Astrophysics from Antarctica
Proceedings IAU Symposium No. 288, 2012
M. G. Burton, X. Cui & N. F. H. Tothill, eds.

doi:10.1017/S1743921312016778

Antarctic meteorites and the origin of planetesimals and protoplanets

Akira Yamaguchi

National Institute of Polar Research 10-3 Midori-cho, Tachikawa, Tokyo 190-8518, Japan
email: yamaguch@nipr.ac.jp

Abstract. Almost all meteorites (about 99% by number) are samples from a few hundreds of asteroids that are leftover from planetesimals and protoplanets formed within several million years after the birth of the Solar System. These meteorites record detailed evolutionary history of dust to planets, including condensation, accretion, aqueous alteration, thermal metamorphism, partial and total melting.

Keywords. Meteorites, planetesimals, protoplanets, asteroids, metamorphism, differentiation

1. Introduction

It is widely accepted that most meteorites were derived from asteroids on the basis of evidence such as the infrared spectra of meteorites being similar to those of asteroids, observations of some meteor falls tracking back to asteroid regions, and cosmogenic ages consistent with asteroidal origin. A small fraction of meteorites have originated from the Earth's Moon and from Mars (about 0.5% by number). We have collected rocks from several hundreds of asteroids (and comets?), the Moon and Mars as meteorites, providing us with samples directly available for a variety of research. As of August 2012, the number of approved meteorites is 44,263 (Meteoritical Society, 2012). About 70% of these meteorites (30,712) were recovered from Antarctica.

Meteorites fall with equal frequency on the Earth. However, the number of recovered meteorites from Antarctica is much greater than those from other areas. On December 10th, 1969, Japanese Antarctic Research Expedition (JARE-10) discovered 9 meteorites with at least 5 distinct groups (E, H, L chondrites, a carbonaceous chondrite, and a diogenite) on blue ice fields from the Yamato Mountains (e.g., Yoshida, 2010). Their discovery implies that some kind of meteorite concentration mechanism operated on the Antarctic ice sheet. The importance of the meteorite discovery was immediately recognized, and many expeditions teams have subsequently been sent to Antarctica.

One might ask why so many meteorites are found in Antarctica? Meteorites fall on the ice, are covered by snow and frozen into the ice. Glaciers that carry meteorites flow toward mountains where the movements of glaciers are stopped, and where ice layers are then removed by ablation (abrasion and sublimination) leaving the meteorites behind. Not all blue ices bear meteorites; special conditions may be needed (Harvey, 2002). It should be noted that since early 1990's, many meteorites have been recovered from other areas, especially hot deserts (e.g., Sahara, Arabian Peninsula), but Antarctica is still the most fertile area for meteorite recovery. Detailed studies of many Antarctic meteorites expand the understanding of the origin of planetesimals and protoplanets.

2. Classification of asteroidal meteorites

Asteroidal meteorites are mainly classified into two groups, chondrites (primitive or undifferentiated meteorites) and achondrites (differentiated meteorites) (e.g., Weisberg *et al.*, 2006) (Figure 1). Chondrites are the most primitive rocks in the Solar System. They have chemical compositions broadly similar to the composition of the Sun, except for hydrogen, helium and other highly volatile elements. Chondrites are composed of four major components: chondrules, refractory inclusions (Ca-Al rich inclusions – CAI), amoeboid olivine aggregates and fine-grained matrix. These components are products of different parts in the solar nebular. Currently, there are 15 chondrites groups, including carbonaceous (CI, CM, CO, CV, CK, CR, CH, CB), ordinary (H, L, LL), enstatite (EH, EL), and R and K chondrites. Ordinary chondrites are the most common types. It is plausible that the members of each group come from a single parent body. Most chondritic meteorites have been affected to some degree by later events such as impacts and aqueous alteration.

