Xiande Xie
Ming Chen

Yanzhuang Meteorite: Mineralogy and Shock Metamorphism

SOUTHERN PUBLISHING AND MEDIA
GUANGDONG SCIENCE & TECHNOLOGY PRESS
Springer

Yanzhuang Meteorite: Mineralogy and Shock Metamorphism

Xiande Xie · Ming Chen

Yanzhuang Meteorite: Mineralogy and Shock Metamorphism

SPM SOUTHERN PUBLISHING AND MEDIA
GUANGDONG SCIENCE & TECHNOLOGY PRESS

Springer

Xiande Xie
Guangzhou Institute of Geochemistry
Chinese Academy of Sciences
Guangzhou, Guangdong, China

Ming Chen
Guangzhou Institute of Geochemistry
Chinese Academy of Sciences
Guangzhou, Guangdong, China

ISBN 978-981-15-0734-2 ISBN 978-981-15-0735-9 (eBook)
https://doi.org/10.1007/978-981-15-0735-9

Jointly published with Guangdong Science and Technology Press, Guangdong, China, 2018
The print edition is not for sale in China Mainland. Customers from China Mainland please order the print book from: Guangdong Science and Technology Press.
ISBN of the Co-Publisher's edition: 978-7-5359-6835-7

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

Hypervelocity collisions between asteroids, presumably chondritic parent bodies, can cause the shock metamorphism of rocks and minerals in sphere of action of shock wave. The studies on the shock effects of rocks and minerals in structures, chemical composition, solidification and crystallization characteristics have great significance in the investigation of evolution of celestial bodies, geology of high pressures and high temperatures, as well as in material sciences. It is well known that the L group chondrites are more heavily shocked than H and LL group chondrites, and only detailed systematic petrographic and mineralogical studies on shock effects in L group chondrites, especially the L6 chondrites, were curried out during the last tens of years, but studies on shock effects in H group chondrites are rare for the rarity of strongly shocked H group meteorites.

The Yanzhuang meteorite is a very strongly shocked stony meteorite, which fell on October 31, 1990 in Yanzhuang, Wengyuan County, Guangdong Province, China. Right after the fall of this meteorite, a group of scientists from the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (CAS) conducted field survey and collection of Yanzhuang meteorite samples. Five pieces in total weight of 3.5 kg of this meteorite was collected. The largest piece is of 823 g in weight. This meteorite is composed of light-colored severely deformed chondritic mass and dark-colored thick melt veins (up to 1.5 cm in width) and large melt pockets (up to $3 \times 4 \times 2$ cm in volume). This implies that Yanzhuang meteorite had been subjected to violent impact event in outer space.

A group of scientists headed by Prof. Xiande Xie in the Guangzhou Institute of Geochemistry, CAS, then conducted a series of study on collected samples and revealed that the Yanzhuang meteorite is a unique chondrite with most abundant shock-induced melt (more than 30% in volume) among all known shock-melt-bearing chondritic meteorites.

The modern micro-mineralogical experimental techniques, including scanning electron microscopy (SEM), transmission electron microscopy (TEM), electron probe microanalysis (EPMA), Raman microprobe spectroscopy (RMS), instrumental neutron activation analysis (INAA), X-ray micro-diffraction analysis (XRMD), micro-proton-induced X-ray emission (PIXE) analysis and laser ablation inductively coupled plasma mass spectroscopy (LA-ICP-MS), have been used to investigate the mineralogy and the shock effects in the Yanzhuang chondrite. The micro-structural and micro-morphological characteristics as well as chemical composition of minerals (phases) were studied in detail.

This meteorite was classified as an H6 chondrite on the basis of chemical composition and petrologic features, and evaluated it as a very strongly (S6) shock-metamorphosed meteorite. The mineral composition of this meteorite consists of olivine (40%), low-Ca pyroxene (30%), clinopyroxene (4%), plagioclase (4%), kamacite (10%), taenite (4%), troilite (6%), and small amount of merrillite and chromite.

The results show that the shock-induced temperature and pressure distribution in the Yanzhuang chondrite was very non-uniform, hence, various transformations both in physics and chemistry, may have been favored in various places depending on the details of the propagation of the highly complex pulse of temperature and pressure.

In the weaker action areas of shock wave (25–35 GPa): olivine and pyroxene display 4–5 sets of planar fractures, high screw dislocation density (from 10^3 to 10^7 mm^{-2}), small size of mosaic blocks (from 20 to 2 μm) and greater difference in crystallographic orientation between neighboring mosaic blocks (from 1° to 10°); plagioclase has partly been transformed into maskelynite, several sets of Neuman lamellae have been observed in kamacite and taenite; mosaicism in troilite is widely spread.

In the stronger action areas of shock wave (45–60 GPa): the brecciated and disorder structures in olivine and pyroxene grains were produced in the prevailing areas of stretching stress; the solid recrystallization and dislocation climbing of olivine and pyroxene were induced in the areas of higher temperature; olivine and pyroxene were transformed into diaplectic glass, melt glass and high-pressure phases in the areas of higher pressures, higher temperatures and fast cooling; kamacite and taenite were partly quenched into martensite, or partly melted and recrystallized; the extensive melt and recrystallization of troilite were produced.

In the strongest action areas of shock wave (>60 GPa): the chondritic mass was melted in-situ and in whole rock, forming dark thick melt veins and large melt pockets which were composed of microlites of recrystallized olivine and pyroxene, FeNi + FeS eutectic blobs in different forms, silicate melt glass and some remained mineral detritus of chondrite; dissociation and vaporization of many kind of minerals including silicates, FeNi metal and sulfides took place to a certain extent; the solidified and recrystallized FeNi metal were mostly quenched into martensite or austenite. Besides, the achievements in micro-mineralogical investigations of the Yanzhuang meteorite also include the following new findings:

1. Natural diaplectic olivine glass and diaplectic pyroxene glass were discovered for the first time in this shocked Yanzhuang meteorite. The diaplectic olivine glass is identified by the stronger Raman frequencies at 1108 cm^{-1} and 1180 cm^{-1}, and the diaplectic pyroxene glass by the weak Raman frequencies at 816–840 cm^{-1}.

