Laboratory Analyses of Marco Polo Samples

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Overview

• Principle Objective of Marco Polo is to return a sample of a primitive NEO to Earth

• Only laboratory analyses can provide the analytical precision, accuracy, sensitivity and sample selectivity required

• Great array of measurements and problems to be addressed
  – What? - types of analyses and studies required
  – How? - the instrumentation, approaches and sample requirements
  – Why? - the science addressed
Expected Sample?

• Sample will be collected from the regolith of a primitive NEO
  – But we have never seen a close up image of a primitive asteroid....

• Eros – fine particle size
  – 10s microns, lots of boulders

Courtesy NASA. Image 12m across
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  – mm to cm regolith plus blocks
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• Carbonaceous chondrites
  – Many regolith breccias
  – Sub-mm to cm particles
Mineralogy of Expected Sample?

- Carbonaceous chondrites – very diverse mineralogy
  - 100nm condensate mineralogy
  - mm chondrules and CAIs
  - Fine phyllosilicate mineralogy

- Carbon content varies by factor 30

Bland et al 2007
Univ Hawaii
Pearson et al 2006
Nature of Expected Sample?

• Assume NEO is derived from larger main belt asteroid
  – Block fragment?
  – Rubble pile?

• Original lithic diversity?
  – Structured body – onion shell?
  – Peak temp/time decreases radially
  – Effects of fluid flow complex

• Unaltered material abundant

• MP sample – mix of lithologies?
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Sample Analysis Outline

• MP sample – regolith with a mix of dust to pebbles and a number of different lithic components. What to do?

• Bulk properties
  – That relate to understanding overall properties of NEO

• Component properties
  – Asteroidal processes – post accretion history
  – Nebula, pre-solar processes – pre-accretion history
  – Organic compounds
  – Space weathering
Bulk Properties I

- Elemental Composition
  - ICPMS, INAA, noble gas MS, gas source MS
  - Each technique requires mg to 10s mg material

- Mineralogy
  - XRD, Mössbauer, ESR, NMR
  - Each technique requires mg to 10s mg material

- Isotopic Composition
  - e.g. Oxygen – requires mg quantities

- Provides comparison with bulk meteorites, Earth, Mars, etc
Bulk Properties II

- **Density & Porosity**
  - Pyncometer – requires large sample (currently)

- **Spectral Properties**
  - UV to near-IR (300nm to 2.5 μm) and mid-IR (up to 50 μm?)
  - Requires ≈20 mg of material

- **Magnetic susceptibility**

- **Non-destructive, contamination-free?**
  - Could use large representative sample

- Understanding overall structure and properties of asteroid

- Cross-characterisation between sample, MP spectrometer, telescopes.

Binzel et al 1996
Identification of Lithologies

• To provide initial characterisation of samples
  – Optimise sample selection for detailed studies, e.g.:
    • Organic rich samples
    • Aqueously altered sample
    • Pristine nebula rich samples
  – No sample preparation
  – Non-destructive techniques
  – Non-contaminating techniques

• Optical microscopy, spectroscopy, magnetic susceptibility, etc
  – Requires some initial feedback from destructive techniques

• Part of sample curation facility activities
Lithology Characterisation

• Bulk composition, mineralogy, spectral and physical properties
  – Same approach as for bulk sample

• Mineralogy & petrography of sample – from nm to mm scale
  – Textures – optical and electron microscopy (SEM, TEM)
  – Mineralogy - optical and electron microscopy (SEM, TEM), μ-XRD, FTIR/Raman spectrometry
  – Mineral chemistry – ASEM, EMPA, XANES, SIMS, LA-ICPMS
  – All in situ techniques – requiring preparation of polished sections
    • Some destructive – e.g. LA-ICPMS, SIMS
  – Preparation of sub-samples from sections
    • E.g. FIB wafers for synchrotron, TEM
Asteroidal Processes

• Much information derived from component characterisation
  – Multiple fragments - range of alteration effects

• Absolute & relative ages require specific phases
  – Known histories (usually simple)
  – Specific compositions - e.g. $^{53}$Mn-Cr dating – range of Mn contents with low Cr contents

• Mostly performed by SIMS
  – If ICPMS/TIMS – large samples
Solar Nebula Processes

• Much information derived from component characterisation
  – Concentrate on those components least affected by asteroidal effects

• Detailed study of sub-components – chondrules, CAIs, AoAs, mineral frags, etc
  – Trace element distributions, isotopic variations – especially oxygen and short lived radionuclides

• Age dating - specific components & well understood histories
  – Which processes are we attempting to date

• Principle techniques – SEM, TEM, EMPA, SIMS, ICPMS, noble gas MS – mix of in situ and separated samples (10s mgs – of specific components
Pre-Solar Grains

- In situ analyses identification – SIMS
  - Followed by both in situ and extraction for characterisation – Raman, XANES, TEM, Auger
  - From polished sections prepared from characterisation
- Statistics benefit from preparation of grain concentrates
  - Acid dissolution
  - Requires large samples – from organic demineralisation
  - Gentle separation – grain mantles

Bernatowicz et al 2002
Mantled SiC

Nguyen & Zinner 2004

17O/16O
Organic Compounds

- Intimately related to asteroidal and nebula studies
  - Relationship to rocky matrix and info derived from matrix
- Inventory of free organic compounds
  - Extraction by various polar and non-polar solvents, pyrolysis
  - GC/GC-MS, LC/LC-MS – 10s mg
  - Amino acid chirality – 10s mg
  - Nucleobases low abundance – 10s to 100mg sample
Organics – Isotopic Ratios

• Introduce a combustion/reduction reactor before MS
  – Isotope ratio MS - D/H, $^{13}$C/$^{12}$C, $^{15}$N/$^{14}$N of individual compounds

• Verification of extra-terrestrial origin

• Important in understanding formation processes
  – Distinctive fractionation patterns
  – Signatures of different environments – e.g. ISM
  – Identifies links between compound classes and mineralogy

• Requires 5 – 10g of C-rich carbonaceous chondrite
  – Separate sample for nucleobases and other organics

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Pizzarello et al 2007

Busemann et al 2006
Organics – Insoluble & *In Situ*

- Organic Macromolecule – very difficult to study
  - Complex, inter-linked structure of PAHs, heterocycles and aliphatics
- Mineral matrix readily removed (very destructively)
- Structure – NMR, Raman, FTIR, XANES, Pyr-GCMS
- Composition – GS-MS, NMR
- NMR requires grams of C-rich meteorite

![Graph and images related to organic compounds and NMR spectra.](image)s
Organics Requirements Summary

• What can be achieved if sample is like CM2 – i.e. few wt% C
• With a few grams of good quality sample, multiple analyses of:
  – All in situ techniques
  – All compound abundance techniques
  – Not structural info on macromolecule
  – Not detailed isotopic measurements

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<th>Scientific Objectives achievable for returned mass (g)</th>
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...Space Weathering

- Galactic/Solar cosmic ray, solar wind, uv irradiation, heating/impacts, etc
- Affects all aspects of sample - organics most susceptible
- Solar Wind and UV – only micron(s) depth penetration
- Many organic analyses low spatial resolution
  - Physically separate irradiated material from interior before analyses
- Heat modification of organics – depth (time) main defense
  - Few cms can have a marked effect
Organic Analyses Requirement

- Integrate mineralogy etc with organics
  - Organic analyses from gram(s) of specific, characterised rock types
  - Range of rock types
- Physical separation of irradiated/non-irradiated material
  - Low surface:volume ratio of irradiated particles
- Protection from peak temperatures
  - Some sampling to shallow depth

**Dust rich sample**
- Mixed lithologies?
- High surface:vol

**Solid rock sample**
- Single lithology
- Carb Chondrite?

**Pebbles (cm sized)**
- Each single lithology?
- Range of lithologies
- Low surface:vol
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Sample Requirements

• Bulk properties, composition and mineralogy – few 10s mgs

• Properties of components – 10s to 100s mg per component
  – Plus sufficient material for polished section(s) – gram amounts

• For each lithology in a regolith of different alteration:
  • Organics – 100s mg for abundances & overall characterisation
  • Organics – 5g plus for isotopic studies – for origin, formation