GLASSES IN METEORITES AND THE PRIMARY LIQUID CONDENSATION MODEL

by

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## Abstract

Meteoritic glasses are quenched samples of the silicate liquid that was involved in the formation of chondritic constituents and achondritic rocks. Conventional genetic models see them as residual liquids from which the associated minerals crystallized – as demonstrated by terrestrial igneous rocks – or as locally produced impact melts. These models are all closely related to our experiences with terrestrial geology and petrology and, consequently, make planetary processes, such as mixing and melting of solid precursors and planetary differentiation primarily responsible for the formation of the large variety of meteoritic rocks. However, different types of glasses (e.g., glass inclusions in minerals, mesostasis glasses, glass pockets, glass veins) in a variety of meteorites (chondrites and achondrites) have particular chemical features that cannot be reconciled with these models:

1) Glasses do not show the chemical signature of crystallization of the minerals they are associated with – a geochemical impossibility;

2) All types of glasses in all types of meteorites reported here show very similar trace element abundance pattern with the refractory lithophile element abundances at ~ 10–20 x CI chondrite abundances.

3) All refractory element abundance patterns in primitive glasses have unfractionated solar relative abundances (they are flat) and medium refractory and volatile elements are depleted relative to the refractory elements.

4) Medium volatile and volatile elements, when present, display chaotic abundance patterns.

The ubiquitous pattern for refractory elements signals vapor fractionation rather than geochemical ("igneous") fractionation or stochastic mixing of precursor minerals (as in shock melts). It indicates that the same process must have been involved in the origin of all glasses in chondritic constituents as well as achondritic rocks and, consequently, in the formation of all meteorite types investigated. The chaotic abundances of volatile elements signal that chaotic processes were involved during condensation.

Here we present a new model - the Primary Liquid Condensation (PLC) model – as an alternative to the currently accepted models for the formation of meteoritic rocks. The PLC model is capable of accommodating all observational and chemical data accumulated so far on meteorites – with the exception of enstatite and SNC meteorites, which record physico-chemical conditions that were different from those of the majority of meteoritic rocks (the processes, however, could have been the same).

The new model identifies a new role for silicate liquids in cosmochemistry as being an essential phase for the formation of early crystalline condensates from the hot solar nebula. Liquids are identified to have been the first major phase to condense from the solar nebula. In order to be capable to produce early liquid condensates, the nebula must have been either enriched in condensable elements over solar abundances (> 500 times) or was at total pressures much higher than the canonically predicted ones (> 500 times, > 0.5 bar ). Our data require that this liquid – we named it "universal liquid" (UL) - had a refractory composition (Ca-Mg-Al-silicate or CMAS) and facilitated condensation of the major minerals for chondritic constituents as well as for achondritic rocks. The process possibly was a variant of the vapor-liquid-solid (VLS) condensation process, which is utilized in industrial crystal growth. Thereby, the liquid condenses first, then nucleates a crystal of the species that is oversaturated in the vapor – in the case of the solar nebula usually olivine. As this olivine grows from the liquid, it depletes the liquid in Mg and Si. The liquid tries to maintain equilibrium with the solar nebula. Thereby, Mg and Si are replenished by condensation from the gas phase and all incompatible elements are kept at an equilibrium concentration by condensation-evaporation equilibrium. Thus, the contents of incompatible refractory elements are kept at an approximately constant level throughout crystallization of the major minerals olivine and pyroxene. This way not only the abundances of incompatible refractory elements are kept at a constant level but also their relative abundances remain unfractionated solar.

The UL also represents the long sought for refractory component of chondritic constituents and appears also to be the source of achondritic "igneous" rocks. Variations in the amount of liquid available, the liquid condensation and crystal nucleation rates, as well as different crystal-liquid mixing proportion will allow the formation of objects of highly variable composition. The final composition (chemical and isotopic) of any chondritic object or achondrite, as well as that of the associated glasses, will be determined by different degrees of post-formational metasomatic elemental exchange processes taking place between solids and the cooling nebular gas. These processes add medium volatile and volatile elements to the products of high temperature condensation. As these processes usually don't run to completion, an infinite number of chaotic compositional variations are produced – and this is exactly what we observe in meteorites.


**Zusammenfassung**
**(Gläser in Meteoriten und das Primäre Flüssigkondensat-Modell)**

Meteoritische Gläser sind abgeschreckte Proben von silikatischen Flüssigkeiten, welche an der Bildung von chondritischen und achondritischen Gesteinen beteiligt waren. Konventionelle genetische Modelle betrachten sie als residuale Flüssigkeiten, welche die mit ihnen assoziierten Minerale kristallisierten – wie wir es von terrestrischen Gesteinen kennen – oder als lokal entstandene Schockwellen-Schmelzen.

Alle diese Modelle haben ihre Wurzeln in der terrestrischen Geologie und Petrologie and machen daher planetare Prozesse, wie Mischen und Schmelzen von präexistenten Mineralen, sowie planetare Differentiationsprozesse für die Entstehung der großen Vielfalt meteoritischer Gesteine verantwortlich. Verschiedene Typen meteoritischer Gläser (z. B. Glas-Einschlüsse in Mineralen, Mesostasis-Glas, Glas-Taschen, Glas-Adern) in Chondriten und Achondriten haben jedoch chemische Eigenheiten, welche mit den konventionellen genetischen Modellen unvereinbar sind:

1) Es fehlen ihnen die chemischen Signale, dass die koexistierenden Minerale aus der Flüssigkeit, die sie repräsentieren, kristallisiert sind - eine geochemische Unmöglichkeit.

2) Alle Glas-Typen aller hier untersuchten Meteoriten zeigen sehr ähnliche Spurenelement-Häufigkeits-Muster mit refraktären lithophilen Elementen bei ~ 10–20 x CI-Chondriten-Häufigkeiten.

3) Die Häufigkeits-Muster der refraktären Elemente in den primitiven Gläsern haben unfraktionierte solare relative Häufigkeiten (sie sind flach) und mittelflüchtige und flüchtige Elemente sind gegenüber den refraktären verarmt.

4) Mittelflüchtige und flüchtige Elemente, wenn vorhanden, zeigen chaotische Häufigkeits-Muster.

Das weit verbreitete Muster der Häufigkeiten refraktärer Elemente signalisiert Dampf-Fraktionierung und nicht geochemische (magmatische) Fraktionierung oder stochastische Mischungen von präexistenten Mineralen (wie in Schockschmelzen). Es zeigt uns, dass ein und derselbe Prozess an der Entstehung der Gläser in chondritischen Bausteinen auch in achondritischen Gesteinen beteiligt gewesen sein musste, also bei der Bildung aller Meteoriten-Arten, welche wir untersuchten. Die chaotischen Häufigkeiten der volatilen Elemente deuten an, dass chaotische Prozesse bei der Kondensation involviert waren.

Wir stellen hier ein neues Modell zur Entstehung meteoritischer Gesteine vor, das "Primary Liquid Condensation (PLC, Primäre-Flüssigkondensat)" Modell – als ein alternatives Modell zu den zurzeit bevorzugten genetischen Modellen. Das PLC Modell kann alle zurzeit bekannten Eigenschaften der meteoritischen Gläser (und auch Gesteine) plausible erklären – ausgenommen jene der Enstatit- und SNC-Meteoriten, welche andere physiko-chemische Bedingungen anzeigen, als die Gläser der Mehrheit der meteoritischen Gesteine (die Bildungsprozesse können aber trotzdem sehr ähnlich gewesen sein).

Das neue Modell erkennt eine bisher nicht beachtete Rolle silikatischer Flüssigkeiten in der Kosmochemie: als essentielle Phase für die Bildung früher Kristall-Kondensate im heißen solaren Nebel. Silikatische Flüssigkeit wurde als die erste Haupt-Kondensationsphase im solaren Nebel erkannt. Um dieses Kriterium erfüllen zu können, muss der solare Nebel entweder an kondensierbaren Elementen angereichert (>500-fach über solare Häufigkeiten) oder einen Gesamtdruck von >500-fach jenem der üblicherweise angenommenen Drücke ausgesetzt gewesen sein. Unsere Daten zeigen, dass diese Flüssigkeit – wir nennen sie „universal liquid – UL („universale Flüssigkeit") – eine refraktäre chemische Zusammensetzung (Ca-Mg-Al-Silikat oder CMAS) hatte und dass sie die Kondensation der Hauptmineralien der Bausteine der Chondrite und auch der achondritischen Gesteine ermöglichte. Dieser Prozess war möglicherweise eine Variante des „vapor-liquid-solid – VLS - (Dampf-flüssig-fest)"-Prozesses, welcher in der industriellen Fertigung von Kristallen angewendet wird. Dabei kondensiert zuerst ein wenig Flüssigkeit, die in der Folge die Keimbildung für das im Nebel übersättigte Hauptmineral ermöglicht. Im solaren Nebel ist das üblicherweise der Olivin.

Der wachsende Olivin verbraucht nun das in der Flüssigkeit gelöste Mg und Si. Die Flüssigkeit versucht, mit dem solaren Nebel im Gleichgewicht zu bleiben und nimmt daher von diesem Mg und Si auf, um das Wachstum des Olivines fortzusetzen. Dabei hält sie auch die Häufigkeit der inkompatiblen Elemente auf einem über lange Strecken konstanten Niveau durch ein Verdampfungs-Kondensations-Gleichgewicht. Auf diese Weise ändert sich der Gehalt der inkompatiblen Elemente nicht mit der fortschreitenden Kristallisation der Hauptminerale Olivin und Pyroxen und auch ihre relativen Häufigkeiten bleiben unfraktioniert, also solar.

Die UL ist offensichtlich auch die seit langem gesuchte refraktäre Komponente der chondritischen Bausteine und sie ist wahrscheinlich auch die Quelle der „magmatischen" achondritischen Gesteine. Variationen in der Menge der Flüssigkeit, der Kondensationsrate und der Keimbildungsraten für die Kristalle sorgen schon für eine große Variabilität in der Zusammensetzung verschiedener Objekte, hauptsächlich definiert durch die Kristall/Flüssigkeits-Proportion. Die endgültige chemische (und isotopische) Zusammensetzung eines jeden einzelnen chondritischen Bausteines oder achondritischen Gesteines, sowie auch der mit diesen assoziierten Gläser wird endgültig bestimmt durch verschieden Grade metasomatischer chemischer Veränderungen, welche diese Objekte im solaren Nebel erfahren. Diese Prozesse fügen die volatile Elemente zu den Produkten der Hochtemperatur-Kondensation. Da diese Prozesse üblicherweise nicht zu kompletten Reaktionsabläufen führen, entstehen unendlich viele chaotische Zusammensetzungsvarianten – und das ist genau das, was wir in Meteoriten vorfinden.


# 1. Introduction

Glasses in meteorites have been observed and admired already by SORBY (1864) and TSCHERMAK (1875, 1883) and were - according to the standard knowledge of that time – correctly attributed to a sort of volcanic genesis of glass-bearing objects. Glass has a precursor – a liquid - and its formation needs fast cooling of that liquid. In addition, glasses are thermodynamically unstable and transform usually in geologically very short times into crystalline rocks. However, glasses in meteorites were miraculously preserved over the 4.56 Ga of our solar system's existence for us to be studied – and nobody knows, why this is so.

With the help of the electron microprobe X-ray analyzer glass inclusions in carbonaceous chondrite olivines were found to be Ca-Al-rich and poor in alkali elements. This finding provoked new debates about new aspects of the genesis of these glass inclusions in the early 1970s. FUCHS et al. (1973) suggested that they could be the result of a condensation process that formed the olivine of the Murchison CM chondrite. Similarly, OLSEN & GROSSMAN (1978) proposed an origin by direct condensation of isolated olivines in type 2 (now CM) carbonaceous chondrites based, among others, on the study of glass inclusions in these olivines. Conversely, MCSWEEN (1977) and ROEDDER (1981) considered the glassy inclusions to be trapped remnants of a bulk parent liquid from which the olivine and whole chondrule formed. This model was successful with and accepted by learned terrestrial igneous petrologists, who studied meteorites, as for them the glass precursor liquid could only be the product of fractional crystallization of a liquid with the composition of the bulk chondrule. Consequently, the interest in glass inclusions in olivines as possible keepers of a primary message vanished.

During our study of glasses (glass inclusions in olivines, glasses in mesostasis, pockets and veins) in terrestrial upper mantle rocks, our interest was triggered toward studying glass inclusions in meteorites, as they share similar host minerals and – in some cases - a similar chemical composition (e.g., VARELA et al., 1998). However, the first trace element abundance determined in a glass inclusion in olivine from the Renazzo (CR) chondrite (KURAT et. al., 1997) strongly suggested a vapor-liquid fractionation background rather than igneous fractional crystallization. This was the first clear indication that glass inclusions are capable of keeping a record on processes that took place in the early solar nebula. These findings triggered detailed studies (e.g., major, minor and trace elements, heating experiments, etc.) of glasses in chondritic and achondritic meteorites. However, our data and observations on glasses of chondritic and achondritic meteorites cannot be reconciled with igneous or impact process, the currently preferred models for the genesis of meteorites. How to reconcile with previous works the fact that the trace elements - the ultimate diagnostic elements for the evaluation of geochemical or cosmochemical processes - signal vapor-liquid/solid fractionation for chondritic and achondritic glasses? (e.g., VARELA et al., 2002a,b, 2005a,b, 2006). The formulation of a new model became necessary.

Here we give a summary of the key observations made on all types of glasses present in chondritic and achondritic meteorites that had led us to build this new genetic model. We briefly give the concepts of this "Primary Liquid Condensation Model" and extend its application to objects of differentiated meteorites. We identify glasses in meteorites as a very important, cosmochemically refractory phase and the carrier of messages from the processes that have taken place in the early solar nebula. This model unifies at least some constituents but probably almost all types of meteorites (chondrite, achondrites or silicate inclusions in irons), except enstatite and SNC meteorites.

## 2. Analytical techniques and samples

Major element chemical compositions of glasses were obtained with a JEOL 6400 analytical scanning electron microscope (NHM, Vienna) as well as SX100 CAMECA (Department of Lithospheric Research, University of Vienna) and Camebax SX50 CAMECA (Center d'analyses Camparis, Université de Paris V) electron microprobes. Microprobe analyses were performed at 15 kV acceleration potential and 10 nA sample current. Analyses of minerals and glasses were performed both with a focused (~1 $\mu$m) and a defocused beam (5 $\mu$m). The samples were first analyzed for Na with a counting time of 5 s followed by the analysis of all other elements with a counting time of 10 s in order to prevent premature Na loss from glasses. Basaltic and trachytic glasses (ALV 981 R24 and CFA 47; METRICH & CLOCCHIATTI, 1989) were used as standards and the on-line ZAF program was used for corrections.

Trace element analyses of glasses were made with the modified Cameca IMS 3F ion microprobes at the Washington University (St. Louis), at the Physikalisches Institut, Universität Bern (Bern), and at the Abteilung für Kosmochemie, Max-Planck-Institut für Chemie (Mainz), following modified procedures of ZINNER & CROZAZ (1986), and with the LA-ICP-MS facility at Memorial University of Newfoundland.(for detailed analytical descriptions see VARELA et al., 2003b, ENGLER et al., 2007).

All samples studied belong to the Natural History Museum (NHM) in Vienna, except the Polished Thin Section (PTS) ALL DI (Allende Dark Inclusion), which belongs to the American Museum of Natural History, New York. The studied meteorites are:

**Carbonaceous chondrites:** Acfer 094, Acfer 182, Acfer 214, Allende, Allende DI, Axtel, Bali, DaG 055, DaG 083, DaG 289, DaG 291, Essebi, HAH 073, Kaba, Mighei, Mokoia, Murchison, Murray, Ningqiang, NWA 801, QUE 97077, Renazzo, Vigarano, and Y 82042.

**Ordinary chondrites:** Bishunpur, Krymka, Mezö-Madaras, NAW 467, Sahara 97210, Tieschitz.

**Howardites and eucrites:** Cachari, HAH 285, NWA 1664.

**Angrite:** D'Orbigny.

**Ureilite:** FRO 90054.

**Winonaite:** HAH 193.

**Iron (IIE):** Kodaikanal.

**Iron (UNGR):** Guin, Tucson.

## 3. Results

3.1. Petrography and major element chemical composition

Glasses occur in meteorites in a variety of locations:

a) As glass inclusions or glass-bearing multiphase inclusions in olivines and pyroxenes (Fig. 1a-f). These inclusions can be isolated or form clusters. Their shapes can be round to ellipsoidal and occasionally controlled by the crystal structure of the host, especially when they occur in pyroxenes (Fig. 1c).

b) As glassy or glass-bearing neck-inclusions (inclusions, which are still connected to the mesostasis by a thin neck, Fig. 1f).

c) As mesostasis glasses in aggregates and chondrules (Fig. 1f).

d) As glasses filling open spaces (cracks and voids), forming glassy or glass-bearing veins - mainly in achondritic meteorites (Fig. 1g-h).

Glasses investigated by us cover all types and only clear glasses without signs of devitrification were selected.

The chemical composition of inclusion glasses in minerals of CR, CM, CV3, CH3, CO3, and CO4 chondrites is typically Al-Ca-rich. The compositional range of glasses in chondritic and achondritic meteorites is summarized in Figures 2a-c. Representative major element chemical composition of glass inclusions in carbonaceous chondrites (CH3, CM, CO3, CO4, CR, CV3, C4, C2), ordinary chondrites (OCs), angrite, eucrites and howardites; iron meteorites (Tucson and the IIE iron), ureilite FRO 90054 and the winonaite HH 193 and the glassy mesostasis of chondrules and aggregates in chondrites are given in Tables 1 to 7, respectively. Glasses in chondritic objects (chondrules, aggregates) are typically poor in MgO and FeO (each < 5 wt.%). $SiO_2$ contents vary widely and range from ~40 (CCs, angrite) to ~80 wt.% (OCs). The CaO content varies between 0 (OCs) and ~25 (CCs) wt.% and that of $Al_2O_3$ between <10 (OCs, angrite and HED) and 35 (CCs) wt.%. The $Na_2O$ content ranges between 0 (CCs) and >14 wt.% (CCs). Minor element contents ($TiO_2$, $Cr_2O_3$, MnO, and $K_2O$) are generally low, vary over wide ranges and are dealt with the trace elements below.

## 3.2 Trace element abundances

Glasses related to olivine-rich objects in chondritic meteorites have generally high (e.g., 6 to 30 x CI) and unfractionated abundances of refractory trace elements and are depleted in moderately volatile and volatile elements (Fig. 3a-c). Common to almost all glasses is a small negative Sc abundance anomaly, occasionally accompanied by small negative Ti and Eu anomalies. Mesostasis glasses (Fig. 3b,c) display also occasional negative Ca abundance anomalies and usually have high and highly variable volatile element abundances (e.g., Rb ~ 1–10 x CI). Abundances and patterns similar to those of glasses in chondritic objects are also shown by glasses in the angrite D'Orbigny (e.g., in glass inclusion in olivine, in glass pockets and in interstitial glasses), in the eucrite Cachari (glass filling fractures) and in the howardite NWA 1664 (glass shards and spherules) (Fig. 3d). They also show small negative Sc abundance anomalies and a wide range in moderately volatile and volatile element abundances. The total range of refractory element abundances, however, is very restricted as compared to that exhibited by glasses from chondritic objects.

Glasses associated with pyroxene-rich objects in chondrites are rare and our single example from a Krymka (LL3) RP chondrule shares a similar pattern to those found in mesostasis glasses of olivine-rich objects with refractory lithophile trace element contents at about 6–10 x CI abundances (Fig. 3c). This glass also has pronounced negative abundance anomalies of Sc (~1 x CI) and Ca (~2 x CI) and a strong positive abundance anomaly of Rb (~23 x CI).