2. As early as in 1992, high-pressure phase minerals including ringwoodite and majorite were found for the first time in H group chondrites. The ringwoodite in Yanzhuang occurs in two different forms: the first is allotriomorphic granular ringwoodite which nucleated and crystallized from diaplectic olivine glass, and the second is euhedral ringwoodite which crystallized from shock-induced silicate melt. It was found that back transformation from spinel (γ-phase) to modified spinel (β-phase), and to olivine took place for more than 90% ringwoodite after the unloading of shock wave. Majorite nucleated and crystallized from diaplectic pyroxene glass. It was also damaged or transformed back to pyroxene after the unloading of shock wave.
3. It was found that the shock wave can cause the structural deformation and structure reorganization of some pyroxene and its high-pressure phase in Yanzhuang. In addition to itself two-bridging Si–O tetrahedral chain structure, some complicated combination of Si–O tetrahedral groups, including the Si–O tetrahedral with one or four non-bridging oxygen as well as fully polymerized Si–O tetrahedral, were partially produced in some "pyroxene".
4. Condensation of shock-induced crystals of olivine, pyroxene, and troilite, as well as whiskers and needles of FeNi metal were found in holes or fractures in the Yanzhuang chondrite. A growth model for FeNi metal whiskers and needles was proposed on the basis of their micro-morphological features.
5. Extremely large eutectic FeNi + FeS blobs up to 1.1 cm in length were observed in the shock-produced melt of Yanzhuang. Three micro-structural and compositional zones and the new "step-type" distribution pattern of Ni content in FeNi metal dendrites in eutectic blobs were discovered, namely, the zone A of FeNi metal is composed of crystallites and non-crystalline phase firstly solidified in the episode of greater cooling speed, and subsequently, the zone B of FeNi metal is composed of coarser crystals crystallized due to the dropping cooling speed; and the zone C of FeNi metal is condensed at last from the remained liquid phase of metal. In contrast to the three-zone micro-structure of FeNi metal in melt veins, the FeNi metal dendrites in melt pockets, having greater volume of molten materials, only show two micro-structural zones, zone B and zone C. They occur in the symmetrical form of crust and nucleus. This implies that the FeNi metal solidified at lower cooling speed and in symmetrical heat radiation field.
6. Specific tetra-concentric-ring growth structure was firstly observed on the head of FeNi metal dendrites of various shapes in Yanzhuang. The development and growth of such growth structure are identical in three dimensional directions. This growth structure is characterized as being multilayered. The formation, propagation and interaction of tetra-concentric-ring growth structures in the same layer are responsible for the growth of dendrite tip and stem, while dendrite sidebranches are grown up at the junction of interaction of coupled tetra-concentric-ring growth steps between the adjacent two layers. Once independent sidebranches are formed, their stems, tips and sidebranches will be developed in the same mechanism of the growth as the tetra-concentric-ring

structures. The repetition of above-described process will result in the formation of an array of dendrite.

7. An assemblage with FeNi metal, troilite, Fe–Mn–Na phosphates and Al-free chromite was identified in a large FeNi + FeS eutectic nodule in the Yanzhuang shock-produced chondritic melt. A few Fe–Mn–Na phosphate globules have composition of Na-bearing graftonite $(Fe,Mn,Na)_3(PO_4)_2$, and the majority of them corresponds to two phosphate minerals: Mn-bearing galileiite $Na(Fe,Mn)_4(PO_4)_3$ and a possible new phosphate mineral of $Na_2(Fe,Mn)_{17}(PO_4)_{12}$ composition. The elements of P, Na and Mn in these minerals came from the dissociation of previous minerals, such as merrillite, plagioclase and chromite in Yanzhuang chondrite. Chromite in this assemblage is Al-free which is quite different with that of chormite (Al_2O_3 = 7.98wt%) in chondritic mass. The contents of minor components in this recrystallized chromite, such as MgO, CaO, MnO, SiO_2, and TiO_2, are also markedly decreased than the chromite in chondrite.
8. The results of several instrumental neutron activation analyses show a similarity in bulk composition between shock-induced melt and unmelted chondritic rock of Yanzhuang, which suggests in-situ melting and fast cooling of the materials in both melt veins and melt pockets. While the major element concentrations of olivine, pyroxene, FeNi metal and troilite remain unchanged, some trace elements were redistributed between these phases. Ga is enriched in the metal; Co, Cr and Zn are enriched in the sulfide; Cr is enriched in olivine and pyroxene, and Ti is enriched in the plagioclase glass.
9. Two special thermo-luminescence (TL) phenomena were found in the Yanzhuang meteorite through the determination of the natural TL, annealed TL and induced TL by β-radiation: (1) when the Yanzhuang sample was annealed at temperature up to 500 °C, the TL peak induced by β-rays shifted to lower temperature with the increasing of irradiation dose; (2) when the annealed temperature is greater than 600 °C, the TL peak temperature of the annealed sample was higher than that of the unannealed sample. This implies that the shock effect could change the TL characteristics of a chondrite. The measured equivalent β-dose for the melted and unmelted parts are 9238 Gy and 25753 Gy, respectively, showing that the thermal event ages for the two phases in the Yanzhuang meteorite are not equal, and their thermal histories are not the same, either.
10. Four shock phases in the Yanzhuang meteorite were divided on the basis of shock effects of its rocks and minerals, namely, shock melt and recrystallized phase (M), very strongly shocked phase (S6), strongly shocked phase (S5), and moderately shocked phase (S4). It was found that the shock effects of different phases can be compared with those of the Jilin (H5) chondrite experimentally shock-loaded from 12 to 133 GPa. Hence, a new approach of using the typical effects observed in experimentally shock-loaded samples to evaluate the P-T history of naturally shocked meteorites was proposed.

