# VII. Chassigny

dunite, ~4 kg

*seen to fall, possibly a shower*

***Figure VII-1.*** *The Chassigny meteorite at the Paris Museum National d'Histoire Naturelle. Piece weighs 215 grams. Photo kindly provided by Claude Perron.*

## Introduction

On October 3, 1815, at about 8:00 a.m., a stone, or perhaps several, fell after detonations near the village of Chassigny on the plateau of Langres in the province of Haute-Marne, France (Pistollet 1816; Graham *et al*. 1985) (figure VII-1). Kevin Kichinka (2001a,b) has performed a nice service by reviewing the circumstances of the fall and telling other aspects of the Chassingy story. Apparently the region surrounding Chassigny has been searched for other pieces with no result. The possible significance of the coincidence of the fall day with that of Zagami has been discussed by Treiman (1992). A nice review of Chassigny can be found in McSween and Treiman (1998).

Chassigny contains mostly olivine and is thus classified as a dunite. Because of its young age, similar oxygen isotopes and REE pattern, this meteorite has been grouped with the nakhlites and the rest of the Martian meteorites. It also has a similar $^{142}$Nd anomaly to that of the nakhlites.

Chassigny is important because it is found to contain noble gasses that are entirely different from those in EETA79001 glass and the Martian atmosphere (Ott 1988; Ott and Begemann 1985). Presumably this rare-gas component is from the Martian mantle (*see section on Other Isotopes*).

Although Brachina was originally classified as a "chassignite", Nehru *et al.* (1983) and Clayton and Mayeda (1983) showed that the brachinites are a different class of meteorites (*i.e.* not from Mars!).

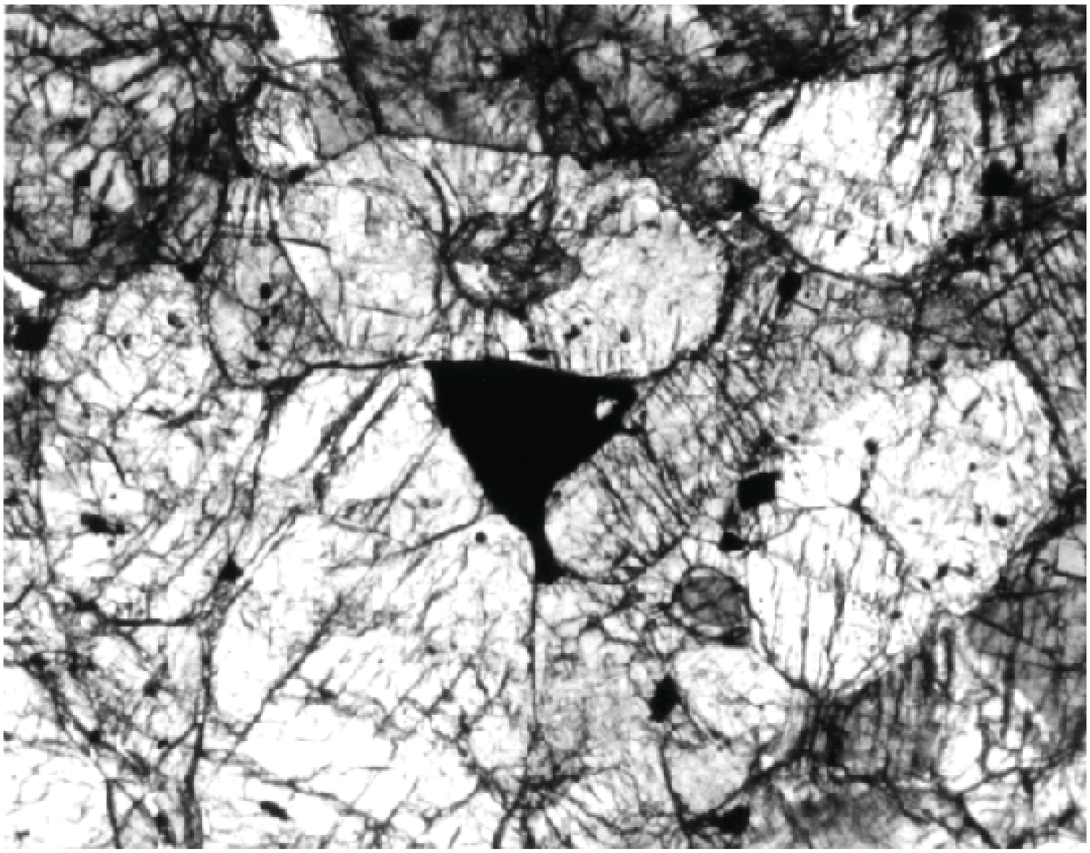

*Figure VII-2. Photomicrograph of thin section of Chassigny meteorite. Field of view 2.2 mm. Section #624-4 loaned by Smithsonian Institution. Note large melt inclusion in olivine and large chromite.*

