it is suggested that chimneys are formed by accumulation of pyrite particles and thermal crystallization along conduits. Diffusive flow is the main formation mechanism in this stage. As the vent chimney grows, conduits were gradually interconnected by dissolution, and fluids were focused in large and elongate voids.

During the second stage, brecciation (perhaps associated with tectonism) along fracture zones resulted in active circulation of fluids, and the enhanced porosity focused the fluid flow, leading to the formation of larger chimneys. With the buildup of chimneys and growth of the initial walls of the chimneys, hot vent fluid is insulated from mixing with cold seawater, thereby causing the fluid to become focused, and crystallization is enhanced in the cores of chimneys. The euhedral sphalerite, pyrite and galena precipitated or recrystallized at high temperature within axial conduits.

During the third stage, the chimney is overgrown by both external precipitation of sulfide particles on its flank and replacement in the axial conduit. Therefore, the outer wall of the chimney grows upward and becomes thick through precipitation of sulfide with focused flow. It also grows inward by a combination of overgrowth and replacement of sulfides, resulting in the formation of a well-zoned chimney, with an inner ring of sphalerite and outer wall of pyrite. These mineralogical successions are related to a progressive increase in temperature of the hydrothermal fluid within chimneys (Haymon, 1983). The replacement and dissolution within the chimney reflect episodic activity of hydrothermal fluid. When the activity declined, the axial conduit was finally filled with silica or carbonate.

In this stage, the chimney is mainly associated with recrystallization of sulfide particles and replacement of marcasite by pyrite and sphalerite. Galena and sphalerite filled the central conduits and interconnecting voids of the outer walls, and earlier-formed pyrite is replaced by sphalerite. No significant barite accumulated within the chimneys, suggesting that the hydrothermal system for venting terminated earlier (Franklin, 1993). It is attributed to lower geothermal gradients with the seafloor graben. The absence of an outer anhydrite wall is generally interpreted as a result of dissolution by seawater after its formation, but may also mean that it may never have formed when the Gaobanhe chimneys and mounds were active.