Yanzhuang chondrite was spalled off its parent body in a collision event between two asteroids at 2.6 Ma ago. The estimated speed of the impact was about 7–8 km/s. The shock peak pressure acted on Yanzhuang was estimated as >60 GPa and the shock peak temperature 2000 °C. Based on the studies in the shock effects of rocks and minerals, it was assumed that the Yanzuang chondrite is really the most heavily shocked ordinary H group chondrite ever found and a unique meteorite that contains most abundant shock induced melt among all known shock-melt-bearing chondritic meteorites.

We are indebted to the National Natural Science Foundation of China for supporting the study of Yanzhuang meteorite under grands 41172046, 40772030, and 40272028. We thank the Guangdong Provincial Science Foundation for financial support under grand 91478. We are grateful to the Guangzhou Institute of Geochemistry, Chinse Academy of Sciences, for its profound concern of studying the Yanzhuang meteorite. We would like to thank Profs. Zhaohui Li, Jingfa Liu, and Ruiying Hu for their help in field survey and related laboratory study of this meteorite. Many thanks to Prof. Xiangping Gu of Central South University for his help in X-ray microdiffraction analysis.

Guangzhou, China
July 2019

Xiande Xie
Ming Chen

Contents

Chapter 1
Samples and Experimental Methods

Abstract This chapter describes samples and analytical techniques used for studying the mineralogy and the shock-induced effects in the Yanzhuang meteorite. These techniques are optical microscopy (OM), scanning electron microscopy (SEM) with energy-dispersive X-ray analysis (EDXA), electron probe microanalysis (EPMA), Raman microprobe analysis (RMA), X-ray micro-diffraction analysis (XRMD), transmission electron microscopy (TEM) and high-resolution transmission electron microscopy (HRTEM), instrumental neutron activation analysis (INAA), proton-induced X-ray emission analysis (PIXE), and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS).

Keywords Yanzhuang chondrite · Sample preparing · Analytical techniques

1.1 Introduction

The Yanzhuang meteorite experienced heavily impact in space, its chondritic material was partly molten and vaporized, and minerals in its unmelted portion were heavily deformed (Xie et al. 1991, 1994). Hence, we selected Yanzhuang No. 3 specimen which contains abundant melt veins and melt pockets, and techniques suitable for the investigation of shock-induced fine structures within minerals, as well as the techniques for analysis of microelements to explore their redistribution during melting and condensation. These mineralogical techniques have been summarized by Edward. C. T. Chao, Xiande Xie, and Ming Chen in their publications (Chao and Xie 1989, 1990; Chen 1992; Xie and Chen 2016, 2018).

1.2 Meteorite Samples

Samples used for this study mainly obtained from Yanzhuang No. 3 specimen of 508 g in weight (Fig. 1.1) and partly from other specimens. This No. 3 specimen was cut into small pieces for making thin sections as it is shown in Fig. 1.2. The prepared samples include:

X. Xie and M. Chen, *Yanzhuang Meteorite: Mineralogy and Shock Metamorphism*,
https://doi.org/10.1007/978-981-15-0735-9_1

(1) **Large polished section**: A large slice of 38 cm^3 in area and 6 mm in thickness was cut off from No. 3 specimen. This slice then was polished to prepare a section for study of the rock facies and fabric and for metallographic study of opaque minerals in Yanzhuang meteorite.
(2) **Small polished sections**: A series of small polished sections of 1.2 × 1.2 × 0.5 cm^3 were prepared for metallographic microstructural and chemical compositional study of opaque minerals.
(3) **Polished thin sections**: Twenty double-polished thin sections of 30 μm in thickness and without cover glasses were prepared. Part of them was glued on the glass slide with epoxy resin for the study of transparent minerals using optical and phase-contrast microscopy, as well as for SEM, EPMA, and RMA, and the another part with Canadian gum for TEM study after ion thinning.
(4) Several small pieces of 1 × 1 × 1 cm^3 in volume with naturally broken surface were used for the study of surface microstructures of some selected minerals.
(5) Several monomineral grains were selected for micromorphological, X-ray diffraction, and other analyses.
(6) Small samples were taken from chondritic rock and different parts of shock-induced melt for instrumental neutron activation analysis of microelements.

Besides above-mentioned samples, 200 g of Yanzhuang No. 3 specimen were preserved as duplicate sample, and the rest portion of this specimen was used for other analysis, such as thermal luminescence, noble gases, PIXE, and LA-ICP-MS.

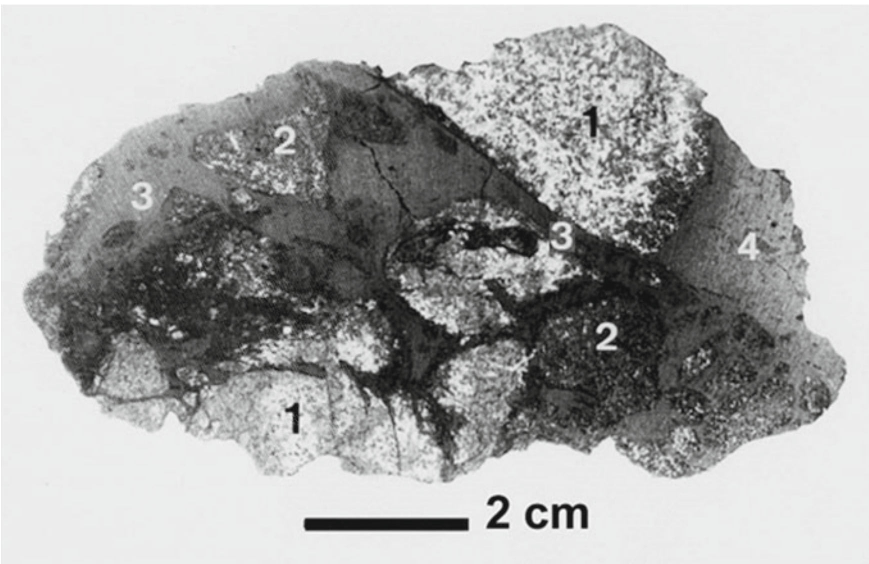

Fig. 1.1 Photography of a cut surface of Yanzhuang fragment No. 3: 1-light-colored unmelted chondritic region; 2-brecciated chondritic region and partially melted, crystallized, and brecciated region; 3-shock-melt veins, and 4-large melt pocket

