5.4 Chondrites and differentiated meteorites

A. Context and state of the art

Meteorites are samples of dozens of small planetary bodies that formed in the early Solar System (Krot and Scott, 2005). They exhibit great petrologic diversity, ranging from primordial accretional aggregates (chondrites), to partially melted residues (primitive achondrites), to once fully molten magmas (achondrites). It has long been thought that no single parent body could be the source of more than one of these three meteorite lithologies. This view is now being challenged by a variety of new measurements and theoretical models, including the discovery of primitive achondrites, paleomagnetic analyses of chondrites, thermal modeling of planetesimals, the discoveries of new metamorphosed chondrites and achondrites with affinities to some chondrite groups, and the possible identification of extant partially differentiated asteroids (Caporzen et al., 2011; Brearley and Krot, 2012; Connelly et al., 2012; Weiss and Elkins-Tanton, 2013; Kruijer et al. 2014). These developments collectively suggest that some chondrites could in fact be samples of the outer, unmelted crusts of otherwise differentiated planetesimals with silicate mantles and metallic cores (Fig. 1). This may have major implications for the origin of meteorite groups, the rates and onset times of accretion, and the interior structures and histories of asteroids.

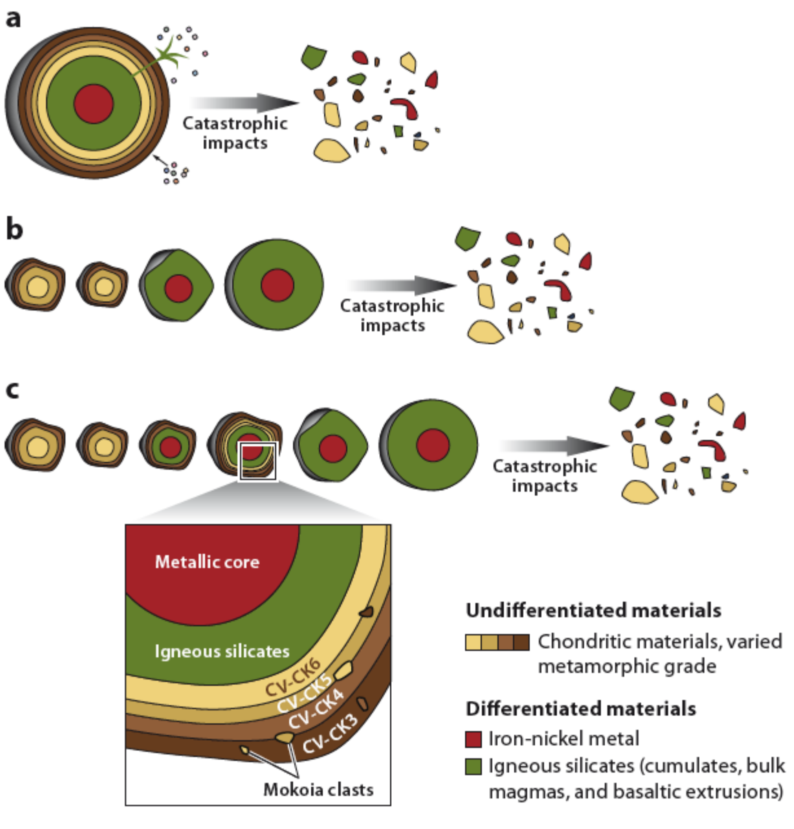

Figure 1: Meteorite parent body models. (*a*) All meteorites originated from one or a few Moon-sized partially differentiated bodies with chondritic surfaces formed by tuffaceous volcanism (Ringwood 1961), impact-induced melting, and/or deposition of exogenous material (Wood 1963). (*b*) Meteorites originated from multiple asteroid-sized bodies. Individual bodies were fully differentiated or fully undifferentiated (Mason 1967). (*c*) Meteorites originated from multiple, asteroid-sized bodies (Anders & Goles 1961). Individual bodies were fully differentiated, fully undifferentiated, or partially differentiated with an unmolten chondritic crust. (*Inset*) Schematic asteroid showing a possible structure of a partially differentiated CV-CK carbonaceous chondrite parent planetesimal (see Section 3.3). Metamorphosed and/or partially melted materials like clasts found in the CV chondrite Mokoia may be samples excavated from the deep interior. From Weiss & Elkins-Tanton (2013).

