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The Bagnone iron meteorite (Tuscany, Italy): History, mineralogy, and chemical classification

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Abstract–Bagnone, the largest Italian iron meteorite (48 kg), was found as a single mass at the beginning of the 20th century while ploughing a field close to the Bagnone Castle (Massa Carrara, northern Tuscany). The morphology of the external surface suggests that Bagnone represents a complete individual. It is classified as a medium octahedrite (average bandwidth = 0.96 mm) of the IIIAB chemical group, based on inductively coupled plasma mass spectrometry analyses.

INTRODUCTION

Bagnone is the largest iron meteorite (48 kg; Table 1) and the second largest meteorite ever found in Italy after the Alfianello L6 chondrite (228 kg). The first and only account of the Bagnone meteorite is given by Bonatti et al. (1970; see also Grady 2000). Accordingly, it was found as a single mass at the beginning of the 20th century near Bagnone (Massa Carrara, northern Tuscany) and identified as an iron meteorite only in the late sixties by Professor Stefano Bonatti and co-workers (Pisa University), who described it as a medium octahedrite.

In this work, we wish to provide a more comprehensive description of the Bagnone iron meteorite, reporting additional information on the circumstances of the finding and specimen distribution, along with further mineralogical data and bulk composition for chemical classification.

THE FINDING AND SPECIMEN DISTRIBUTION

We obtained new first-hand information about the finding of the Bagnone meteorite from Mr. Giuseppe Lazzeroni who made this report to us: "As a young boy, I lived in Cà d'Bernard (Home of Bernardo), a farmhouse of the Bagnone Castle estate owned by the noble Noceti family, together with my mother's brother, Mr. Antonio Bassignani, who worked on the farm as a share cropper. My uncle told me that in 1904 or perhaps 1905, he unearthed the strange, heavy, iron stone while ploughing a field close to the farmhouse (~44°19′N 10°00′E). I remember the stone, abandoned for many years on the edge of the field. I also remember that in the summer of 1967, my cousin Silvio Bassignani, Antonio's son, moved the iron stone to the castle using a sled pulled by two cows." In the summer of 1967, Dr. Lorenzo Ruschi Noceti brought the iron mass to the attention of Professor Stefano Bonatti, who recognized it as a meteorite and bought it on behalf of the former Istituto di Mineralogia e Petrografia of Pisa University. So far, no historical record of the fall has been found.

At present, the main mass of the Bagnone meteorite (48 kg, catalogue nr 14704; Perchiazzi and Mellini 1995; Fig. 1a) is on display at Pisa University's Museo di Storia Naturale. Two small portions from an endcut are held by Milan's Civico Planetario and Museo Civico di Storia Naturale (146 g; Folco et al. 2002) and by "La Sapienza" University's Museo di Mineralogia in Rome (51.1 g; Cavarretta Maras 1975).

APPEARANCE AND DIMENSIONS

Observations of the main mass held at Pisa University's Museo di Storia Naturale, showed that Bagnone is a complete meteorite with a roughly prolate lens shape and approximate dimensions of 40 × 21 × 17 cm (Fig. 1a). Most of the original fusion crust has been spalled off by terrestrial weathering and replaced by a dark brown coat of oxidation products. Despite weathering, Bagnone shows smooth, roughly round, shallow regmaglypts, up to ~5 cm in diameter (Fig. 1a), and two nearly flat and weakly undulated surfaces, which may represent broken surfaces during ablative flight. In places, the Widmanstätten pattern can be guessed from regularly oriented ridges in the weathered crust. An 8 × 3 cm polished and etched window was cut to obtain samples for research, and the specimens are held in Rome and Milan.

Table 1. Iron meteorites from Italy.

Name	Time of fall/find	TKW[a]	Structural group[b]	Chemical group	References
Bagnone	Find, 1904 or 1905	48 kg	Om	IIIAB	Bonatti et al. (1970); this work
Masua	Find, 1967	1460 g	Og	IAB	Wasson et al. (1989), Choi et al. (1995)
Barbianello	Find, 1960 or 1961	860 g	D	Ungrouped	Fioretti et al. (2001)
Patti	Fall, 1922 (?)	12 g	O	Unclassified	Baldanza and Pialli (1969)

[a]TKW = total known weight.
[b]Om = medium octahedrite, Og = coarse octahedrite, D = ataxite, O = octahedrite.