The achondrites lack chondritic textures, and are igneous rocks or breccias of igneous rocks, or iron and stony-iron meteorites that formed by melting events in the parent bodies. The degree of melting varies from partial melting to total melting that produced a magma ocean. The latter meteorites may have been derived from protoplanets. Some meteorites have achondritic (igneous or metamorphic) textures but have similar chemical compositions to those of chondrites. These meteorites are called primitive achondrites. Achondrites consist of differentiated achondrites (angrites, aubrites, howardites-eucrites-diogenites (HEDs), mesosiderites, 3 groups of pallasites, groups of iron meteorites and primitive achondrites (ureilites, brachinites, acapulcoites, lodranites), plus many ungrouped achondrites.

3. Metamorphism in planetesimals

At the first stage, primordial components aggregated into planetesimals. Planetesimals experienced various types of secondary processing caused by internal heating. One of the most plausible heat sources is the heat caused by rapid decay of ^{26}Al (half live = 0.7 million years) that existed in the early Solar System. ^{26}Al was incorporated into planetesimals during accretion, and the planetesimals were heated by varying degrees. The degree of heating depends on several factors, including the initial abundance of ^{26}Al,

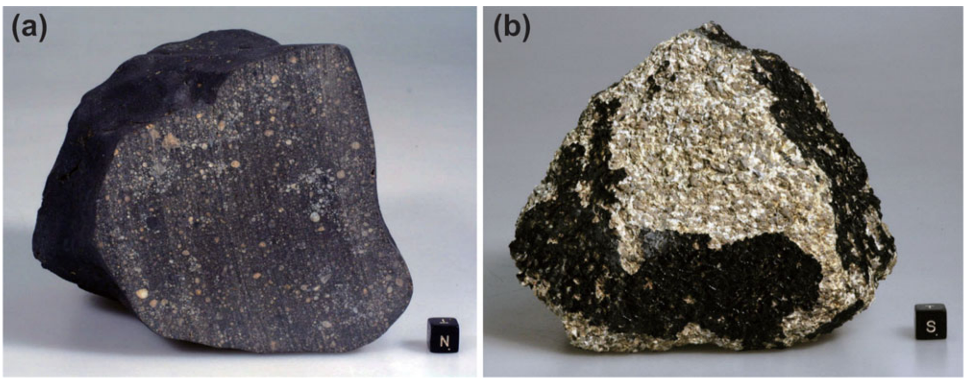

Figure 1. (a) Ordinary chondrite (LL3), Yamato-790448. The cut surface shows a typical chondritic texture. (b) Achondrite (gabbroic eucrite), Yamato-980433. This meteorite is partly covered by fa usion crust (black). Broken surfaces show an igneous texture (upper middle). The size of the black cube on the lower right is 1 cm.

https://doi.org/10.1017/S1743921312016778 Published online by Cambridge University Press

the sizes of the bodies, and the timing of accretion. Impact events played an important role for the geologic history of asteroids as seen in shocked and brecciated meteorites and heavily cratered surfaces of asteroids. Impacts have been suggested for the source of early heating events. However, impact events are not effective for global heating for the sizes of planetesimals (Keil *et al.*, 1997). Development of regolith layers by repetitive impacts on the surface, which are poor conductors of the heat, will insulate the interior from it. Large impact events would have destroyed planetesimals, causing rapid cooling of the hot interiors.

Chondrites experienced secondary processing to varying degrees. Thermal metamorphism of chondritic precursors caused recrystallization that blurred original chondritic textures and chemical homogenization of mineral such as olivine ($(Mg,Fe)_2SiO_4$) and pyroxene ($(Mg,Fe,Ca)SiO_3$). Many chondrites are primarily classified into six petrologic types (type 1–6). Types 1 and 2 are only represented by some groups of carbonaceous chondrites, with a different kind of processing – aqueous alteration. The subsequent reactions between solid and fluid on parent bodies led to the formation of secondary minerals such as carbonates and magnetite, the alteration of primary silicate minerals (olivine, pyroxene) to phyllosilicates, and the oxidation of metal and sulfide grains.