*Figure 1: (next page)*

*a) Transmitted light image of a primary glass inclusion in an olivine of the LEW 85311-25 CM2 chondrite.*

*b) Transmitted light image of a primary glass inclusion in an olivine of the Murchison CM2 chondrite. Note that the olivine grain is a relic and is surrounded by pyroxene.*

*c) Transmitted light image of primary glass inclusions in enstatite of the NWA 1235 aubrite. Note the control of the inclusions shape by the pyroxene structure.*

*d) Transmitted light image of a cluster of primary glass inclusions in an isolate olivine of the Allende CV3 chondrite (detail is shown in the inset).*

*e) Transmitted light image of a primary glass inclusion in an olivine of the Tucson (UNGR) iron meteorite (black: metal).*

*f) Back-scattered electron (BSE) image of a PO chondrule in the Tieschitz H3.6 chondrite showing the co-existence of glass inclusions (circle), neck inclusion (arrow) and the glassy mesostasis in between euhedral olivine crystals. Scale bars in images a, b, c, d, e and f: 20 μm.*

*g) Transmitted light image of a glass vein in the eucrite Cachari.*

*h) Transmitted light image of a polished section of the angrite D'Orbigny showing a black glass sphere (GS) and a black glass patch (GP).*

LEW 85311-25

Ol

**a**

Murchison

Px

Ol

**b**

NWA 1235

Px

**c**

Allende

**d**

Tucson

20 μm

**e**

Tieschitz

**f**

**g**

GP

GS

1 mm

**h**
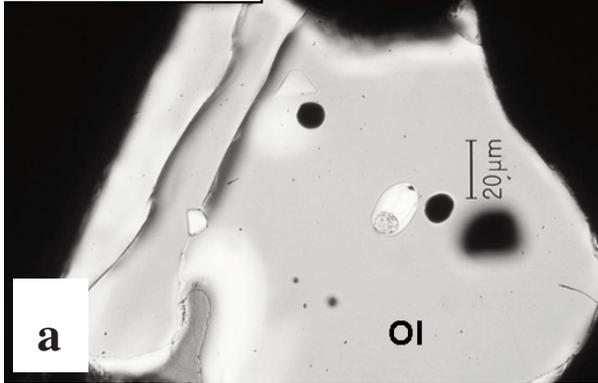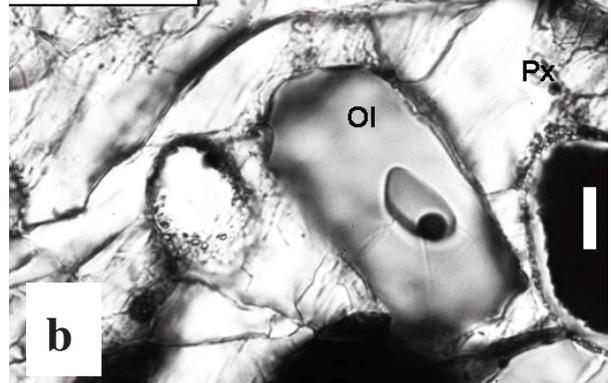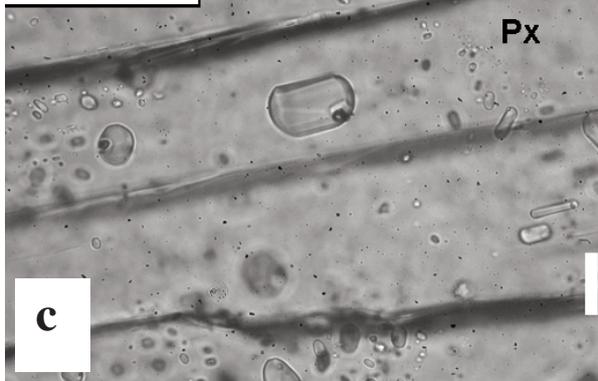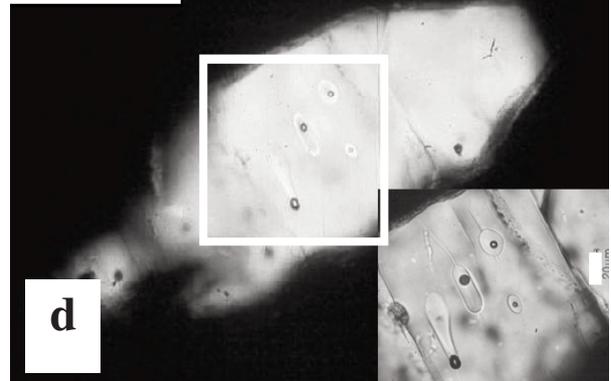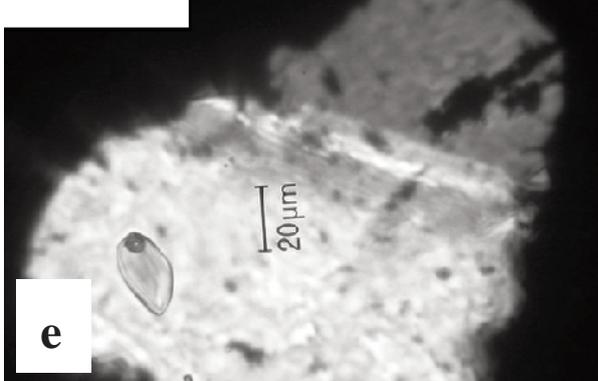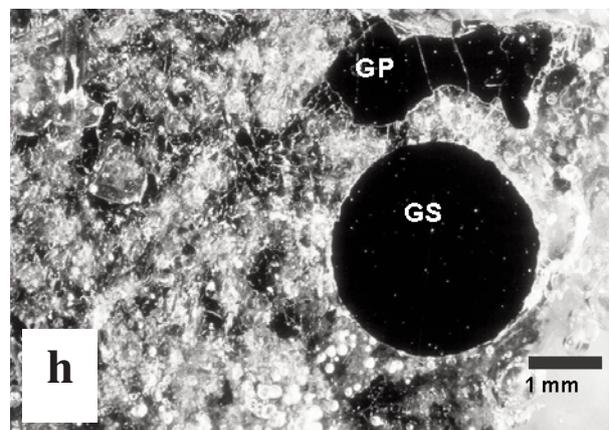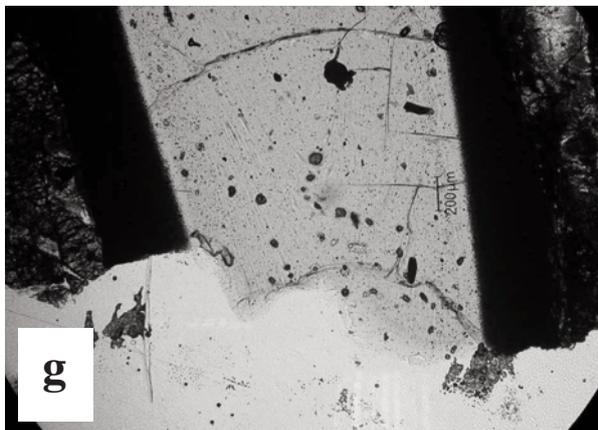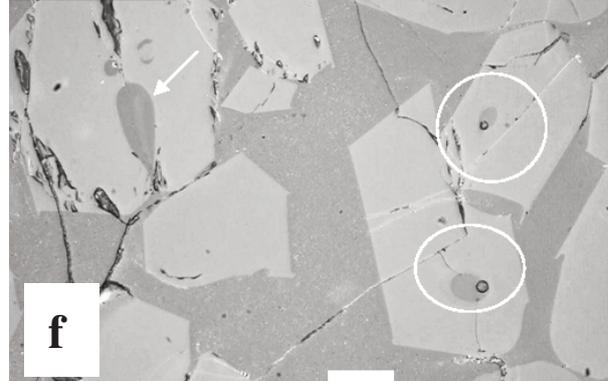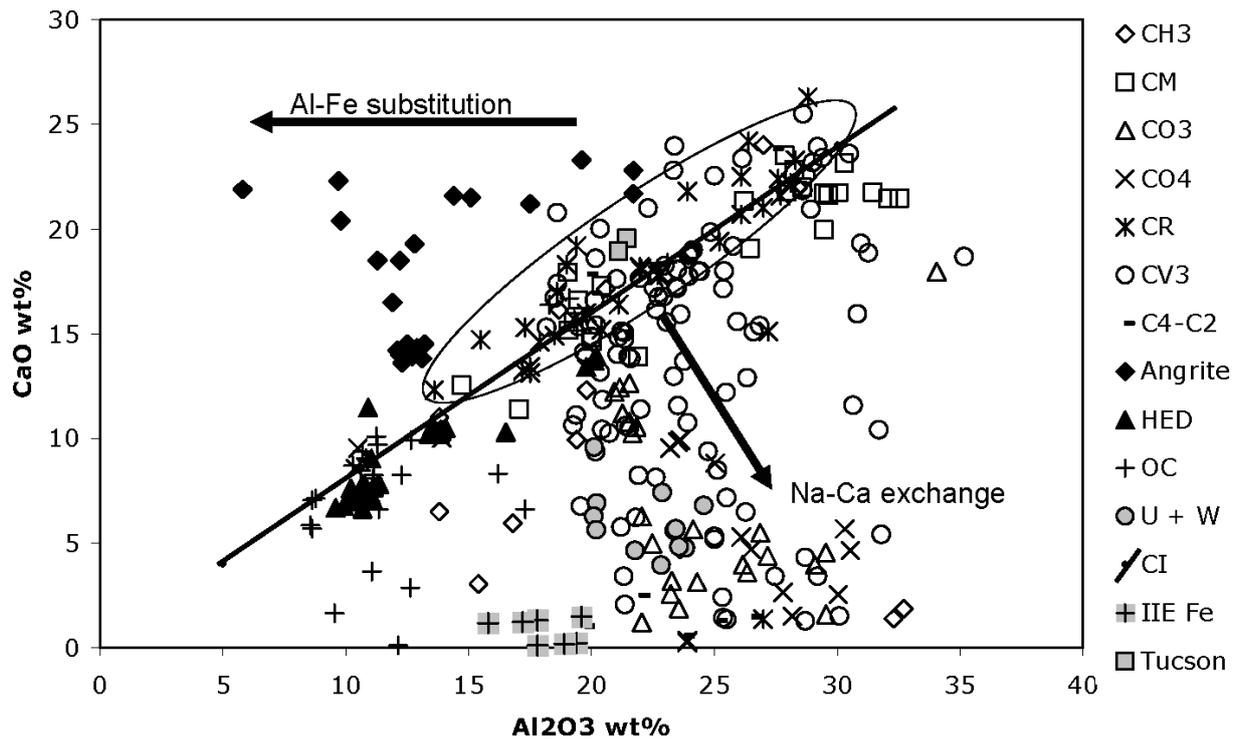
*Figure 2a:*

*CaO vs. Al$_2$O$_3$ diagram of all types of glasses encountered in carbonaceous (CH3, CM, CO3, CO4, CR, CV3, C4, C2) and ordinary (OC) chondrites, the angrite D'Orbigny, HEDs, ureilites and winonaites (U+W), Tucson and the IIE iron (Fe IIE) achondritic meteorites. The ellipse covers the compositional range of glasses in CR chondrites. The directions of compositional changes via Na-for-Ca and Fe-for-Al exchange of glasses with the nebular gas are indicated by arrows.*
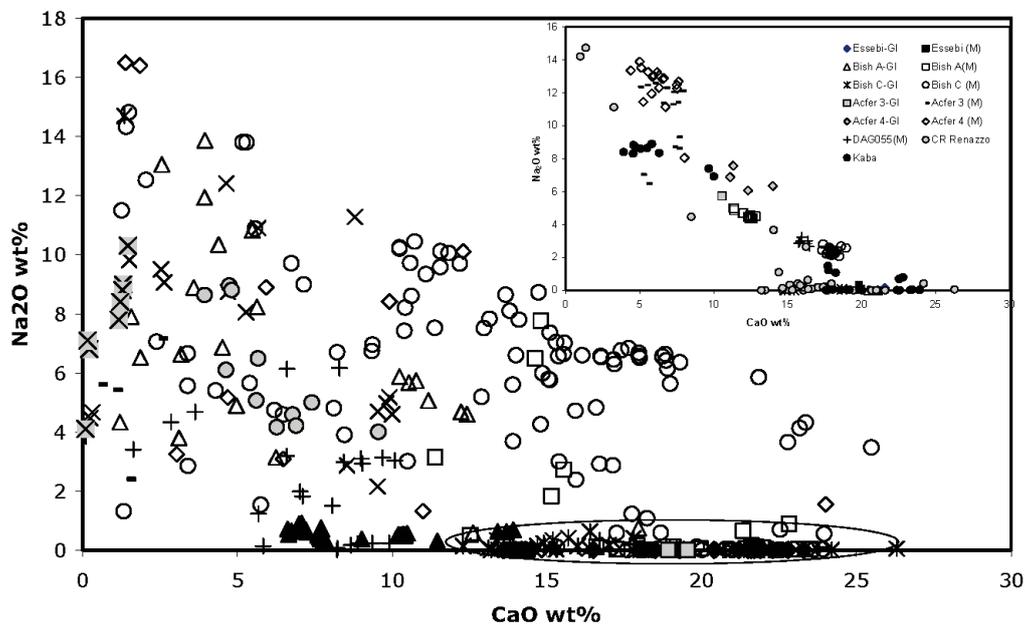


*Figure 2b:*

*Na$_2$O vs. CaO diagram of all types of glasses, the Na-rich glasses have anti-correlated Na$_2$O and CaO contents. The ellipse covers the compositional range of glasses in CR chondrites. Inset in Figure b shows the Na$_2$O vs. CaO diagram of glasses that behaved as open systems (glass inclusions reached by fractures, glasses of mesostasis and neck inclusions) in Essebi, Bishunpur (Bish), Acfer, DaG 055, Kaba, and Renazzo chondrites.*
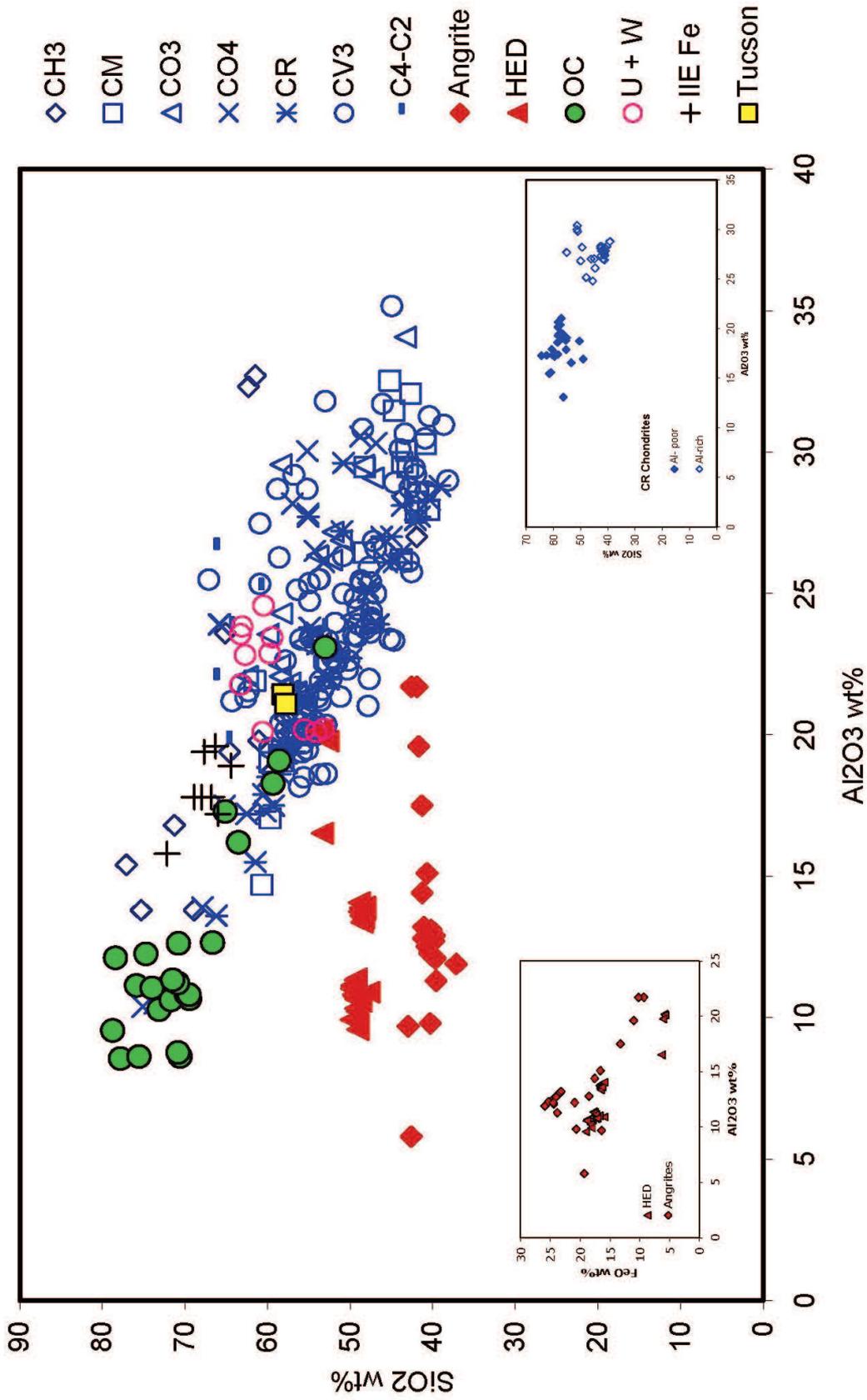
*Figure 2c:*

*$SiO_2$ vs. $Al_2O_3$ diagram of all types of glasses (glass inclusions and glass filling open spaces) in carbonaceous and ordinary chondrites, in ureilites, and winonaites (U+W), in the Tucson iron, in IIE irons, in the angrite D'Orbigny and in HED meteories. Glasses show two compositional trends governed by either Si-addition (as shown by the Al-rich and Al-poor glasses in the CR chondrites, right inset) or Al-Fe substitution (as shown by glasses in angrites and eucrites, left inset). Data from Tables 1 - 7 and from KURAT et al. (2002 a-b, 2003b, 2005 a-b), VARELA et al. (2003, 2007), VARELA et al. (2002 a-b, 2003b, 2005 a-b).*

## Glass inclusions in Ol-rich objects
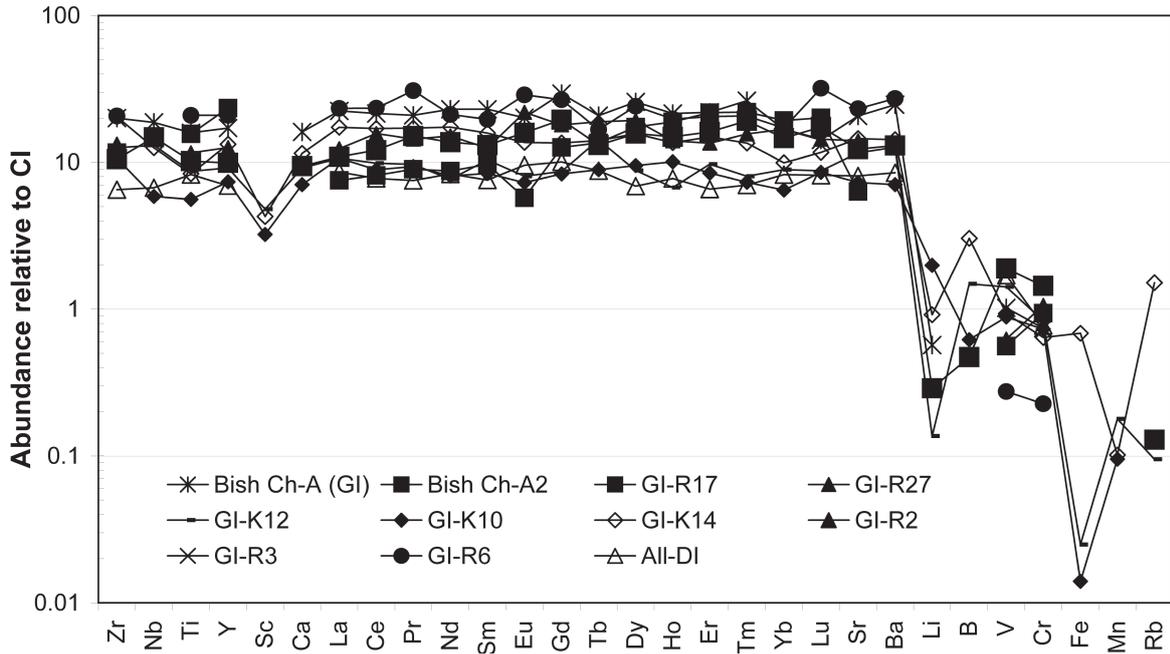


Figure 3a:

CI-normalized trace element abundances in glasses of primary glass inclusions (GI) in olivines of carbonaceous chondrites Bishunpur (Bish), Renazzo (R), Kaba (K) and Allende Dark Inclusion (ALL-DI) (KURAT et al., 1997; VARELA et al., 2002a; 2002b).