On the other hand, linking meteorites to their parent asteroid is a complicated issue (DeMeo & Carry, 2014), despite the tremendous progress made in the last decades both in cosmochemistry and in astrophysics. The difficulty is even more acute when dealing with the most pristine objects: the carbonaceous chondrites and their putative parent body, as for instance Pallas, Eulalia, Polana, which are now hypothesized from their reflectance spectra to be most closely analogous to the primitive material found in carbonaceous chondrite meteorites (although it is not clear if we have any material from this body, or if it is even possible for Earth to intercept meteorites from Pallas).

B. Current activity and future steps

Two major projects involving chondrites and differentiated meteorites are currently investigated in closed collaboration with Géoazur and CEMEF, and will continue in the frame of C4PO. The first one is devoted to a better understanding of the internal structure of CV chondrite parent bodies by studying the conditions prevailed during the aqueous alteration and/or thermal metamorphism. The latter is aimed at documenting the processes of metal-silicate differentiation in differentiated meteorites, notably by looking for an alternative scenario to the gravity-driven liquid metal percolation in small bodies of the Solar System.

B.1. Internal structure of CV chondrite parent bodies and their link with primitive asteroids

Chondritic meteorites are lithified samples of materials that originate from small asteroidal bodies from within the main Asteroid belt ~ 3 AU (astronomical units) from the Sun or possibly further out from the Sun ("Grand Tack model"? Walsh et al. 2011). They are our best witness-samples to understand the formation and evolution of the early solar system, i.e., the period of the protoplanetary disk (Krot and Scott, 2005). It is generally accepted that chondrites, the most pristine unequilibrated meteorites, represent a tangible record of astrophysical and geologic processes that occurred during the very earliest stages of solar system history within the protoplanetary disk that surrounded the proto-Sun.

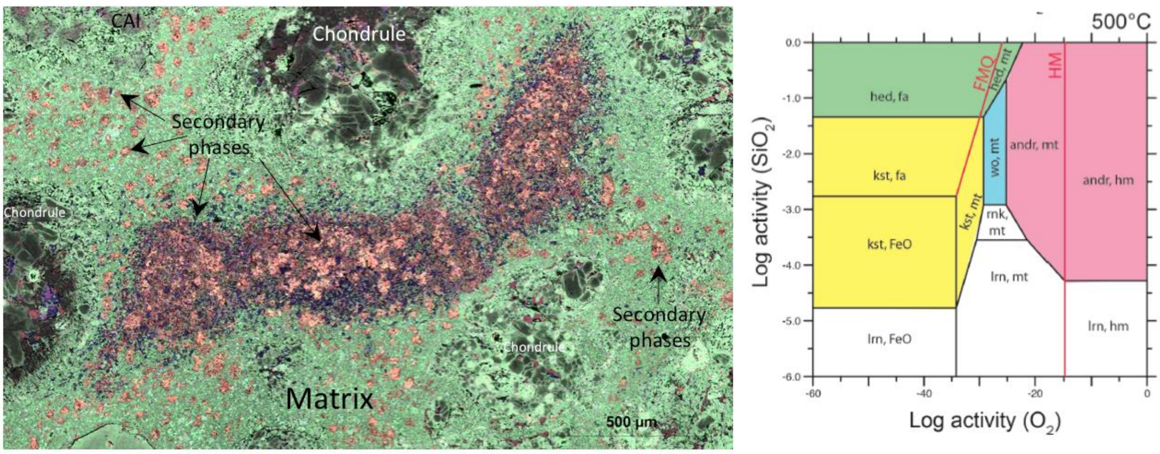

Figure 2: (left) EDS-SEM chemical map (green: Fe, Blue: Al, red:Ca) of Allende $CV3_{oxA}$ carbonaceous chondrites acquired at CEMEF (Suzanne Jacomet) showing chondrules and CAI's (grey) embedded in a fine grained olivine bearing matrix (green). Notice the high modal abundance of secondary phases (Ca-Fe silicates in pink: hedenbergite, andradite and wollastonite and alkali, halogen-rich minerals in purple: nepheline and sodalite) in the matrix as well as in chondrules. (right) Example of calculated thermodynamic conditions of the Ca-Fe secondary phases.