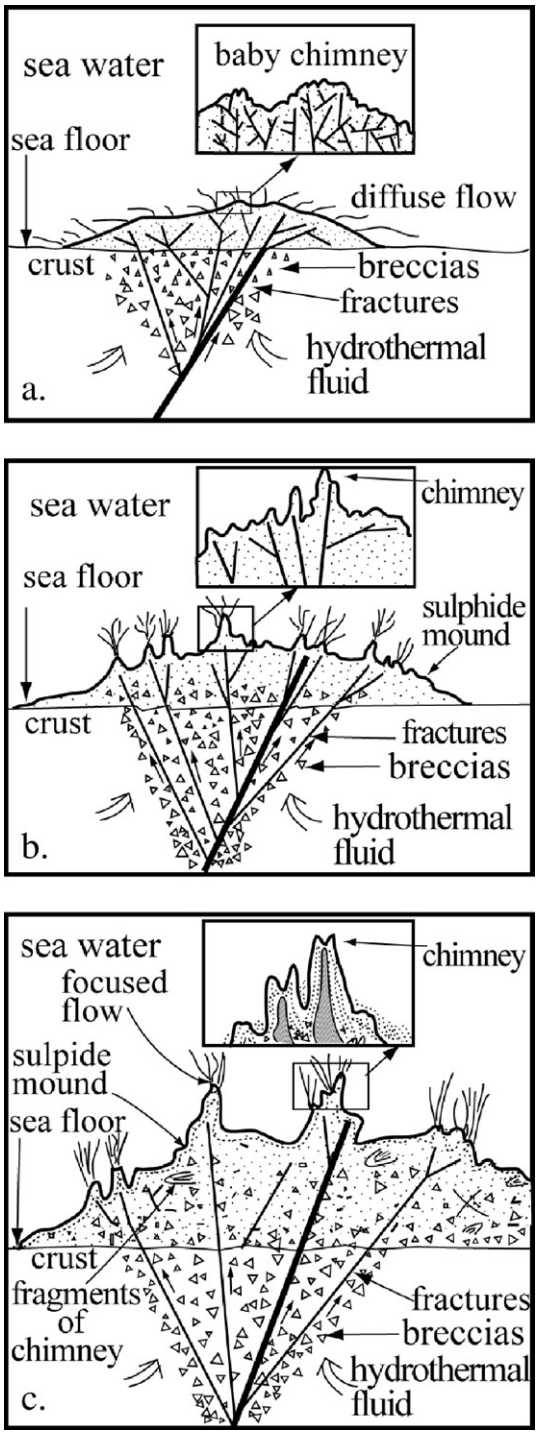


Fig. 11. Schematic model for growth and evolution of black smoker chimney, North China (See text for explanation).

Fragments of chimneys and relevant textures can be recognized in sulfide mounds (Fig. 11), suggesting that tectonism may result in collapse of chimneys when they were active. Alternatively, the chimneys may have grown to unstable heights and collapsed under their own weight. As a result, sulfide mounds accumulated around former venting sites. Many cycles of hydrothermal fluid activities of black smokers and tectonism/collapse may have been responsible for the mineralization of the

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

ARTICLE IN PRESS

massive sulfide deposits. When the hydrothermal activity of chimney ceases, they are buried by sulfide of the plume or muddy sediments.

6. Black smoker vents and microbialites; implications for early life

We present a simple model that explains variations in morphology and internal texture of the chimneys and locations of microbialites, incorporating variations in flow rate and temperature of the hydrothermal fluid, as in modern vents on the Atlantic seafloor (Fouquet et al., 1993). The morphology of columnar to conical chimneys indicates that focused flow is responsible for their growth and formation in the center of sulfide mounds. In contrast, round chimneys form from diffuse lateral fluid flow or seepage through sulfide talus and breccias. Initial growth of chimneys involves precipitation and accumulation around venting sites, followed by circulation within the axial channelways and thickening of inner walls (Fig. 11). Circulation of hydrothermal fluids was responsible for recrystallization and replacement within conduits. Chimneys provided paths for focused venting of hydrothermal fluid to the seafloor of the graben, and provided nutrients and heat for organisms that produced the microbial structures. Hydrothermal fluid was insulated within the chimney from outside, keeping sharp redox and temperature gradients across the chimney wall — thus, cores of chimneys are characterized by crystallization and replacement of sulfides.

Very few ancient analogues of hydrothermal vent sites have been recognized (Larter et al., 1981; Boyce et al., 1983; Haymon et al., 1984; Hannington and Scott, 1988; Crane, 1991; Vearncombe et al., 1995; Zaykov et al., 1996; Little et al., 1997, 1998, 1999a,b). Furthermore, most chimneys reported are very small, and complete chimneys are rarely preserved. It is difficult to compare them with modern analogs from the seafloor. Modern vent hydrothermal activities have also been reported from continental rifts (Crane, 1991; Tiercelin et al., 1993), yet no large black smoker chimneys have been identified from these sites, so little is known about the black smoker venting processes of continental graben settings. The discovery of small and large chimneys associated with microbialites from the North China craton fills a major gap in understanding hydrothermal processes in Precambrian continental grabens. The vent fragments and contained microfossils recognized in the North China craton are the largest and oldest known from the geological record, yet are relatively small compared with those of modern active chimneys on the seafloor (Cook and Stakes, 1995; Herzig and Hannington, 1995; Brown and McClay, 1998; Hannington et al., 1998; Herrington et al., 1998). Lower flow rates and temperatures of venting hydrothermal fluids may explain this phenomenon (Banks, 1985; Crane, 1991; Tiercelin et al., 1993). Moreover, barite and anhydrite are rare in chimneys, also supporting the idea that the Gaobanhe chimneys formed from lower temperature venting fluids than typical of the modern seafloor ocean ridges.

Rich microbial remains are preserved around the ancient vent chimneys of Gaobanhe (Xia et al., 2000). The microbialites commonly overlie a layer of sulfides. We suggest that colonization and activity of sulfur-reducing, chemosynthetic and thermophyllic microbes was concentrated in the vicinity of warm vents with slow emission of fluid, similar to modern vent chimneys (Jannasch and Mottl, 1985). The sulfide microbiolites are widely distributed on the fringes of the chimneys, providing tantalizing suggestions that early life may have developed and remained sheltered in deep sea hydrothermal vents until surface conditions became favorable for organisms to inhabit the land.

Acknowledgements

We are grateful to Jun Feng, Xianglong Niu, Zheng Jinwu, and Chen Zheng for their assistance during many field excursions, and Jin Chen for the help with the electron microscopy. This work was supported by a National Science Foundation of China (Project No. 40242014), Peking University (to Jianghai Li) and the U.S. National Science Foundation (awards no. 02-07886, and 01-25925 to T. Kusky).

References

Bai, J., 1993. The Precambrian Geology and Pb–Zn mineralization of Northern margin of North China Craton, vol. 340. Geological Publishing House, Beijing. 111 pp.

Banks, D.A., 1985. A fossil hydrothermal worm assemblage from the Tynagh lead–zinc deposit in Ireland. Nature 313, 128–131.

Binns, R.A, Scott, S.D., 1993. Actively forming polymetallic sulfide deposits associated with felsic volcanic rocks in the Eastern Manus back-arc basin, Papua New Guinea. Economic Geology 88, 2226–2236.

Binns, R.A., Scott, S., Bogdabov, Y.A., Lisitzin, A.P., Gordeev, V.V., Gurvich, E.G., Finlayson, E.J., Boyd, T., Dotter, L.E., Wheller, G.E., Muravyev, K.G., 1993. Hydrothermal oxide and gold-rich sulfate deposits of franklin seamount, western Woodlark Basin, Papua New Guinea. Economic Geology 88, 2122–2153.

Boyce, A.J., Coleman, M.L., Russell, M.J., 1983. Formation of fossil hydrothermal chimneys and mounds from Silvermines, Ireland. Nature 306, 545–550.

Brown, D., McClay, K.R., 1998. Data report: sulfide textures in the active TAG massive sulfide deposit, 260N, mid-Atlantic ridge. In: Herzig, P.M., Humphris, S.E., Miller, D.J., Zierenberg, R.A. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 158, pp. 193–200.

Cook, T.L., Stakes, S., 1995. Biogological mineralization in deep-sea hydrothermal deposits. Science 267, 1975–1979.

Crane, K., 1991. Hydrothermal vents in Lake Baikal. Nature 350, 281.

Davies, P., 2001. The origin of life I: when and where did it begin? Scientific Progress 84, 1–16.

Delaney, J.R., Kelley, D.S., Lilley, M.D., Butterfield, D.A., Baross, J.A., Wilcock, W.S.D., Wimbley, R.W., Summit, M., 1992. The quantum ascent of oceanic crustal accretion: impacts of diking at mid-ocean ridges. Science 5374, 222–230.

De Ronde, C.E.J., Ebbesen, T.W., 1996. 3.2 b.y. of organic compound formation near sea-floor hot-springs. Geology 91, 791–794.

Edward, K.J., McCollom, T., Konishi, H., Buseck, P., 2003. Seafloor bioalteration of sulfide minerals: results from in situ incubation studies. Geochimica et Cosmochimica Acta 67, 2843–2856.

Farmer, J.D., 2000. Hydrothermal systems: doorways to early biosphere evolution. GSA Today 10, 1–9.

Felbeck, H., 1981. Chemoautotrophic potentials of the hydrothermal vent tube worm. *Riftia pachyptila* (vestimentifera). Science 213, 336–338.

Feng, Z.Y., Zhang, X.Y., 1985. On the geologic character and geneses of the stratiform sulfides ore deposits in Eastern Hebei Province, China. Mineralium Deposita 4, 1–6.

Fortin, D., Ferris, F.G., Scott, S.D., 1998. Formation of Fe-silicates and Fe-oxides on bacterial surfaces in samples collected near hydrothermal vents on the Southern Explorer Ridge in the northeast Pacific Ocean. American Mineralogist 83, 1399–1408.

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

Fouquet, Y., Stackelberg, U., Charlou, J.L., Erzinger, J., Herzig, P.M., Muhe, R., Wiedicke, M., 1993. Metallogenesis in back-arc environments: the Lau Basin example. Economic Geology 88, 2154–2181.

Franklin, J.M., 1993. Volcanic-associated massive sulphide deposits. In: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.), Geological Association of Canada Special Paper, vol. 40, pp. 315–334.

Halbach, M., Halbach, P., Luder, V., 2002. Sulfide-impregnated and pure silica precipitates of hydrothermal orogin from the central India Ocean. Chemical Geology 182, 357–375.

Hannington, M.D., Scott, S., 1988. Mineralogy and geochemistry of a hydrothermal silica–sulfide–sulfate spire in the caldera of axial seamount, Juna de Fuca ridge. Canadian Mineralogist 26, 603–625.

Hannington, M.D., Galley, A.G., Herzig, P.M., Petersen, S., 1998. Comparison of the TAG mound and stockwork complex with Cyprus-type massive sulfide deposits. In: Herzig, P.M., Humphris, S.E., Miller, D.J., Zierengberg, R.A. (Eds.), Proceedings of The Ocean Drilling Program, Scientific Results, vol. 158, pp. 389–415.

Haymon, R.M., 1983. Growth history of hydrothermal black smoker chimneys. Nature 301, 695–698.

Haymon, R.M., Koski, R.A., Sinclair, C., 1984. Fossils of hydrothermal vent worms from Cretaceous sulfide ores of the Samail Ophiolite, Oman. Science 223, 1407–1409.

Haymon, R.M., et al., 1993. Volcanic eruption of the mid-ocean ridge along the East Pacific Rise crest at 9.5–52'N: direct submersible observations of seafloor phenomena associated with an eruption event in April, 1991. Earth and Planetary Science Letters 119, 85–101.

Hein, J.R, Koski, R.A., Embley, R.W., Reid, J., Chang, S.W., 1999. Diffuse-flow hydrothermal field in an oceanic fracture zone setting, Northeast Pacific: deposit composition. Exploration and Mining Geology 8, 299–322.

Hekinian, R., Fevrier, M., Bischoff, J.L., Picot, P., Shanks, W.C., 1980. Sulfide Deposits from the East Pacific Rise Near 21N. Science 207, 1433–1444.

Herrington, R.J., Maslennikov, V.V., Spiro, B., Zaykov, V.V., Little, C.T.S., 1998. Ancient vent chimney structures in the Silurian massive sulfides of the Urals. In: Mills, R.A., Harrision, K. (Eds.), Modern Ocean Floor Processes and the geological Record. Geological Society of London, Special Publications, vol. 148, pp. 241–257.

Herzig, P.M., Hannington, M.D., 1995. Polymetallic massive sulfides at the modern seafloor: a review. Ore Geology Reviews 10, 95–115.

Jannasch, H.W., 1985. The chemosynthetic support of life and the microbial diversity at deep-sea hydrothermal vents. Proceedings of the Royal Society of London. B, Biological Sciences 225, 277–297.

Jannasch, H.W., Mottl, M.J., 1985. Geomicrobiology of deep-sea hydrothermal vents. Science 251, 717–725.

Jannasch, H.W., Nelson, D.C, Wirsen, C.O., 1989. Massive natural occurrence of unusually large bacteria (Beggiatoa sp.) at a hydrothermal deep-sea vent site. Nature 342, 834–836.

Juniper, S.K., Fouquet, Y., 1988. Filamentous iron-silica deposits from modern and ancient hydrothermal sites. Canadian Mineralogist 26, 859–869.

Kelley, D.S., Karson, J.A., Blackman, D.K., 2001. An off-axis hydrothermal vent field near the Mid-Atlantic Ridge at 30°N. Nature 412, 145–148.

Kimura, H., Asada, R., Masta, A., Naganuma, T., 2003. Distribution of microorganisms in the subsurface of the Manus basin hydrothermal vent field in Papua New Guinea. Applied and Environmental Microbiology 69, 644–648.

Knott, R., Fouquet, Y., Honnorez, J., Petersen, S., Bohn, M., 1998. Petrology of Hydrothermal mineralization: a vertical section through the TAG mound. In: Herzig, P.M., Humphris, S.E., Miller, D.J., Zierenberg, R.A. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 158, pp. 5–26.

Konhauser, K.O., 1998. Diversity of bacterial iron mineralization. Earth-Science Reviews 43, 91–121.

Kusky, T.M., Li, J.H., 2003. Paleoproterozoic tectonic evolution of the North China Craton. Journal of Asian Earth Sciences 22, 383–397.

Larter, R.C.L., Boyce, A.J., Russell, M.J., 1981. Hydrothermal pyrite chimneys from the Ballynoe Baryte Deposit, Silvermines, county Tipperary, Ireland. Mineralium Deposita 16, 309–318.

Little, C.T.S., Herrington, R.J., Maslennikov, V.V., Morris, N., Zaykov, V.V., 1997. Silurian hydrothermal-vent community from the southern Urals, Russia. Nature 385, 146–148.

Little, C.T.S., Cann, J.R., Herrington, R.J., Morisseau, M., 1998. The fossil record of hydrothermal vent communities. In: Mills, R.A., Harrison, K. (Eds.), Modern Ocean Floor Processes and the Geological Record. Geological Society of London, Special Publication, vol. 148, pp. 259–270.

Little, C.T.S., Cann, J.R., Herrington, R.J., Morisseau, M., 1999a. Late Cretaceous hydrothermal vent communities from the Troodos ophiolite, Cyprus. Geology 27, 1027–1030.

Little, C.T.S., Herrington, R.J., Haymon, R.M., Danelian, T., 1999b. Early Jurassic hydrothermal vent community from the Franciscan complex, San Rafael Mountains, Califonia. Geology 27, 167–170.

Maginn, E.J., Little, C.T.S., Herrington, R.J., Mills, R.A., 2002. Sulphide mineralisation in the deep sea hydrothermal vent polychaete, Alvinella pompejana: implications for fossil preservation. Marine Geology 181, 337–356.

Marchig, V., Rosch, H., 1988. Mineralogical zonation and radiochronological relations in a large sulfide chimney from the East Pacific Rise at 18025S. Canadian Mineralogist 26, 541–554.

Maruyama, S., Isozaki, Y., Nakashima, S., Windley, B.F., 2002. History of the Earth and life. In: Nakashami, S. (Ed.), Geochemistry and the Origin of Life. Universal Academic Press.

Mojzsis, S.J., Harrison, T.M., 2000. Vestiges of a beginning: clues to the emergent biosphere recorded in the oldest know sedimentary rocks. GSA Today 10, 1–9.

Oudin, E., Constantinou, G., 1985. Black smoker chimney fragments in Cyprus sulphide deposits. Nature 308, 349–353.

Prieur, D., 1997. Microbiology of deep-sea hydrothermal vents. TIBTECH 15, 242–244.

Prieur, D., Erauso, G., Jeanthon, C., 1995. Hypermophilic life at deep-sea hydrothermal vents. Planetary and Space Science 43, 115–122.

Rasmussen, B., 2000. Filamentous microfossils in a 3235 Ma old volcanogenic massive sulfide deposit. Nature 405, 676–679.

Reysenbach, A.L., Cady, S.L., 2001. Microbiology of ancient and modern hydrothermal systems. Trends in Microbiology 9, 79–86.

RISE Project Group, 1980. East Pacific Rise: hot springs and geophysical experiments. Science 207, 1421–1432.