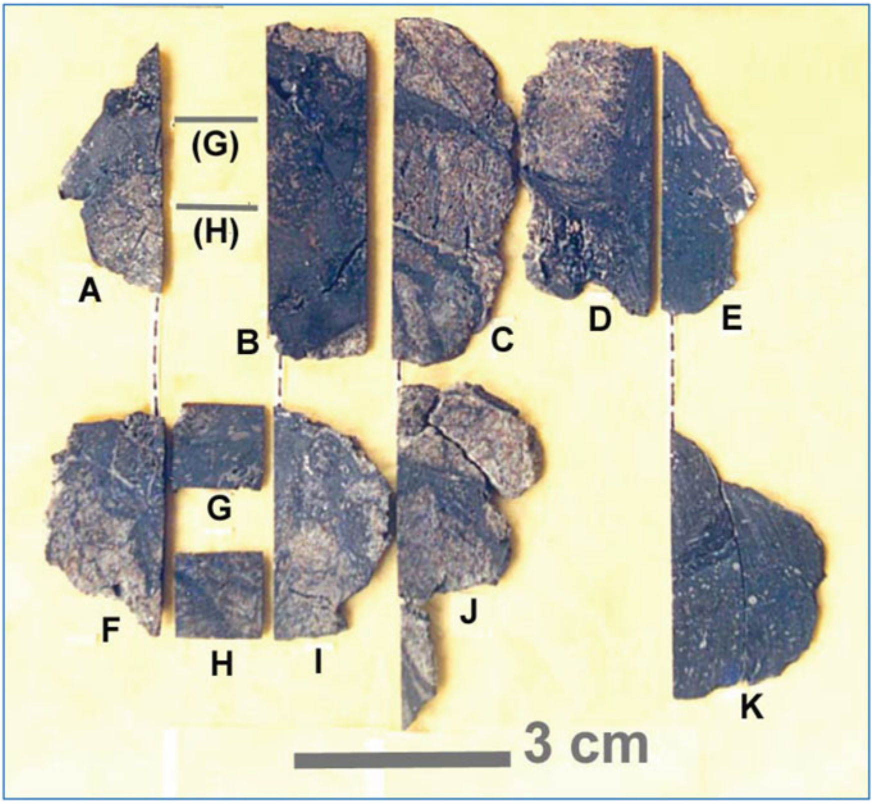

Fig. 1.2 Slice samples cut from Yanzhuang fragment No. 3. The English letters are numbers of slices

1.3 Experimental Techniques

1.3.1 Petrographic and Phase-Contrast Microscopies

The petrographic microscope is a basic tool to be used to identify mineral assemblages, optical properties, structural and textural relationships, some internal fine structures, and deformation features in Yanzhuang minerals. Microscopic study is also an important prerequisite for utilization of many other experimental methods. In this study, the phase-contrast microscope is specially used to observe and analyze the shock-induced change of microstructures in minerals. It is an effective tool for observation of refractive index change of transparent minerals.

1.3.2 Scanning Electron Microscopy–energy-Dispersive X-ray Analysis

A JSM-35C scanning electron microscope equipped with an EDAX-9100 X-ray energy-dispersive spectrometer has been used for SEM–EDX studies of Yanzhuang meteorite. In analyses, the working accelerating voltage is 20 kV. We utilized SEM–EDX to study: (1) surface microstructure of minerals. (2) Metallographic microstructures of FeNi metal after etching. (3) Chemical composition of tiny minerals (phases) and linear/planar distribution of certain elements.

1.3.3 Electron Probe Microanalysis

An EPM-810Q electron microprobe equipped with an EDAX-9100 X-ray energy-dispersive spectrometer were used for analyzing the Yanzhuang minerals (phases). In wavelength-dispersive analysis, the working accelerating voltage is 20 kV, the beam current is 20 nA, and the data were corrected using a ZAF program. Natural and synthetic phases of well-known similar compositions were used as standards. In non-standard EDX analysis, the counting time is 80 s. In this study, we use EPMA technique to analyze the chemical compositions of different mineral phases in Yanzhuang, as well as the linear or planar distribution of certain elements.

1.3.4 Transmission Electron Microscopy

The H-700, JEM-200CX, and JEM-200EX transmission electron microscopes were successively used for study the mineralogy and fine structures of minerals in the Yanzhuang meteorite. They all were equipped with the EDAX-9100 X-ray energy-dispersive spectrometer. The working accelerating voltage is 200 kV. Samples for TEM analysis were prepared mainly by selected area ion thinning of thin sections. Only a few samples were prepared by powder dispersion of single minerals. In our study, TEM techniques were used for observation of microstructures of different minerals (phases) in the meteorite. At the same time, the selected area electron diffraction patterns were obtained to explore some crystal structure information. High-resolution TEM was also used for some samples to search residual high-pressure phases.

1.3.5 Raman Microprobe Analysis

A Yvon U-1000 laser Raman microprobe (Ar^+ laser, laser power of 400 mW and 488 nm green line) has been used for recording Raman spectra of different minerals and polymorphous phases of the Yanzhuang meteorite. A microscope was used to focus the excitation laser beam to 1–2 μm spot. The running speed is 2 cm^{-1}/10 s. The range of frequency scanning is 200–1300 cm^{-1}. Each Raman spectrum was obtained through 5–8 time of scanning. In this study, laser Raman microprobe technique was used to identify mineral species and observe the change of microstructures of different shock phases in the Yanzhuang meteorite.