Once the various chondrite components (CAIs, chondrules and matrices) had formed, they accreted into meteorite parent bodies within the disk. If few chondrites still preserve a pristine record of this early solar nebular evolution, the great majority has been affected by secondary processes occurring prior or after their accretion in their asteroidal parent bodies. These (fluid-assisted) secondary thermal processes, including gas-solid interactions, aqueous alteration, metasomatism and metamorphism, have all acted to modify the very early record of these chondrites to different degrees (e.g. Brearley and Krot, 2012, for a review), by affecting to diverse degrees several primordial components (including refractory inclusions, chondrules, matrix, dark inclusions, see theme 5.1) of different chondrite groups (CV, CM , CR, CO…).. It is therefore fundamental to better constrain these secondary processes, not only to gain access to the primary record of chondrites, but also to get information on their asteroidal parent bodies themselves, by shedding light on their internal structure and dynamics.

In order to progress in this challenging field, we have launched a new thematic of research on the internal structure of CV chondrite parent bodies, supposed to be among the most primitive ones and their link with primitive asteroids. By studying the (fluid-assisted) thermal processes that have modify the primary chondritic components in CV chondrites, and using the most up to date concepts and analytical tools (EBSD, FEG-SEM, CL, etc…), our aim is to shed light on the respective conditions (fluid and rock chemical potentials, pressure, temperature, fluid/rock ratio, etc) that have prevailed during the secondary phase transformations in response to aqueous alteration and/or thermal metamorphism occurring in meteorite parent bodies (Figure 2). This novel mineralogical and thermodynamical approach will help us in deciphering in a level of unreached accuracy the internal structure of the CV chondrite parent bodies as well as their internal dynamics, e.g., P-T-X paths, by analogy to Earth metamorphic rocks (Ganino et al., 2014).

By providing a true statistical treatment, this multidisciplinary approach will able us to tot up the different secondary parageneses occurring in the components (CAIs, chondrules and matrices) of the selected CV chondrites, and to quantify their respective conditions of formation. This will thus help us to address several questions, some of which shared in common with studies of terrestrial metamorphism: (1) How did metamorphism/alteration modify the primary (nebular) record contained in chondritic meteorites? (2) On what scale did alteration/metamorphism occur? Are the effects of fluids heterogeneously developed within chondrites? (3) What is the composition (and the source) of the (iron-alkali-halogen) fluids? (4) What were the physical and chemical conditions under which metamorphism occurred? (5) From all these data, is it possible to reconstruct the internal structure of CV chondrite parent body? (6) Are CV chondrites originated from unprocessed crusts of internally differentiated early planetesimals?

Future steps concern the possibility to give some new guidelines for the search of primitive asteroids by remote spectral observations. This project may help in this task by making the difference between mineralogical assemblages originating from the parent body formation process and those due to other external processes such as space weathering.

B.2. Liquid metal infiltration in refractory materials with applications to small planetary bodies.

Astronomical observations of asteroid surfaces, compositions of meteorites and recent chronology data provide strong evidence that partial melting and differentiation were widespread among small bodies, i.e., planetesimals, within the initial few millions years of the solar system. Involving the separation of a metallic liquid that forms the core from the silicate that subsequently solidifies and evolves into a mantle and a crust, differentiation of planetesimals results in a wide range of differentiated parent bodies, from which stony (achondrites), stony-iron and iron meteorites are supposed to be originated from. Radiogenic decay energies of the short lived nuclei ^{26}Al and ^{60}Fe provide the heat sources for melting and differentiation as stated by Urey in 1955; impact heating being insignificant for such pristine bodies.

Metal-silicate differentiation is therefore the major chemical events on planetary bodies, and a key process to understand the early evolution of our solar system in defining planetary building blocks. It is therefore not surprising than core formation and mantle crystallization received so many efforts in the last decades. Recently, a robotic spacecraft mission to a metal world, the M-type asteroid (16) Psyche, have been even selected by the NASA’s Discovery program for directly examining the building blocks of a differentiated body, which otherwise could not be seen, in the hope of doing fundamental advances in understanding planetary formation and interiors.