Ordinary chondrites are subdivided into four petrologic types (types 4–6) on the basis of the degree of thermal metamorphism. Peak temperatures of 750–950°C are suggested for type 6 chondrites (the most metamorphosed) and 400–600°C for those of type 3 chondrites (e.g., McSween and Patchen, 1989). Cooling rates are estimated to be a few tens of degrees per million years. Heating by ^{26}Al decay of planetesimals caused concentric zones of different metamorphic grades, i.e., high metamorphic grade in centre, and low metamorphic grades near the surface. This structure is referred to as the onion shell model. Most ordinary chondrites are breccias composed of various metamorphic grades. This implies that the parent bodies are mixtures of various metamorphic grades from various depths of the onion shell bodies, which is referred to as the rubble-pile model. The presence of type 6 (most metamorphosed) fragments derived from the centre indicates that the parent bodies are totally disrupted and reassembled. Such structures are inferred from direct observations of asteroids. Itokawa is composed of LL chondrite like material, but the density is very low (1.9 g/cm^3), indicating a rubble pile structure with significant pore spaces inside (Fujiwara *et al.*, 2006).

Primitive achondrites experienced more intense heating than did chondrites. These meteorites have roughly similar bulk chemical compositions to those of chondritic precursors, but experienced some degrees of partial melting of silicate and FeNi-FeS. They were heated at around 1000–1100°C and experienced partial melting. Primitive achondrites with the lowest metamorphic grades in some cases are remnants of chondrules, whereas the highest ones are completely recrystallized.

4. HED meteorites and other asteroidal igneous rocks

Howardites, eucrites, diogenites meteorites (HEDs) are a suite of achondrites that are genetically related, and are among the largest group of achondrites, and probably derived from a large asteroid Vesta (530 km in diameter). Eucrites are basalts or gabbros and diogenites are orthopyroxenites and harzburgites (pyroxene-olivine rocks). Howardites are mechanical mixtures mainly composed of eucrites and diogenites.

Several lines of mineralogical, geochemical and isotopic evidence suggest that the differentiation of Vesta was triggered by a magma ocean in its early history (e.g., Hewins and Newsom, 1988; Greenwood *et al.*, 2005; Takeda, 1997). In the magma ocean model, eucrites were residual liquids after extensive fractional crystallization, and diogenites were cumulate rocks accumulated beneath the magma ocean (e.g., Righter and Drake, 1997; Takeda, 1997). A metallic FeNi core may have formed before the silicate fractionation (Hewins and Newsom, 1988).

However, the increasing diversity of diogenites revealed by recent finds has challenged this view. First, the minor and trace element abundances indicate that diogenites crystallized from multiple magmatic bodies (e.g., Barrat *et al.*, 2008, 2010 and references therein). Some diogenites have geochemical evidence for remelting of some cumulate lithologies crystallized in a magma ocean and interactions of the outer eucritic crust. Also, several diogenites probably crystallized near the surface arguing against a deep crustal origin (Yamaguchi *et al.*, 2010). Thus, it can be inferred that parental melts of some diogenites intruded the eucritic crust (post-magma ocean volcanism). This view is broadly consistent with results from the recent DAWN mission (Russell, *et al.*, 2012).

To date, five anomalous basaltic asteroidal basalts from distinct asteroids have been identified, HED meteorites (Vestan crustal rocks, see above), NWA 011 (and paired meteorites), Dho 700, Ibitira (e.g., Yamaguchi *et al.* 2002; Scott *et al.* 2010; Greenwood *et al.*, 2012). These rocks are petrologically very similar to eucrites, but from a distinct origin mainly on the basis of oxygen isotopic compositions. Presumably, parent bodies of these meteorites experienced similar igneous, metamorphic, and impact histories as did asteroid 4 Vesta. The presence of andesitic meteorites (GRV06128 and 06129) implies a different style of early melting and fractionation (e.g., Day *et al.*, 2009)

Iron meteorites provide more evidence for the presence of differentiated asteroids. Magmatic iron meteorites are believed to have been cores of differentiated planetesimals or protoplanets. Wasson *et al.* (2012) argued that at least 26 extensively differentiated asteroids were disrupted in the inner asteroid belt on the basis of iron meteorite data. Yang *et al.* (2007) suggested that some iron meteorites originated from cores of protoplanets that formed several million years after the birth of Solar System. Thus, numerous differentiated bodies similar to Vesta might have existed in the early Solar System.