## Petrography

Chassigny is a dunite with rare poikilitic, Ca-rich, pyroxenes containing lamellae of exsolved Ca-poor pyroxene (Johnson *et al.* 1991) (figure VII-2). The olivine often has melt inclusions (Floran *et al*. 1978; Mason *et al.* 1975). Prinz *et al*. (1974) gives the mode as 91.6 % olivine, 5 % pyroxene, 1.7 % plagioclase, 1.4 % chromite, and 0.3 % melt inclusions. Floran *et al*. (1978) reported minor alkali feldspar, chlorapatite, marcasite, pentlandite, troilite (?), ilmenite, rutile and baddeleyite as accessory minerals. Wadhwa and Crozaz (1995) reported poikilitic pigeonite in Chassigny and determined the trace element compositions of the phases.

Igneous chromite contains substantial $Fe^{+3}$ (Floran *et al*. 1978) proving crystallization under oxidizing conditions.

Magmatic melt inclusions found in olivine range in size from the optical limit up to 190 microns (figure VII-2). These inclusions are found to include hydrous kaersutitic amphibole (Floran *et al.* 1978), high and low-Ca pyroxene, chlorapatite, magnetite, chromite, troilite, pyrite, pentlandite and alkali feldspar-rich glass. These melt inclusions have been studied by Floran *et al*. (1979), Johnson *et al.* (1991), Righter *et al.* (1997), Delaney and Dyar (2001) and Varela *et al.* (1997, 1998, 2000). Varela *et al.* report relatively high Cl contents of glass in melt inclusions. Righter *et al*. (1998) determined Mo, Ce, Ba, Y and Rb contents of glasses in melt inclusions.

Shock features were studied by Sclar and Morzenti (1971) and Floran *et al*. (1978) who reported planar features in olivine. Greshake and Langenhorst (1997), Langenhorst and Greshake (1999) and Malavergne *et al.* (2001) find that Chassigny experienced shock about 35 GPa.

## Mineral Chemistry

***Olivine*:** Olivine is $Fo_{68}$, which is relatively iron-rich for a cumulate (Prinz *et al.* 1974) and appears to be in equilibrium with pyroxene. Smith *et al.* (1983) carefully determined Ni, Ca, Mn, Cr and other minor elements in olivine. The relatively high CaO (0.17-

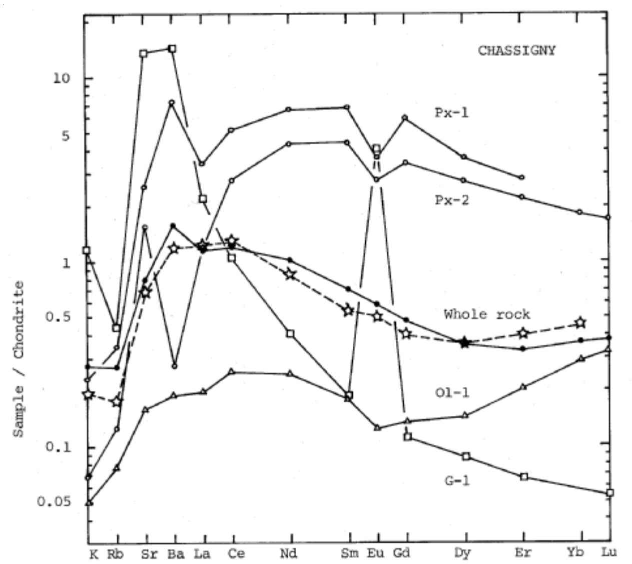


*Figure VII-3. Composition diagram for mineral separates and whole rock samples of Chassigny meteorite. This is figure 1 in Nakamura et al. 1982. The dashed line is data for the bulk rock sample from Mason et al. 1975, Meteoritics **11**, 21.*