## Glass, neck inclusions and mesostasis glass in a PO chondrule
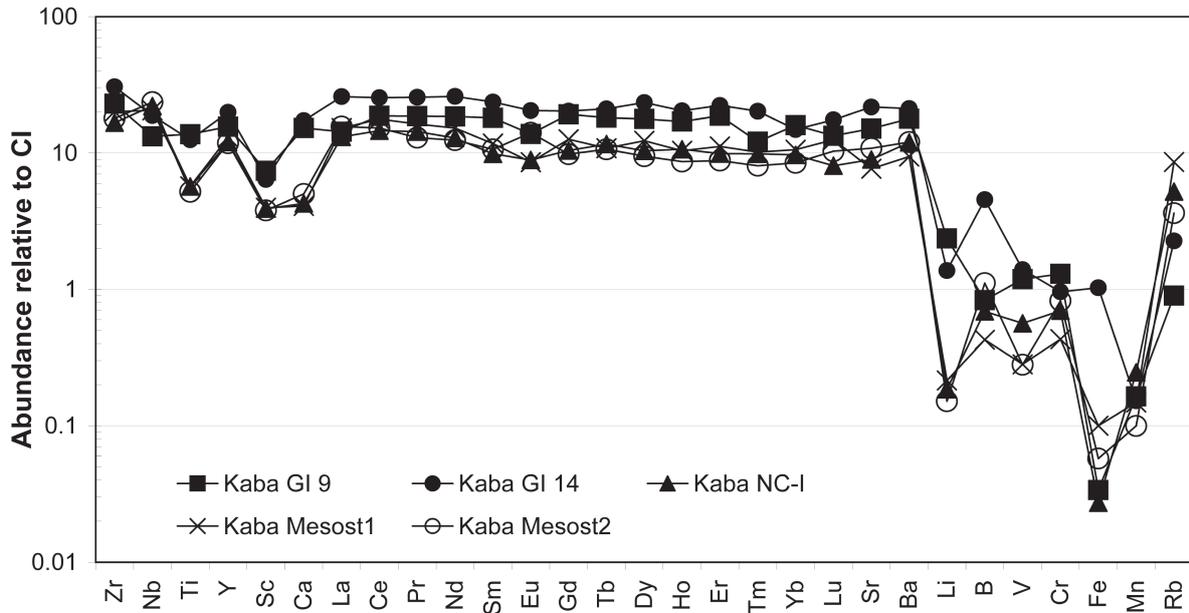


Figure 3b:

CI-normalized trace element abundances in glasses of primary glass inclusions (GI), a neck inclusion (NC-I), and mesostasis glasses (Mesost) in a PO chondrule of the Kaba CV3 chondrite (VARELA et al., 2005).

**Glass inclusion and mesostasis glass in BO and RP chondrules**
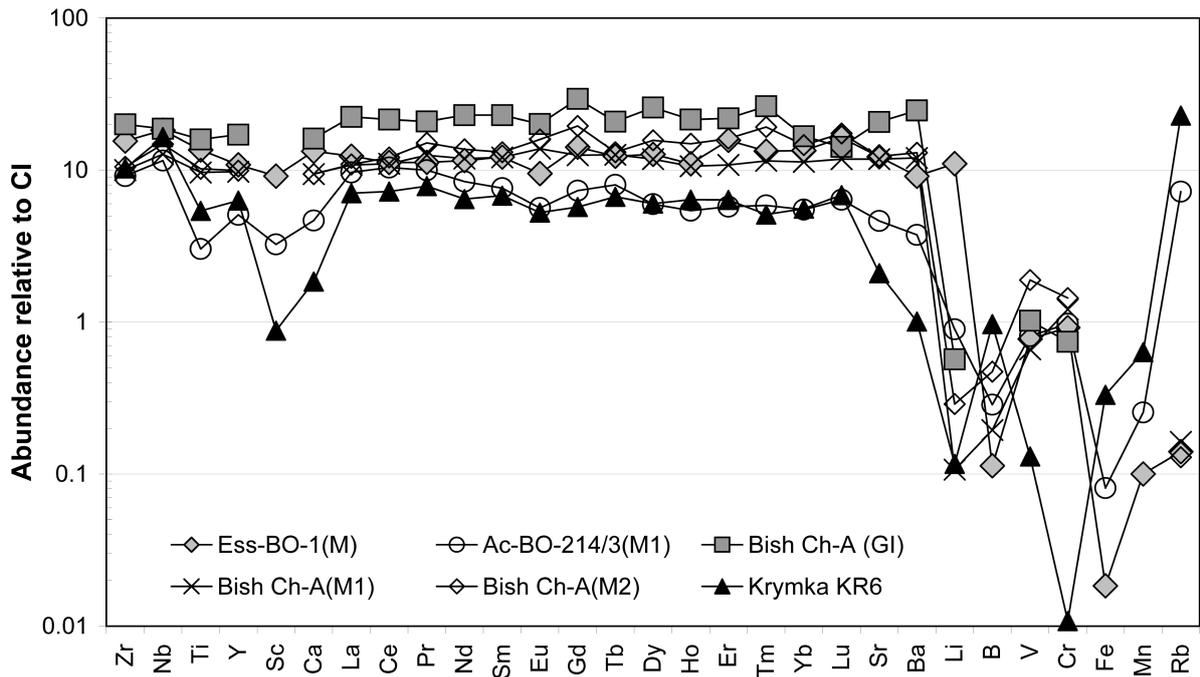
*Figure 3c:*

*CI-normalized trace element abundances in glasses of primary glass inclusion (GI) in olivine and mesostasis glasses (M) of Essebi (Ess-BO-1), Acfer 214 (Ac-BO-214/3) and Bishunpur (Bish Ch-A) BO chondrules (VARELA et al., 2006) and mesostasis glass in pyroxene-rich object Krymka KR6 (ENGLER et al., 2007).*
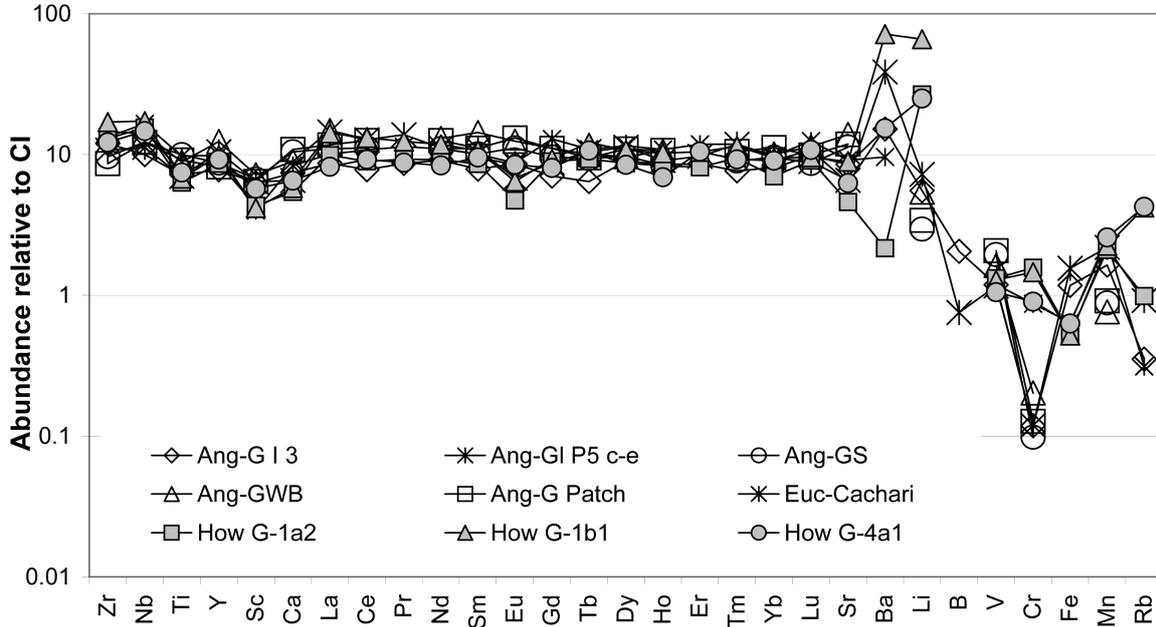


*Figure 3d:*

*CI-normalized trace element abundances in glasses of primary glass inclusions (GI), glass pocket (GP), glass sphere (GS), glass patch (G Patch), and glass with bubbles (GWB) in the angrite D'Orbigny (Ang), glass filling a fracture in the eucrite Cachari, and glassy objects (G) in the howardite NWA 1664 (How) (Kurat et al., 2003; VARELA et al., 2003b; VARELA et al., 2005b). CI chondrite data used here and in the following graphs is from LODDERS & FEGLEY (1998).*

# 4. Discussion

Glasses in any rocky object (terrestrial and extra-terrestrial) are mainly found in two occurrences: as glass inclusions in a host mineral or as glass filling spaces in between crystals or veins. The first case is represented by glass inclusions formed during growth of the host. Such primary glass inclusions in many cases are well protected by the host mineral and, therefore, can behave as isolated closed systems that can record conditions prevailing during formation of the host, provided that secondary alteration processes did not succeed in changing their properties. Because such glasses are in contact with a single mineral phase (e.g., olivine), the glass inclusions had chemically to remain on a single-phase (e.g., olivine) subtraction line. This record can be obliterated if metasomatic processes chemically alter glass inclusions. They can be successful either because of proper force and duration or by facilitating fractures that can serve as pathways for ion exchange with the environs. Thus, we can expect glass inclusions to record original growth conditions as well as subsequent alteration processes, provided these processes were intense enough to reach the glass inside crystals. As a result, we can also expect inclusion glasses to record all possible stages of alteration between the pristine and the final composition. This, of course, applies to chemical composition as well as elemental isotopic compositions.

Mesostasis glasses are also primary but unprotected and open to the environment around the object – they are open systems. Open system glasses are apt to communicate with the environment and consequently record – in addition to some features of the primary processes - also those of processes taking place after the object had formed. Thus, we can expect matrix glasses of, e.g., chondritic objects, to more commonly record post-formation alteration processes than inclusion glasses. This applies to chemical as well as isotopic changes.

Glasses in pockets, veins and other former open spaces in any rock are secondary in origin. They where introduced when at least the local mineral assemblage already existed and are naturally also open systems. All open system glasses (e.g., chondrule mesostasis or interstitial glasses in achondrites) can easily experience ion exchange reactions with the surrounding medium (e.g., fluid/gas – compare early results reported by KURAT, 1967, 1971) and thus can record the latest environmental changes during the formation of the rock. Because these glasses form irregular domains and are in contact with several phases they may have followed quite different lines of evolution as compared to those of the glass inclusions in minerals.

Thus, glasses of primary glass inclusions can keep information related mainly to the primary events during crystal growth (e.g., KURAT et al., 1997; VARELA et al., 2002a, 2005a), while the glasses filling open spaces will reveal some hints about the conditions prevailing during the post-formation events that affected the particular object (e.g., VARELA et al., 2003b, 2005a, 2006). Different types of glasses keep memory of different types of events.

## *4.1 - Do glasses in meteorites and in terrestrial rocks document the same processes?*

In the following paragraphs we discuss the elemental abundances in all glasses (closed and open systems), which conducted us to propose that glasses in meteorites do not document processes similar to those recorded by glasses in terrestrial rocks.

## 4.1.1 - The case of glass inclusions

*Major and minor element contents of glasses:* In primitive chondritic and achondritic meteorites, the chemical composition of inclusion glasses is Al-Ca-rich with about chondritic $CaO/Al_2O_3$ and $Al_2O_3/TiO_2$ ratios (VARELA et al., 2002a, 2005a).

*Trace element contents of glasses:* Inclusion glasses in chondritic and achondritic meteorites are characterized by having unfractionated ~10 to 20 x CI-normalized abundances of refractory trace elements and being depleted in moderately volatile and volatile elements (Fig. 3a-c, Fig. 4) (KURAT et al., 1997; VARELA et al., 2002a,b, 2005a, 2005b, 2006).
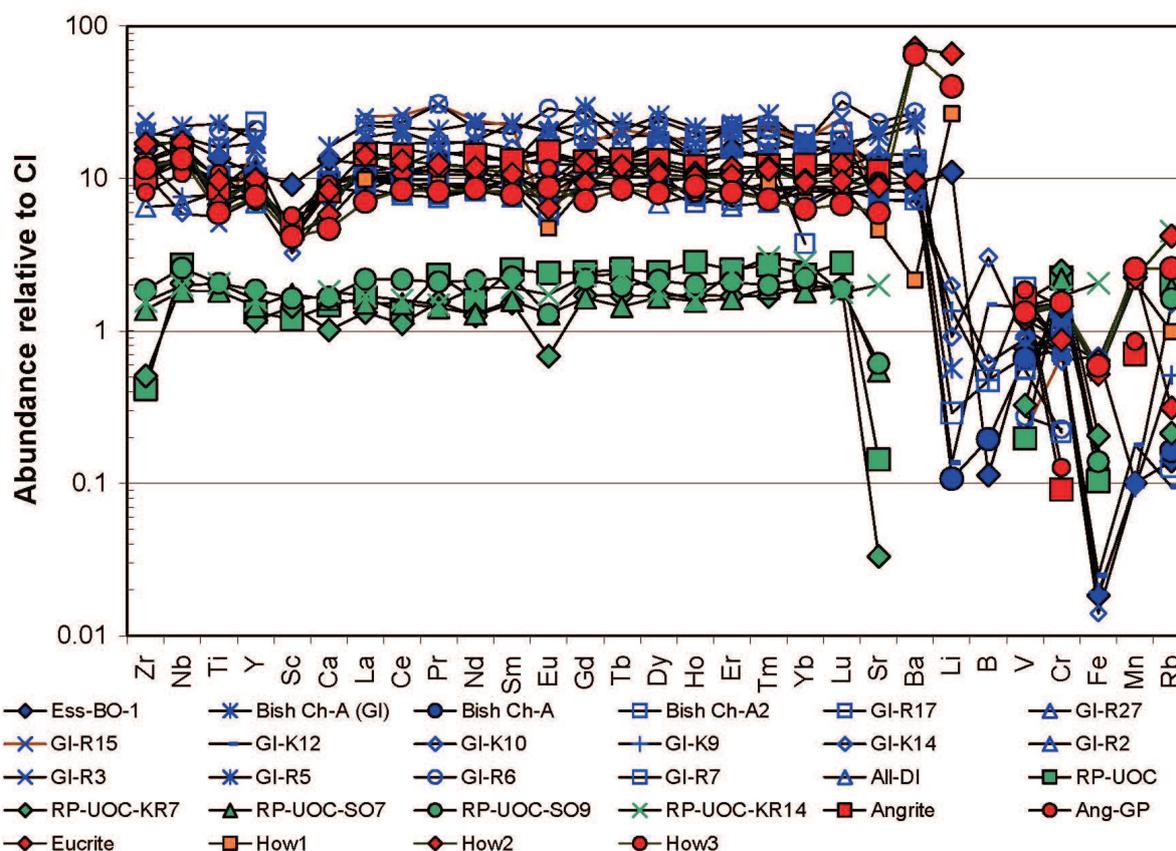


*Figure 4:*

*CI-normalized trace element abundances of the glasses rich in refractory elements (olivine-rich and achondritic objects, ~ 10–20 x CI) and glasses poor in refractory trace elements (in pyroxene-rich objects, mostly about 1–2 x CI, ENG-LER et al., 2007).*

This trace element pattern is common to all studied glass inclusions. It clearly indicates vapor-liquid fractionation and is incompatible with both, geochemical (liquid-crystal) fractionation as well as stochastic mixing of precursor minerals. The negative anomaly in the abundance of V, a refractory element (e.g., LODDERS & FEGLEY, 1998), which is also common in many glass inclusions, possibly indicates that condensation took place under reducing conditions (KURAT et al., 1997).

Very common in all glasses is also a small negative Sc abundance anomaly, which can be primary (condensation of a Sc-rich refractory phase before liquid nucleation?) or secondary (concerted mobilization with Al during nebular alteration). The moderately volatile elements have strong negative abundance anomalies. As all these elements have high diffusion rates in glasses as well as Mg silicates (e.g., FREER, 1981), the lowest abundances found are likely upper limits for the primitive original liquid: Li ~ 0.1, B ~ 0.5, V ~ 0.2, Cr ~ 0.2, Fe ~ 0.01, Mn ~ 0.1, and Rb ~ 0.1 x CI. The chaotic abundances of these elements in glass inclusions likely are the result of metasomatic processes (solid – gas exchange) in the solar nebula (see below).

Analyses of glass inclusions in olivines of the Tucson iron meteorite show that these glasses have a similar trace element abundance pattern (VARELA et al., 2008). Consequently, they clearly belong to the family of chondritic and achondritic primitive glasses and indicate a close genetic relationship between the silicates in the Tucson (IRUNGR) iron and chondrites – in agreement with previous conclusions reached by PRINZ et al. (1987).

*Evidence for nebular processes:* The search of C and N by Nuclear Reaction Analysis (NRA) in glasses of glass inclusions (VARELA & METRICH, 2000; VARELA et al., 2000, 2003a) in olivines of CV3, CO3, CR, C4, CH3 and LL chondrites show variable and uncorrelated contents of these elements (Fig. 5). This heterogeneity, even observed in glass inclusions occurring in the same olivine grain (e.g., glass inclusions in a single olivine in the Kaba meteorite: inclusion Kaba2: 190 ppm N – 250 ppm C; inclusion Kaba3: 30 ppm N - 2090 ppm C; inclusion Kaba4: 200 ppm N - 610 ppm C) is suggestive of trapping of solid carrier phases during formation of the constituents of chondrules. The carrier phase must have been individual ones for C and N, respectively, as is documented by the lack of correlation between their abundances (Fig. 5) (VARELA & METRICH, 2000; VARELA et al., 2000, 2003a).