1.3.6 X-ray Micro-Diffraction In-Situ Analysis

X-ray micro-diffractometer is an effective tool for obtaining X-ray diffraction data of tiny size of minerals and materials, usually less than 1 mm, directly on thin sections or plane blocks containing the mineral or material of interest. A Rigaku D/Max Rapid IIR X-ray micro-diffractometer has been used in in-situ study of some Yanzhuang minerals. It is mainly composed of the following parts. The diffraction effect of the sample is recorded on 2D image plate of the area 470 × 256 mm^2 arranged in 4700 × 2560 pixels. The pixel coordinates of a diffraction dot on the image are related to the incident angle (θ) of X-ray and the dipping angle (β) of the normal line of the sample plane. Numerous diffraction dots with the same θ constitute a Debye ring. Intensity integration along the Debye rings yields one-dimensional 2θ-I data similar to the pattern of powder diffraction.

1.3.7 Instrumental Neutron Activation Analysis

The instrumental neutron activation analysis of Yanzhuang samples was conducted for several times. As early as in 1991, the authors of this book had conducted neutron activation analysis of Yanzhuang whole rock with the help of Professor Zhou Rongsheng of the Chengdu Geological College (Chen 1992). Begemman et al. (1992) conducted instrumental neutron activation analysis of trace elements and determination of noble gas contents for both light-colored unmelted chondritic rock and black-colored shock melt of the Yanzhuang meteorite. Zhong et al. (1995) analyzed major elements, rare earth elements, and some other trace elements in light-colored phase, black melt phase, and metal particles in Yanzhuang meteorite using neutron activation technique. Chen et al. (1994) also used the instrumental neutron activation method to determine the trace element concentrations in Yanzhuang shock melt, unmelted chondritic rock, and magnetic metal phase. They also discussed the shock effects and thermal history of the Yanzhuang meteorite on the bases of its noble gas contents and shock features in the Yanzhuang parent body. Kong and Xie (2003) not only conducted the instrumental neutron analysis for the Yanzhuang unmelted and melted phases, but also determined trace element concentrations for FeNi metal, sulfide, and silicate phases. The detailed results of above-related analyses will be given in Chap.10 of this book.

1.3.8 Proton-Induced X-ray Emission Analysis

Proton-induced X-ray emission is a unique technique developed in the late 1960s for performing non-destructive analysis, which is based on the measurements of characteristic X-rays induced by energetic focused proton beam directed onto the surface of a specimen held under vacuum. A high-energetic Si(Li) semiconductor detector is used to measure the energy and intensity of induced X-ray to achieve X-ray spectroscopic analysis. The space resolving power can reach a few micrometers. This technique has been successfully used for analysis of various types of samples to estimate the trace multielement concentration in several types of systems. Wu Xiankang of the Shanghai Institute of Nuclear Research, Chinese Academy of Sciences in cooperation with Li Zhaohui of the Institute of Geochemistry, CAS, performed trace element analysis of Yanzhuang FeNi metal using the SINR nuclear microprobe facility with a 3 MeV proton beam (Wu et al. 1995). The sample is of 50–100 pm and the scanning area of proton beam is $180 \times 150\ \mu m^2$ and the induced X-ray is received by Si(Li) detector, and the elemental maps are given by a computer.

1.3.9 Laser Ablation ICP-MS

In the study of our Yanzhuang minerals, an Agilent 7500a ICP-MS coupled with a Resonetics RESOlution M-50 laser ablation system in the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, was used to analyze the trace elements. RESOlution M-50 laser ablation system consists of an excimer (193 nm) laser, a two-volume laser ablation cell, a Squid smoothing device, and a computer-controlled high-precision X-Y stage. The two-volume laser ablation cell is designed to avoid cross-contamination and reduce background flushing time. The Squid smoothing device can reduce statistic error induced by laser ablation pulses. The accuracy of the X-Y stage is better than 0.1 μm. The laser beam spot diameters are 30 and 60 μm, respectively. Our results indicate that the relative standard deviations are mostly less than 5%, and relative deviations of obtained average concentrations from reference values are mostly less than 10%, while the external standards MPI-Ding glass is used (Tu et al. 2011).

References

Begemann F, Palme H, Spettel B, Weber HW (1992) On the thermal history of heavily shocked Yanzhuang H-chondrite. Meteoritics 27:174–178

Chao ECT, Xie XD (1989) Micro-mineralogical techniques in geological investigations. Science Press, Beijing, pp 215 (in Chinese)

Chao ECT, Xie XD (1990) Mineralogical approaches to geological investigations. Science Press, Beijing, p 388

Chen M (1992) Micro-mineralogy and shock metamorphism of Yanzhuang meteorite. Ph. D Thesis, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, pp 95 (in Chinese with English abstract)

Chen YH, Dai CD, Wang DD, Xie XD, Li ZH, Fang H, Cai ZF (1994) Chemical composition and shock effects of naturally shocked meteorites. Geochemica 23:25–32 (in Chinese with English abstract)

Kong P, Xie XD (2003) Redistribution of elements in the heavily shocked Yanzhuang chondrite. Meteorit Planet Sci 38:739–746

Tu XL, Zhang H, Deng WF, Ling MX, Liang HY, Liu Y, Sun WD (2011) Application of RESOlution in-situ laser ablation ICP-MS in trace element analyses. Geochemica 40(1):83–98 (in Chinese with English abstract)

Wu JK, Zhu JQ, Li ZH (1995) Quantitative micro-PIXE analysis of Yanzhuang meteorite. Phys Res B 104:445–449

Xie XD, Chen M (2016) Suizhou meteorite: mineralogy and shock metamorphism. Springer and Guangdong Science & Technology Press, Berlin Heidelberg, Guangzhou, p 258

Xie XD, Chen M (2018) Yanzhuang meteorite: mineralogy and shock metamorphism. Guangdong Science & Technology Press, Guangzhou, pp 202 (in Chinese with English abstract)

Xie XD, Li ZH, Wang DD, Liu JF, Hu RY, Chen M (1991) The new meteorite fall of Yanzhuang, a severely shocked H6 chondrite with black molten materials. Meteoritics 26:411

Xie XD, Li ZH, Wang DD, Liu JF, Hu RY, Chen M (1994) The new meteorite fall of Yanzhuang, a severely shocked H6 chondrite with black molten materials. Chin J Geochem 12:39–46

