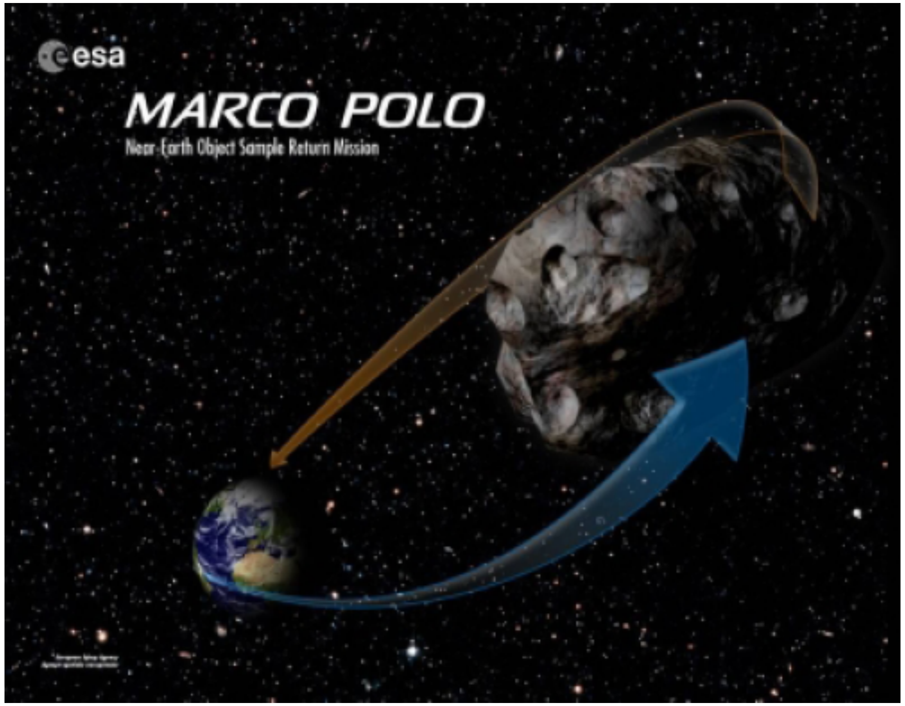

The Open University

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

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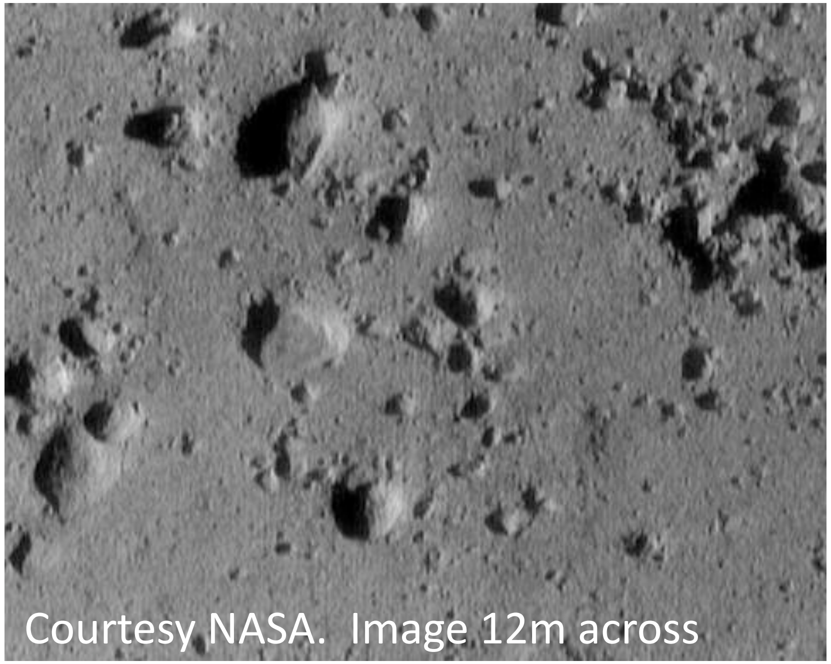
Expected Sample?

- 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



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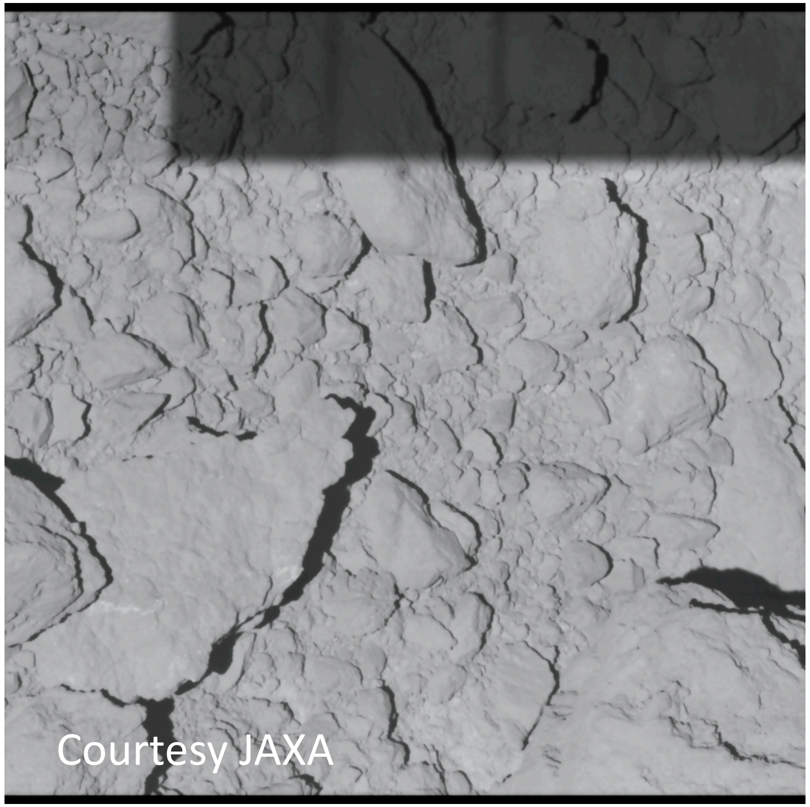
- Itokawa – coarser particles
  - mm to cm regolith plus blocks