*Elemental partitioning:* With respect to the element partitioning between glass (= liquid) and olivine, studies of carbonaceous chondrites show that, although olivine and glass trace element abundances tend to adjust to the olivine-liquid distribution coefficients (e.g., GREEN, 1994), they appear not to be equilibrated (e.g., KURAT et al., 1989b,c, 1992). Olivines are commonly too rich in trace elements in order to be in equilibrium with the co-existing mesostasis or inclusion glass. The trace element abundances in the olivine require co-existing liquids with very high contents of light rare earth elements (LREEs, >100 x CI), Zr and Sm (~100 x CI) and Ti, Y, and Lu (~50 x CI) (KURAT et al., 1992; VARELA et al., 2002a). In the Kaba CV3 chondrite, abundances of Nb, Sm, Gd, Ho, Er, Ti, and Yb in olivine suggest disequilibrium with co-existing glasses (= liquids) as such high contents would require co-existing liquids with ~30 to ~200 x CI trace element abundances, much higher than the ~10 x CI abundances observed (VARELA et al., 2005a). A similar situation is observed for olivines and inclusion glasses of an Allende dark inclusion (VARELA et al., 2002b) and the angrite D'Orbigny (VARELA et al., 2003b). All our data show that, while the primary trace elements are out of equilibrium, the secondarily introduced elements Cr, Mn and Fe are not. Incorporation of these elements must have taken place under conditions that allowed their proper diffusion in all the co-existing phases. Due to their higher diffusion rates, as compared to most tri- and tetravalent trace elements (e.g., FREER, 1981), their equilibrium partitioning could have been achieved while disequilibrium prevailed in the distribution of other elements. Because this is a very common feature of meteoritic constituents, it could be utilized for a nebula thermometer.

Crystal-melt interactions as well as mixing of precursor phases are the cornerstone processes of the currently entertained chondrule formation models, which – on the basis of our observations – need to be revised. The same holds for the current achondrite formation models as - based on existing knowledge – practically all achondrites cannot be crystallization products of melts formed by partial melting of a chondritic precursor.
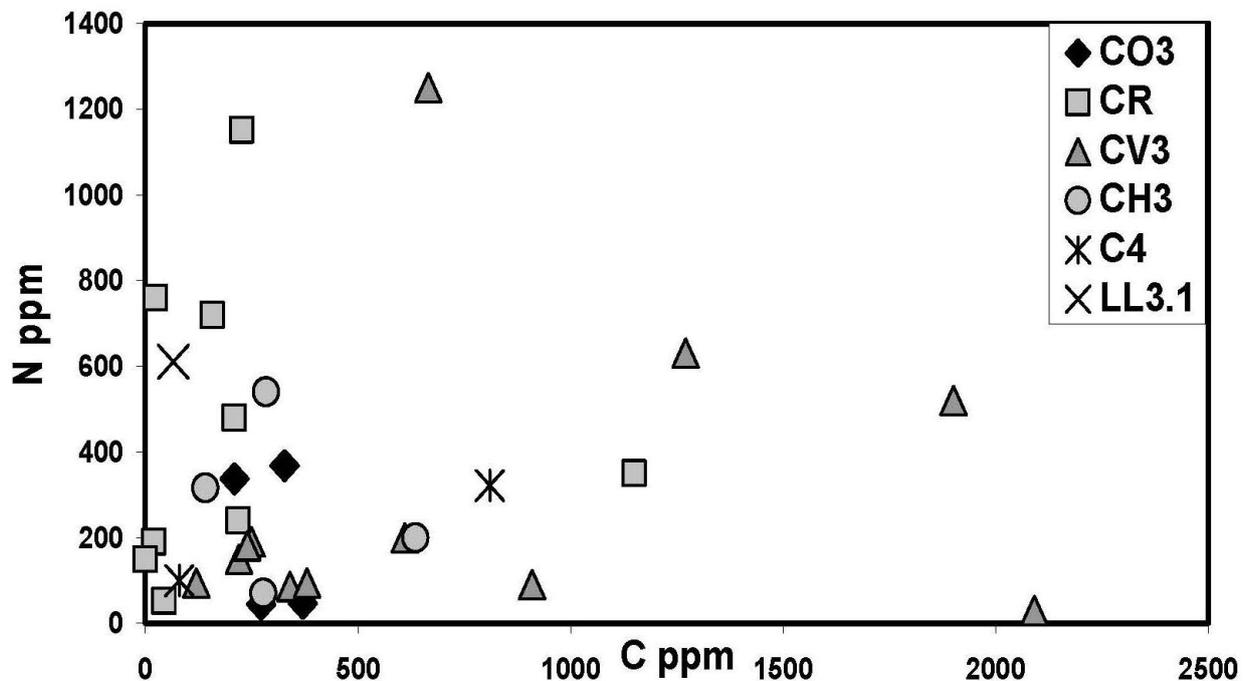


*Figure 5:*

*C vs. N contents (in ppm) of inclusion glasses in olivines of CO3, CR, CV3, CH3, C4 and LL3.1 chondrites. The uncorrelated data points toward individual carrier phases for C and N. Data from VARELA et al., 2000, 2003a).*

### 4.1.2 - The case of glass filling open spaces

*Chemical composition of glasses:* Open system glasses (neck inclusions, mesostasis, veins) rarely have chemical compositions that are identical to those of many glass inclusions in olivines (e.g., Fig. 3c, Bishunpur). They usually are rich in medium volatile and volatile elements, such as Na, K and Rb. In some cases – as in a POP aggregate from the Kaba CV chondrite (Varela et al., 2006) – alkali-free inclusion glass co-exists with alkali-rich mesostasis glass. Obviously, the inclusion glass carries the message of the early formation process – the mesostasis must have suffered some additional changes – metasomatic alteration in the solar nebula.

*Open system processes:* Chaotic variations in the chemical composition of glasses indicate that secondary processes did take place. Such processes can be manifold but in principle involve mobilization and exchange of certain elements with a reservoir. Such a reservoir needs to consist of a highly mobile phase (liquid, better fluid or gas) that carries elements, which are not present in proper amounts in the object that they invade.

We have identified a solid/liquid-vapor exchange process as the most likely one that ultimately leads to metasomatic changes of the solid object in an attempt to chemically equilibrate with the vapor. Very common examples of this process are Fe, Mn and Cr diffusion rims in olivine of CC chondrites, which document attempted but not achieved equilibration with a gaseous environment (e.g., KURAT, 1975, 1987a,b, 1988; BLANDER, 1983; KURAT et al., 1985, 1989a,b, 2002; PECK & WOOD, 1987; DOHMEN et al., 1998; DOHMEN & CHAKRABORTY, 2003). Also widespread in chondrites are alkali diffusion zones in glasses of chondritic objects that document attempted but not achieved equilibration with an environment that was out of equilibrium (e.g., KURAT, 1967). Metasomatism exclusively involves medium volatile or volatile elements on the add-on side, but naturally always involves refractory elements on the subtraction side. We may give as a typical example the very common metasomatic exchange of Ca for Na in chondritic objects. At first sight this looks contradictory, as a refractory element needs to be mobilized. However, mobilization of Ca is a consequence of cool and oxidizing conditions (HASHIMOTO, 1992) – exactly what can be expected to take place in a cooling solar nebula gas. Accordingly, it is no surprise to find exchange reaction of Ca for Na so widespread in chondritic (and also other) objects. This is also the way glasses can acquire $Na^+$ and $K^+$ (and other alkalis) for $Ca^{2+}$ according to the reaction (for plagioclase component dissolved in the glass):

$$CaAl_2Si_2O_8(solid) + 2Na(OH)(gas) \Leftrightarrow Na_2Al_2Si_2O_8(solid) + Ca(OH)_2(gas)$$

This can also affect anorthite crystals and create non-stoichiometric plagioclase compositions (plagioclase–nepheline mixtures) as described by KURAT & KRACHER (1980) from the Lancé OC chondrite.

The $Na_2O$ vs. CaO anti-correlation (Fig. 2b) is omnipresent in glasses that have acted as open systems. There the Na-Ca exchange reaction was studied in detail (see Fig. 2b inset), e.g., in glass inclusions touched by fractures in CR chondrites (VARELA et al., 2002a), neck inclusions and mesostasis in CV3 chondrites and BO chondrules (VARELA et al., 2005a, 2006). Also exchange of $Mg^{2+}$ for $Fe^{2+}$ (and $Cr^{3+}$, $Mn^{2+}$ etc.) is very common (e.g., VARELA et al., 2002a, 2005a, 2006).

Another secondary exchange reaction, identified in glasses of the angrite D'Orbigny and HED meteorites, comprises a substitution of Al by Fe (see inset in Fig. 5 and VARELA et al., 2003b). Primary glass inclusions trapped in olivines (one of the first phases to crystallize in the angrite D'Orbigny) can be divided into two groups, according to their chemical composition: those rich in $Al_2O_3$ (17.5–21.7 wt.%) and poor in FeO (9.3–13.2 wt.%) and those that have contents of FeO, $Al_2O_3$ and MgO within the chemical compositional range of all other glasses in D'Orbigny (9.8–12.8 wt.% $Al_2O_3$ and 18.5–23.8 wt.% FeO) (Table 5). As discussed in VARELA et al. (2003b), the correlation line through glass inclusions and some glass pockets ($\Delta FeO/\Delta Al_2O_3 \sim 1.4$) seems to suggest that a Fe-Al exchange (mole FeO / $^1/_2$ mole $Al_2O_3$: 1.4) took place following:

$$Al_2O_3(solid) + 3Fe(OH)_2(gas) \Leftrightarrow 3FeO(solid) + 2Al(OH)_3(gas)$$
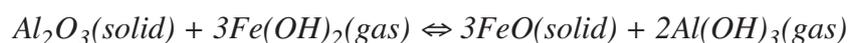
*Lack of indications of mineral growth:* The chemical (major and trace element) composition of mesostasis glass in a POP (porphyritic olivine pyroxene) aggregate of the Kaba CV3 chondrite (VARELA et al., 2005a) and of the interstitial glasses in the angrite D'Orbigny (VARELA et al., 2003b) document a surprising property: These glass compositions do not show the signature of crystallization of the minerals they are associated with.

The normalized abundances of refractory trace elements in all glasses of both chondritic and achondritic meteorites are high (10–20 x CI) and unfractionated and those of the moderately volatile and volatile elements are depleted with respect to the refractory ones (Fig. 3b, d). An important feature of all glasses in the angrite D'Orbigny is that their trace element contents are independent of the major element contents. That is, fertile liquids (e.g., glass spheres, glass patches: Ang-GS and Ang-G Patch, Table 5, Fig. 3d) and residual liquids (e.g., glass inclusions and glass pockets: Ang-GI3, Ang-GI P5, Table 5, Fig. 3d) have the same trace element contents, which is not possible in an igneous system where the first, fertile melt shall have incompatible trace element abundances of the bulk rock and the residual melt much higher ones (5 to 10 x rock).

The trace element pattern of glasses of a primary glass inclusion in olivine in the angrite D'Orbigny turned out to be the same as those of glass patches and glass spheres in the rock and also similar to those of glass shards in a howardite and of the glass veins in a eucrite (Fig. 3d). Even more astonishing is that this pattern is also very similar to that observed in glass inclusions in olivines and mesostasis glass in carbonaceous and primitive ordinary chondrites. Glasses in contact with only one phase (e.g., glass inclusion in olivine, Fig. 3a) or those in contact with several (e.g., mesostasis in chondrules, Fig. 3b, c) or glasses in achondrites, (e.g., in contact with olivine, pyroxene, anorthite) (Fig. 3d) have very similar and - surprisingly – unfractionated trace element abundances (see also Fig. 4, refractory glasses).

This key observation shows that glasses do not have the composition of the residual melt from which the crystals (documented by glass inclusions), or aggregates and chondrules (documented by mesostasis glass), or the whole rock (documented by glass that fills open spaces in achondrites) were formed (VARELA et al., 2002a, 2003b, 2005a). A geochemical impossibility if glasses are considered to represent the residual liquid of an igneous rock.

In summary, glasses in meteorites:

1) Lack a crystallization signature of the phases they are associated with (e.g., glass inclusions and the host minerals, mesostasis glass and co-existing minerals).

2) Show no fractionation among the abundances of geochemically very different elements but there is always present the very same fractionation in the abundance pattern of cosmochemically refractory elements being enriched over all the more volatile elements – a clear case of vapor fractionation.

3) The contemporaneous entrapment of individual carrier phases for C and N in the liquids (=glasses) indicates the presence of very fine-grained refractory dust, which cannot be created in silicate melts and also indicates derivation of the object from a gas phase, the solar nebula vapor in our case.

## 4.2 - The new view

Glasses have a chemical composition that is unlike that of a residue left after crystallization of the major and minor minerals of a given object from its bulk liquid. This clearly suggests that most liquids in meteoritic constituents were a phase that was independent from the crystalline ones and that they carry their own characteristic features.

If $SiO_2$ and $Al_2O_3$, the two major components of all meteoritic glasses - in closed or open systems - are considered, grouping of glasses in different types of meteorites is visible in simple projection plots. Glass inclusions in olivines of ureilites, winonaites and in the Tucson (UNGR) iron project into the area defined by glasses in carbonaceous chondrite objects (Fig. 2c). Glasses from ureilites and winonaites seem also to have suffered secondary elemental exchange processes (e.g., acquired Na for Ca) like many glasses from carbonaceous chondrite objects, as is suggested by their slight negative Na-Ca correlation (Fig. 2b). Glasses from the IIE irons cover a gap between carbonaceous and ordinary chondrites, and they are more akin to glasses that belong to what we call the "reduced pocket", a study of which is on the way.

Projection of analyses in the $SiO_2$ vs. $Al_2O_3$ diagram (Fig. 2c) defines two compositional trends or "evolution" lines. Glasses in objects of chondrites (with the exceptions indicated above) define a compositional trend with their major element composition ranging between two extremes, from refractory Al-Ca-rich toward a Si-rich one. The compositional ranges from Al-rich to Al-poor glasses of glass and neck inclusions and mesostasis glass within a single POP aggregate in the Kaba CV3 chondrite suggest that this chemical variation is due to evolutionary secondary processes, most likely an addition of Si to the object from its environs, the nebula (VARELA et al., 2005a).

Heating experiments performed on glass inclusions in olivines of the Allende CV3 chondrite (VARELA, 2008) show that the major variations in the chemical composition of the heated and re-melted glass are mainly related to the two major components FeO and MgO. Due to dissolution of the host olivine in the melt, the initially low contents of MgO and FeO of the original glass (MgO: 1.59 wt.%, FeO: 0.86 wt.%, $SiO_2$: 52 wt.% mean composition of 82 glass inclusions), can reach values of 9 wt.%, 3.05 wt.%, 51.9 wt.% and 10.5 wt.%, 6.8 wt.%, 48.1 wt.%, respectively, in glass inclusions heated to 1100°C and 1450°C, respectively. Clearly, the variations in the $SiO_2$ content observed in glass inclusions are not related to the precipitation of the olivine host but appear to have pristine roots.

Study of glass inclusions located at the center and near the rim of an olivine crystal in the same chondrule suggests that this chemical variation could be due to Si-addition (VARELA et al., 2002a, 2005a). We find the inclusion glass to be Al-rich ($Al_2O_3$ ~ 28 wt.%) and the mesostasis glass Al-poor ($Al_2O_3$ ~ 18 wt.%, Fig. 2c). There seems to be a simple relationship between the Al-rich and Al-poor glasses: the chemical composition of the latter can be derived by adding ~30 mol% silica to the Al-rich glass. The high Si content could reflect the increased Si activity in the vapor that also led to the formation of low-Ca pyroxene by the reaction of the liquid (fed by the gas) with the previously precipitated olivine (e.g., VARELA et al., 2005a):

$$Mg_2SiO_4(solid) + SiO_2(liquid, gas) \Leftrightarrow 2MgSiO_3(solid)$$
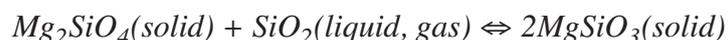
This reaction, very commonly documented in chondritic objects, has recently received additional support by the study of oxygen isotopes in chondrules of CV and CR chondrites (CHAUSSIDON et al., 2008).

The compositional trend towards the composition of glass in OC objects probably has the same origin. The end-member chemical composition ($SiO_2$ > 70 wt.%, $Al_2O_3$ ~ 10 wt.%) is found in pyroxene-rich objects, also objects that apparently formed from all-liquid droplets (RP chondrules, e.g., ENGLER et al., 2007).

A very different compositional trend is documented by the composition of glasses in some achondritic meteorites (angrites and HED) with the chemical compositions also varying between two end points: refractory Al-Ca-rich and Al-poor. However, this compositional trend in HED and angrite glasses follows an Al-Fe substitution (inset in Fig. 2c; and VARELA et al., 2003b), which is not observed in chondritic objects.

Thus, the major element compositions of glasses show that chondritic and achondritic glasses could share the same root - the refractory (Al-Ca) end-member composition - but seem to have been processed in different ways and with different intensities.

Beside the variation shown by glasses in their major elemental composition, the more diagnostic elements, the trace elements, show very little variation in their abundances and the same pattern in all types of glasses (e.g., glass inclusions or mesostasis glass) and in all types of meteorites (chondrites and achondrites) (Fig. 3, 4). This ubiquitous pattern not only signals vapor fractionation but also that the same process must have been involved in the origin of all glasses. (KURAT et al., 1997; VARELA et al., 2002a, b, 2003b, 2005a, b, 2006).

Thus, meteoritic glasses strongly indicate derivation of most meteoritic rocks from one source: an initial liquid - refractory in composition - formed by a single process: condensation from a vapor with solar relative abundances of the condensable chemical elements.

*The initial liquid:* The first major liquid condensate (closely following Ca-Al-rich liquids to form Ca-Al-rich inclusions, CAIs), dubbed the Universal Liquid by VARELA & KURAT (2004), could have a chemical composition close to that of glass inclusions in primitive olivines with some olivine component added ($SiO_2$: 42 wt.%, MgO: 14 wt.%, $Al_2O_3$: 23 wt.%, $TiO_2$: 1 wt.%, CaO: 19 wt.%, Tab. 2, Kaba GI + 20% forsterite). For this unique liquid we have proposed a totally new and crucial role in the formation of meteoritic matter: it serves as support to grow crystals from the vapor (Fig. 6, details of the growth process are given in VARELA et al., 2005a). This is a very important task: to help form well-ordered crystalline phases, which without a liquid cannot be grown from the vapor (see, e.g., GIVARGIZOV, 1987, and recent experiments by RIETMEIJER et al., 2002). This liquid-aided crystal growth process is known as the vapor-liquid-solid (VLS) process (e.g., GIVARGIZOV, 1987). In that process, which is widely utilized in industrial applications, an almost infinitely small amount of liquid suffices to bridge the interface between the vapor and the growing solid by providing a highly efficient accommodation agent for the condensing species and a diffusion pathway for ions needed for the growth of the phase that is oversaturated in the vapor. Based on the VLS process, we have formulated the Primary Liquid Condensation (PLC) model (e.g., VARELA & KURAT, 2004; KURAT et al., 2004a; VARELA et al., 2005a, 2006), which provides a basis for creating many of the meteoritic rocks known to us (Fig. 7).