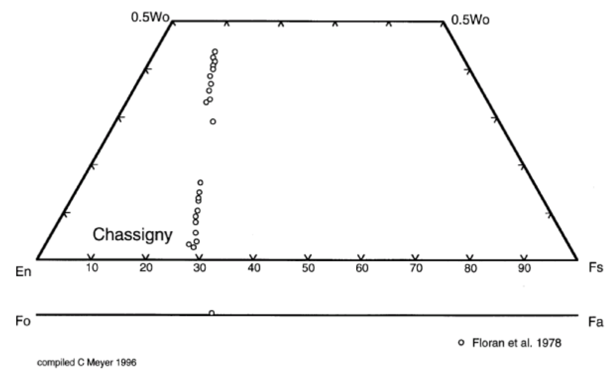


*Figure VII-4. Pyroxene and olivine composition diagram for Chassigny meteorite. Data is from Floran et al. 1978, GCA **42**, 1213.*

0.26 wt. %) in olivine reported by Smith *et al.* seems to indicate that this rock did not form in a "plutonic" environment. Nakamura *et al.* (1982c) determined trace elements in mineral separates including an olivine separate (figure VII-3). Olivine is found to contain symplectic exsolution aligned parallel to (100) of the host olivine.

***Chromite***: Tschermak (1885) reported distinct octahedrons of chromite. According to Floran *et al.* (1978), chromite was the first phase to crystallize (it is found as inclusions in olivine) and continued throughout the crystallization sequence. Floran *et al.* made the important observation that this chromite contained substantial $Fe^{+3}$. Bridges and Grady (2001) and Varela *et al.* (2000) report analyses of chromite.

***Pyroxene***: Poikilitic pyroxene grains consist of a Ca-rich host ($Wo_{33}En_{49}Fs_{17}$) with thin, exsolved Ca-poor ($Wo_3En_{68}Fs_{28}$) lamellae on the (011) plane. Pyroxene is unzoned and appears to be in equilibrium with the olivine (figure VII-4). One thin section contains pyroxene as a single poikilitic grain 6.4 mm in length (Floran *et al.* 1978). Harvey and McSween (1994) have reported cumulate orthopyroxene in Chassigny. Wadhwa and Crozaz (1995) reported poikilitic pigeonite. Floran *et al.* (1978) reported trace element analyses for pyroxenes and these are compared with those of other Martian meteorites in figure 3 of Smith *et al*. (1983).

***Plagioclase***: Mason *et al.* (1975) and Floran *et al.* (1978) determined the plagioclase composition to be $An_{32}Ab_{64}Or_4$.

***Potassium feldspar***: Interstitial potassium feldspar is found as 100-300 micron grains $Or_{47}Ab_{48}An_5$.

***Biotite:*** Johnson *et al.* (1991) discovered biotite in Chassigny and found that it contained 2.3 % F and 0.4 % Cl. Watson *et al.* (1994) found 0.5 wt % $H_2O$ in the biotite with heavy D/H.

***Kaersutite (Ti-rich amphibole):*** Floran *et al*. (1978) reported pleochroic amphibole (up to 75 microns) as a "conspicuous constituent" of the larger melt inclusions. Floran *et al.* reported H by ion microprobe. Johnson *et al.* (1991) reported that kaersutite contained 0.5 % F and 0.1 % Cl. Watson *et al.* (1994) determined the D/H ratio and water content of kaersutite grains in Chassigny by ion probe. Varela *et al.* (2000) give analyses of kaersutite in silica-rich melt inclusions.

***Baddeleyite***: Floran *et al*. (1978) report the composition of a baddeleyite grain found adjacent to rutile.

***Apatite***: The apatite in Chassigny contains 3.6 % Cl (Floran *et al.* 1978). Wadhwa and Crozaz (1995) determined the REE content of chlorapatite.

***Sulfides***: Analyses of three different sulfides (troilite, marcasite, pentlandite) have been reported by Floran *et al.* (1978). One grain of pentlandite was found to contain with 13 % Cu! Greenwood *et al.* (1997, 1998,

2000) reported the isotopic composition of pyrite.

***Symplectite:*** Greshake *et al.* (1997) reported lamellar inclusions of symplectite (augite and magnetite) in olivine.

***Wadsleyite***: Malavergne *et al.* (2001) have identified small grains of wadsleyite in heavily shocked olivine by TEM studies.