Courtesy JAXA

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- Eros – fine particle size
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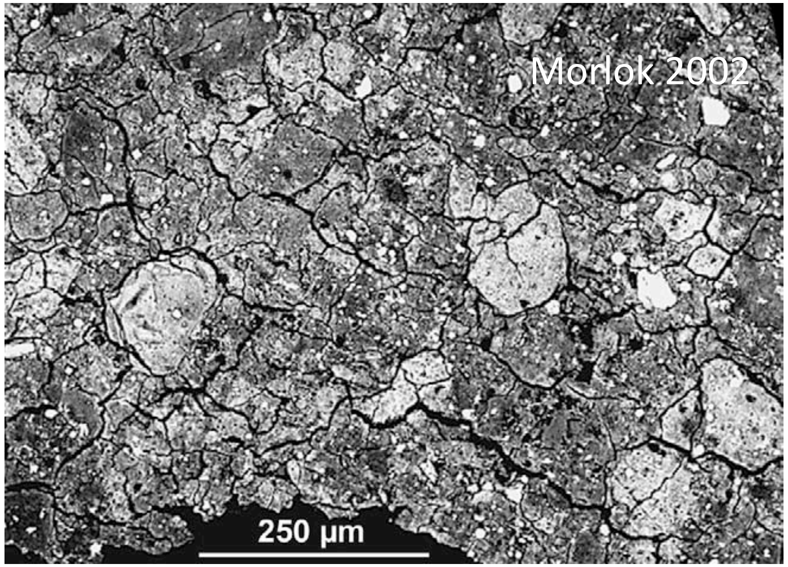
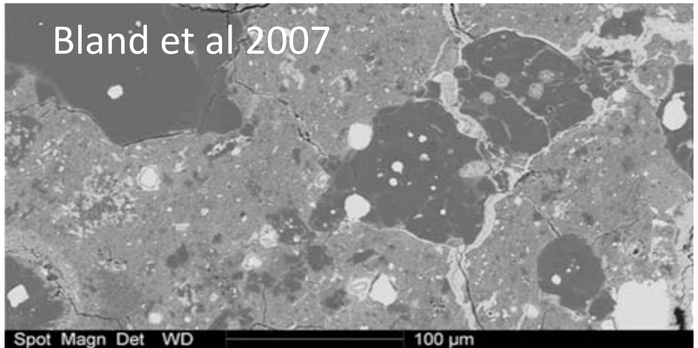
- Itokawa – coarser particles
  - mm to cm regolith plus blocks
- Carbonaceous chondrites
  - Many regolith breccias
  - Sub-mm to cm particles

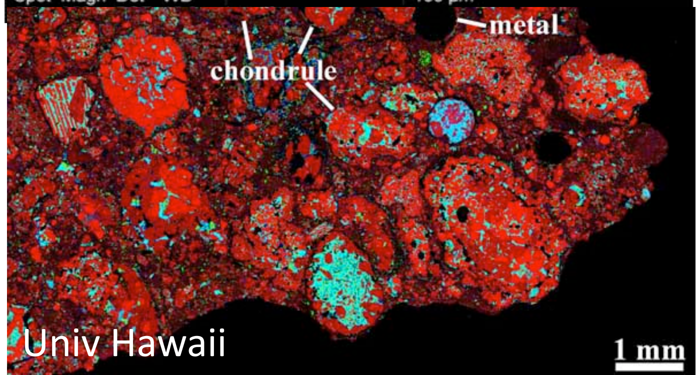


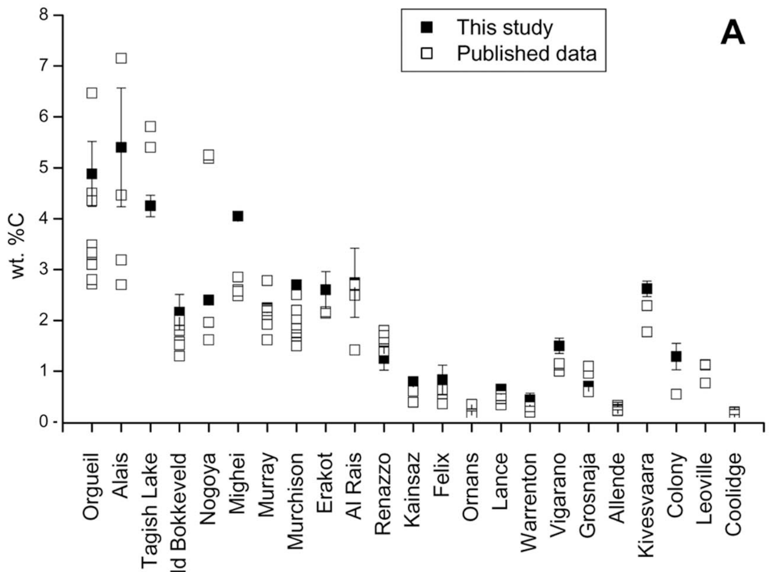
Mineralogy of Expected Sample?