## 4.3 Severe constraints to the currently accepted models

The particular features shown by meteoritic glasses cannot be reconciled with the currently entertained genetic models, which consider them to represent residual liquids of the bulk melt (after crystallization of main minerals) or melts created by shock waves. The PLC model - as any other too - has to be capable to give answers to two key observations:

*1) Glasses do not show the chemical signature of crystallization of the minerals they are associated with.*

The PLC model has a solution to the conundrum of this geochemical impossibility and insurmountable barrier for the igneous model: In the PLC model for the condensation of major phases from the solar nebula, a liquid nucleates and condenses first. It allows the nucleation of a crystal of the liquidus phase, which at the same instant is the phase oversaturated in the vapor (Fig. 6). The liquid then serves as a support to grow this and also whatever crystal phase becomes oversaturated in the vapor of the cooling nebula.

Thus, the PLC model proposes that crystals are not precipitation products of the liquid (e.g., as in an igneous systems) but are growing from the vapor with the help of the liquid (Fig. 6 and see Fig. 8 in VARELA et al., 2005a). Such a liquid maintains equilibrium with the growing crystal and at the same time also with the vapor. Glasses are then the remnants of the (thin or thick, depending on the conditions prevailing) liquid layer that helped to grow crystals from the vapor by bridging the vapor and the growing crystal (Fig. 6a, b). This liquid is the glass precursor (VARELA et al., 2005a).

The elements used for growing the crystal are replenished by condensation from the vapor (which is oversaturated in all condensable elements) into the liquid and the content of incompatible elements is buffered by condensation-evaporation exchange between the liquid and the vapor. By this way, the liquid is crystallizing the condensing phase by serving as a gateway for the major elements condensing and at the same time it maintains an approximately constant trace (= incompatible) element composition. The crucial point is that both phases maintain equilibrium with each other and at the same time with the vapor. Consequently, this growth mechanism makes glasses that show no sign of geochemical fractionation but a clear one for vapor fractionation - and this is exactly what is observed.

However, if this situation were evaluated from an igneous point of view, the observed lack of a geochemical fractionation would imply that the minerals and the glasses are "independent" phases, "out of equilibrium" (e.g., LIBOUREL et al., 2006). But this seems not to be the case. If conditions are such that the olivine is a primitive high-Ca olivine and the glass keeps its pristine composition (e.g., Ca-Al-rich with Ca/Al chondritic ratio), both phases are in equilibrium with respect to their CaO contents (VARELA et al., 2005a). Unaltered high-Ca olivines such as the host of glass inclusions in olivine of the Kaba CV3 chondrite (CaO: 0.54 wt.%), the host of the inclusions in All DI (CaO: 0.45 wt.%), the host of inclusions of Allende (CaO: 0.58 wt.%), or those in the ordinary chondrite Tieschitz (CaO: 0.55 wt.%) are in equilibrium with the inclusion glass (distribution coefficient Dol-gl: 0.022, 0.024 Kaba, 0.023 All DI and 0.024 Allende, 0.026 Tieschitz, respectively), as compared to the experimental equilibrium value Dequ: 0.025, suggesting that these olivines crystallized from a liquid with the chemical composition of this particular inclusion glass (WEINBRUCH et al., 2000; VARELA et al., 2002a, PACK & PALME, 2003).

*2) In spite of different major element compositions, all glasses show the same trace element pattern that is suggestive of vapor fractionation.*

The PLC model proposes that elements that will not easily enter the structure of the growing crystal (e.g., the incompatible elements like Ca, Al and REE) will be concentrated in the vapor-crystal liquid interface (Fig. 6a). Incompatible refractory elements, therefore, accumulate in the liquid until the concentration in the liquid reaches an equilibration value at which evaporation compensates for condensation.

**a)**

Liquid Nucleus (UL)

CMAS

Oversaturated in condensable elements

Vapor

FO

Growing crystal

Thin film of liquid (Al-Ca-rich)

Liquid droplet+ Crystal nucleus

**b)**

Part of the film of liquid can be trapped as a glass inclusion during olivine growth

G.I.

**c)**

1

2

3
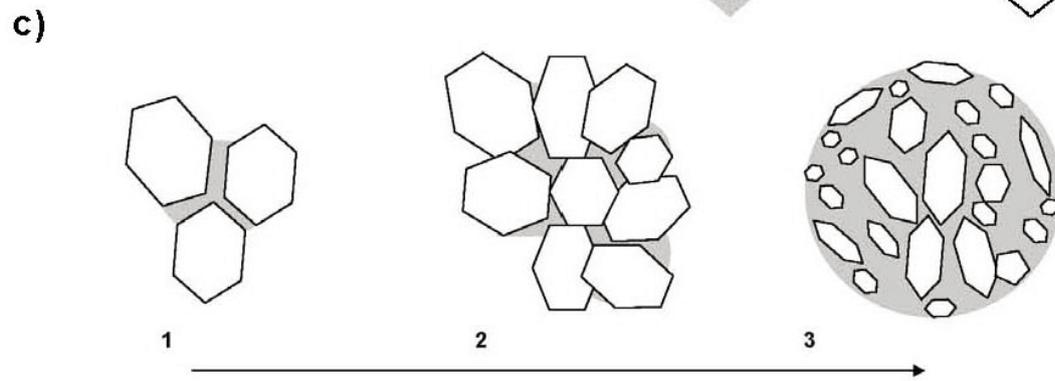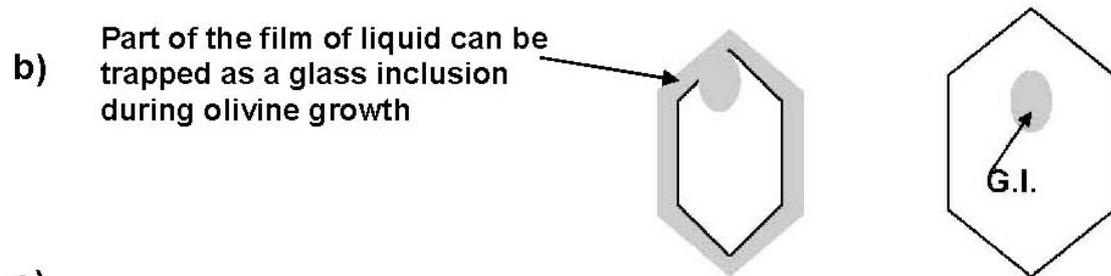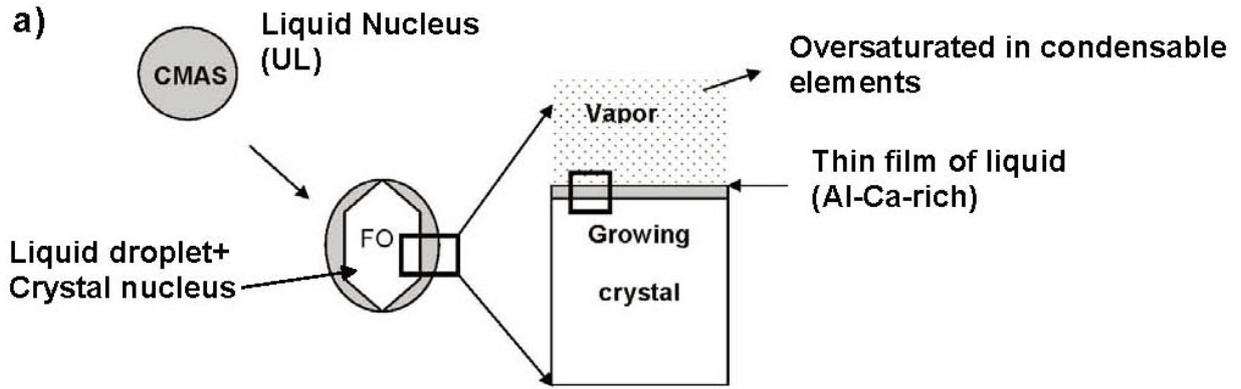
Increasing amount of liquid available

**d)**

CMAS

Liquid nucleus (UL)

Liquid droplet

BO Chondrule

**e)**

SM

SM Late Liquid

Liquid droplet

RP Chondrule (ALL-SHE)

300
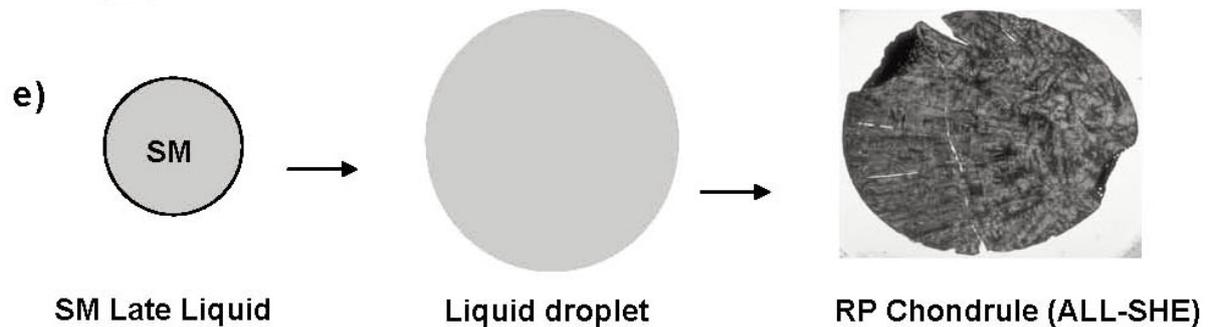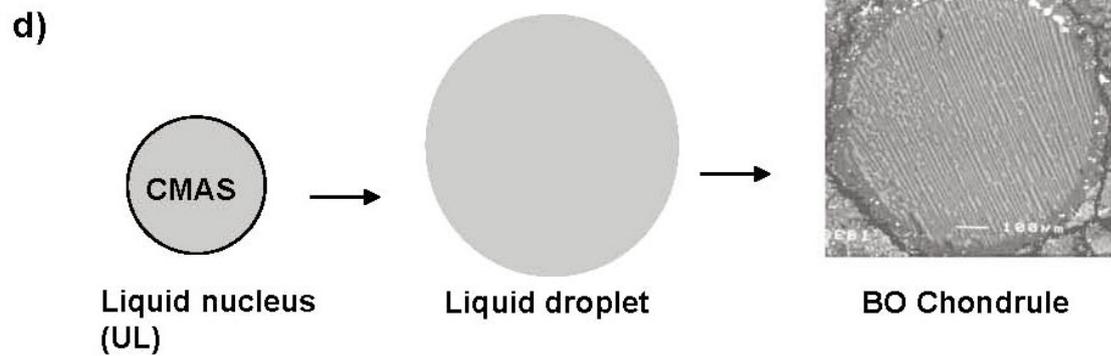
*Figure 6:*

*Schematic representation of the Primary Liquid Condensation Model.*

*The initial CMAS (Ca-Mg-Al-Si) liquid nucleus forms, the early condensate liquid dubbed Universal Liquid (UL); the liquid droplet homogeneously or heterogeneously nucleates a crystal; three phases are involved in the process of crystal growth: vapor (oversaturated in condensable elements), a thin film of liquid with high accommodation coefficient for all condensing species and the crystal growing with the help of the liquid from the vapor (modified after VARELA et al., 2005a). b) Schematic sketch of the formation of a primary glass inclusion as remnant of the thin liquid layer. c) Schematic sketch of formation of different types of olivine-rich objects. From c1 to c3 the quantity of liquid available increases and helps to create (pseudo-igneous) PO aggregates and PO chondrules. d) Evolution from a CMAS nucleus to a Mg-rich liquid droplet and a barred olivine chondrule. Such chondrules likely formed from a highly undercooled liquid droplet that failed to nucleate olivine in time (as shown in Fig.6a). Nucleation of an olivine led to spontaneous crystallization of the BO texture. e) Evolution of a SM (Silica-Magnesium) liquid droplet and spontaneous crystallization of the first pyroxene nucleus from undercooled liquid forming a radiating pyroxene (RP) chondrule. The SM liquid is a late one, rich in Si (e.g., Si addition or Si-Al exchange) and poor in refractory elements.*
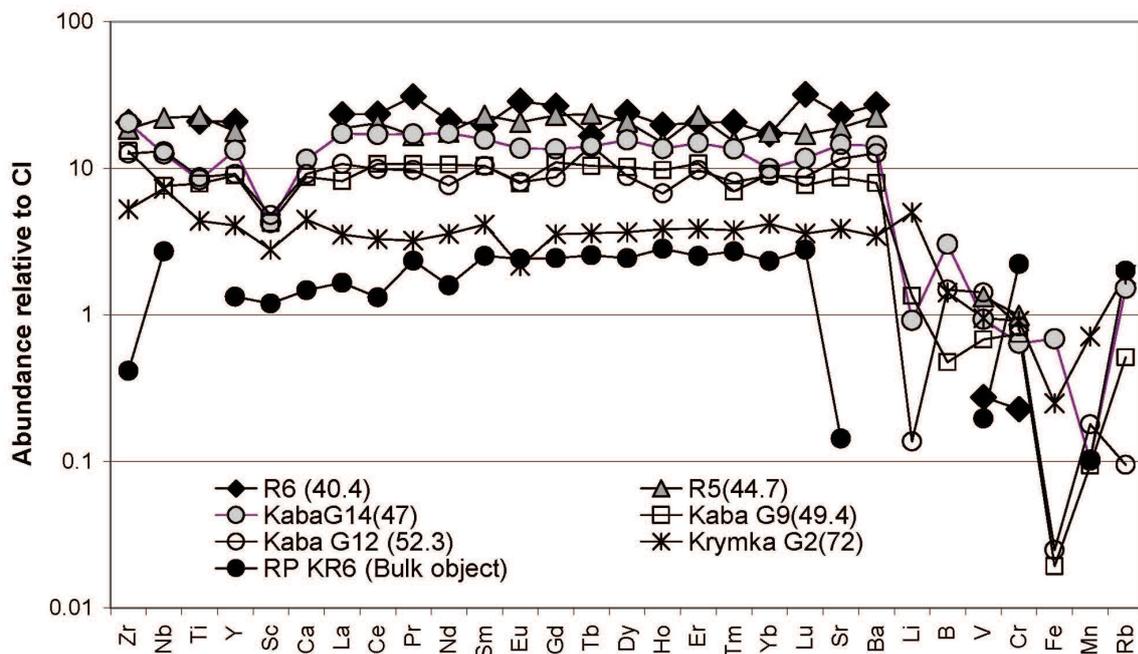


*Figure 7:*

*CI-normalized trace element abundances of the glasses of primary glass inclusions in olivines. In brackets is given the $SiO_2$ content of the glass. Note the progressive depletion in trace element contents with increasing $SiO_2$ content of the glasses. This trend is opposite to that of terrestrial fractional crystallization that leads to residual liquids rich in Si and rich incompatible trace elements. Note the low and chaotic behavior of the abundances of moderately volatile and volatile elements, which are not correlated and manifest depletion with respect to the RLE and subsequent individually variable additions (by metasomatic exchange processes in the nebula).*

Consequently, we can expect that such chilled liquids (= glasses, Fig. 6b) keep a memory of the vapor conditions. This is what is observed: primary glasses in chondrites and achondrites are rich in refractory incompatible elements and poor in medium volatile and volatile elements (Fig. 3a-d). They remember the composition of the vapor (solar) as well as the process of their formation: condensation. Typical Al-Ca-rich liquids of the first hour can be found in chondrites (CAIs, BO chondrules, glass inclusions in olivines). As the role of this liquid is to serve as a support to grow any phase that is oversaturated in the vapor (Fig. 6a), the refractory trace element contents in the liquid will always be high – while keeping equilibrium with the vapor - and, consequently, will not show a geochemical relationship to the crystal the liquid is associated with (VARELA et al., 2005a) – as it will have to do in a closed system.

Variations in the major element composition can be due to interaction of liquids and/or glasses (and all solids) with the cooling nebula gas. This leads to a large variety of chemical alterations mainly by elemental exchange:

*        Ca for alkali elements (see inset in Fig. 2b),
*        Mg for $Fe^{2+}$ (and Mn, Cr, V, etc.)
*        Al and Sc for $Fe^{2+}$ (e.g., mechanism for alteration of glass and rock compositions, see inset in Fig. 2c).
*        REE mobilization mainly from the glass and chondrules.

These exchange processes are very well documented for chondritic constituents (isolated olivines, aggregates, chondrules, etc., e.g., KURAT, 1975, 1985, 1988; KURAT & KRACHER, 1980; KURAT et al., 1985, 1989a,b, 2002; VARELA et al., 2002a,b, 2005a; 2006; ENGLER et al., 2003, 2004), achondrites (HED meteorites, angrites, VARELA et al., 2003b, 2005b; KURAT et al., 2003, 2004b) and silicate inclusions in iron meteorites (e.g., Kodaikanal, IIE, KURAT et al., 2007). Because these exchange processes usually cannot achieve equilibrium, unlimited numbers of chemical (and isotopic) compositional variations can be produced this way – this is exactly what we observe.

### 4.4 Formation of single crystals, aggregates, chondrules and rocks by a single process

The PLC model also is capable of creating a large variety of objects by a single process (condensation) in a single sequence of events at a single location. For that, only two parameters need to be taken into account:

*The quantity of liquid available:* formation of several objects such as isolated single crystals (olivine) (Fig. 6b), or olivine-anorthite intergrowths (as those present in angrites), or mineral aggregates, or chondrules (e.g., PO, POP, Fig. 6c), or even pseudo-magmatic rocks (achondrites) can be the result of the same process and formation of one or another will depend mainly on the quantity of liquid available. Thus, crystals (e.g., olivine) growing from the nebular gas the way proposed by the PLC model either stayed single (isolated) or aggregated to form aggregates and chondrules.

The liquid film not only provides an accommodation site for the condensing elements but also can serve as a sticking agent for aggregate formation (Fig. 6c). Small amounts of liquids help create irregularly shaped olivine (+/- pyroxene) aggregates as growing crystals can meet and stick to each other (Fig. 6c, 1), helped by the liquid surface tension that will pull crystals together.

If a larger amount of liquid is available, it can be sucked into open space between the crystals giving rise to irregular aggregates with liquid mesostasis – pseudo-igneous rocks (Fig. 6c). Elevated amounts of liquids force the formation of droplets of crystal-liquid mush (KURAT et al., 2004a; VARELA et al., 2005a), round objects: chondrules (Fig. 6c, 3).

*The liquid condensation/crystal nucleation rates:* if condensation of liquid is faster than nucleation of an olivine (or pyroxene) crystal, a chondrule-sized droplet can form, which at a high degree of undercooling will homogeneously or heterogeneously nucleate a crystal. In this way and according to the chemical composition of the liquid, barred olivine or non-porphyritic pyroxene and pyroxene/olivine chondrules can be formed (Fig. 6d, e) (VARELA et al., 2006; ENGLER et al., 2007). Large accumulations of liquid could be the sites for ophitic pseudo-igneous rock formation, such as eucrites and angrites.

Formation of all these objects needs first nucleation of a liquid (e.g., the UL with a CMAS composition, Fig. 6a). Liquids can nucleate from a gas much easier than crystalline solids because they accommodate all condensing species without gross discrimination. However, for liquids to become stable in a gas of solar composition, the chemical elements must be present at high partial pressures. This can either be achieved by a high total pressure (excluded by current solar nebula formation models) or by enrichments in condensable elements to a sufficiently high degree over solar photospheric abundances (e.g., WOOD & HASHIMOTO, 1993). One way to achieve such enrichment is to increase the dust content of the local solar nebula (advertised as "dust enrichment") before it gets fully evaporated. That will increase the oxygen fugacity, the partial pressures of condensable species, as well as condensation temperatures to temperatures at which liquids are stable (e.g., EBEL & GROSSMAN, 2000; EBEL, 2005). Thus, regions with either enhanced condensable element/H ratios (e.g., "dust-enriched regions") or enhanced total pressure are those to be considered optimum regions in the solar nebula where formation of all meteoritic objects, chondritic constituents as well as achondrites, seem to be possible as condensates from vapor.