Figure 3: Left: Fukang pallasite, showing cm-sized olivine (Mg-Fe_2SiO_4) crystals embedded in a metallic Fe-Ni matrix (taenite and kamacite) © 2015 Southwest Meteorite Laboratory. Center: Estherville mesosiderite © Collecting Meteorites. Interconnected metal network (white) in the silicate portion. Right : Lodranite NWA 5210. Notice Fe-Ni metal blebs (white) at olivine and pyroxene grain boundaries. Combination of transmitted and reflected light. Total length is 7 mm. © T. E. Bunch, 2009. Notice the significant changes in metal/silicate modal abundances through these 3 examples.

However, how planetesimals with their small radii and low gravity can be differentiated is still not well understood. In contrast to terrestrial planet differentiation models, in which the iron component - the core - is invariably found at the center of the body due to its high density, many meteorites show an intimate metal-silicate mixing with no physical segregation. As noted by Lord Rayleigh in 1942, the paradox posed by pallasites, stony-iron meteorites made mainly of olivine crystals, embedded in a metallic Fe-Ni matrix with variable amount of FeS, is that olivine and metal seemingly should have separated into layers in their parent body. Samples of quiescent core-mantle boundaries or resulting from violent mixtures of cores and mantle materials in impact environments, pallasite formation modes are still elusive (Yang et al., 2010; Boesenberg et al., 2012, Tarduno et al., 2012). The same is also true for other stony-iron meteorites like mesosiderites and lodranites.

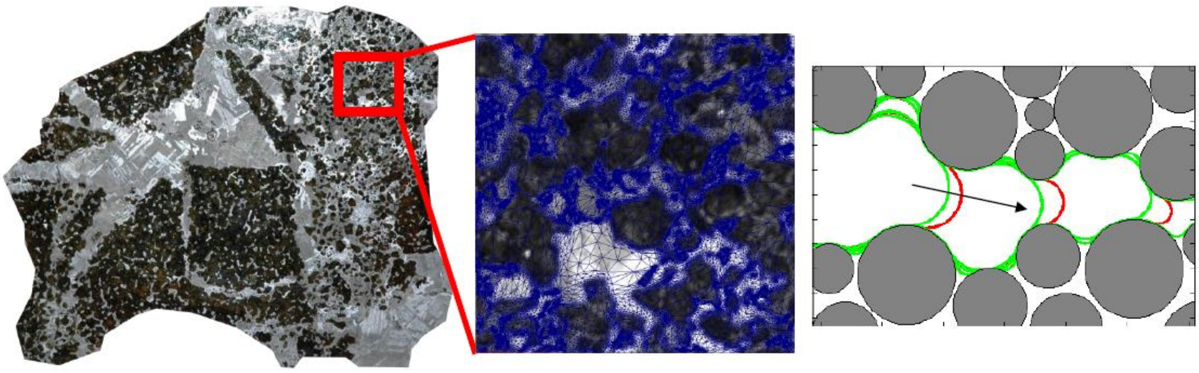

Figure 4: Illustration of the methodology for wetting, anisotropic meshing and flow model during infiltration of metal liquid in porous ceramic media. Example from Seymchan stony-iron meteorite (pallasite) showing infiltration of Fe-Ni metal in an olivine-bearing matrix (Photograph R.A. Langheinrich, Monig meteorite gallery).

In fact, infiltration of liquid metal into a porous refractory (olivine-bearing) body is a complex process that relies on two main issues: i) a physical problem: liquid metal infiltrates at high temperature a porous refractory body with various grain size and topologies, pore sizes and permeability, ii) a chemical and/or thermodynamical problem: interactions between the different phases in presence, i.e. liquid metal + silicate melt or silicate melt + refractory mineral solid phases during infiltration and upon cooling, may eventually alter depending on the kinetics the pristine properties of the system, e.g. number of phases and their compositions, interfacial energies, critical penetration depth, etc.