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

- Carbon content varies by factor 30



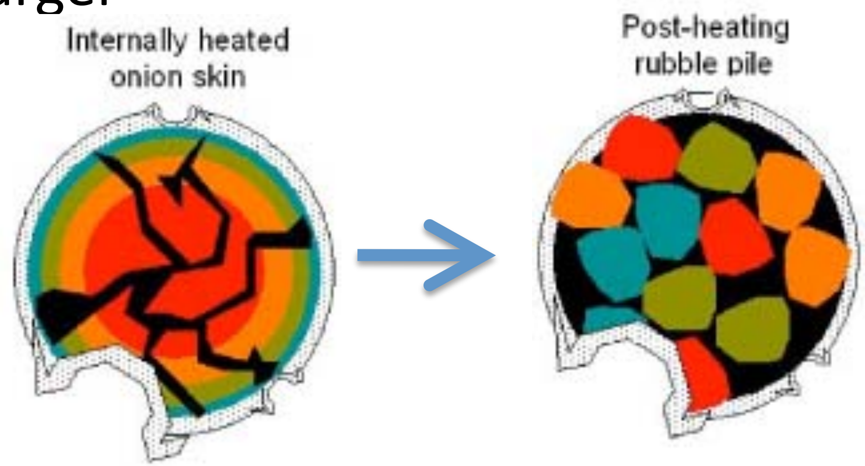




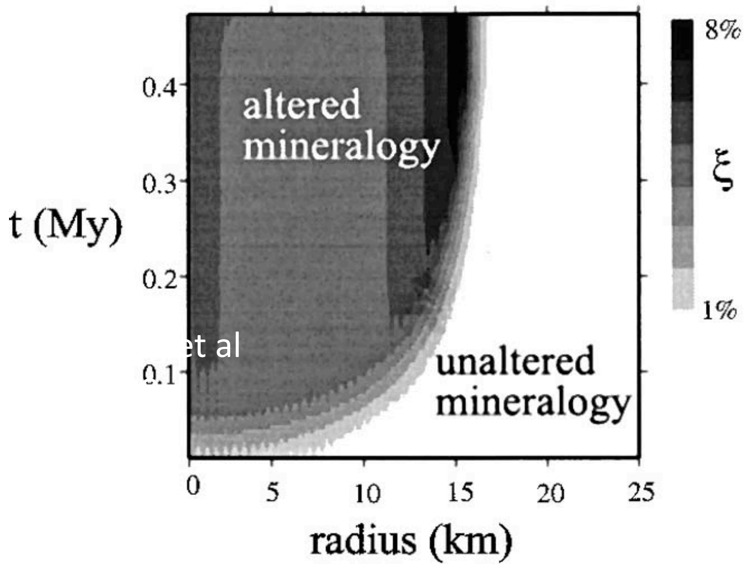
Pearson et al 2006

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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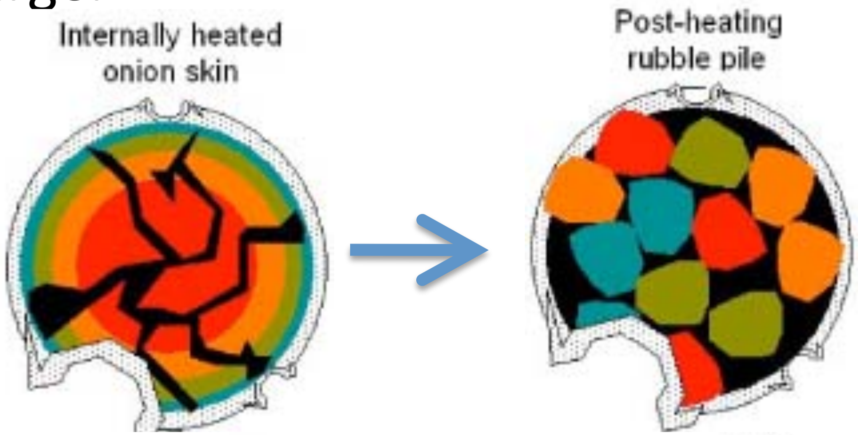
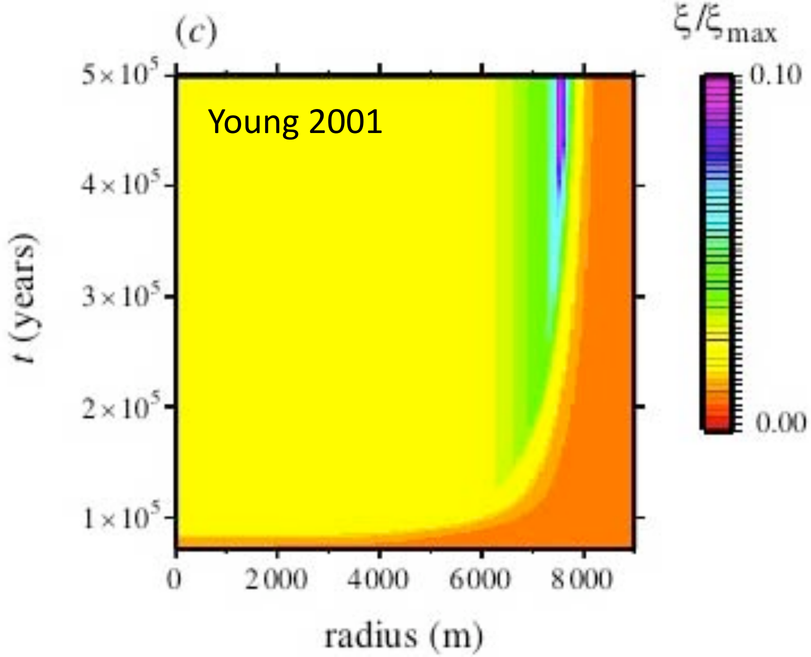