5. Summary

Almost all meteorites were derived from asteroids (and comets?) that are remnants from the building blocks of the Solar System. These asteroidal meteorites are very old, formed less than a few tens million years after the formation of Solar System, allowing us to understand the early geologic processes that took place in planetesimals and protoplanets. In comparison to other extraterrestrial samples available for direct studies, meteorites are robots with respect to their sizes and masses. Among the recovery sites, Antarctica is the most fertile area for meteorite recovery. Continued efforts in meteorite recovery from Antarctica, as well as from other areas such as hot deserts, and space missions will help us to understand the origin of the Solar System.

References

Barrat, J. A., Yamaguchi, A., Greenwood, R. C., Beniot, M., Cotten, J., Bohn, M., & Franchi, I. A. 1995, *Meteor. Planet. Sci.*, 30, 490

Barrat, J. A., Yamaguchi, A., Zanda, B., Bollinger, C., & Bohn, M. 1993, *Geochim. Cosmochim. Acta*, 74, 6218

Day, J. M., Ash, R. D., Liu, Y., Bellucci, J. J., Rumble III, D., McDonough, W., Walker, R., & Taylor, L. A. 2009, *Nature*, 457, 179

Fujiwara A. *et al.* 2006, *Science*, 312, 1330

Greenwood, R. C., Franchi, I. A., Jambon, A., & Buchanan, P. C. 2006, *Nature*, 435, 916

https://doi.org/10.1017/S1743921312016778 Published online by Cambridge University Press

Greenwood, R. C., Barrat, J. A., Scott, E. R. D., Janots, E., Franchi, I. A., Hoffman, B., Yamaguchi, A., & Gibson, J. M. 2012, *Lunar Planet. Sci.*, 43, 2771

Harvey, R. 2003, *Chem. Erde*, 63, 93

Hewins, R. H. & Newsom, H. E. 1998, *Meteorite and Early Solar System, ed. by Kerrige J.F. & Matthews, M.S.*, 631, 976

Keil K., Stoffler, D., Love, S. G., & Scott, E. R. D. 1997, *Meteor. Planet. Sci.*, 32, 349

McSween, H.Y., Jr., & Patchen, A.D., 1989 *Meteoritics*, 24, 219

Righter, K. & Drake, M. J. 1997, *Meteor. Planet. Sci.*, 32, 929

Russell, C. T., *et al.* 2012, *Science*, 336, 684

Scott E. R. D., Greenwood, R. C., Franchi, I. A., & Sanders, I. S. 2009, *Geochim. Cosmochim. Acta*, 73, 5835

Takeda H. 1997, *Meteor. Planet. Sci.*, 32, 841

Wasson, J. T. 2012, *Lunar Planet. Sci.*, 43, 2931

Weisberg, M. K., McCoy, T. J., & Krot, A. N. 2012, *Meteorite and Early Solar System II. ed. Lauretta, D.S., & McSween Jr., H.Y.,*, 43, 2931

Yamaguchi A., *et al.* 2002, *Science*, 296, 334

Yamaguchi, A., Barrat, J. A., Ito, M., & Bohn, M. 2011 . 2011, *J. Geophys. Res.*, 116, 334, E08009, doi:10.1029/2010JE003753

Yang, J., Goldstein, J. I., & Scott, E. R. D. 2007, *Nature*, 446, 888

Yoshida, M. 2010, *Polar Science*, 3, 272