According to published and our own calculations, BO chondrules could have formed in regions of the solar nebula with a "CI dust enrichment" (proxy for increased elemental partial p) of ~700 x over the solar composition (VARELA et al., 2006). Also, enstatite can become a stable liquidus phase in a ~800 x CI "dust-enriched nebular gas" at a $p_{tot}$ of $10^{-3}$ atm., after about 72 % of the originally present Mg was removed (as forsterite?) from the system (EBEL et al., 2003; ENGLER et al., 2004; 2007). Because pyroxene-dominated chondrules need "dust-enriched" regions with similar dust/gas ratios (>500 x CI) as those needed to form BO chondrules (~700 x CI) both objects could have shared the same nebular region as their birth place, as they usually share the same chondrite hosts.

The subtraction of the high quantity of Mg needed to get enstatite as a stable liquidus phase can be achieved if olivine-rich objects (e.g., single crystals, aggregates or chondrules) are formed first in these regions. Thus, the elemental composition of the very first glasses (glass inclusions or mesostasis glass) related to all-olivine or olivine-rich objects will be refractory (Al-Ca-rich), as it is observed (Tables 1 - 8). Formation of these objects (e.g., olivine-rich + glasses) will leave a nebular reservoir progressively depleted in refractory elements and enriched in Si, as documented by the chemical composition of the glasses related to pyroxene-rich objects (Fig. 4, 6, 7). In addition, the moderately volatile Si becomes increasingly oversaturated in the cooling nebula gas forming Si-enriched liquids for pyroxene formation.

The dilution of refractory elements is also evident in the trace element content of glasses. Glasses related to olivine-rich objects have generally high (e.g., 10–20 x CI) abundance of refractory trace elements and those associated with pyroxene-rich objects become poorer (< 9 x CI – glass in Krymka RP) until reaching trace element contents at about chondritic values (most bulk RP chondrules, Fig. 7). The progressive decrease in the abundance of the refractory trace elements with the Si content of the glasses increasing is clearly documented if we take into account glasses from primary glass inclusions hosted by olivines in different chondrites [from the Renazzo (CR), Kaba (CV3), Bishunpur and Krymka (LL3.1) chondrites] as well as the non-porphyritic pyroxene chondrules (Fig. 7). This trend is opposite to that of terrestrial fractional crystallization that leads to residual liquids rich in Si and rich in incompatible trace elements - an additional indication that liquids in meteorites do not behave like those in igneous systems.
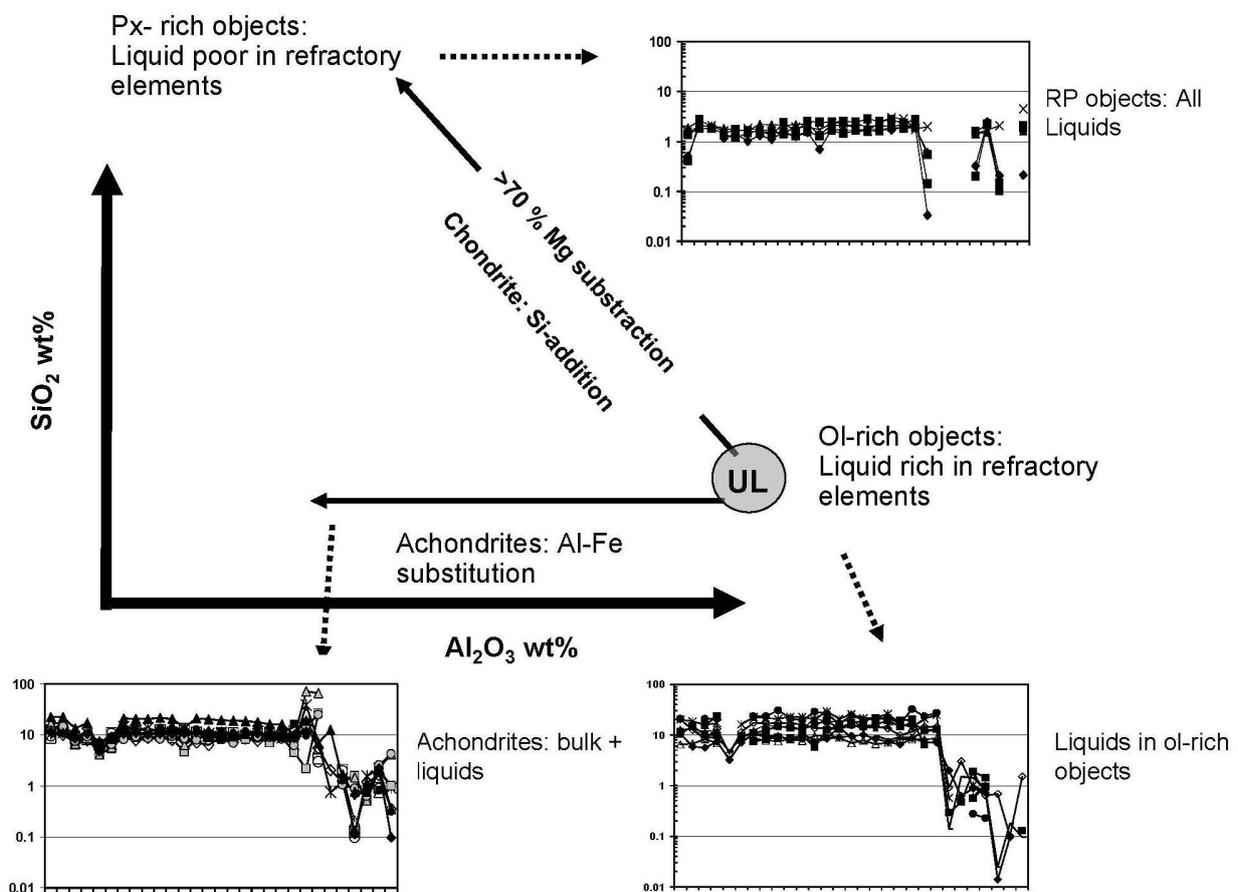


*Figure 8:*

*Schematic representation of the Primary Liquid Condensation Model. Glasses define two trends: the chondritic and the achondritic one with the same refractory root, the Universal Liquid (UL). In the achondritic trend the main metasomatic process is Al-Fe substitution while in the chondritic one it is Si-addition. Because pyroxene-dominated chondrules need "dust-enriched" (= high p) regions with similar dust/gas ratios (>500 x CI) to those needed to form BO chondrules (>700 x CI), both objects could have shared the same nebular region. All glasses show the same refractory trace element pattern (details in Fig. 3 and 4), indicating that they are samples of the very same reservoir. Moderately volatile and volatile element abundances are the result of metasomatic alterations in the nebula and, accordingly, are chaotic. Data are from references given in Figs. 3 and 4.*

On the other hand, glasses associated with olivine-rich objects in chondrites and those in achondrites (angrites, howardites, and eucrites) are similarly enriched in refractory elements suggestive of their formation in a similar - if not the same - region, before enstatite could become a stable liquidus phase (Fig. 3d, 8). Mesostasis glasses of aggregates and chondrules of chondrites and of achondrites have trace element abundances indistinguishable from those in glass inclusions, suggesting that they are samples of the very same liquid (e.g., UL in Fig. 8). Under this new view, achondrites (e.g., D'Orbigny and also eucrites) and CAIs (groups IA and IB) represent pristine objects formed from such refractory element-rich liquids in possibly the very same region of the nebula. Angrites have been considered as possible CAIs that grew larger than the ones we know from C chondrites and that have seen and recorded a variety of changing conditions (KURAT et al., 2004b). Angrites reproduce most of textures and structures of CAIs: crystallized liquids (Asuka 881371, LEW 87051), metasomatic granoblastic rocks (LEW 86010, Angra dos Reis?) and at least one aggregate (D'Orbigny). The trace element abundances of the bulk angrite D'Orbigny are similar to those in its glasses (VARELA et al., 2003b), and also similar to those in eucrites (e.g., KITTS & LODDERS, 1998) (see Fig. 3d), in glasses of olivine-rich objects in chondrites (Fig. 3a-c and KURAT et al., 1997; VARELA et al., 2002a,b, 2005a, 2006) and those in matrices of Allende chondrules (KURAT et al., 1992; PALME et al., 1992). The unfractionated abundances of the refractory lithophile elements (at about 10 x CI abundances) indicate formation of some angrites as a refractory (liquid) condensate from a source with chondritic abundances of refractory lithophile elements. Taking into account the chemical similarities between all previously listed objects, to which CAIs (e.g., GROSSMAN, 1980) need to be added, refractory matter appears to have been widespread in the solar nebula. The root of all these materials seems to be the primary refractory solar nebula liquid condensate (e.g., the Universal Liquid (UL), Fig. 8.

### 4.5 - The PLC model and oxygen isotope data

As we have previously pointed out, interaction between solid/liquid objects and the cooling nebula gas will change the chemical composition of crystalline phases and glasses. The solid-gas exchange processes are not restricted to cations but also must involve the main element of silicates, O. Isotopic variations, e.g., of O, could be produced in the same way as the chemical ones because liquids and solids could primarily condense with an $^{16}O$ signature of the solar nebula (the sun) and subsequently exchange $^{16}O$ for $^{17}O$ and $^{18}O$ to isotopically adjust to the abundances in the new nebula region they traveled to (e.g., CLAYTON, 1993). Grouping of different types of meteorites - as suggested by the chemical glass data and the PLC model - also find support from the oxygen isotope data.

Oxygen isotope data of ureilites fall along an extrapolation of the $^{16}O$ mixing line defined by constituents of Allende and other CV3 chondrites (CLAYTON & MAYEDA, 1988). Because oxygen isotopic composition and the iron content of olivine and pyroxene of ureilites correlate, CLAYTON & MAYEDA (1996) concluded that both variations (the isotopic and the major chemical one) were inherited from nebular and not planetary processes – in accordance with genetic models proposed by MUELLER (1969) and KURAT (1988). In a similar way, the study of the silicate components in Bencubbin, Kakangari, Renazzo and Tucson - showing all highly reduced ultra-mafic chondritic mineral assemblages as well as oxygen isotopic similarities - led

PRINZ et al. (1987) to propose a common origin in a specific region of the solar nebula. Most IAB silicates and winonaites are mineralogically similar to chondritic meteorites (PRINZ et al., 1983) and a clear relationship is indicated by their identical O isotopic compositions (CLAYTON et al., 1983). Also, the silicates in IIE irons very closely resemble H chondrites (CLAYTON & MAYEDA, 1996), which strongly suggests a genetic association between H chondrites and IIE irons. Also, angrites are scarcely resolvable from eucrites in their oxygen isotope composition (CLAYTON & MAYEDA, 1996) – in addition to their very similar chemical, CAI-like compositions. Recent data obtained for the eucrite-like achondrite NWA 011 show that the oxygen isotopic composition falls near the range of the CR chondrites (YAMAGUCHI et al., 2002), apparently a case of non-attained isotope exchange equilibrium that gives us a clear hint on the roots of the original liquid, namely a UL-derived original liquid.

However, the more spectacular examples of non-attained isotopic equilibrium - that strengthen the PLC model - are those reported by JONES et al. (2004), KITA et al. (2007) and CHAUSSIDON et al. (2008). The isotopic heterogeneities between individual grains in chondrules from the Mokoia CV3 chondrite (in which there are no obvious differences in chemical composition or texture between the objects), is the first reported example of olivines in ferromagnesian mineral aggregates (unfortunately called "chondrules") that show a richness in $^{16}O$ equivalent to that of Al-rich phases in CAIs ($\delta^{18}O$ around -50 ‰, JONES et al., 2004). This is in our opinion a clear example that many olivines of aggregates (and chondrules) are able to keep a memory of their roots in the solar nebula.

The isotopic disequilibrium found in co-existing olivine, pyroxenes and glassy mesostasis from CV and CR chondrites (CHAUSSIDON et al., 2008) gives additional support to the PLC model. However, the conclusion drawn that olivines and pyroxenes of a given object are not co-magmatic and that the glassy mesostasis is not the parent liquid of the olivine was apparently reached without considering the possible post-magmatic chemical alterations experienced by these objects in the solar nebula. The data of CHAUSSIDON et al. (2008) corroborate that the addition of Si from the nebular gas (VARELA et al., 2005a, LIBOUREL et al., 2006) seems to have taken place and points towards a common nebular gaseous reservoir for CV and CR chondrite objects ("chondrules"). The oxygen isotopic study of mesostasis glasses in Semarkona (LL3.0) (KITA et al., 2007) gives another example of how each object (their "chondrules") can isotopically adjust to the abundances in the new nebula region they traveled to (e.g., CLAYTON, 1993).

The PLC model envisages that: if objects were shielded and protected from post-formation processes, their composition will remain pristine or close to pristine (e.g., olivines having $\delta^{18}O$ values around -50 ‰, JONES et al., 2004). If not, continuing communication of such solids with the cooling nebula will lead to a variety of elemental exchanges (e.g., gas-solid isotopic elemental exchange as those shown by KITA et al., 2007, and CHAUSSIDON et al., 2008). Because these exchange processes attempt to but rarely reach equilibrium, we can expect a countless variety of compositions – within a given object as well as between different meteoritic objects – and we can expect that glass inclusions in olivines with their pristine solar O isotope composition shall be present in primitive meteorites.

## 5. Conclusions

The major problem with many glass formation models is that different scenarios can, or must, be invoked to explain formation of every unique (or few-member group) object. This has led to the existence of a voluminous variety of models explaining, in a correct way, many of the observed features. However, we are proposing something different: Unification. Our studies suggest that liquids (the glass precursor) seem to be the leading thread in the formation of all meteorite objects.

Glasses are omnipresent in meteorites and are the quenched remnants of former silicate liquids, which – unlike in terrestrial igneous rocks – do not represent the residual liquids of igneous crystallization processes, but rather represent a primary condensate liquid that facilitated growth of crystalline solids from the solar nebula gas.

These liquids are primarily refractory in composition and are the chemical refractory component of all meteoritic objects. They are the essential phase for crystal growth from the vapor for which they provide an accommodation site for all condensing elements that are oversaturated in the vapor – the VLS process. Variations of two parameters, the amount of liquid available as well as the liquid condensation and crystal nucleation rate, will allow the formation of a variety of different objects, such as single crystals, aggregates, chondrules and pseudo-igneous rocks. The PLC model describes a process that can create all major chondrite constituents inclusive chondrule types, BO, PO, POP and RP, some CAIs, some silicate inclusions in irons and some common achondrites (e.g., eucrites, howardites, angrites, ureilites, winonaites, etc.) in the same region of the solar nebula. However, provided recent model calculations give correct results, this region of the solar nebula either must have had an >500-fold enrichment of condensable matter as compared to today's solar photosphere or – more likely - has seen an unconventionally high total pressure, but it had solar relative abundances of condensable elements.

In the PLC model, the Universal Liquid is the long searched-for refractory compound in chondritic constituents and achondritic meteorites. It is the root (mother) of all liquids. Its chemical composition was buffered by the vapor and therefore was gradually changing (major elements) and at the same time stayed relatively constant (trace elements) throughout various processes during cooling and evolution. Glass inclusions in minerals and glass matrices in objects of all studied meteorites document this process. Variation in the primary composition of objects formed this way is determined by changing the crystal-liquid mixing proportion. For the chondritic (and achondritic) trend this can be achieved by varying the proportions of olivines (and olivine-anorthite) and the trace element-rich liquid, the carrier of the refractory elements. But the final composition of all objects as well as that of the associated glasses, the one that is observed and studied in the samples available to us, could be achieved by additional metasomatic elemental exchange processes between solids and the gas. If objects were shielded and protected from these post-formation processes, their composition will remain pristine or close to pristine. If not, continuing communication of such solids with the cooling nebula will lead to a variety of elemental exchanges. As these metasomatic processes usually cannot achieve equilibrium or run to completion, unlimited numbers of chemical and isotopic compositional variations can be produced – exactly what we observe in meteorites. Because chondrites were the only meteorites able to collect the great variety of the majority of these objects, they can offer us an almost complete view of the way in which the PLC and metasomatic processes operated and also remember the bulk chemical composition of the solar nebula.

## Acknowledgements

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|  | Renazzo | | | | | Acfer 182 | | El Djouf 001 | | (30) | Host | (28) | Host |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SiO$_2$ | 44.7 | 45.6 | 58.5 | 61.5 | 57.7 | 51.6 | 57.5 | 60.0 | 65.2 | 43.3 | 40.8 | 59.2 | 43.3 |
| TiO$_2$ | 1.83 | 1.20 | 1.36 | 0.60 | 1.10 | 1.26 | 1.10 | 0.86 | 0.22 | 0.71 | 0.00 | 0.73 | 0.00 |
| Al$_2$O$_3$ | 26.1 | 26.1 | 18.6 | 15.5 | 19.0 | 22.8 | 19.8 | 18.5 | 17.5 | 27.4 | 0.2 | 18.7 | 0.1 |
| Cr$_2$O$_3$ | 0.42 | 0.09 | 0.49 | 0.00 | 0.40 | 0.65 | 0.34 | 0.71 | 0.50 | 0.27 | 0.26 | 0.45 | 0.58 |
| FeO | 0.94 | 0.18 | 0.48 | 1.50 | 0.70 | 1.47 | 1.13 | 1.31 | 0.50 | 0.31 | 3.19 | 1.21 | 2.17 |
| MnO | 0.00 | 0.00 | 0.04 | 0.20 | 0.20 | 0.00 | 0.14 | 0.05 | 0.00 | 0.09 | 0.00 | 0.07 | 0.00 |
| MgO | 3.51 | 3.87 | 3.14 | 5.10 | 3.20 | 4.23 | 4.29 | 3.02 | 2.98 | 4.35 | 54.9 | 3.29 | 53.6 |
| CaO | 20.7 | 22.5 | 17.0 | 14.7 | 18.3 | 17.8 | 16.0 | 14.9 | 13.1 | 21.0 | 0.00 | 15.6 | 0.00 |
| Na$_2$O | 0.00 | 0.00 | 0.18 | 0.10 | 0.00 | 0.00 | 0.14 | 0.23 | 0.07 | 0.21 | 0.00 | 0.43 | 0.00 |
| K$_2$O | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.06 | 0.00 |
| P$_2$O$_5$ | 0.00 | 0.15 | 0.25 | 0.00 | 0.00 | 0.07 | 0.00 | 0.18 | 0.00 | 0.25 | 0.00 | 0.12 | 0.00 |
| Total | 98.2 | 99.7 | 100.0 | 99.2 | 100.6 | 99.9 | 100.4 | 99.8 | 100.1 | 97.9 | 99.3 | 99.9 | 99.8 |