Sample Analysis Outline

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

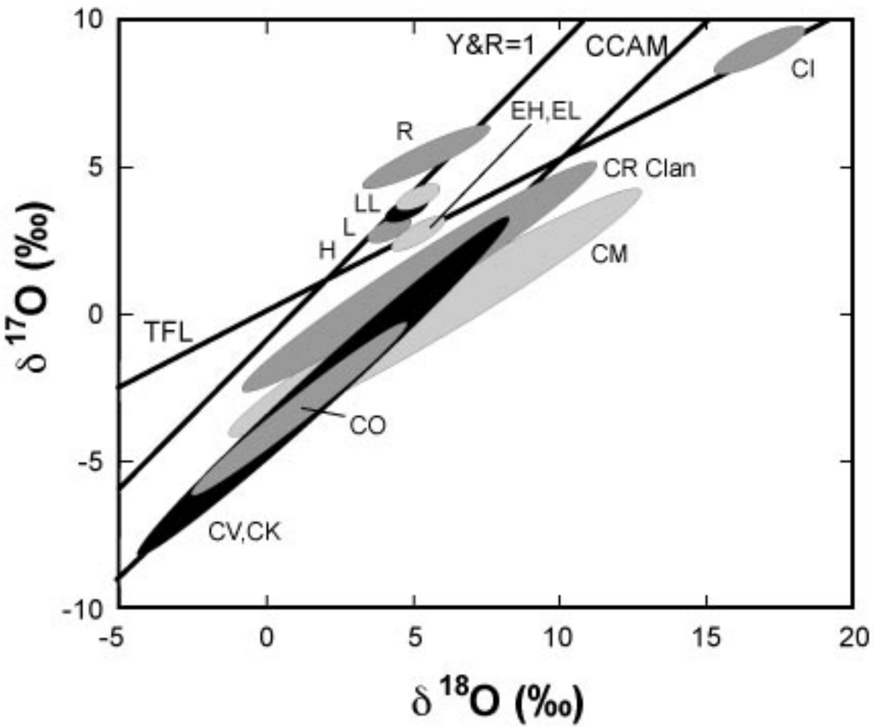
- Bulk properties
  - That relate to understanding overall properties of NEO

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

Bulk Properties I

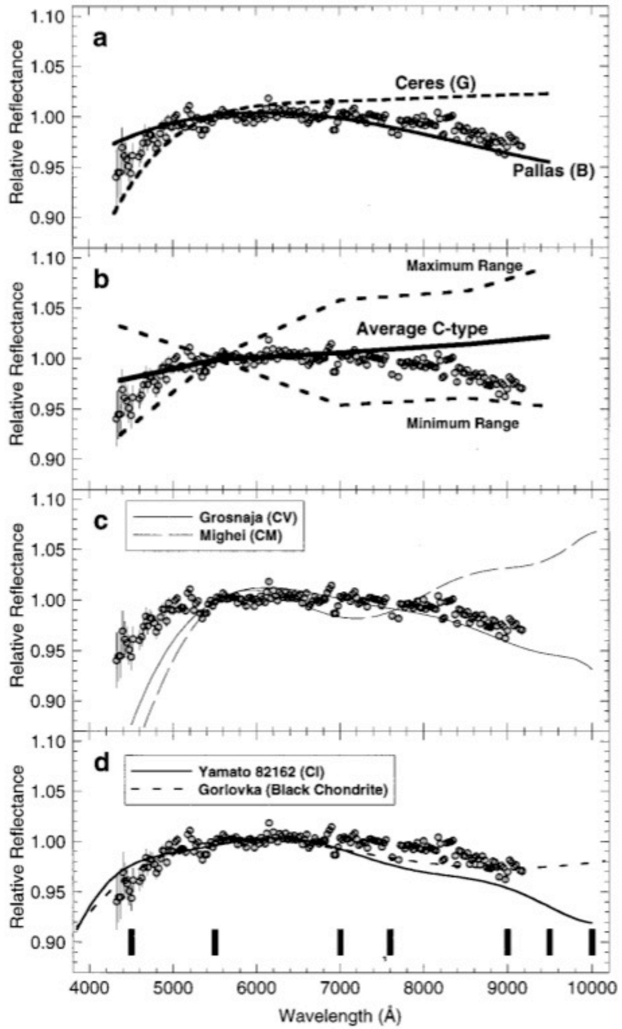
- Elemental Composition
  - ICPMS, INAA, noble gas MS, gas source MS
  - Each technique requires mg to 10s mg material
- Mineralogy
  - XRD, Mössbauer, ESR, NMR
  - Each technique requires mg to 10s mg material
- Isotopic Composition
  - e.g. Oxygen – requires mg quantities

- Provides comparison with bulk meteorites, Earth, Mars, etc



Bulk Properties II

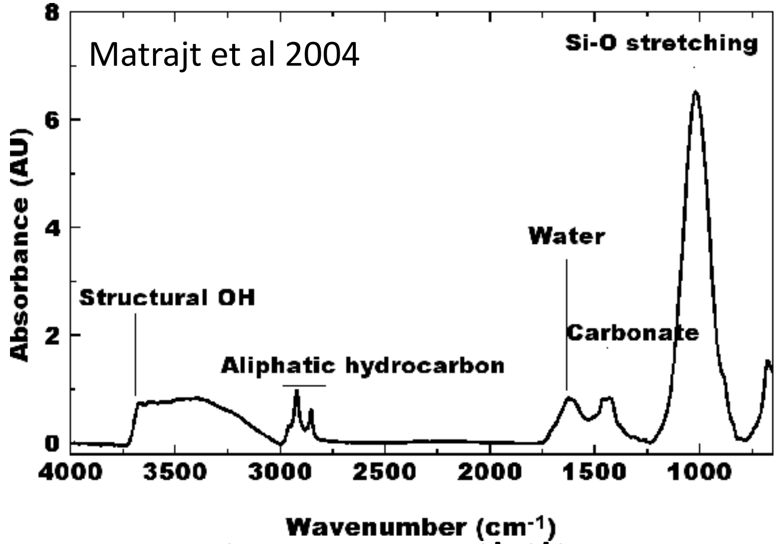
- Density & Porosity
  - Pyncometer – requires large sample (currently)
- Spectral Properties
  - UV to near-IR (300nm to 2.5 μm) and mid-IR (up to 50 μm?)
  - Requires ≈20 mg of material
- Magnetic susceptibility
- Non-destructive, contamination-free?
  - Could use large representative sample
- Understanding overall structure and properties of asteroid
- Cross-characterisation between sample, MP spectrometer, telescopes.