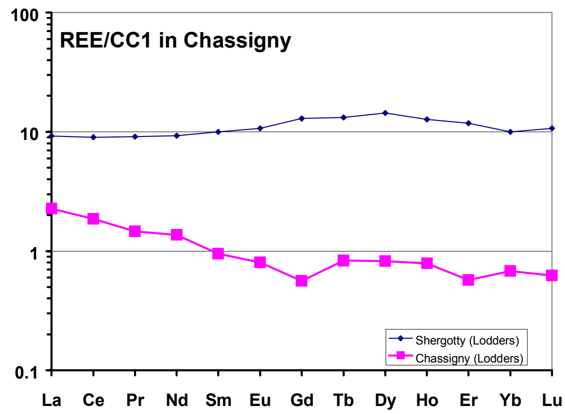


***Figure VII-5.*** *Chondrite normalized rare-earth-element diagram for Chassigny compared with Shergotty. Data from Lodders 1998.*

## Whole-rock Composition

Early analyses were performed by Vauquelin (1816) and Damour (1862). Prinz *et al.* (1974) noted that Chassigny is iron-rich for a cumulate dunite. Mason *et al.* (1975), Boynton *et al.* (1976), and Burghele *et al.* (1983) reported complete analyses (table VII-1)(figure VII-5). Nakamura *et al.* (1982c) reported REE for 'whole rock' and 'mineral' separates (figure VII-3) and confirmed the data of Mason *et al.* for the bulk sample.

Chassigny has relatively high Ni (400 ppm), Co (120 ppm), Ir (~2 ppb) and Os (1.8 ppb) (table VII-1). ElGoresy *et al.* (1999) reported similar values for bulk samples, and provide petrographic observations of "thin metal sheaths" in olivine. In addition to the data table, Curtis *et al.* (1980) determined 6.3 ppm B for Chassigny. Gibson *et al.* (1985) determined 360, 440, 300, 330 ppm S on different splits. Burgess *et al.* (1989) studied the temperature release of S.

Karlsson *et al.* (1992) found 1020 ppm $H_2O$, Leshin *et al.* (1996) found 0.095 wt. % $H_2O$ with no D enrichment *and one might suspect isotopic exchange (museum contamination).*

## Radiogenic Isotopes

Although it is generally difficult to date a "dunite" sample, there has been remarkable agreement in attempts to date Chassigny. Lancet and Lancet (1971) reported a K-Ar age for Chassigny of 1.39 ± 0.17 Ga. Bogard and Nyquist (1979) reported an Ar39-40 age of 1.2 - 1.4 Ga; later refined by Bogard and Garrison (1999) to 1.32 ± 0.07 Ga (figure VII-6). Jagoutz (1996) determined an age of 1.362 ± 0.062 Ga by Sm-Nd (figure VII-7). Nakamura *et al.* (1982) obtained a Rb-Sr isochron with an age of 1.226 ± 0.012 Ga with initial $^{87}Sr/^{86}Sr$ = 0.70253 ± 4.

## Cosmogenic Isotopes and Exposure Ages

Lancet and Lancet (1971) reported cosmic-ray exposure

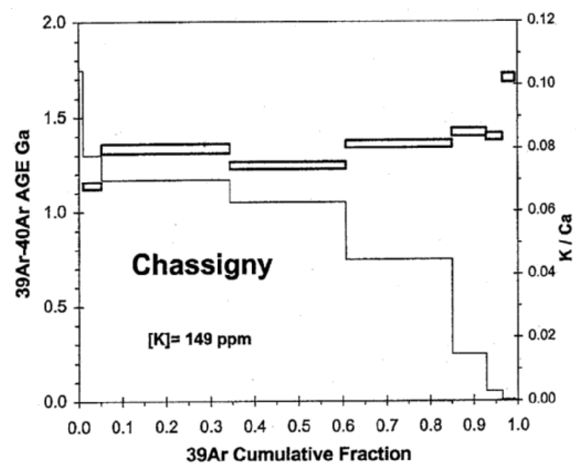


***Figure VII-6.*** *Ar release pattern and age of Chassigny meteorite (figure 1 in Bogard and Garrison 1999, M&PS* ***34****, 451).*