**CM Chondrites**

|  | Acfer 094 | | Mokoia | | Mighei | | | Murray | | Y 82042 | | QUE97077.7 | | Murchison | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SiO$_2$ | 43.0 | 43.3 | 58.6 | 55.6 | 42.0 | 41.8 | 60.7 | 56.9 | 61.5 | 40.9 | 43.2 | 58.5 | 48.3 | 39.3 | 43.6 | 59.2 | 60.6 |
| TiO$_2$ | 1.15 | 1.12 | 0.56 | 0.52 | 1.20 | 1.09 | 0.59 | 0.56 | 0.29 | 0.55 | 0.56 | 0.96 | 1.67 | 0.66 | 1.44 | 0.33 | 0.63 |
| Al$_2$O$_3$ | 30.3 | 31.1 | 19.3 | 19.8 | 27.9 | 28.6 | 14.7 | 20.4 | 21.9 | 30.3 | 30.1 | 18.6 | 26.5 | 31.4 | 26.3 | 19.8 | 19.8 |
| Cr$_2$O$_3$ | 0.36 | 0.36 | 0.39 | 0.57 | 0.15 | 0.20 | 0.11 | 0.30 | 0.06 | 0.10 | 0.14 | 0.39 | 0.14 | 0.00 | 0.00 | 0.24 | 0.42 |
| FeO | 0.36 | 0.32 | 1.01 | 0.79 | 0.27 | 0.30 | 4.31 | 0.28 | 0.53 | 0.21 | 0.18 | 0.76 | 0.24 | 0.18 | 0.37 | 0.62 | 1.12 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.07 | 0.18 | 0.02 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.07 | 0.01 | 0.14 | 0.00 |
| MgO | 3.88 | 3.45 | 2.20 | 0.32 | 3.78 | 3.64 | 2.57 | 3.51 | 2.15 | 3.08 | 3.70 | 3.19 | 3.62 | 3.66 | 3.28 | 4.15 | 2.86 |
| CaO | 20.9 | 20.5 | 15.5 | 14.8 | 23.5 | 22.0 | 12.5 | 17.3 | 13.9 | 23.1 | 21.7 | 17.5 | 19.1 | 23.1 | 24.8 | 15.3 | 14.3 |
| Na$_2$O | 0.10 | 0.05 | 2.72 | 7.75 | 0.03 | 0.07 | 0.51 | 0.00 | 0.00 | 0.00 | 0.00 | 0.15 | 0.10 | 0.03 | 0.02 | 0.02 | 0.07 |
| K$_2$O | 0.00 | 0.00 | 0.16 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.02 | 0.02 | 0.01 | 0.02 | 0.00 | 0.01 | 0.00 | 0.02 | 0.00 |
| P$_2$O$_5$ | 0.00 | 0.00 | 0.16 | 0.15 | 0.27 | 0.22 | 0.50 | 0.25 | 0.20 | 0.37 | 0.30 | 0.00 | 0.00 | 0.28 | 0.59 | 0.19 | 0.21 |
| Total | 100.1 | 100.2 | 100.6 | 100.3 | 99.1 | 97.9 | 96.7 | 99.5 | 100.7 | 98.6 | 99.8 | 100.1 | 99.6 | 98.7 | 100.4 | 100.0 | 100.0 |

*Table 1:*
*Representative major element composition of inclusion glasses in olivines of carbonaceous chondrite (EMPA in wt.%)*

**CV3- Chondrites**

| | Allende | | | Allende DI | | | Kaba | | | | Ningqiang | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SiO$_2$ | 47.2 | 58.2 | 41.8 | 60.9 | 53.8 | 49.2 | 47.8 | 51.8 | 54.8 | 42.0 | 56.4 | 55.3 | 55.2 | 62.3 |
| TiO$_2$ | 1.64 | 0.64 | 1.18 | 0.73 | 0.86 | 1.24 | 1.12 | 0.89 | 1.13 | 1.06 | 1.00 | 0.64 | 1.29 | 0.79 |
| Al$_2$O$_3$ | 26.9 | 19.3 | 28.6 | 25.3 | 25.5 | 23.5 | 21.0 | 24.0 | 23.5 | 29.2 | 25.1 | 20.1 | 28.7 | 21.6 |
| Cr$_2$O$_3$ | 0.91 | 0.56 | 0.06 | 0.42 | 0.99 | 0.63 | 0.30 | 0.40 | 0.17 | 0.26 | 1.25 | 0.55 | 0.44 | 0.62 |
| FeO | 0.76 | 0.92 | 0.36 | 0.56 | 0.55 | 0.25 | 0.22 | 0.68 | 0.13 | 0.28 | 0.64 | 0.14 | 0.49 | 0.45 |
| MnO | 0.00 | 0.03 | 0.00 | 0.00 | 0.05 | 0.04 | 0.11 | 0.06 | 0.03 | 0.01 | 0.07 | 0.00 | 0.00 | 0.03 |
| MgO | 0.40 | 1.02 | 0.84 | 1.95 | 1.70 | 0.70 | 9.9 | 3.24 | 2.70 | 3.20 | 1.88 | 0.60 | 0.54 | 0.37 |
| CaO | 15.4 | 10.6 | 21.9 | 2.40 | 7.2 | 17.2 | 17.6 | 17.8 | 17.3 | 23.9 | 8.5 | 16.6 | 11.5 | 10.5 |
| Na$_2$O | 6.6 | 8.6 | 5.9 | 7.0 | 9.0 | 6.4 | 0.00 | 1.23 | 0.58 | 0.02 | 3.90 | 4.83 | 11.5 | 3.00 |
| K$_2$O | 0.18 | 0.00 | 0.11 | 0.60 | 0.39 | 0.14 | 0.00 | 0.01 | 0.09 | 0.00 | 0.15 | 0.02 | 0.53 | 0.00 |
| P$_2$O$_5$ | 0.08 | 0.12 | 0.00 | 0.00 | 0.00 | 0.00 | 0.16 | 0.00 | 0.25 | 0.28 | 0.10 | 0.31 | 0.00 | 0.19 |
| Total | 99.9 | 99.9 | 100.7 | 100.0 | 100.0 | 99.3 | 98.3 | 100.0 | 100.6 | 100.3 | 99.0 | 99.1 | 100.0 | 99.8 |

**CV3 Chondrites**

| | Bali | | | Vigarano | | | | Axtell | | |
|---|---|---|---|---|---|---|---|---|---|---|
| SiO$_2$ | 38.2 | 44.7 | 46.1 | 47.5 | 56.2 | 50.8 | 51.6 | 45.0 | 58.8 | 58.6 |
| TiO$_2$ | 1.07 | 1.35 | 1.16 | 1.26 | 0.87 | 0.98 | 0.53 | 0.07 | 1.82 | 1.14 |
| Al$_2$O$_3$ | 29.0 | 23.3 | 31.7 | 25.4 | 21.5 | 25.0 | 22.5 | 35.2 | 28.7 | 26.3 |
| Cr$_2$O$_3$ | 0.08 | 0.27 | 0.00 | 0.48 | 0.00 | 0.32 | 0.00 | 0.14 | 0.03 | 0.38 |
| FeO | 0.28 | 0.49 | 1.26 | 0.22 | 0.53 | 1.77 | 0.26 | 0.25 | 0.16 | 0.33 |
| MnO | 0.09 | 0.00 | 0.00 | 0.00 | 0.11 | 0.00 | 0.04 | 0.00 | 0.03 | 0.00 |
| MgO | 2.08 | 1.84 | 1.65 | 0.44 | 0.61 | 1.26 | 0.75 | 0.29 | 0.40 | 1.15 |
| CaO | 23.2 | 22.8 | 10.4 | 18.0 | 13.9 | 5.3 | 17.2 | 18.7 | 4.30 | 6.5 |
| Na$_2$O | 4.12 | 3.65 | 7.4 | 6.5 | 5.6 | 13.8 | 6.3 | 0.59 | 5.4 | 4.59 |
| K$_2$O | 0.03 | 0.00 | 0.18 | 0.03 | 0.06 | 0.56 | 0.09 | 0.00 | 0.14 | 0.13 |
| P$_2$O$_5$ | 0.22 | 0.19 | 0.12 | 0.20 | 0.33 | 0.03 | 0.08 | 0.25 | 0.07 | 0.07 |
| Total | 98.3 | 98.6 | 100.0 | 100.0 | 99.7 | 99.8 | 99.4 | 100.4 | 99.8 | 99.2 |

*Table 2:*
*Representative major element composition of inclusion glasses of glass in olivines of CV3 carbonaceous chondrites (EMPA in wt.%)*

**Table 3 (upper section): CH3, CO4, C4-UNGR, CM2 chondrites**

| | CH3 Chondrite Acfer 214 | | | | CO4 chondrite HAH 073 | | | | C4- UNGR Coolidge | | CM2 chondrite EET 96016.9 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 41.9 | 61.5 | 55.6 | 59.5 | 48.8 | 65.8 | 73.6 | 53.2 | 60.7 | 66.2 | 42.3 | 53.0 |
| $TiO_2$ | 1.56 | 0.38 | 1.25 | 0.59 | 0.92 | 0.47 | 0.43 | 0.90 | 0.00 | 0.05 | 1.49 | 0.67 |
| $Al_2O_3$ | 27.0 | 22.3 | 18.0 | 18.7 | 30.5 | 23.9 | 10.5 | 26.1 | 25.2 | 26.6 | 27.4 | 23.7 |
| $Cr_2O_3$ | 0.12 | 0.20 | 1.46 | 0.38 | 0.76 | 0.00 | 0.00 | 0.06 | 0.00 | 0.10 | 0.18 | 0.29 |
| $FeO$ | 0.12 | 1.98 | 2.07 | 0.70 | 1.24 | 0.82 | 1.62 | 2.22 | 0.42 | 0.36 | 0.20 | 0.24 |
| $MnO$ | 0.02 | 0.08 | 0.05 | 0.01 | 0.00 | 0.00 | 0.02 | 0.08 | 0.00 | 0.04 | 0.00 | 0.00 |
| $MgO$ | 2.63 | 3.16 | 1.10 | 4.01 | 0.36 | 0.58 | 0.43 | 3.60 | 0.27 | 0.34 | 3.49 | 3.01 |
| $CaO$ | 24.0 | 4.43 | 11.2 | 16.1 | 4.64 | 0.32 | 9.5 | 5.3 | 1.28 | 1.46 | 23.9 | 18.5 |
| $Na_2O$ | 1.55 | 4.88 | 9.18 | 0.05 | 12.4 | 4.66 | 2.15 | 8.1 | 8.9 | 2.40 | 0.05 | 0.05 |
| $K_2O$ | 0.00 | 0.38 | 0.16 | 0.02 | 1.29 | 3.32 | 1.26 | 0.58 | 2.19 | 1.09 | 0.00 | 0.01 |
| Total | 98.9 | 99.3 | 100.0 | 100.1 | 100.9 | 99.9 | 99.5 | 100.1 | 98.9 | 98.6 | 99.0 | 99.6 |

**CO3 chondrites (lower section)**

| | DAG 055 | | | | | DAG 289 | | | | DRG 291 | | | DAG 083 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 51.3 | 57.3 | 58.8 | 62.5 | 51.1 | 50.4 | 64.2 | 42.2 | 53.1 | 55.0 | 46.7 | 40.2 | 52.6 | 40.9 | 61.1 | 63.8 |
| $TiO_2$ | 1.13 | 0.62 | 1.13 | 0.74 | 1.30 | 0.96 | 0.45 | 1.68 | 0.35 | 0.80 | 0.82 | 1.33 | 1.16 | 1.55 | 0.20 | 0.78 |
| $Al_2O_3$ | 25.7 | 21.8 | 25.0 | 24.6 | 26.9 | 32.4 | 19.0 | 25.8 | 25.8 | 24.2 | 26.6 | 28.2 | 27.3 | 28.0 | 25.2 | 17.8 |
| $Cr_2O_3$ | 0.36 | 0.00 | 0.00 | 0.00 | 0.00 | 0.21 | 0.25 | 0.19 | 0.02 | 0.86 | 0.11 | 0.06 | 0.00 | 0.00 | 0.34 | 0.98 |
| $FeO$ | 1.78 | 0.42 | 1.71 | 1.75 | 1.78 | 0.84 | 1.83 | 1.55 | 0.22 | 0.87 | 0.33 | 0.28 | 2.45 | 0.50 | 1.09 | 1.89 |
| $MnO$ | 0.07 | 0.04 | 0.03 | 0.00 | 0.04 | 0.00 | 0.04 | 0.19 | 0.05 | 0.00 | 0.00 | 0.03 | 0.04 | 0.03 | 0.00 | 0.04 |
| $MgO$ | 1.86 | 2.98 | 2.30 | 1.30 | 2.68 | 1.05 | 3.58 | 2.22 | 3.32 | 1.11 | 1.45 | 2.81 | 1.60 | 2.94 | 1.11 | 0.60 |
| $CaO$ | 3.87 | 10.5 | 3.42 | 1.88 | 5.5 | 6.3 | 4.24 | 18.2 | 15.7 | 10.0 | 19.3 | 24.8 | 3.78 | 17.0 | 0.61 | 4.89 |
| $Na_2O$ | 13.9 | 5.7 | 7.1 | 6.8 | 10.8 | 7.6 | 5.9 | 7.5 | 1.96 | 6.8 | 4.80 | 2.03 | 9.9 | 7.2 | 8.7 | 8.2 |
| $K_2O$ | 0.46 | 0.14 | 0.23 | 0.10 | 0.56 | 0.40 | 0.46 | 0.34 | 0.06 | 0.45 | 0.00 | 0.00 | 1.13 | 0.26 | 1.66 | 0.73 |
| Total | 100.4 | 99.5 | 99.7 | 99.6 | 100.6 | 100.2 | 99.9 | 99.9 | 100.5 | 100.1 | 100.2 | 99.7 | 99.9 | 98.4 | 100.0 | 99.7 |

*Table 3:*
*Representative major element composition of inclusion glasses in olivines of carbonaceous chondrites (EMPA in wt.%)*

| | Ordinary Chondrites | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bishunpur LL3.1 | | | | NW 467 | Krymka LL3.1 | | | | |
| SiO$_2$ | 53.0 | 58.6 | 75.9 | 71.6 | 77.8 | 71.7 | 78.4 | 63.5 | 70.8 | 75.5 |
| TiO$_2$ | 1.44 | 0.87 | 0.32 | 0.52 | 0.29 | 0.55 | 0.29 | 0.59 | 0.45 | 0.35 |
| Al$_2$O$_3$ | 23.1 | 19.1 | 11.1 | 10.9 | 8.6 | 10.6 | 12.1 | 16.2 | 8.8 | 8.6 |
| Cr$_2$O$_3$ | 0.16 | 0.47 | 0.28 | 1.26 | 0.45 | 0.09 | 1.20 | 0.44 | 0.64 | 0.24 |
| FeO | 0.92 | 0.87 | 1.16 | 2.71 | 1.86 | 2.83 | 0.91 | 0.89 | 3.79 | 2.79 |
| MnO | 0.04 | 0.08 | 0.02 | 0.04 | 0.03 | 0.16 | 0.12 | 0.14 | 0.30 | 0.06 |
| MgO | 2.53 | 2.73 | 1.56 | 0.21 | 2.86 | 2.22 | 0.55 | 2.89 | 3.52 | 2.49 |
| CaO | 18.4 | 16.7 | 8.2 | 8.9 | 5.8 | 8.5 | 0.11 | 8.3 | 7.1 | 5.7 |
| Na$_2$O | 0.00 | 0.33 | 0.06 | 0.22 | 0.13 | 2.98 | 3.85 | 6.2 | 1.82 | 1.24 |
| K$_2$O | 0.04 | 0.03 | 0.86 | 3.11 | 0.33 | 0.26 | 2.17 | 0.89 | 2.23 | 1.10 |
| P$_2$O$_5$ | 0.12 | 0.12 | 0.08 | 0.18 | 0.14 | 0.18 | 0.00 | 0.09 | 0.00 | 0.11 |
| Total | 99.8 | 99.9 | 99.6 | 99.6 | 98.3 | 100.0 | 99.7 | 100.1 | 99.4 | 98.2 |

| | Ureilite | | | | | | Winonaite | | |
|---|---|---|---|---|---|---|---|---|---|
| | FRO 90054 | | | | | | HH193 | | |
| SiO$_2$ | 60.5 | 59.7 | 53.2 | 54.1 | 59.5 | 60.6 | 63.1 | 63.3 | 62.7 |
| TiO$_2$ | 0.18 | 0.49 | 1.26 | 1.27 | 0.37 | 0.57 | 0.06 | <0.02 | 0.03 |
| Al$_2$O$_3$ | 24.6 | 22.9 | 20.2 | 20.1 | 23.4 | 20.1 | 23.8 | 23.6 | 22.8 |
| Cr$_2$O$_3$ | 0.05 | 0.04 | 0.05 | 0.07 | 0.05 | 0.10 | 0.00 | 0.11 | 0.03 |
| FeO | 1.40 | 1.84 | 7.10 | 6.41 | 1.60 | 2.09 | 0.51 | 0.49 | 0.89 |
| MnO | 0.21 | 0.26 | 0.38 | 0.30 | 0.19 | 0.20 | 0.00 | 0.00 | 0.06 |
| MgO | 1.66 | 2.08 | 1.47 | 1.27 | 1.39 | 1.39 | 0.00 | 0.00 | 0.03 |
| CaO | 6.8 | 7.4 | 6.9 | 6.3 | 5.7 | 9.6 | 4.75 | 4.82 | 3.94 |
| Na$_2$O | 4.58 | 4.99 | 4.21 | 4.16 | 6.5 | 4.00 | 9.0 | 8.8 | 8.6 |
| K$_2$O | 0.08 | 0.08 | 1.16 | 1.24 | 0.15 | 0.07 | 0.30 | 0.32 | 0.38 |
| P$_2$O$_5$ | 0.34 | 0.19 | 4.08 | 3.63 | 0.50 | 1.02 | 0.00 | 0.00 | 0.05 |
| Total | 100.3 | 100.0 | 100.0 | 98.8 | 99.3 | 99.7 | 101.5 | 101.4 | 99.6 |

*Table 4:*

*Representative major element composition of inclusion glasses in olivines in ordinary chondrites, ureilite FRO 90054 and winonaite HH193 (EMPA in wt.%)*

**Angrite D'Orbigny**

| | Glass inclusions | | | Glass pockets | | | Glass patches | | Av(15) | Glass spheres P(15) | P(10) | Av(60) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SiO$_2$ | 42.6 | 41.3 | 41.1 | 41.3 | 40.7 | 43.0 | 41.1 | 40.7 | 39.8 | 39.7 | 40.4 | 40.1 |
| TiO$_2$ | 1.43 | 1.45 | 1.80 | 1.52 | 1.98 | 2.35 | 0.81 | 1.04 | 0.50 | 0.85 | 0.82 | 0.84 |
| Al$_2$O$_3$ | 21.7 | 17.5 | 12.8 | 14.4 | 15.1 | 9.7 | 13.2 | 12.5 | 12.9 | 12.1 | 12.3 | 12.2 |
| Cr$_2$O$_3$ | 0.04 | 0.04 | 0.05 | 0.03 | 0.10 | 0.14 | 0.16 | 0.05 | 0.07 | 0.08 | 0.08 | 0.08 |
| FeO | 9.3 | 13.2 | 18.5 | 17.5 | 16.6 | 16.4 | 23.2 | 24.5 | 23.8 | 24.4 | 25.3 | 24.5 |
| MnO | 0.12 | 0.18 | 0.25 | 0.19 | 0.20 | 0.17 | 0.25 | 0.28 | 0.27 | 0.25 | 0.27 | 0.25 |
| MgO | 2.31 | 5.73 | 6.10 | 3.61 | 4.39 | 5.7 | 7.7 | 7.5 | 7.6 | 7.8 | 8.0 | 7.7 |
| CaO | 22.8 | 21.2 | 19.30 | 21.6 | 21.5 | 22.3 | 14.5 | 14.5 | 14.3 | 14.2 | 13.6 | 14.0 |
| Total | 100.3 | 100.6 | 99.70 | 100.2 | 100.6 | 99.8 | 100.9 | 101.1 | 99.2 | 99.4 | 100.8 | 99.7 |