Binzel et al 1996

Identification of Lithologies

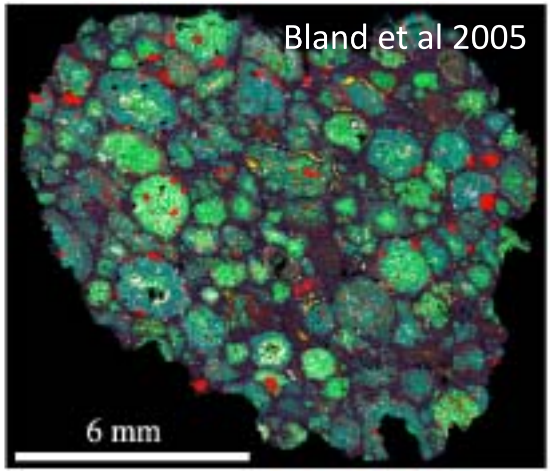
- To provide initial characterisation of samples
  - Optimise sample selection for detailed studies, e.g.:
    - Organic rich samples
    - Aqueously altered sample
    - Prisitine nebula rich samples
  - No sample preparation
  - Non-destructive techniques
  - Non-contaminating techniques



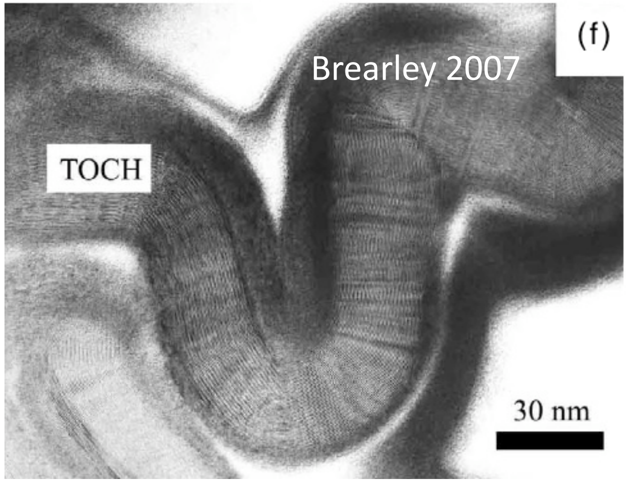
- Optical microscopy, spectroscopy, magnetic susceptibility, etc
  - Requires some initial feedback from destructive techniques
- Part of sample curation facility activities

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



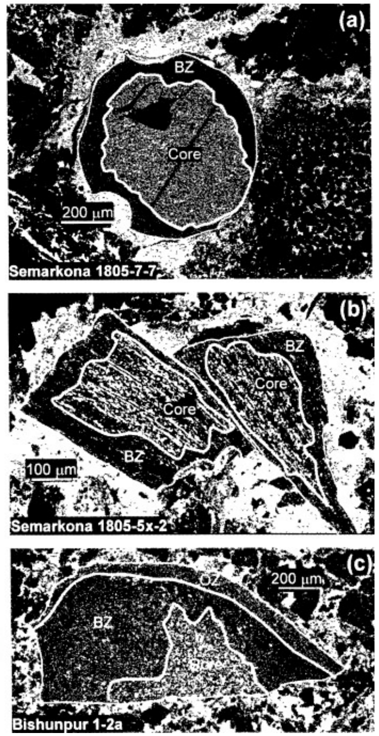
Bland et al 2005



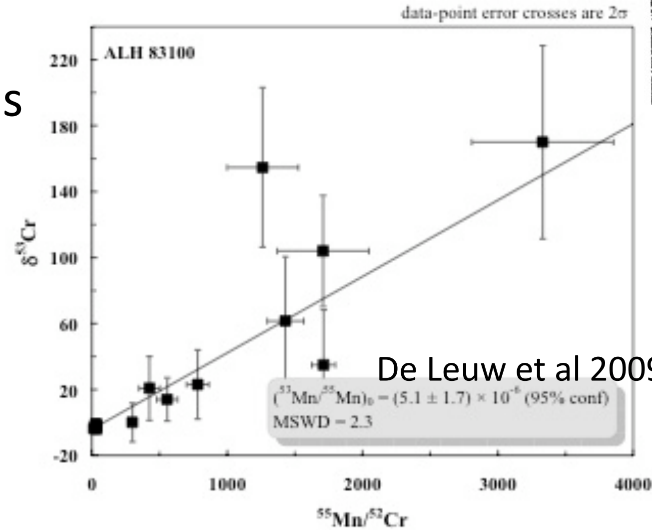
Brearley 2007

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



Grossman et al 2000



De Leuw et al 2009

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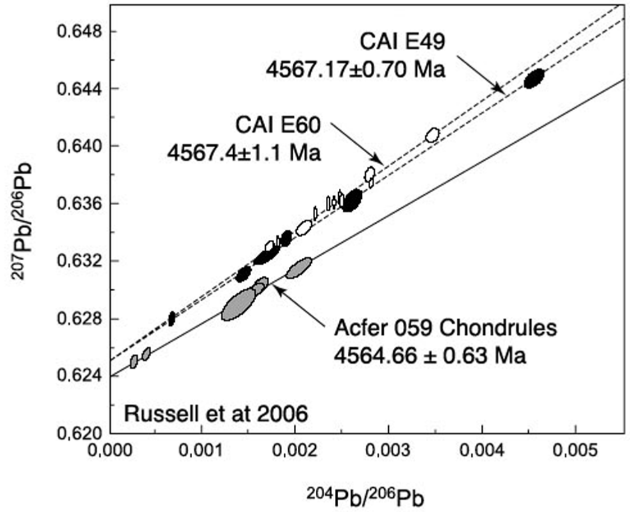
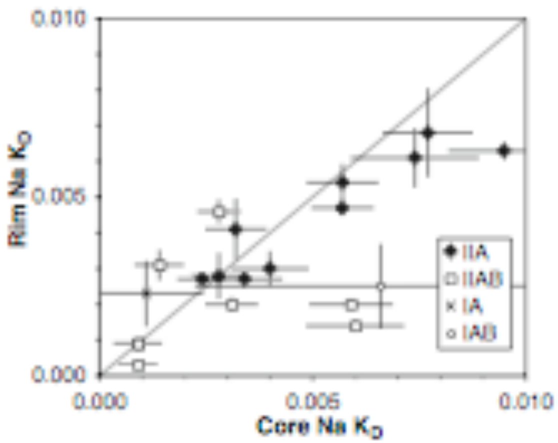
Solar Nebula Processes

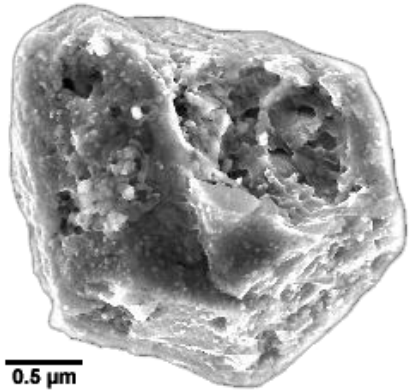
- Much information derived from component characterisation
  - Concentrate on those components least affected by asteroidal effects
- Detailed study of sub-components – chondrules, CAIs, AoAs, mineral frags, etc
  - Trace element distributions, isotopic variations – especially oxygen and short lived 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

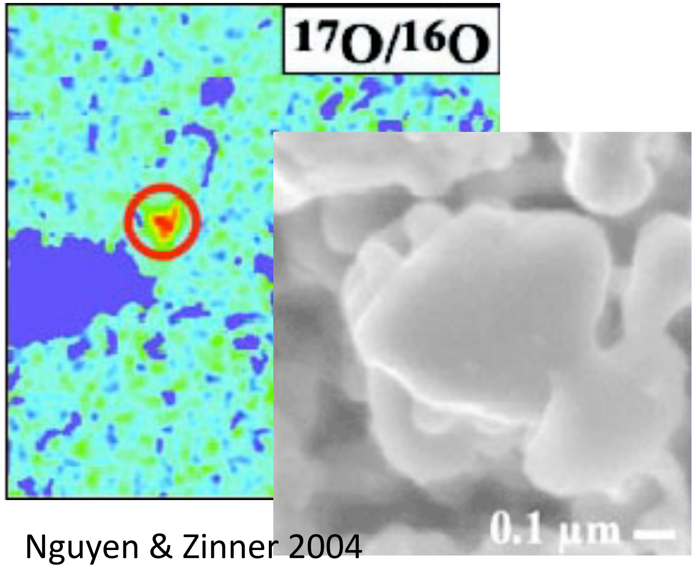




Pre-Solar Grains

- 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 demineralistaion
  - Gentle separation – grain mantles

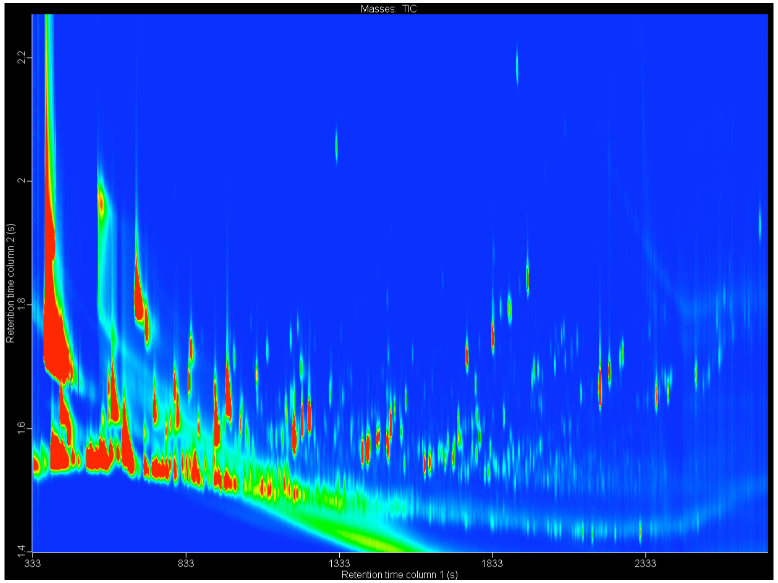


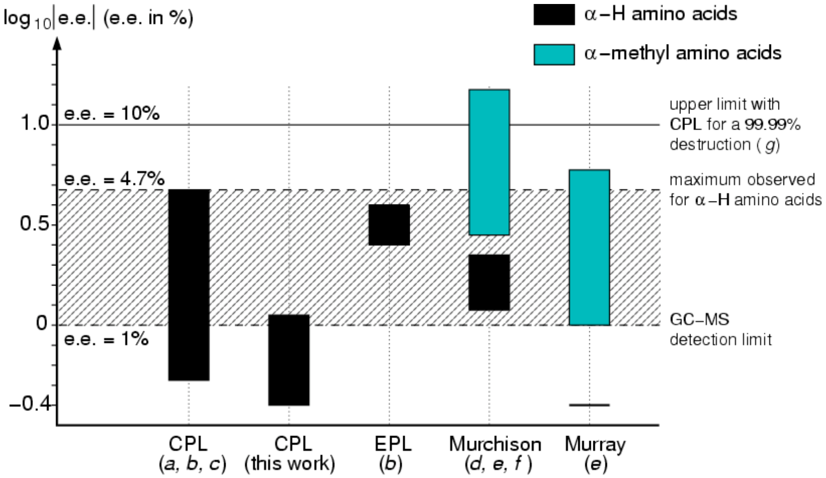


Nguyen & Zinner 2004

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





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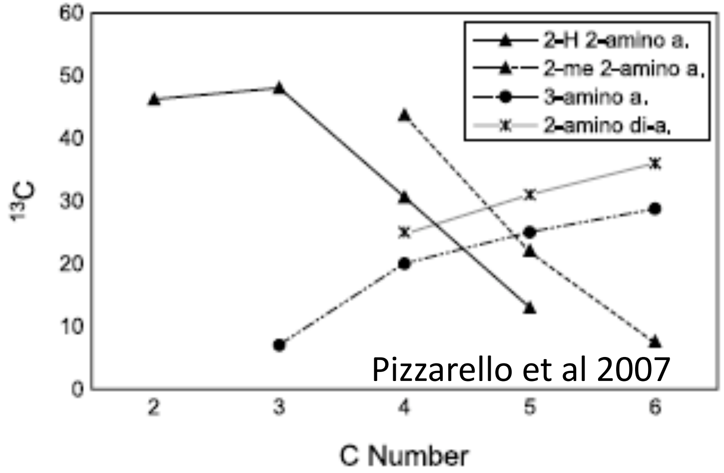
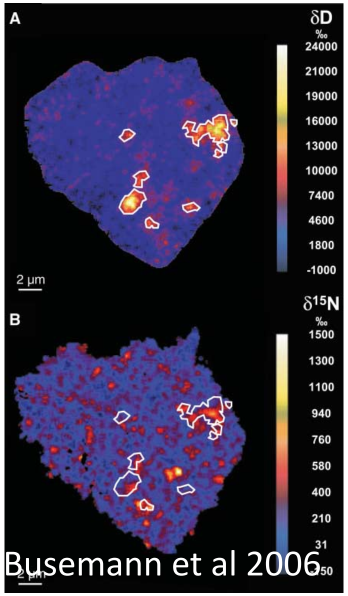
Organics – Isotopic Ratios

- 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



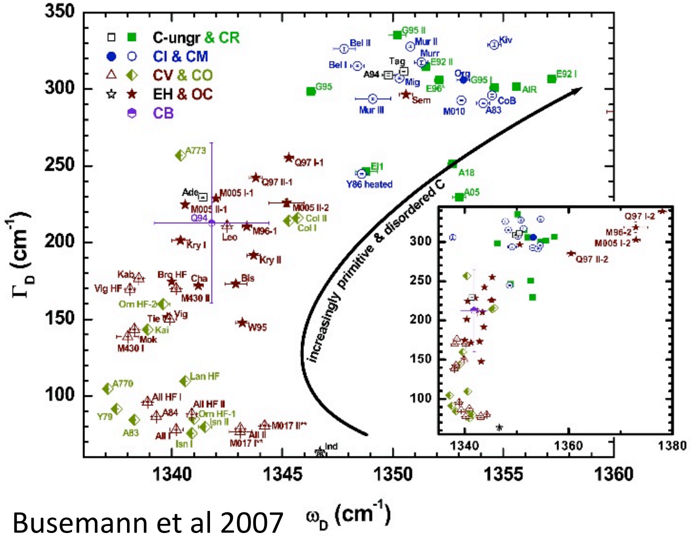
Pizzarello et al 2007



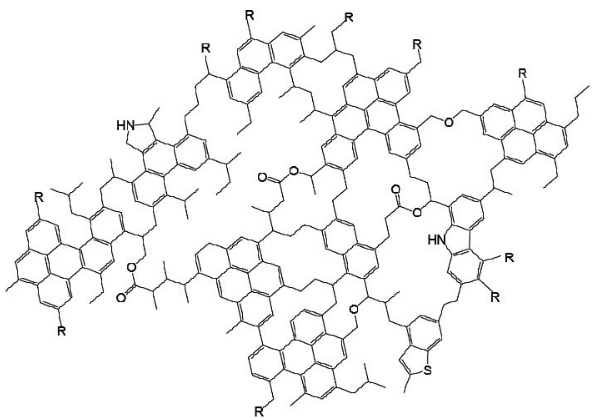
Busemann et al 2006

Organics – Insoluble & *In Situ*

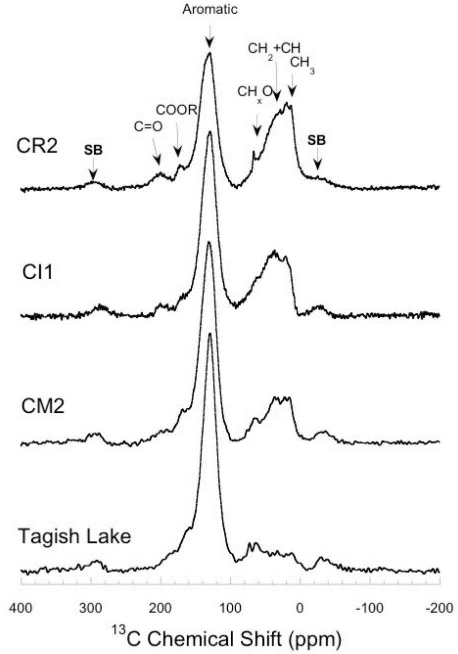
- Organic Macromolecule – very difficult to study
  - Complex, inter-linked structure of PAHs, heterocycles and aliphatics
- Mineral matrix readily removed (very destructively)
- Structure – NMR, Raman, FTIR, XANES, Pyr-GCMS
- Composition – GS-MS, NMR
- NMR requires grams of C-rich meteorite



Busemann et al 2007



Laurent Remsaut



Cody & Alexander 2005

Organics Requirements Summary

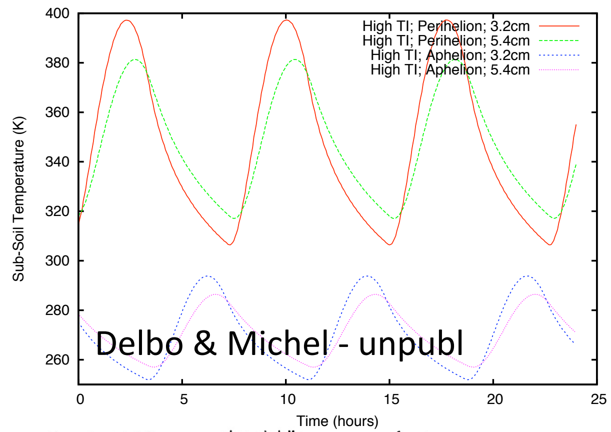
- What can be achieved if sample is like CM2 – i.e. few wt% C
- With a few grams of good quality sample, multiple analyses of:
  - All in situ techniques
  - All compound abundance techniques
  - Not structural info on macromolecule
  - Not detailed isotopic measurements

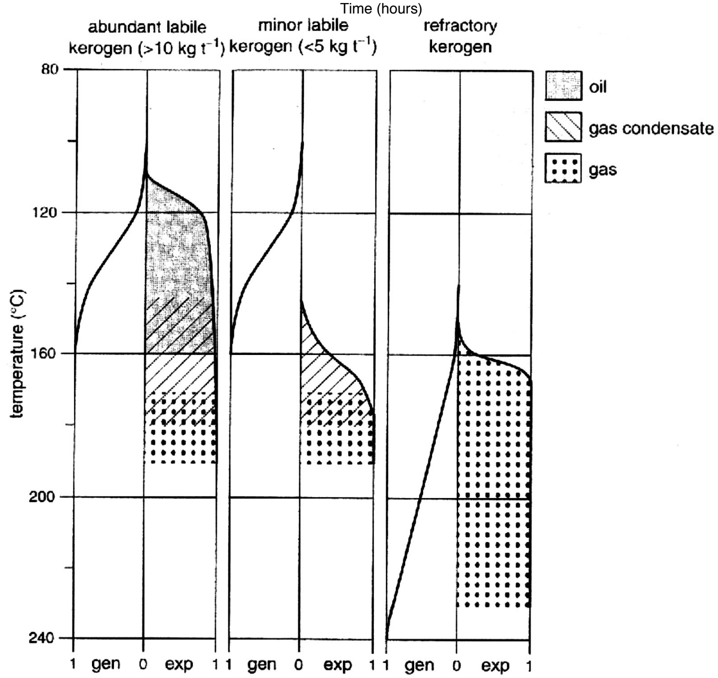
Technique		Scientific Objectives achievable for returned mass (g)				
	*	1	5	10	50	100
Fluorescence	N					
PAS	P					
XANES	P					
L2MS	Y					
IR-VIS spectroscopy	P					
TOF-SIMS	Y					
nSIMS	Y					
Step combustion-MS	Y					
µRaman	N					
TEM	P					
LC-GC-MS	P					

Technique		Scientific Objectives achievable for returned mass (g)				
	*	1	5	10	50	100
Free solvent extractable Organics Abundance	P					
Free water extractable Organics Abundance	P					
Macromolecule component abundance	P					
Whole-rock Hyrdo and Hydrous-Pyrolysis - abundance	Y					
Nucleobase Abundance	P					
NMR	P					
Whole-rock Hyrdo and Hydrous-Pyrolysis - isotopes	Y					
Nucleobase Isotopes	P					
Free solvent extractable Organics Isotopic	P					
Free water extractable Organics Isotopic	P					
Macromolecule component isotopes	P					

…Space Weathering

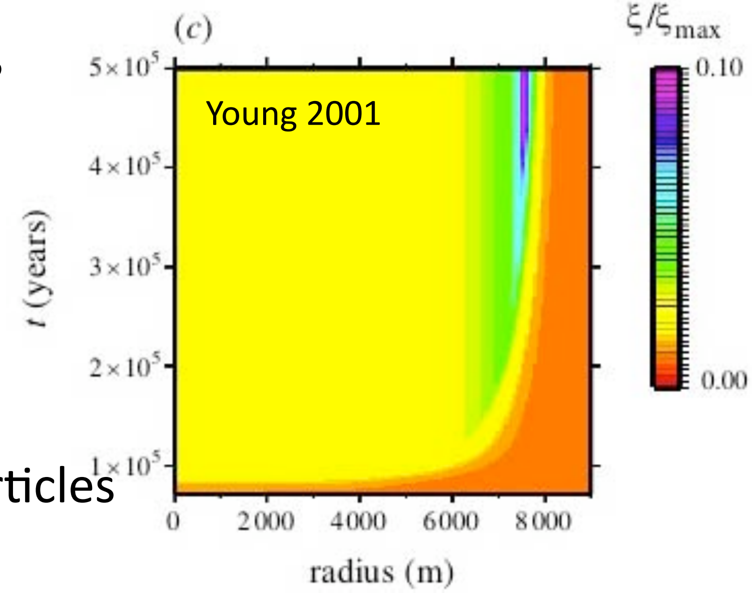
- Galactic/Solar cosmic ray, solar wind, uv irradiation, heating/ impacts, etc
- Affects all aspects of sample - organics most susceptible
- Solar Wind and UV – only micron(s) depth penetration
- Many organic analyses low spatial resolution
  - Physically separate irradiated material from interior before 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	**Solid rock sample**	**Pebbles (cm sized)**
Mixed lithologies?	Single lithology	Each single lithology?
High surface:vol	Carb Chondrite?	Range of lithologies
		Low surface:vol

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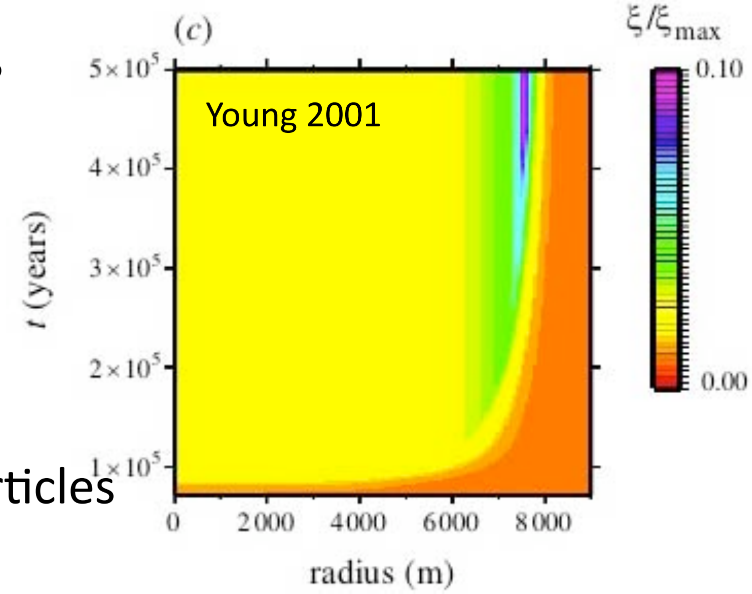

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High surface:vol	Carb Chondrite?	Range lithologies
		Low surface:vol

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