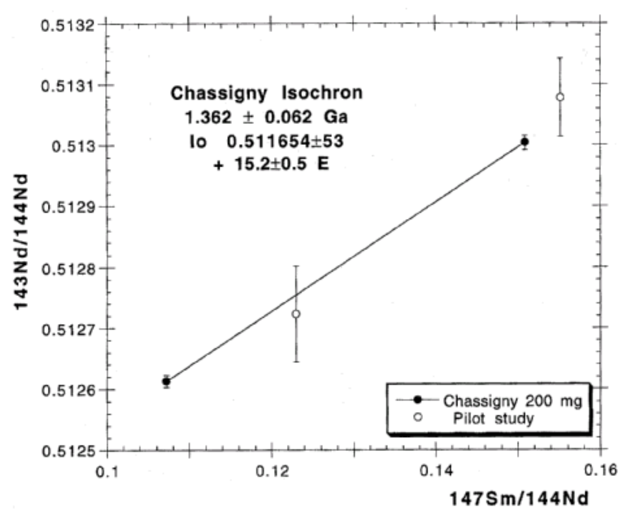


***Figure VII-7.*** *Sm-Nd isochron diagram for Chassigny from Jagoutz 1996, LPS* ***XXVII****, 598.*

ages of 9.4 ± 0.3 Ma for $^3$He, 7.6 ± 0.2 Ma for $^{21}$Ne and 6.7 ± 0.6 for $^{38}$Ar. Bogard *et al.* (1984b) calculated an exposure age of about 10 Ma. Using new production rates, Bogard (1995) calculated 12 Ma from $^{21}$Ne data and 10 Ma from $^{38}$Ar data for Chassigny. Terribilini *et al.* (2000) determined a $^{81}$Kr exposure age of 10.7 ± 1.8 Ma. Terribilini *et al.* (1998) and Nyquist *et al.* (2001) calculate average exposure ages of 11.6 ± 1.5 Ma and 11.3 ± 0.6 Ma, respectively, and note that this is similar to the nakhlites.

## Other Isotopes

Clayton and Mayeda (1983, 1996) and Franchi *et al.* (1999) reported the oxygen isotopes for Chassigny (figure I-3). Karlsson *et al.* (1992) found that the oxygen isotopes in water released from Chassigny was enriched in $^{17}$O, indicating that the past hydrosphere on Mars was from a different reservoir than the lithosphere. Romanek *et al.* (1996, 1998) reported additional data for oxygen isotopes in Chassigny using a newly developed laser-fluoridation technique. Wiechert *et al.* (2001) have precisely determined the isotopic ratio of oxygen.

Watson *et al.* (1994) and Boctor *et al.* (2000) reported high deuterium contents in hydrous amphiboles, biotite and glass. However, Leshin *et al.* (1996) found that the δD for water released from bulk samples of Chassigny was *"indistinguishable from typical terrestrial values"* (figure VII-8).

Jagoutz (1996) has reported a large $^{142}$Nd/$^{144}$Nd anomaly in Chassigny, which implies that the reservoir from which Chassigny was formed was depleted in light REE as early as 4.5 Ga *(see also Harper et al. 1995).* Lee and Halliday (1997) reported the isotopic composition of W.

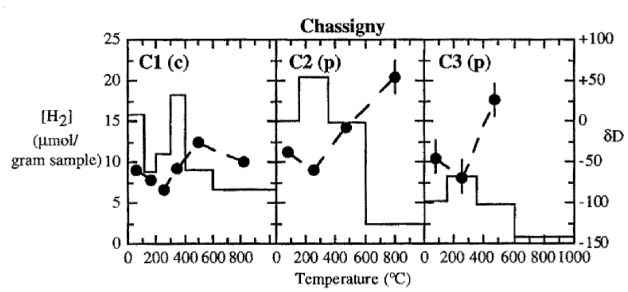


***Figure VII-8.*** *Hydrogen isotopic composition of water released by stepwise heating of Chassingy meteorite. This is figure 4 in Leshin et al. 1996, GCA **60**, 2641.*

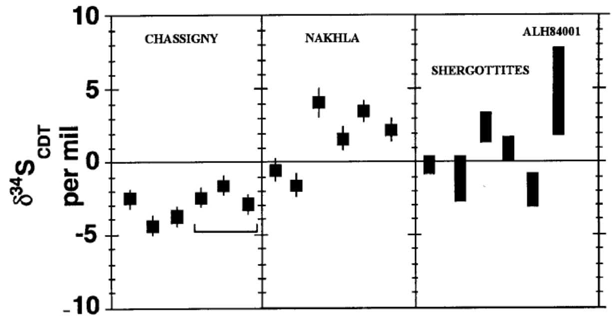


***Figure VII-9.*** *Sulfur isotopic composition of sulfides in Martian meteorites including Chassigny (from Greenwood et al. 1998, LPSC **XXIX** #1643).*

Birck and Allègre (1994) and Branden *et al.* (1997, 2000) have studied the Re-Os isotopic systematics of Chassigny.

The carbon and nitrogen content and isotopic composition has been reported by Wright *et al.* (1992). Marty *et al.* (1997) studied the nitrogen isotopic composition of individual olivine grains. Mathew and Marti (2001) found that light nitrogen ($\delta^{15}$N= -30‰) was associated with the interior "solar-like" Xe component.

Greenwood *et al.* (1997) reported the isotopic composition of sulfides (figure VII-9).