**Howardites**

| | Eucrite Cachari | | | HAH 285 | | | NWA 1664 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SiO$_2$ | 48.6 | 48.6 | 48.7 | 53.4 | 53.9 | 53.3 | 49.3 | 49.6 | 49.3 | 49.6 | 48.7 |
| TiO$_2$ | 0.71 | 0.68 | 0.72 | 0.55 | 0.58 | 0.43 | 0.63 | 0.59 | 0.58 | 0.55 | 0.69 |
| Al$_2$O$_3$ | 13.8 | 13.6 | 13.6 | 20.2 | 20.1 | 16.5 | 10.7 | 11.1 | 11.0 | 10.8 | 10.6 |
| Cr$_2$O$_3$ | 0.25 | 0.25 | 0.26 | 0.40 | 0.58 | 0.60 | 0.50 | 0.59 | 0.57 | 0.52 | 0.52 |
| FeO | 16.7 | 16.4 | 16.3 | 5.83 | 5.70 | 6.31 | 17.8 | 17.4 | 16.7 | 17.1 | 18.9 |
| MnO | 0.50 | 0.50 | 0.51 | 0.34 | 0.35 | 0.32 | 0.64 | 0.54 | 0.56 | 0.59 | 0.66 |
| MgO | 6.2 | 6.0 | 5.9 | 3.26 | 3.09 | 10.06 | 11.9 | 12.0 | 11.8 | 12.2 | 12.3 |
| CaO | 10.3 | 10.4 | 10.4 | 13.9 | 13.7 | 10.3 | 7.7 | 7.1 | 9.0 | 7.7 | 7.0 |
| Na$_2$O | 0.51 | 0.52 | 0.48 | 0.69 | 0.62 | 0.53 | 0.73 | 0.91 | 0.37 | 0.75 | 0.66 |
| K$_2$O | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.10 | 0.12 | 0.12 | 0.12 | 0.10 |
| P$_2$O$_5$ | 0.17 | 0.19 | 0.15 | | | | | | | | |
| SO$_2$ | 0.24 | 0.24 | 0.18 | | | | | | | | |
| Total | 98.0 | 97.5 | 97.2 | 98.6 | 98.7 | 98.4 | 100.0 | 99.9 | 100.0 | 99.9 | 100.0 |

*Table 5:*

*Representative major element composition of glasses in angrites, eucrites, and howardites (EMPA in wt.%)*

*Av. (15): Average of 15 analyses; P (15): Mean value of a 15 spots profile.*

| | Guin (IRUNGR) multiphase inclusion | | | | | Kodaikanal (IIE) glassy inclusion | | | Tucson(IRUNGR) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | G.I. | M |
| SiO$_2$ | 68.0 | 72.2 | 66.3 | 66.8 | 66.0 | 68.9 | 67.7 | 64.4 | 57.0 | 48.9 |
| TiO$_2$ | 0.29 | 0.15 | 0.28 | 1.00 | 0.22 | 0.41 | 0.46 | 0.51 | 0.00 | 0.00 |
| Al$_2$O$_3$ | 17.8 | 15.8 | 19.6 | 17.8 | 17.2 | 17.8 | 19.4 | 18.9 | 21.4 | 28.1 |
| Cr$_2$O$_3$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.14 | 0.20 | 0.15 | 0.00 | 0.00 |
| FeO | 1.80 | 1.60 | 0.69 | 2.11 | 4.20 | 0.48 | 0.82 | 1.19 | 0.19 | 0.81 |
| MnO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.13 | 0.17 | 0.18 | 0.00 | 0.00 |
| MgO | 0.03 | 0.04 | 0.00 | 0.03 | 0.00 | 0.10 | 0.08 | 0.13 | 1.58 | 3.17 |
| CaO | 1.31 | 1.17 | 1.47 | 1.30 | 1.22 | 0.10 | 0.21 | 0.16 | 19.6 | 19.6 |
| Na$_2$O | 9.0 | 7.8 | 10.3 | 8.8 | 8.4 | 4.10 | 6.8 | 7.1 | 0.00 | 0.00 |
| K$_2$O | 0.72 | 0.59 | 0.73 | 1.00 | 0.65 | 6.4 | 3.70 | 2.70 | 0.00 | 0.00 |
| P$_2$O$_5$ | 0.19 | 0.20 | 0.07 | 0.25 | 0.21 | 0.20 | 0.20 | 0.25 | 0.00 | 0.00 |
| Total | 99.1 | 99.6 | 99.4 | 99.1 | 98.1 | 98.8 | 99.7 | 95.7 | 99.8 | 100.6 |

G.I.: Glass inclusion in olivine; M: Mesostasis glass

Table 6:
*Representative major element composition of glasses in glass-bearing inclusions in iron meteorites (EMPA in wt.%)*

**Barred Olivine Chondrules**

| | Essebi | | Bish Ch-C Av. (10) | Bish Ch-A Av. (7) | Ac-BO-214/3 | | Ac-BO-214/4 | | DAG 055 | |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 53.1 | 54.4 | 51.2 | 58.7 | 52.0 | 53.6 | 50.2 | 48.9 | 48.7 | 48.3 |
| $TiO_2$ | 1.00 | 0.97 | 0.96 | 0.54 | 0.54 | 0.53 | 0.29 | 0.43 | 0.04 | 0.05 |
| $Al_2O_3$ | 23.3 | 22.7 | 19.6 | 16.8 | 22.1 | 20.1 | 22.7 | 23.0 | 32.2 | 32.5 |
| $Cr_2O_3$ | 0.42 | 0.39 | 0.47 | 0.52 | 0.24 | 0.35 | 0.45 | 0.25 | 0.03 | 0.04 |
| $FeO$ | 0.32 | 0.35 | 0.59 | 0.95 | 2.00 | 2.32 | 2.46 | 2.55 | 0.46 | 0.45 |
| $MnO$ | 0.06 | 0.05 | 0.03 | 0.05 | 0.02 | 0.06 | 0.02 | 0.04 | 0.00 | 0.04 |
| $MgO$ | 3.95 | 3.83 | 4.70 | 5.3 | 3.81 | 3.79 | 3.36 | 3.87 | 0.45 | 0.31 |
| $CaO$ | 17.4 | 17.2 | 18.1 | 12.0 | 5.9 | 6.9 | 5.9 | 6.6 | 16.3 | 16.5 |
| $Na_2O$ | 0.25 | 0.20 | 2.38 | 4.70 | 12.4 | 11.0 | 13.0 | 12.8 | 2.40 | 2.25 |
| $K_2O$ | 0.00 | 0.00 | 0.02 | 0.2 | 1.08 | 1.17 | 1.14 | 1.08 | 0.04 | 0.02 |
| Total | 99.8 | 100.1 | 98.1 | 99.8 | 100.0 | 99.8 | 99.5 | 99.5 | 100.6 | 100.5 |

**Non-Porphyritic Pyroxene Chondrules**

| | Sahara 97210 | | | Tieschitz | Bishunpur | Krymka | | | Mezö-Madaras | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 67.3 | 98.5 | 68.9 | 60.4 | 72.7 | 98.5 | 70.2 | 71.1 | 68.8 | 71.6 | 61.1 |
| $TiO_2$ | 0.43 | 0.08 | 0.42 | 0.50 | 0.24 | 0.05 | 0.52 | 0.50 | 0.18 | 0.44 | 0.96 |
| $Al_2O_3$ | 10.4 | 0.94 | 18.6 | 13.7 | 6.5 | 0.64 | 16.6 | 17.3 | 20.0 | 14.7 | 19.1 |
| $Cr_2O_3$ | 0.22 | 0.03 | 0.15 | 0.21 | 0.19 | 0.03 | 0.03 | 0.05 | 0.17 | 0.08 | 0.47 |
| $FeO$ | 4.18 | 0.40 | 2.21 | 4.40 | 8.2 | 0.38 | 5.6 | 2.90 | 1.45 | 1.21 | 3.6 |
| $MnO$ | 0.13 | 0.02 | 0.05 | 0.11 | 0.25 | 0.03 | 0.09 | 0.12 | 0.08 | 0.04 | 0.09 |
| $MgO$ | 5.8 | 0.11 | 2.63 | 7.3 | 4.90 | 0.64 | 0.23 | 1.03 | 2.65 | 1.11 | 6.2 |
| $CaO$ | 7.8 | 0.13 | 2.21 | 10.1 | 0.95 | 0.11 | 1.63 | 0.48 | 0.89 | 0.91 | 4.9 |
| $Na_2O$ | 1.71 | 0.17 | 2.89 | 2.61 | 2.33 | 0.19 | 1.76 | 5.4 | 4.61 | 2.77 | 3.21 |
| $K_2O$ | 0.64 | 0.04 | 0.42 | 0.06 | 0.80 | 0.00 | 1.10 | 0.02 | 0.61 | 3.5 | 0.19 |
| Total | 98.6 | 100.4 | 98.5 | 99.3 | 97.0 | 100.6 | 97.8 | 98.9 | 99.4 | 96.4 | 99.8 |

*Table 7:*

*Representative major element composition of mesostasis glass in BO and non-porphyritic pyroxene chondrules.(EMPA in wt.%).*

*Av. (7): Average of 7 analyses.*

| | Ac214/3 Meso-BO | error | Bish Ch-A GI | error | Kaba GI | error | Kaba Meso 2 | error | Renazzo GI2 | error | Krymka KR6 Meso-RP | error |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Li | 1.40 | 0.06 | 0.84 | 0.07 | 0.21 | 0.06 | 0.24 | 0.01 | 1.70 | 0.08 | 0.18 | 0.01 |
| B | 0.28 | 0.04 | | | 1.46 | 0.28 | 1.09 | 0.07 | | | 0.95 | 0.06 |
| Sc | 18.7 | 0.4 | | | 27.6 | 1.7 | 21.8 | 0.3 | 54 | 0.71 | 5.05 | 0.19 |
| Ti | 1315 | 5 | 6910 | 94 | 3778 | 33 | 2261 | 5 | 6944 | 42 | 2345 | 3.4 |
| V | 46 | 0.7 | 57 | 1 | 80 | 3 | 15.9 | 0.3 | 204 | 2 | 7.4 | 0.2 |
| Cr | 2570 | 7 | 1970 | 8 | 2198 | 19 | 2174 | 4 | 2182 | 10 | 28 | 0.4 |
| Mn | 500 | 3 | | | 354 | 8 | 197 | 1.2 | | | 1254 | 3 |
| Co | 6.4 | 0.4 | | | 6.9 | 1.2 | 8.5 | 0.45 | 8.6 | 0.7 | 32 | 0.9 |
| Rb | 17 | 0.8 | | | <0.42 | | 8.3 | 0.45 | | | 53 | 1.1 |
| Sr | 37 | 0.6 | 162 | 6 | 91.7 | 3.5 | 88.0 | 0.8 | 85 | 1 | 17 | 0.3 |
| Y | 8 | 0.3 | 26.2 | 0.5 | 14.3 | 1.3 | 18.0 | 0.3 | 21 | 0.6 | 9.8 | 0.2 |
| Zr | 34 | 0.9 | 79 | 1 | 46.5 | 3.5 | 66.0 | 0.9 | 66 | 2 | 38 | 0.7 |
| Nb | 2.90 | 0.20 | 4.6 | 0.3 | 3.27 | 0.56 | 5.9 | 0.3 | 5.9 | 0.5 | 4.11 | 0.21 |
| Ba | 8.5 | 0.5 | 58 | 1 | 28.7 | 2.5 | 27 | 0.6 | 43 | 0.9 | 2.28 | 0.15 |
| La | 2.30 | 0.20 | 5.3 | 0.3 | 2.50 | 0.38 | 3.7 | 0.2 | 3.25 | 0.18 | 1.66 | 0.09 |
| Ce | 6.4 | 0.3 | 13.3 | 0.6 | 6 | 0.8 | 9.4 | 0.3 | 8.3 | 0.3 | 4.46 | 0.22 |
| Pr | 0.93 | 0.09 | 1.90 | 0.20 | 0.90 | 0.16 | 1.21 | 0.08 | 1.15 | 0.11 | 1.73 | 0.05 |
| Nd | 3.80 | 0.20 | 10 | 0.5 | 3.50 | 0.35 | 5.7 | 0.2 | 5.69 | 0.25 | 2.94 | 0.12 |
| Sm | 1.10 | 0.10 | 3.30 | 0.40 | 1.55 | 0.26 | 1.58 | 0.13 | 1.85 | 0.19 | 1.01 | 0.08 |
| Eu | 0.32 | 0.02 | 1.10 | 0.20 | 0.45 | 0.10 | 0.78 | 0.05 | 0.56 | 0.08 | 0.29 | 0.02 |
| Gd | 1.40 | 0.10 | 5.9 | 0.7 | 1.70 | 0.34 | 1.9 | 0.2 | 2.37 | 0.32 | 1.12 | 0.14 |
| Tb | 0.28 | 0.03 | 0.70 | 0.20 | 0.50 | 0.14 | 0.38 | 0.04 | 0.44 | 0.07 | 0.24 | 0.03 |
| Dy | 1.50 | 0.09 | 6.4 | 0.4 | 2.16 | 0.32 | 2.32 | 0.11 | 3.12 | 0.19 | 1.47 | 0.08 |
| Ho | 0.30 | 0.02 | 1.20 | 0.20 | 0.37 | 0.09 | 0.47 | 0.03 | 0.61 | 0.08 | 0.35 | 0.03 |
| Er | 0.93 | 0.06 | 3.50 | 0.30 | 1.56 | 0.20 | 1.41 | 0.07 | 1.92 | 0.16 | 1.02 | 0.06 |
| Tm | 0.15 | 0.01 | 0.60 | 0.10 | 0.20 | 0.05 | 0.20 | 0.02 | 0.36 | 0.06 | 0.13 | 0.02 |
| Yb | 0.87 | 0.08 | 2.80 | 0.30 | 1.42 | 0.44 | 1.35 | 0.11 | 1.83 | 0.16 | 0.88 | 0.08 |
| Lu | 0.16 | 0.02 | 0.40 | 0.10 | 0.20 | 0.07 | 0.25 | 0.03 | 0.22 | 0.06 | 0.16 | 0.02 |

*Table 8:*

*Representative ion microprobe analyses (in ppm) of glass inclusions and glassy mesostasis.*

*Secondary-ion mass spectrometry (SIMS) data in ppm*

*References: Meso: Mesostasis; GI: Glass Inclusion; BO: Barred olivine chondrule;*

*RP: Radiating pyroxene chondrule; GP: Glass Pocket, How1: Howardite1*

*Analyses taken from: ENGLER et al. (2003, 2007), KURAT et al. (1997, 2003), VARELA et al. (2002a, 2003b, 2005b), and unpublished.*

| | Krymka GI-3 | error | Cachari | error | D´Orbigny GI | error | D´Orbigny GP 5a-b | error | NWA1664 How1 | error | NWA1664 How2 | error |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Li** | **2.05** | *0.05* | **8.3** | *0.10* | **4.40** | *0.10* | **5.6** | *0.20* | **42** | *0.3* | **103** | *0.6* |
| **B** | **4.15** | *0.11* | **0.75** | *0.05* | **0.60** | *0.07* | **0.53** | *0.09* | **0.55** | *0.05* | **1.11** | *0.09* |
| **Sc** | **13** | *0.2* | **23** | *0.9* | **58** | *0.6* | **100** | *1* | **25** | *0.4* | **24** | *0.4* |
| **Ti** | **2739** | *4* | **4232** | *17* | **4630** | *10* | **7400** | *19* | **2746** | *5* | **2931** | *6* |
| **V** | **29** | *0.3* | **68** | *0.6* | **123** | *10* | **190** | *2* | **75** | *0.6* | **73** | *0.8* |
| **Cr** | **1052** | *2* | **2312** | *13* | **500** | *2.5* | **415** | *4* | **4137** | *7* | **3846** | *8* |
| **Mn** | **1596** | *3* | **4768** | *6* | **2800** | *7* | **4200** | *13* | **4152** | *7* | **4446** | *9* |
| **Co** | **19** | *0.5* | **21** | *0.7* | **120** | *2* | **96** | *3* | **46** | *1* | **11** | *0.6* |
| **Rb** | **34** | *0.8* | | | **<1.8** | | | | **2.26** | *0.59* | **9.7** | *0.9* |
| **Sr** | **62** | *0.5* | **71** | *0.7* | **17** | *0.4* | **14** | *0.6* | **36** | *0.5* | **70** | *0.8* |
| **Y** | **9.4** | *0.2* | **15** | *0.3* | **18** | *0.4* | **17** | *0.6* | **13** | *0.3* | **16** | *0.3* |
| **Zr** | **36** | *0.5* | **53** | *2* | **56** | *1* | **115** | *2.3* | **48** | *0.8* | **63** | *1* |
| **Nb** | **3.36** | *0.2* | **4.05** | *0.22* | **1.70** | *0.14* | **0.53** | *0.06* | **3.87** | *0.23* | **4.31** | *0.29* |
| **Ba** | **18** | *0.4* | **22** | *0.6* | **1.50** | *0.09* | **3.20** | *0.30* | **19** | *0.6* | **162** | *2* |
| **La** | **1.80** | *0.09* | **2.35** | *0.11* | **1.60** | *0.09* | **1.00** | *0.10* | **2.33** | *0.15* | **3.33** | *0.21* |
| **Ce** | **4.49** | *0.18* | **6.5** | *0.3* | **4.40** | *0.20* | **3.90** | *0.28* | **5.51** | *0.27* | **8.1** | *0.4* |
| **Pr** | **0.67** | *0.05* | **1.01** | *0.06* | **0.90** | *0.06* | **0.60** | *0.08* | **0.86** | *0.07* | **1.15** | *0.09* |
| **Nd** | **3.06** | *0.11* | **4.96** | *0.18* | **4.90** | *0.20* | **3.80** | *0.20* | **4.19** | *0.18* | **5.38** | *0.25* |
| **Sm** | **0.91** | *0.07* | **1.47** | *0.12* | **1.40** | *0.10* | **1.70** | *0.20* | **1.27** | *0.11* | **1.59** | *0.17* |
| **Eu** | **0.21** | *0.02* | **0.49** | *0.04* | **0.44** | *0.03* | **0.35** | *0.04* | **0.26** | *0.03* | **0.34** | *0.11* |
| **Gd** | **0.94** | *0.11* | **2.52** | *0.21* | **2.10** | *0.25* | **2.00** | *0.30* | **1.76** | *0.21* | **1.83** | *0.26* |
| **Tb** | **0.19** | *0.02* | **0.39** | *0.04* | **0.39** | *0.05* | **0.40** | *0.06* | **0.33** | *0.04* | **0.43** | *0.06* |
| **Dy** | **1.37** | *0.08* | **2.79** | *0.12* | **3.00** | *0.15* | **2.90** | *0.20* | **2.12** | *0.14* | **2.63** | *0.16* |
| **Ho** | **0.27** | *0.03* | **0.60** | *0.05* | **0.57** | *0.04* | **0.60** | *0.07* | **0.46** | *0.05* | **0.56** | *0.06* |
| **Er** | **0.89** | *0.05* | **1.87** | *0.09* | **1.90** | *0.10* | | | **1.29** | *0.09* | **1.67** | *0.11* |
| **Tm** | **0.15** | *0.01* | **0.28** | *0.02* | **0.28** | *0.03* | **0.30** | *0.04* | **0.23** | *0.02* | **0.28** | *0.03* |
| **Yb** | **0.83** | *0.07* | **1.58** | *0.09* | **1.78** | *0.13* | **1.80** | *0.20* | **1.11** | *0.12* | **1.51** | *0.13* |
| **Lu** | **0.14** | *0.02* | **0.30** | *0.03* | **0.29** | *0.04* | **0.35** | *0.07* | **0.22** | *0.03* | **0.23** | *0.04* |

*Table 8:*

*continued*