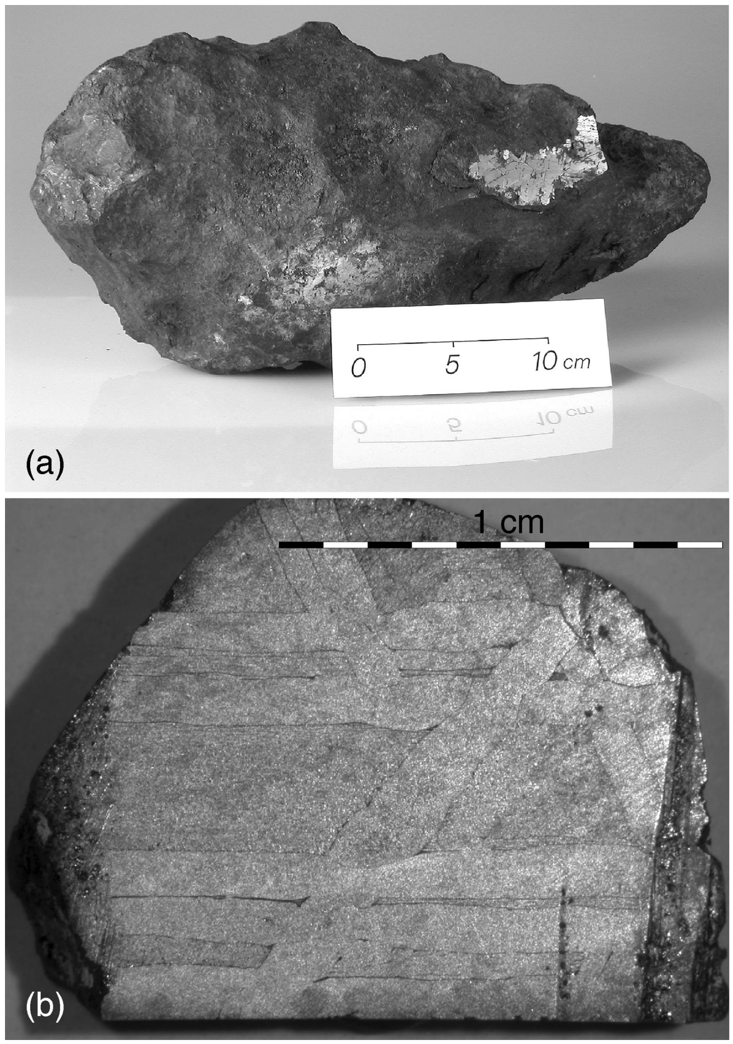

Fig. 1. a) The main mass of the Bagnone iron meteorite held at Museo di Storia Naturale (Certosa di Calci, Pisa, Italy); b) the polished and etched slice studied in this work.

MINERALOGY AND BULK COMPOSITION

Previous Work

The only published work on Bagnone is by Bonatti et al. (1970), who classified the meteorite as a medium octahedrite based on the macrostructure of etched sections. Kamacite, taenite, schreibersite, and myrmekitic troilite were identified under the microscope. The whole sample was described as an intergrowth of bands of pure kamacite with domains of kamacite plus lamellae and plates of taenite (lamellar plessite). The authors also obtained powder diffraction spectra of the sample before and after annealing at 380 °C for 10 hr. The kamacite peaks and the (110) taenite peak were identified. The computed cell parameter a = 0.287 nm for kamacite indicated 6 wt% Ni, which does not match the bulk chemical composition determined from an unaltered fragment of the meteorite. Indeed, the analysis indicated 8.46 wt% Ni

Table 2. Analytical ions, isotopic abundances, and corrected interferences.

Analytical ion	Isotopic abundance	Corrected interferences
^{52}Cr	83.79	–
^{59}Co	100	–
^{60}Ni	26.22	–
^{69}Ga	60.11	–
^{74}Ge	36.28	$^{58}Fe^{16}O$, $^{58}Ni^{16}O$, $^{57}Fe^{16}O^{1}H$
^{75}As	100	$^{58}Fe^{16}O^{1}H$, $^{58}Ni^{16}O^{1}H$
^{95}Mo	15.92	–
^{101}Ru	17.05	–
^{103}Rh	100	–
^{108}Pd	26.46	^{108}Cd
^{115}In	95.71	^{115}Sn
^{121}Sb	57.21	–
^{182}W	26.50	–
^{185}Re	37.40	–
^{193}Ir	62.7	–
^{195}Pt	33.8	–
^{197}Au	100	–

(along with 92.86 wt% Fe; 0.54 wt% Co; and 0.34 wt% P), while taenite in the bulk sample was only estimated between 1.7 and 2.3 vol%.