Chassigny contains trapped noble gases with isotopic ratios similar to solar abundance (Ott 1988, and others). Swindle (2002) has used the isotopic composition of Chassigny as the starting point for mass fractionation

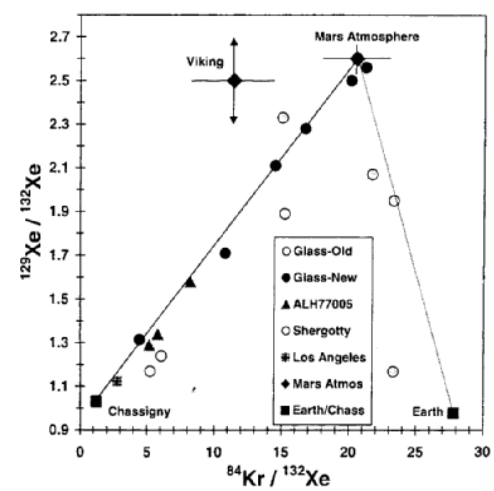


***Figure VII-10:*** *Rare gas isotope plot showing mixtures of Mars atmosphere and Mars interior (represented by Chassigny) and terrestrial contamination (this is figure 3 in Bogard et al. 2001).*

## Table VII-1a. Chemical composition of Chassigny.

| *reference* | D'yako-60 | Jeremine62 | Jerome 70 | McCarthy74 | Boynton76 | Burghele83 | Nakamura | Mittlefehldt96 |
|---|---|---|---|---|---|---|---|---|
| *weight* | | | | *2.1 grams* | *.458 g* | | | |
| SiO2 | 37.44 | 36.79 | 37.3 | 37.1 | | 38.16 | | |
| TiO2 | 0.08 | | | 0.07 | 0.15 | 0.1 | | |
| Al2O3 | 1.07 | 1.17 | 0.47 | 0.36 | 0.64 | 0.69 | | |
| FeO | 26.55 | 27.58 | 26.78 | 27.45 | 25.7 | 27.1 | | 26.6 |
| MnO | 0.74 | 0.25 | 0.55 | 0.53 | 0.51 | 0.526 | | |
| CaO | 0.52 | 0.6 | 0.75 | 1.99 | 0.71 | 0.6 | | |
| MgO | 32.17 | 31.95 | 32.7 | 32.83 | 30.2 | 31.6 | | |
| Na2O | 1.09 | 0.27 | 0.13 | 0.15 | 0.114 | 0.128 | | 0.097 |
| K2O | 0.07 | 0.16 | 0.04 | 0.03 | 0.038 | 0.041 | | 0.029 |
| P2O5 | 0.07 | 0.11 | | 0.04 | | 0.058 | | |
| ***sum*** | **99.8** | **98.88** | **98.72** | **100.46** | | **99.003** | | |
| | | | | | | | | |
| Li ppm | | | | | | 1.3 | | |
| Sc | | | 8 | | 4.8 | 5.4 | | 5.36 |
| V | | | 50 | | 34 | | | |
| Cr | 6700 | 5300 | 4500 | 5700 | 3763 | 4297 | | 4796 |
| Co | **Treiman86** | | 100 | | 124 | 126 | | 124 |
| Ni | 450 | | 475 | | 400 | 480 | | 510 |
| Cu | | | <3 | | | 2.6 | | |
| Zn | 69 | | | | | 74 | | 68 |
| Ga | | | | | | 0.7 | | |
| Ge | 0.011 | | | | | | | |
| As | | | | | | 0.008 | | |
| Se | 0.037 | | | | | | | |
| Br | 0.11 | **Mason 75** | | | | 0.066 | | 0.2 |
| Rb | 1.05 | 0.4 | | | | | 0.47 | |
| Sr | | 7.2 | <5 | | | | 7.3 | |
| Y | | 0.64 | <10 | | | | | |
| Zr | | 1.5 | | | | | | |
| Nb | | 0.32 | | | | | | |
| Mo | | | | | | | | |
| Pd ppb | <15 | | | | | | | |
| Ag ppb | 2.6 | | | | | | | |
| Cd ppb | 14 | | | | | | | |
| In ppb | 3.9 | | | | | | | |
| Sb ppb | 0.87 | | | | | | | |
| Te ppb | 50 | | | | | | | |
| I ppm | | | | | | <0.01 | | |
| Cs ppm | 0.037 | | | | | | | 0.037 |
| Ba | | 7.1 | 8 | | | | 3.6 | |
| La | | 0.39 | | | 0.6 | 0.59 | 0.36 | 0.44 |
| Ce | | 1.12 | | | | | 0.88 | 1.5 |
| Pr | | 0.13 | | | | | | |
| Nd | | 0.54 | | | | 0.7 | 0.6 | |
| Sm | | 0.11 | | | 0.14 | 0.16 | 0.133 | 0.136 |
| Eu | | 0.038 | | | 0.045 | 0.52 | 0.045 | 0.045 |
| Gd | | 0.11 | | | | | 0.13 | |
| Tb | | 0.02 | | | | 0.04 | | 0.019 |
| Dy | | 0.12 | | | | 0.27 | 0.11 | |
| Ho | | 0.03 | | | | 0.058 | | |
| Er | | 0.09 | | | | | 0.07 | |
| Tm | | | | | | | | |
| Yb | | 0.1 | | | 0.1 | 0.12 | 0.08 | 0.07 |
| Lu | | | **Lee&Halliday97** | | 0.012 | 0.018 | 0.013 | 0.012 |
| Hf | | | 0.04435 | | | <0.1 | | 0.06 |
| Ta | | | | | | <0.02 | | 0.022 |
| W ppb | | | 41.06 | **Birk&Allegre94** | | 46 | | |
| Re ppb | 0.054 | | | 0.0711 | | | | |
| Os ppb | 1.36 | | | 1.796 | | | | |
| Ir ppb | 1.85 | | | | 6 | 2.4 | | 2.6 |
| Au ppb | 0.56 | | | | 6 | 1 | | |
| Tl ppb | 3.7 | | | | | | | |
| Bi ppb | 0.37 | | | | | | | |
| Th ppm | | 0.057 | | | | <0.2 | | 0.04 |
| U ppm | 0.0149 | 0.021 | | | | <0.1 | | |
| *technique:* | | | | | | | | |

**Table VII-1b. Chemical composition of Chassigny** (continued).

| *reference* | *Lodders 98* | Brandon 2000 | | | | | | Wang 98 | | Warren 87 |
|---|---|---|---|---|---|---|---|---|---|---|
| *weight* | *averages* | 419 mg | 664 mg | 410.7 mg | 526.7 mg | 302.4 mg | | | | |
| SiO2 | *37.4* | | | | | | | | | 37.44 |
| TiO2 | *0.08* | | | | | | | | | |
| Al2O3 | *0.72* | | | | | | | | | 0.64 |
| FeO | *27.3* | | | | | | | | | 27.27 |
| MnO | *0.53* | | | | | | | | | 0.537 |
| CaO | *0.66* | | | | | | | | | 0.88 |
| MgO | *31.8* | | | | | | | | | 31.83 |
| Na2O | *0.12* | **Lancet 71** | **Bogard 99** | | | | | | | 0.125 |
| K2O | *0.036* | 0.054 | 0.018 | | | | | | | |
| P2O5 | *0.071* | | | | | | | | | |
| *sum* | | | | | | | | | | |
| | | | | | | | | | | |
| Li ppm | *1.4* | | | | | | | | | |
| Sc | *5.3* | | | | | | | | | 5.9 |
| V | *39* | | | | | | | | | 42 |
| Cr | *5240* | | | | | | | | | 5100 |
| Co | *123* | | | | | | | 73.2 | (c ) | 123 |
| Ni | *500* | | | | | | | | | 452 |
| Cu | *2.6* | | | | | | | | | |
| Zn | *72* | | | | | | | 113 | (c ) | 72 |
| Ga | *0.7* | | | | | | | 0.835 | (c ) | 0.7 |
| Ge | *0.011* | | | | | | | | | |
| As | *0.008* | | | | | | | | | |
| Se | *0.037* | | | | | | | 0.0251 | (c ) | 0.09 |
| Br | *0.088* | | | | | | | | | |
| Rb | *0.73* | | | | | | | 0.518 | (c ) | |
| Sr | *7.2* | | | | | | | | | |
| Y | *0.64* | | | | | | | | | |
| Zr | *2.1* | | | | | | | | | |
| Nb | *0.34* | | | | | | | | | |
| Mo | | | | | | | | | | |
| Pd ppb | *0.15* | | | | | | | | | |
| Ag ppb | *2.6* | | | | | | | 2.67 | (c ) | |
| Cd ppb | *14* | | | | | | | 9.49 | (c ) | |
| In ppb | *3.9* | | | | | | | 31 | (c ) | |
| Sb ppb | *0.87* | | | | | | | 1.4 | (c ) | |
| Te ppb | *50* | | | | | | | 28.9 | (c ) | |
| I ppm | *<0.01* | | | | | | | | | |
| Cs ppm | *37* | | | | | | | 0.108 | (c ) | |
| Ba | *7.6* | | | | | | | | | |
| La | *0.53* | | | | | | | | | 0.53 |
| Ce | *1.12* | | | | | | | | | |
| Pr | *0.13* | | | | | | | | | |
| Nd | *0.62* | | | | | | | | | |
| Sm | *0.14* | | | | | | | | | 0.137 |
| Eu | *0.045* | | | | | | | | | 0.045 |
| Gd | *0.11* | | | | | | | | | |
| Tb | *0.03* | | | | | | | | | |
| Dy | *0.2* | | | | | | | | | |
| Ho | *0.044* | | | | | | | | | |
| Er | *0.09* | | | | | | | | | |
| Tm | | | | | | | | | | |
| Yb | *0.11* | | | | | | | | | 0.107 |
| Lu | *0.015* | | | | | | | | | 0.015 |
| Hf | *<0.1* | | | | | | | | | |
| Ta | *<0.02* | | | | | | | | | |
| W ppb | *46* | | | | | | | | | |
| Re ppb | *0.063* | 0.328 | 0.459 | 0.316 | 0.127 | 0.264 | (a) | | | |
| Os ppb | *1.58* | 0.861 | 1.193 | 1.542 | 1.178 | 0.702 | (a) | | | 1.4 |
| Ir ppb | *2.1* | | | | | | | | | 2.1 |
| Au ppb | *0.73* | | | | | | | 0.329 | (c ) | 0.8 |
| Tl ppb | *3.7* | | | | | | | 2.8 | (c ) | |
| Bi ppb | *0.37* | | | | | | | 0.66 | (c ) | |
| Th ppm | *0.057* | | | | | | | | | |
| U ppm | *0.018* | | | | | | | 0.0125 | (c ) | |

*technique: (a) IDMS, (b) Ar, (c ) RNAA* of the Martian atmosphere (figure I-6). Marti and Mathew (1997) and Mathew and Marti (2001) reported temperature-release patterns for isotopes of Ar, Kr and Xe in Chassigny. There is some isotopic variability in the different temperature releases indicating more that one component, but Chassigny seems to lack the noble gas component of the current Martian atmosphere. The composition of the noble gas in Chassigny is often used as one end member in mixing diagrams used to explain the gases released from Martian meteorites (figure VII-10).

## Experimental Results

Terho *et al.* (1996), Collinson (1997) and Rochette *et al.* (2001) have reported magnetic data (see Table VI-3).

## Extra-terrestrial Weathering

Wentworth and Gooding (1994) reported trace amounts of Ca-carbonate, Ca-sulfate and Mg-carbonate in cracks inside Chassigny. They emphasize *"that water-precipitated salts in Chassigny comprise unmistakable physical evidence for the invasion of Chassigny by aqueous fluids"*. However, the isotopic data for hydrogen indicates that water in Chassigny is terrestrial in origin, possibly due to isotopic exchange (see above).

## Processing

Although this meteorite apparently originally weighed ~4 kg, only a small amount of this unique rock is apparently available for research today. The distribution of samples is given in figure VII-11. As a dunite might be expected to have slightly different lithology in different places, each piece should be examined.


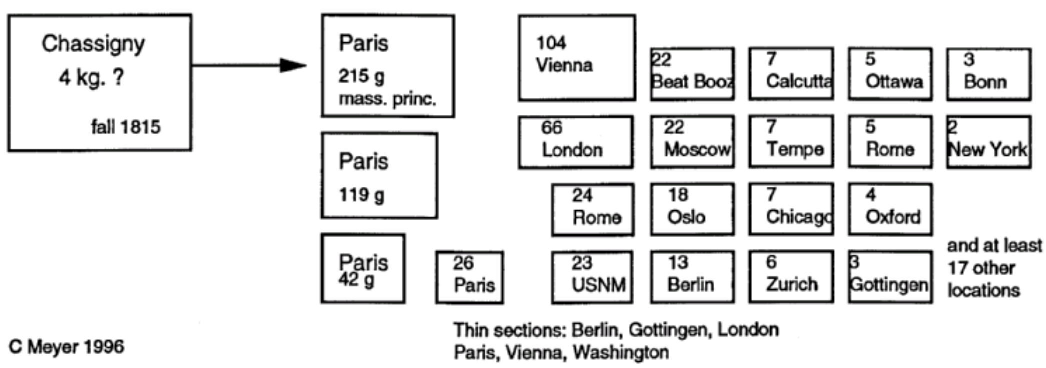


***Figure VII-11.*** *World location for remaining pieces of Chassigny meteorite.*