Zhong HH, Huang JQ, Ling YY, Jiang LJ, Hu GH, Li ZH, Yi WX, Wang DD (1995) A preliminary study on the cosmochemical characteristics of elements in the Yanzhuang meteorite by INAA. J Instrum Anal 14:7–11

Chapter 2
General Introduction of the Yanzhuang Meteorite

Abstract On October 31, 1990, at 21:45 Beijing time, the Yanzhuang meteorite fell in the field of the Yanzhuang village, Wengyuang County, Guangdong Province. Ten fragments, totaling 3.5 kg, were recovered during the field survey. This meteorite is assigned to an H6 (S6) chondrite. It is composed of light-colored unmelted chondritic rock and black-colored molten mass. Constituent minerals in the Yanzhuang unmelted chondritic rock comprise olivine, orthopyroxene, clinopyroxene, plagioclase, maskelynite, kamacite, taenite, troilite, and small amount of merrillite, chromite, and ilmenite. The shock-induced melt is composed of microcrystalline olivine, pyroxene, plagioclase, FeNi and FeS nodules, and glassy materials.

Keywords On-spot survey · Yanzhuang chondrite · Unmelted chondritic rock · Shock-produced melt

2.1 Introduction

The Yanzhuang meteorite is a fall and was classified as an H6 chondrite. Right after the fall of this meteorite, the first author of this book organized a group of scientists including Zhaohui Li, Jingfa Liu, and Ruiying Hu from the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, to conduct field survey and collect the meteorite samples. This group then conducted systematic studies on collected samples. Especially, Ming Chen completed his Ph.D. thesis on the study of micromineralogy and shock effects in this Yanzhuang chondrite (Chen 1992). During the recent years, members of this group continued studying of this meteorite in laboratories using advanced techniques and obtained a series of interesting and valuable new results (Xie and Chen 2018). In this chapter, we describe the results of on-spot investigations together with a brief introduction of this Yanzhuang meteorite.

X. Xie and M. Chen, *Yanzhuang Meteorite: Mineralogy and Shock Metamorphism*,
https://doi.org/10.1007/978-981-15-0735-9_2

2.2 Falling Phenomenon of the Yanzhuang Meteorite

On October 31, 1990, at 21:45 Beijing time, an incandescent fireball of pink and light yellow color was rapidly sweeping through the air over several counties in the central and northern parts of Guangdong Province. The fireball flight was observed by thousands of local residents at Guangzhou, Qingyuan, Shaoguan, Heyuan, Lianping, Wengyuan, and Yingde, while shock wave sounds were also heard. The flight direction of this fireball runs from southeast to northwest, that is, from Heyuan through Lianping to Wengyuan. This fireball violently exploded in the sky over the Lianping County. Residents in these areas saw this elliptical fire body turned into a string of bead-like bodies swept the sky and heard heavy but oppressive roar right upon the explosion. The fragments then fell in the field of the Yanzhuang village, Wengyuang County. Its geographical coordinates are N24° 34′-E114° 10′ (Fig. 2.1).

Right after the fall of this meteorite on October 31, 1990, the first author of this book organized a group of scientists including Zhaohui Li, Jingfa Liu, and Ruiying

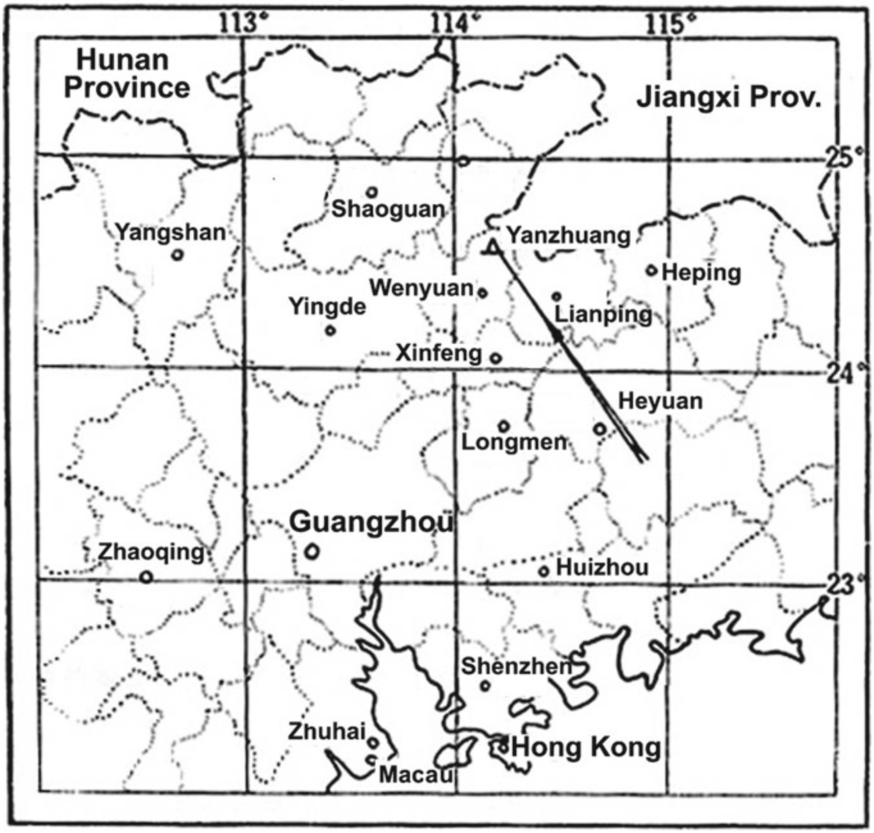

Fig. 2.1 Sketch map showing the flying path and the location of the Yanzhuang meteorite

Hu from the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, to conduct field survey and collect the meteorite samples. During our on-spot survey, the farmers in the village told us that the Yanzhuang meteorite was broken into several pieces, and one piece of them hit and penetrated the eaves of the Guo family's house, and fell on the cement floor forming a hole of 30 cm in diameter. Another piece hit the eaves of neighbor family's house and fell on the wooden floor of its balcony (Fig. 2.2). There was also a fragment hit the granite outcrop aside a village road forming a small and shallow pit of 2 cm deep.