The Study Sample: Structure and Mineral Composition

The investigated sample was a slice 11 × 13 × 3.5 mm in size, weighing ~3.5 g (Fig. 1b). The angles between the kamacite lamellae indicate that the slice was cut at an inclination of 13.5° along an octahedral plane. The slice was slightly abraded with SiC powders to remove the altered surfaces and polished on the widest face for microanalytical scanning electron microscopy (SEM-EDS). The polished surface was subsequently etched with nital to reveal the Widmanstätten pattern.

By volume, about two thirds of Bagnone consists of kamacite lamellae with straight or slightly curved margins; their average bandwidth, measured following Frost (1965) on the study sample and on the larger sample held in Milan, is 0.96 ± 0.20 mm (1σ; N = 42). SEM-EDS analyses of kamacite revealed a homogeneous composition (Ni = 5.2 ± 0.1 wt%). The rest of the meteorite consists of polyhedral masses of plessite and thin (up to 100 μm) lamellae of taenite. The Ni-rich phase (Ni = 13.6–30.2 wt%) is localized between adjoining kamacite lamellae and at the interface between kamacite and plessite. Plessite occurs in the textural varieties described in literature as comb, net or honey-comb plessite (e.g., Buchwald 1975; Yang et al. 1997).

The phase assemblage is completed by tiny schreibersite crystals ($Fe_{1.55}Ni_{1.45}P$), 5–10 μm in size, commonly found close to the taenite lamellae. Troilite, a mineral found in Bagnone by Bonatti et al. (1970), was not present in the study sample. Micrometer-size vermicular exudations of lawrencite were observed close to the original external surface.

The density of the meteorite sample determined with the Westphal balance is 7.907 g cm^{-3}, in agreement with Bonatti et al. (1970). Before acid dissolution, the sample was cut into three small aliquots (A = 685.95 mg, B = 318.76 mg, and C = 1049.79 mg), preserving the phase proportions in the original sample as much as possible.

Inductively Coupled Plasma Mass Spectrometry Analysis

Aliqouts A and B were selected for bulk chemical analysis by inductively coupled plasma mass spectrometry (ICP-MS). After replicate washing with ultrapure water in an ultrasonic bath, aliquot A was dissolved in 10 ml of 6N HNO_3 and aliquot B in 4 ml of Aqua Regia. The concentrated HCl and HNO_3 (Aristar grade) used to prepare the acid mixtures were both purified by sub-boiling in FEP bottles. The water used to dilute the solutions was Milli-Q (18.2 Mohm cm) further purified by sub-boiling in FEP bottles. The Aqua Regia dissolution was fast and effective, while the HNO_3 acid attack left a very small residue that was dissolved by adding 1 ml concentrated HNO_3 and gentle boiling. The sample solutions were then diluted with water in polypropylene bottles to a final total dissolved solid concentration of about 3 g l^{-1}. The solution obtained with aliquot B (Aqua Regia) was used to determine the elements Ru, Rh, Pd, In, Re, Ir, Pt, and Au, while the solution obtained with aliquot A (HNO_3) was used to determine the elements Cr, Co, Ni, Ga, Ge, As, Mo, Sb, and W. The latter elements were determined in the nitric acid solution because chlorine-rich acid matrices produce significant interfering peaks in the 51–74 mass/charge interval. Moreover, chlorine forms volatile compounds with Ge, As, and Sb with the potential loss of these elements from the sample solution. Platinum group elements plus In, Re, and Au were determined in the Aqua Regia solution due to the much higher solubility of these elements in this acid medium.

The selected analytical masses and interferences for which correction was made are listed in Table 2. ^{9}Be, ^{85}Rb, and ^{209}Bi were selected as internal standards because their