To deal with that complexity, our objectives are: **1-** to understand the physics and the macroscopic aspects of the infiltration kinetics that involve capillary or external pressure driven flows of one (metallic) or two immiscible liquids (metallic and silicate) at high temperature in complex 3D porous refractory structures, **2-** to characterize the microstructural and thermochemical evolution of these multiphase systems during infiltration, **3-** to perform analogical (model) experiments to study the infiltration kinetics in "astromimetic" microfluidic 2D and 3D systems with immiscible fluids at ambient conditions, **4-** to develop mathematical and numerical models able to predict both macroscopic and microscopic structures obtained by infiltration, and finally **5-** to propose an alternative scenario to the gravity-driven liquid metal percolation for the formation of the stony iron meteorites in small bodies of the Solar System.

To achieve these objectives, three laboratories specialized in astrophysics, cosmochemistry and earth science (Observatoire de la Côte d'Azur-OCA regrouping Lagrange and Geoazur, Nice), in computational physics and dynamics of fluids, metallurgy and solidification processing and modelling (Armines-CEMEF, Sophia-Antipolis), in condensed matter physics and physical chemistry (Laboratoire de Physique de la Matière Condensée-LPMC), decided to merge their resources and their competences to create a unique scientific initiative to tackle these issues.

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D. International collaborations

Close collaborations are taking places with Alexander Krot and Kazuhide Nagashima from HIGP, University of Hawaii, (USA) since G. Libourel (OCA) is also affiliated professor at the HIGP; A. Krot being one of the best experts in the world on chondritic meteorites and parent body alteration. We are also collaborating with the university of Kobe in Japan (team of Prof. Arakawa and Prof.

Nakamura) and with the South West Research Institute (SWRI, Boulder, USA) to perform impact experiments on metallic objects.

E. List of people involved in the project

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Suzanne Jacomet, IE/R, CEMEF
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F. Most significant publications of the team

Villeneuve, J., Chaussidon, M., & Libourel, G. (2009). Homogeneous distribution of ^{26}Al in the solar system from the Mg isotopic composition of chondrules. *Science*, *325*(5943), 985-988.

Libourel, G., Corrigan, C. (2014). Asteroïds: new targets, new challenges. *Elements*, Vol. 14, 1, 11-17.

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Short CV of participants

Guy Libourel, Professor Université de la Côte d'Azur (UCA), belonging to Lagrange Laboratory at OCA and affiliated Professor, Hawai'i Institute of Geophysics and Planetology (HIGP), University of Hawaii, USA, expert in cosmochemistry, meteorites, experimental petrology and material science, Co-I on the NASA OSIRIS-REx mission, Humboldt fellow, Bronze CNRS medal, 100 refereed publications.

Clément Ganino, Géoazur, Associate Professor, expert in geochemistry and metamorphic and igneous petrology, Pedagogic head of the Licence of Earth Sciences at the University of Nice-Sophia Antipolis. Co-organiser of the international workshops on primitive material in the solar system (2014; 2016).

Rudy Valette, MINES-ParisTech Associate Professor, head of the Rheology, Microstructure and Processing group and deputy head of the Computing and Fluids group, expert in complex fluids rheology and non-newtonian fluids mechanics, board member and international delegate of the French Society of Rheology, PhD Prize of the French Society of Rheology (2001)

Elie Hachem, MINES-ParisTech Associate Professor, head of the Computing & Fluids research group (CFL), is an expert in computational fluid dynamics with particular focus on multiphase flows. He spent almost a year at Stanford University, invited in 2012 as an assistant professor to work on immersed methods for fluid-structure interaction. His work on computational fluid dynamics with high performance computing was recognized by the IBM Faculty Awards 2015. His PhD was awarded twice, by SMAI-GAMNI (best PhD thesis in applied mathematics in France) and by ECCOMAS (best PhD thesis in CFD in Europe).

Nathalie Bozzolo, Professor in Physical Metallurgy at CEMEF MINES-ParisTech. Expert in quantitative analysis of microstructures and textures, identification of metallurgical mechanisms and recrystallization phenomena. Holder of the OPALE ANR-Safran industrial chair. Member of the national board of the French Society for Metallurgy and Materials (SF2M). Head of research group "Metallurgy, Structure, Rheology"

Suzanne Jacomet, Engineer in charge of Electron Microscopy and related techniques (EDS, EBSD, in-situ annealing) at CEMEF MINES ParisTech