Three larger pieces (referred to as Yanzhuang meteorites No. 1, No. 2, and No. 3) and several smaller fragments of the meteorite were recovered after its falling. Though the total volume of this meteorite was unknown, meteorite samples recovered by our group weighted 3.5 kg in total with the largest piece measuring 823 g in weight (Xie et al. 1991) (Fig. 2.3). The most marked feature of this meteorite is that it contains a big amount of black melt veins and melt pockets. Obviously, this meteorite had subjected heavy collision by another asteroid in space. Though thousands of meteorites of various types have been recovered up to now on our Earth, the great scale of shock-induced melting and specific-metamorphic features of the Yanzhuang meteorite are very unique and rare in meteorite family (Xie et al. 1991, 1994; Chen 1992; Chen et al. 1995, 1994; Chen and Xie 1997; Xie and Chen 2016, 2018).

Fig. 2.2 Photograph showing the farmers of the Yanzhuang village show the damaged wooden balcony to Prof. Zhaohui Li (sixth on right) and Prof. Ruiying Hu (fourth on right)

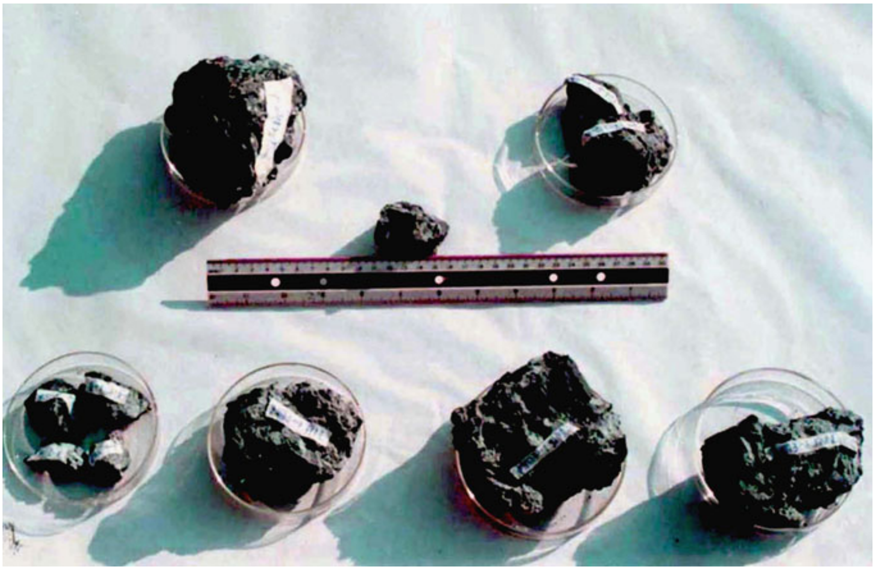

Fig. 2.3 Photograph showing the Yanzhuang meteorite samples recovered by the survey group from the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences

Our group then conducted systematic studies on collected samples. Especially, Ming Chen completed his Ph.D. thesis on the study of micromineralogy and shock effects in this Yanzhuang chondrite (Chen 1992). During the recent years, members of this group continued studying of this meteorite in laboratories using advanced techniques and obtained a series of interesting and valuable new results (Xie and Chen 2018).

It is clear that comprehensive study of the Yanzhuang meteorite would provide important formation for understanding of the physic-chemical characteristics of asteroid surface and evolution of celestial bodies, and provide direct evidence for study of high-pressure and high-temperature geology and mineralogy of the Earth's mantle, as well as for the study of the structure of cosmic masses. Especially, the study of heavily shocked and partly molten Yanzhuang meteorite is of great theoretical significance and application value for understanding the shock-induced vaporization, melting, decomposition, and recrystallization of minerals, and differentiation and redistribution of elements of cosmic masses, and condensation and solidification of molten phases.

2.3 General Characteristics of the Meteorite

The recovered stones are roughly lenticular and ovoid in shape, with a maximum length of about 10 cm. The meteorite was covered with black fusion crust measuring in ~1 mm in thickness. The No. 3 stone is a representative among all collected

Fig. 2.4 Cut surface of the Yanzhuang No. 3 meteorite showing the black melt pocket (right dark region) and the black melt veins penetrating the light-colored chondritic rock of the meteorite

samples. It is of 10 × 5 × 4.5 cm^2 in volume, and about one-forth of its surface was covered by black molten crust of 1–2 mm thick. The other three-forth are fresh broken surface exposed after the explosion of this meteorite. The exposed interior of the meteorite is composed of light-colored and strongly deformed chondritic rock, and black-colored completely molten phase in the form of veins and pockets (or blocks). These unique features are clearly seen on the cut surface of the Yanzhuang No. 3 meteorite (Fig. 2.4). The melt veins (0.1–15 mm in width) and the melt pockets (up to 2 × 3 × 4 cm^3 in volume) connected and interweaved with each other and occur in the light-colored chondritic host rock. The tensile cracks in this meteorite sample are very well developed.

2.3.1 Light-Colored Chondritic Rock

The light-colored unmelted chondritic rock is the main part of the meteorite, with coarse-grained minerals in it. Due to heavy impact, the meteorite has been severely fractured and become crumbly. The chondritic rock adjacent to black melt pockets or veins usually has darker color, and many fine metal and sulfide veinlets of 0.01–0.5 mm in width filled the cracks and fractures occurred inside silicate minerals, thus forming so-called blackened areas (Fig. 2.5). The region right adjacent to the blackened area is the brecciated area, in which minerals were heavily smashed. Beyond the brecciated area is the area of unmelted but weakly deformed chondritic host rock, or simply call it weakly deformed area (Fig. 2.6). It should be pointed out that some local strongly deformed parts can also be observed in this weakly deformed area.