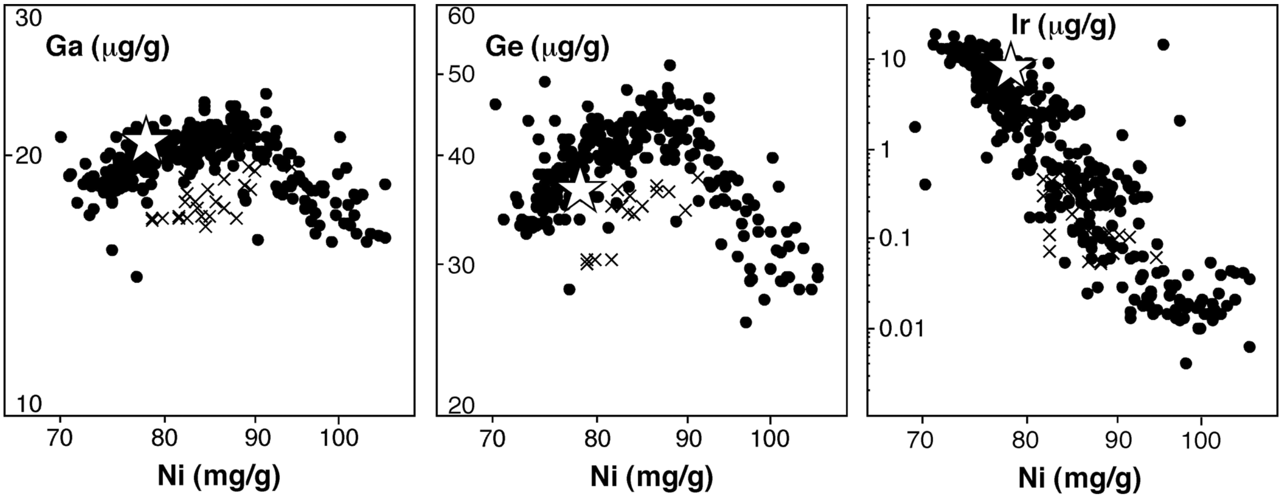

Fig. 2. Ga, Ge, and Ir versus Ni log diagrams for Bagnone (star), IIIAB (black circles), and IIIE (crosses) irons from literature.

Table 3. Bulk chemistry data.

		Bagnone		North Chile		North Chile
		Aliquot A	Aliquot B	"San Martin"		Literature data[a]
Element	Unit	685.95 mg (HNO_3)	318.76 mg (Aqua Regia)	321.07 mg (HNO_3)	136.40 mg (Aqua Regia)	Min-Max
Cr	μg/g	75	–	–	–	43–85
Co	mg/g	5.14	–	4.64	–	4.4–4.7
Ni	mg/g	78.0	–	57.2	–	55.4–60.2
Ga	μg/g	20.8	–	65.7	–	57.0–66.5
Ge	μg/g	36.6	–	181	–	154–188
As	μg/g	5.10	–	5.63	–	3.2–4.73
Mo	μg/g	6.4	–	7.2	–	7.85–7.9
Ru	μg/g	–	10.8	–	17.6	15.2–24.0
Rh	μg/g	–	1.59	–	2.50	2.5–2.9
Pd	μg/g	–	2.07	–	1.75	1.7–2.8
In	ng/g	–	<20	–	<20	–
Sb	ng/g	46	–	50	–	–
W	μg/g	1.22	–	2.76	–	2.50–2.86
Re	μg/g	–	0.84	–	0.207	0.20–0.25
Ir	μg/g	–	8.3	–	3.20	2.5–4.0
Pt	μg/g	–	14.6	–	24.2	20.7–29.0
Au	μg/g	–	0.540	–	0.557	0.53–0.65

[a]Literature values for North Chile are taken from Kracher et al. (1980); Wasson et al. (1986); Pernicka and Wasson (1987); Wasson et al. (1989); Ryan et al. (1990); Hoashi et al. (1993); Wasson et al. (1998); Campbell and Humayun (1999); and Spettel (personal communication). "–" = not determined.

masses embrace the mass interval of interest and because they are not contained in detectable amount in Bagnone. The concentrations of the sample solution were determined by external calibration using synthetic calibration standards prepared from single element 10 μg ml^{-1} stock solutions (Peak Performance, CPI International, Amsterdam). Three standard solutions were prepared: Standard A contained Cr, Ga, Ge, As, Mo, Sb, W at a concentration of 50 ng ml^{-1} in a 2% HNO_3 matrix; Standard B contained Ru, Rh, Pd, In, Re, Ir, Pt, and Au at a concentration of 50 ng ml^{-1} in a 4% Aqua Regia matrix; and Standard C contained Ni and Co at a concentration of 100 ng ml^{-1} and 40 ng ml^{-1}, respectively, in a 2% HNO_3 matrix. The intensities of the analytic ions, measured with a PQ II Plus ICP-MS, were corrected for blank contribution, interferences, and drift. Details on the dissolution procedures, mass-spectrometric measurements, interference corrections, and the overall precision of the method are reported in D'Orazio and Folco (2003).

The analysis of Bagnone was performed along with the North Chile IIAB hexahedrite ("San Martin") using the same analytical protocol. North Chile is a reasonably homogeneous meteorite, for which a sufficient amount of high quality

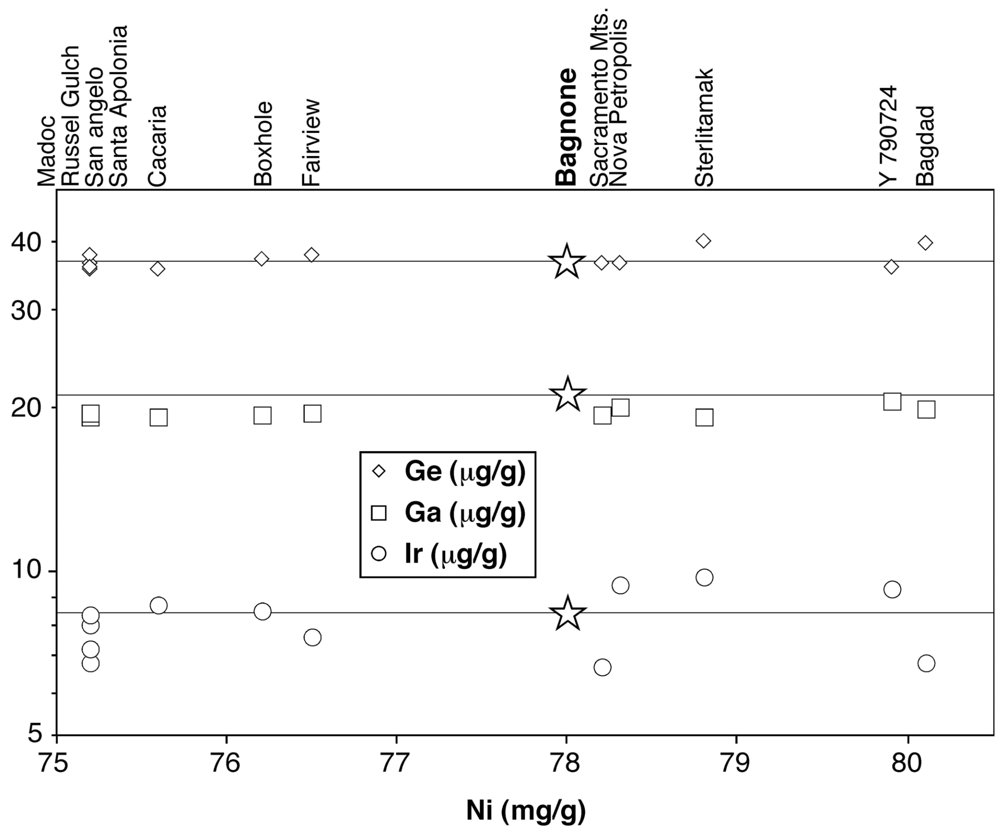

Fig. 3. Ga, Ge, Ir versus Ni diagram showing the iron meteorites with compositions similar to Bagnone.

analytical data is available. In this work, it was used to validate the accuracy of chemical data on the Bagnone meteorite.

Chemical Classification

The Ni (78.0 mg g^{-1}), Ga (20.8 µg g^{-1}), Ge (36.6 µg g^{-1}), and Ir (8.3 µg g^{-1}) contents of Bagnone are typical of the magmatic IIIAB group (Table 3; Fig. 2; Wasson and Kimberlin 1967), which is the largest chemical group gathering about one third of all classified iron meteorites (e.g., Mittlefehldt et al. 1998). The concentrations of other diagnostic trace elements such as Co, W, Sb, Au, and As are consistent with this grouping. Due to the low Ni content and high Ir content, Bagnone is a poorly differentiated member of this group. Based on published chemical data from IIIAB irons, we conclude that Bagnone is both chemically and structurally very similar to Madoc (Canada), Russel Gulch, San Angelo, Fairview, Sacramento Mountains, Bagdad (USA), Santa Apolonia, Cacaria (Mexico), Boxhole (Australia), Nova Petrópolis (Brazil), Sterlitamak (Russia) and Yamato-790724 (Antarctica). All these irons are medium octahedrites with a kamacite bandwidth between 0.95 and 1.3 mm, and all have bulk rock concentrations of the key elements Ni, Ga, Ge, and Ir within ±5% (Ni), ±10% (Ga and Ge), and ±15% (Ir) of the Bagnone values (Fig. 3).

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