Rona, P.A., Scott, S.D., 1993. A special issue on sea-floor hydrothermal mineralization: new perspectives, preface. Economic Geology 88, 1935–1975.

Rona, P.A., Klinkhammer, G., Nelsen, T.A., 1986. Black smokers, massive sulphides and vent biota at the Mid-Atlantic Ridge. Nature 321, 33–37.

Russell, M.J., Hall, A.J., 1997. The emergence of life from iron monosulphide bubbles at a submarine hydrothermal redox and PH front. Journal of the Geological Society (London) 154, 377–402.

Scott, S., 1981. Small chimneys from Japanese Kuroko deposits. In: Goldie, R., Bottrill, T.J. (Eds.), Seminars on Sea-Floor Hydrothermal Systems. Geoscience Canada, vol. 8, pp. 103–104.

Scott, S., 2002. Minerals on land, minerals in sea. Geotimes 47, 1–8.

Summit, M., Baross, J.A., 2001. A novel microbial habitat in the mid-ocean ridge subseafloor. Proceedings of the National Academy of Sciences 98, 2158–2163.

Takai, K., Komatsu, T., Inagaki, F., Horikoshi, K., 2001. Distribution of Archaea in a black smoker chimney structure. Applied and Environmental Microbiology 67, 3618–3629.

Tiercelin, J., Pflumio, C., Castrec, M., Boulegue, J., Gentle, P., Rolet, J., Coussement, C., Stetter, K.O., Huber, R., Buku, R., Mifundu, W., 1993. Hydrothermal vents in Lake Tanganyika, East African rift system. Geology 21, 499–502.

Travis, J., 1993. Probing the unsolved mysteries of the deep. Science 259, 1123–1124.

Vearncombe, S., Barley, M.E., Groves, D.I., Mcnaughton, N.J., Mikucki, E.J., Vearncombe, J.R., 1995. 3.26 Ga black smoker-type mineralization in the Strelley belt, Pilbara craton, Western Australia. Journal of the Geological Society (London) 152, 587–590.

Verati, C., de Donato, P., Prieur, D., Lancelot, J., 1999. Evidence of bacterial activity from micrometer-scale layer analyses of black-smoker sulfide structures (Pito Seamount Site, Easter microplate). Chemical Geology 158, 257–269.

Xia, X.H., Liu, C.T., Li, Z.M., 1999. The geology of Eastern Hebei Proterozoic polymetallic sulfide deposits and its mineralization. Geology, Chemistry and Minereralogy 21, 129–140.

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024

ARTICLE IN PRESS

Xia, X.H., Liu, C.T., Li, Z.M., Yan, F., 2000. Organic materials of pyritic stromatolite sulfide deposit and its contribution to mineralisation of Xinglong–Kuancheng area, East Hebei. Mineralium Deposita 19, 61–67.

Zaykov, V.V., Maslennikov, V.V., Zaykov, E.V., Herrington, R.J., 1996. Hydrothermal activity and segmentation in the Magnitogorsk–West Mugodjarian zone on the margins of the Urals palaeo-ocean. In: Macleod, C.J., Tyler, P.A., Walker, C.L. (Eds.), Tectonic, Magmatic, Hydrothermal and Biological Segmentation of Mid-Ocean Ridges. Geological Society Special Publication, vol. 118, pp. 199–210.

Zierenberg, R.A., Schiffman, P., 1990. Microbial control of silver mineralization at a sea-floor hydrothermal site on the northern Gorda Ridge. Nature 348, 155–157.

Zierenberg, R.A., Adams, M.W.W., Arp, A., 2000. Life in extreme environments: hydrothermal vents. Proceedings of the National Academy of Sciences 97, 12961–12962.

Please cite this article as: Li, J., Kusky T.M. World's largest known Precambrian fossil black smoker chimneys and associated microbial vent communities, North China: Implications for early life. Gondwana Research (2006), doi:10.1016/j.gr.2006.10.024