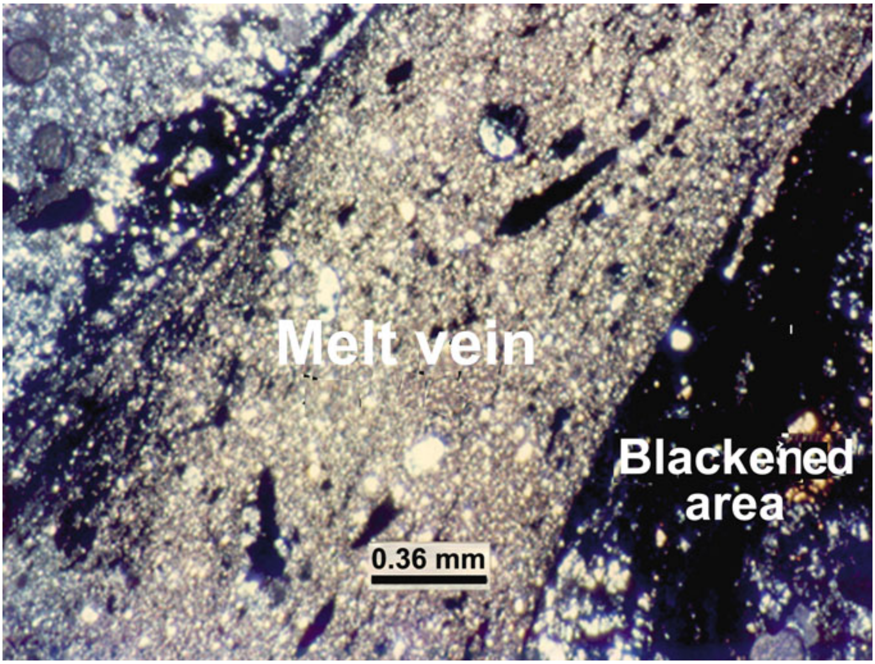

Fig. 2.5 Photomicrograph of the blackened area adjacent to a melt vein showing the smashed fractures of minerals and lack of chondrules (crossed Nicols)

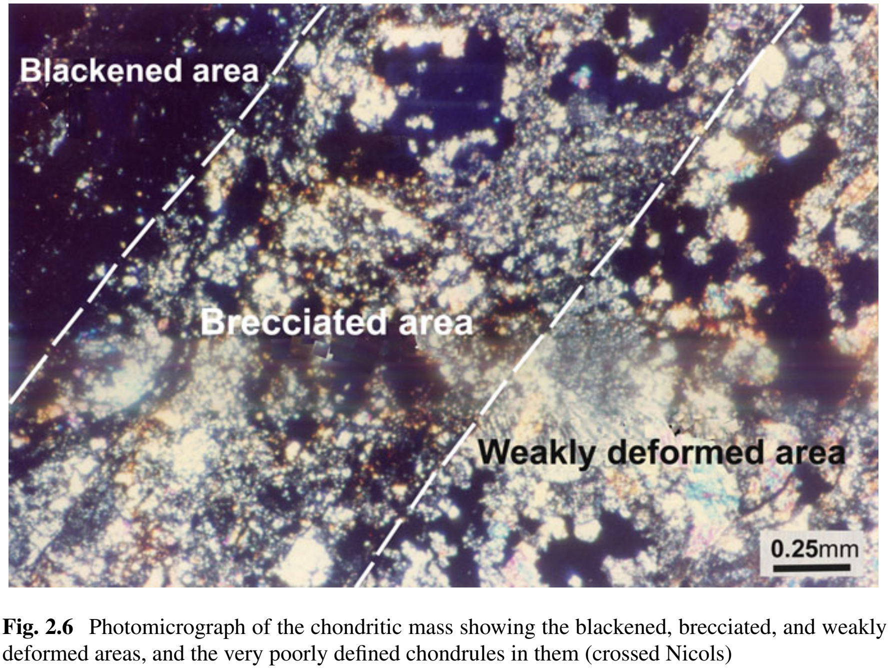

Fig. 2.6 Photomicrograph of the chondritic mass showing the blackened, brecciated, and weakly deformed areas, and the very poorly defined chondrules in them (crossed Nicols)

Constituent minerals in the Yanzhuang unmelted chondritic mass comprise olivine (40%), orthopyroxene (30%), clinopyroxene (4%), plagioclase and maskelynite (4%), kamacite (10%), taenite (4%), troilite (6%), and small amount of merrillite, chromite, and ilmenite.

2.3.2 Black Melt Pockets and Veins

The molten materials in the Yanzhuang meteorite occur in the form of black melt pockets and melt veins. They are very compact and hard and composed of recrystallized mineral crystallites, rounded or elliptic FeNi + FeS eutectic nodules/blobs, silicate melt glass, and small amount of mineral fragments. In the Yanzhuang No. 3 meteorite, the melt pockets are up to 2 × 3 × 4 cm in size, and the melt veins are of 0.1–15 mm in width. The veins connect with each other, penetrating the whole meteorite body. The detailed features of these molten materials will be described in Chap. 4.

2.3.3 Metal–Sulfide Veinlets

In the regions directly adjacent to black melt veins or melt pockets, there are some fine veinlets of FeNi-FeS composition distributed in fractures in silicate minerals. They are 1–2 mm in width. Because of the development of such fine veinlets, these regions are blackened (Fig. 2.5).

2.4 Structures and Textures

2.4.1 Textural Types of Chondrule

In thin sections, the Yanzhuang chondritic rock exhibits equilibrated ordinary chondritic texture. Both poorly defined chondrules and their broken fragments are present in the recrystallized meteorite groundmass. Chondrules are about 0.02–2 mm in size. In most cases, the boundaries between chondrules and the groundmass are indistinct. Although the meteorite was heavily deformed and fragmented by shock waves, and the chondrules experienced marked destruction, some chondrules can still be recognized in local regions of the meteorite. On the basis of texture characteristics observed under microscope, the Yanzhuang chondrules can be classified into the following textural types: