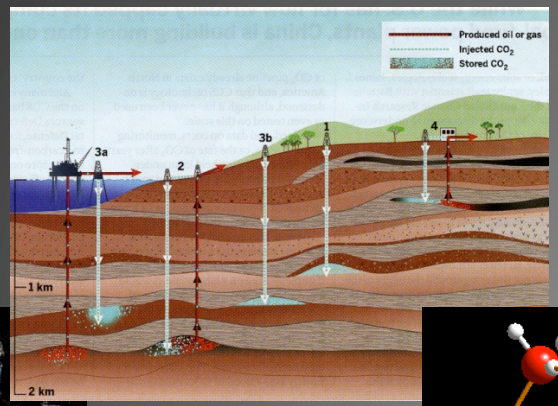
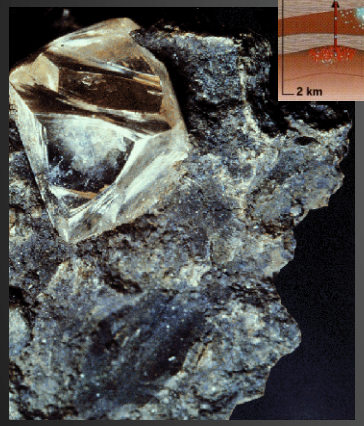
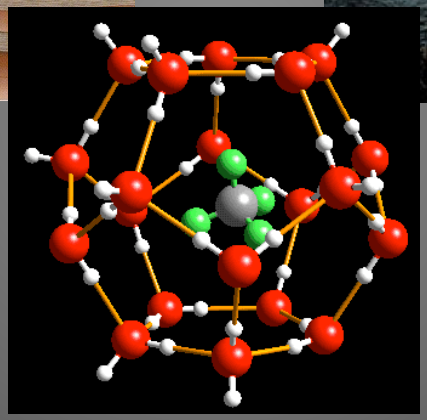
Unanswered Questions in Deep Carbon Research





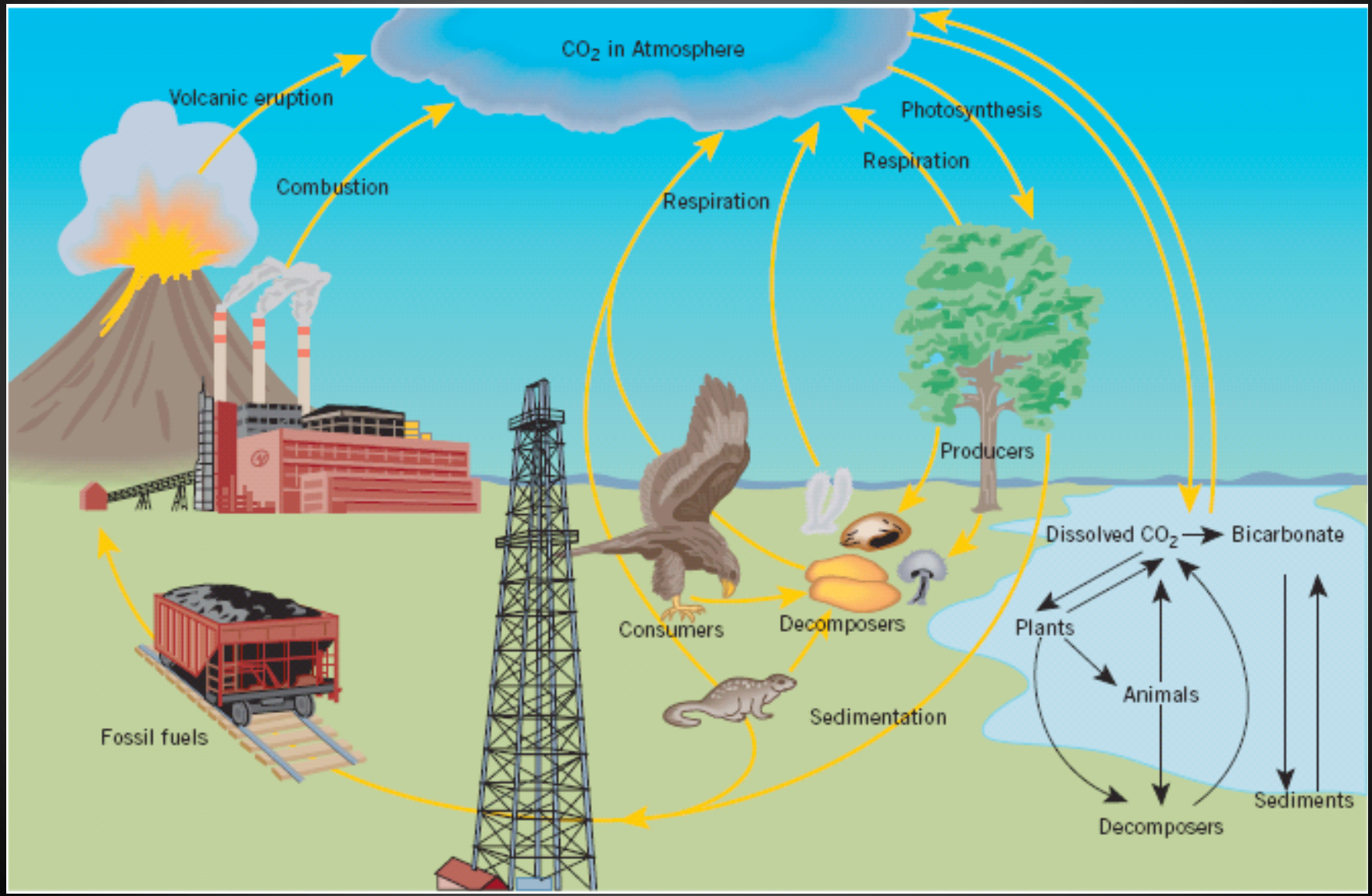


CARNEGIE INSTITUTION FOR SCIENCE

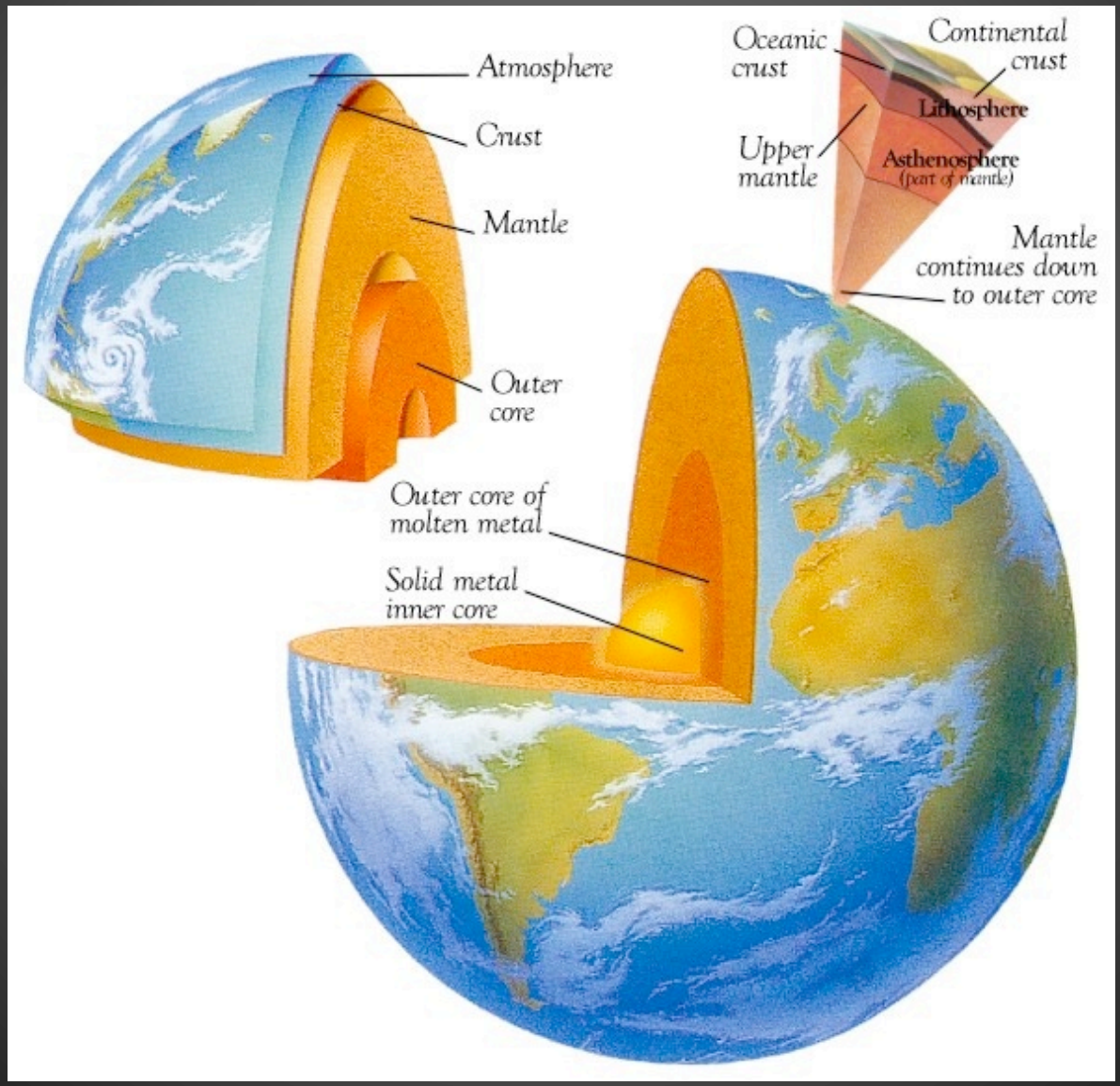
Deep Carbon Observatory

ALFRED P. SLOAN FOUNDATION 1934

The Carbon Cycle



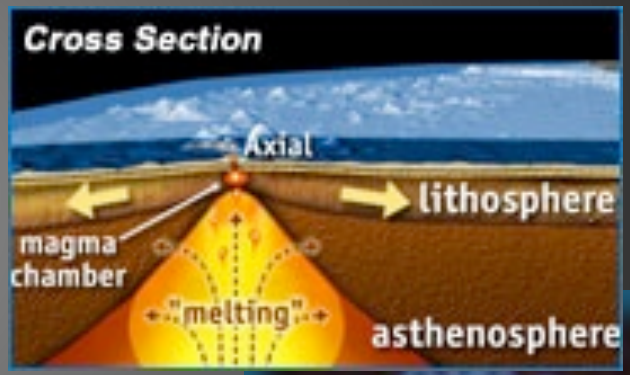
The Deep Carbon Cycle



Deep Carbon: Unanswered Questions

May 2008: We need fundamental advances in understanding Earth's deep carbon:

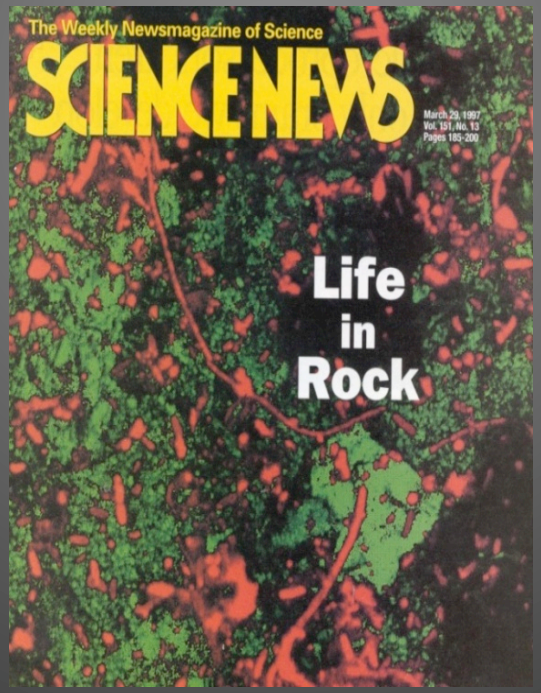
- **Where is the deep carbon & how much is there?**
- **How does carbon move among deep reservoirs and the surface?**
- **Is there a deep source of organics?**
- **What is the nature and extent of deep microbial life?**



We do not know how much carbon is stored within the Earth.

Estimates of Earth's carbon vary by a factor of >20:

- *Total from known reservoirs:* ***0.07 wt %*** [Kerridge, *Geochim. Cosmochim. Acta* (1985)]
- *Highest literature estimate:* ***1.5 wt %*** [Javoy, *Geophys. Res. Lett.* (1997)]
- *Average carbonaceous chondrites:* ***3.2 wt. %*** [Mason, *USGS Prof Paper* (1979)]

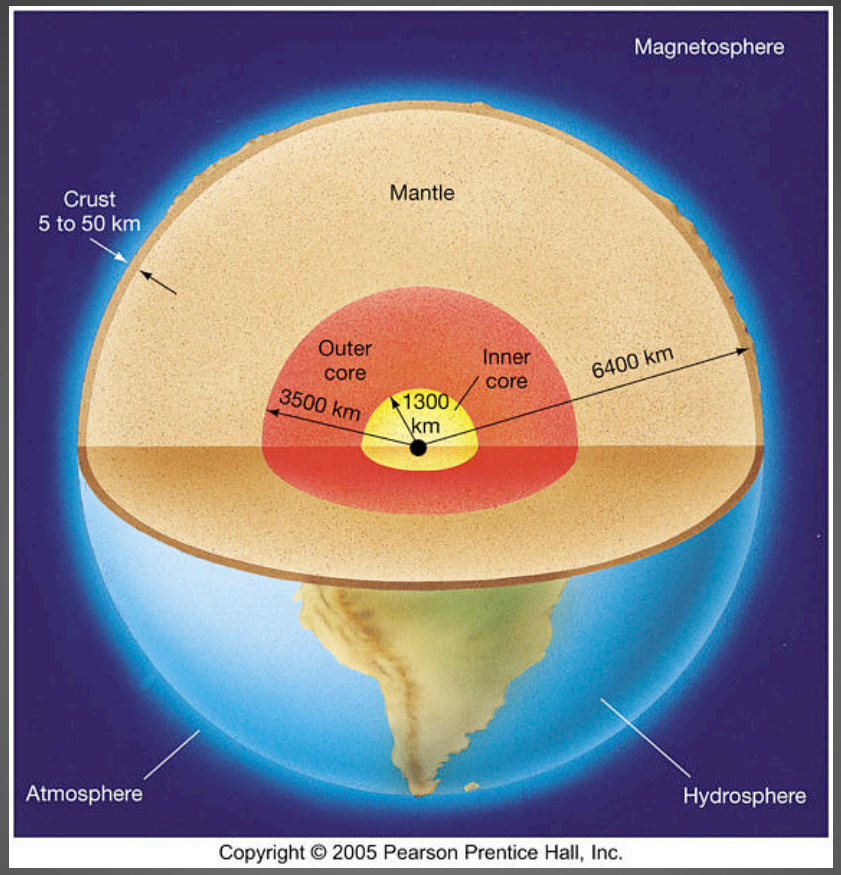


How much & where is Earth's carbon?

Atmospheric CO_2: 380 ppm

Crust: 200 ppm

Mantle: ? ppm



Seawater C: 30 ppm

Continental crust: 4000 ppm

Core: ? ppm

- *Where is Earth's carbon?*
- *How much is there?*
- *What are carbon speciation and phases?*

We do not know how much carbon is stored in Earth's deep interior.

Reservoir	Composition	Structure	Atom % C	Depth	Abundance
Diamond	C	diamond	100	> 150 km	<< 1%
Graphite	C	graphite	100	< 150 km	<< 1%
Carbonates	$(Ca,Mg,Fe)CO_3$	unknown	20	0 to ???	???
Carbides	SiC, FeC, Fe_3C	moissanite, cohenite	50 ???	???	
Metal	Fe,Ni	kamecite/awaurite	minor ???	???	???
Silicates	Mg-Si-O	various	trace ???	???	???
Oxides	Mg-Fe-O	various	trace ???	???	???
Sulfides	Fe-S	various	trace ???	???	???
Silicate melts	Mg-Si-O	--	trace ???	???	???
CHON fluids	C-H-O-N	--	variable	???	???
Methane	CH_4	--	20	???	???
Clathrates	*e.g.*, $[H_2O+CH_4]$	clathrate	variable	???	???
Hydrocarbons	C_nH_{2n+2}	--	variable	???	???
Organic Species	C-H-O-N	--	variable	???	???
Deep Life	C-H-O-N-P-S	--	variable	< 15 km	???

- ***The nature of these deep repositories is not known.***

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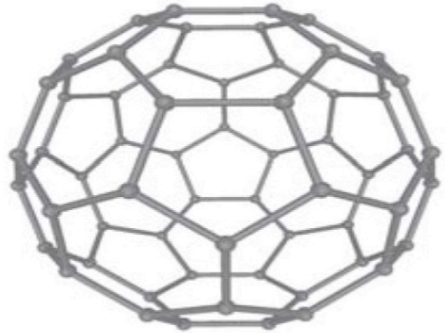
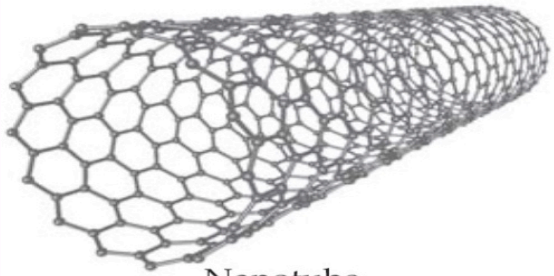
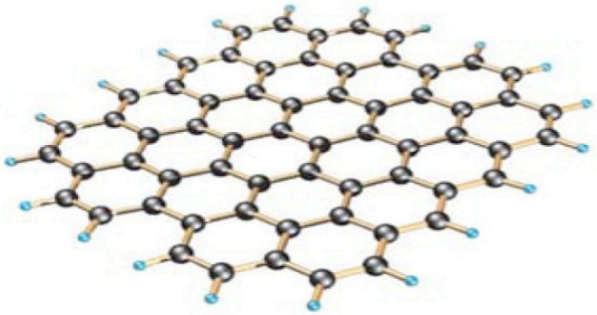
Carbon exhibits rich polymorphism, regimes of stability and metastability, and dimensionality.



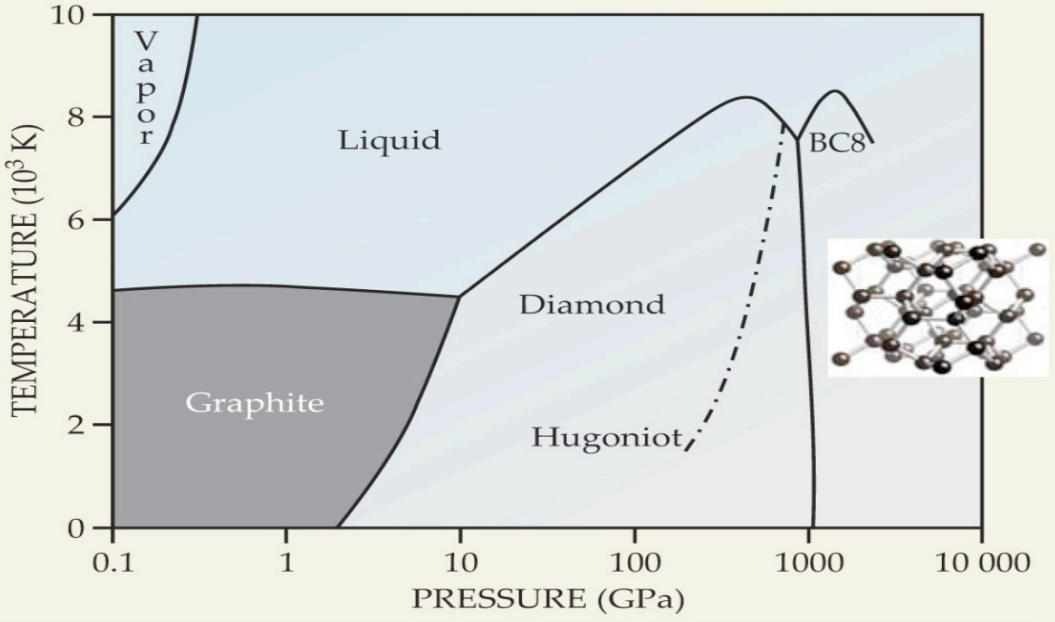
Fullerene

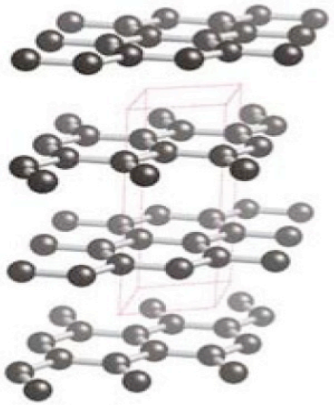


Nanotube

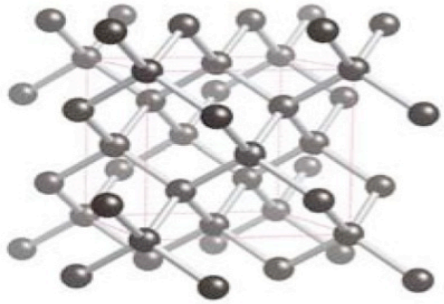


Graphene





Graphite



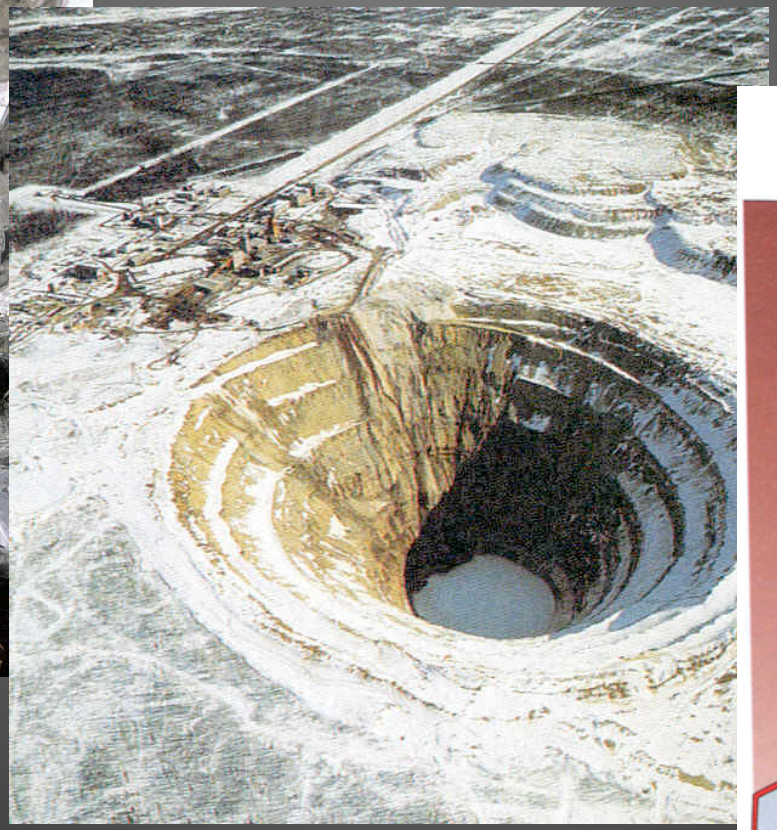
Diamond

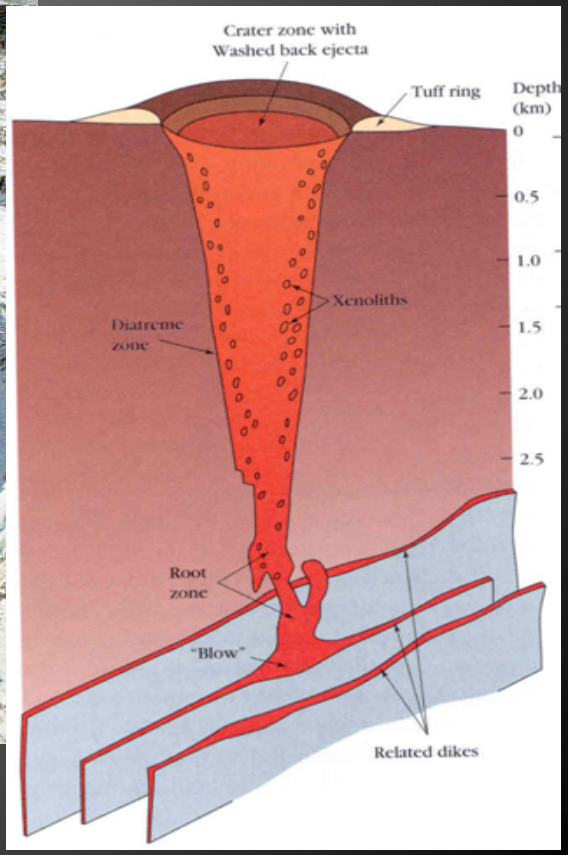
[Hemley, Crabtree & Buchanan, *Physics Today* (2009)]

Carbon in the Mantle – Diamonds

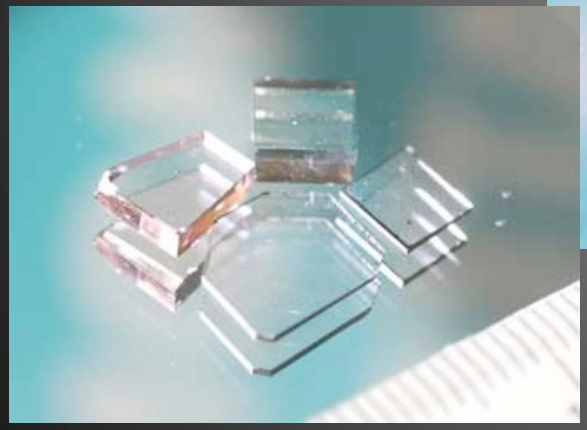
How do diamonds form?

By what mechanism do they reach Earth's surface?





Geophysical Lab advances in diamond technology



Design and manufacture of a new generation of supertough synthetic diamonds.

We do not know how much carbon is stored in Earth's deep interior.

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CHON fluids	C-H-O-N	--	variable	???	???
Methane	CH_4	--	20	???	???
Clathrates	*e.g.*, $[H_2O+CH_4]$	clathrate	variable	???	???
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Deep Life	C-H-O-N-P-S	--	variable	< 15 km	???

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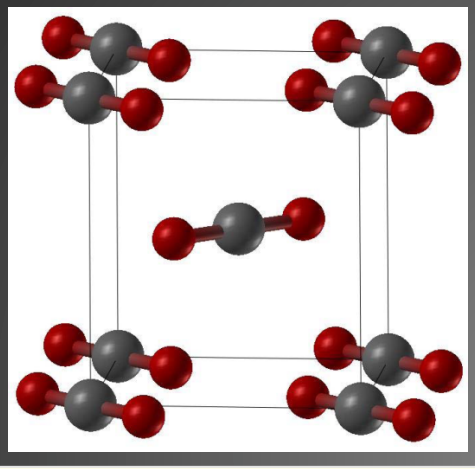
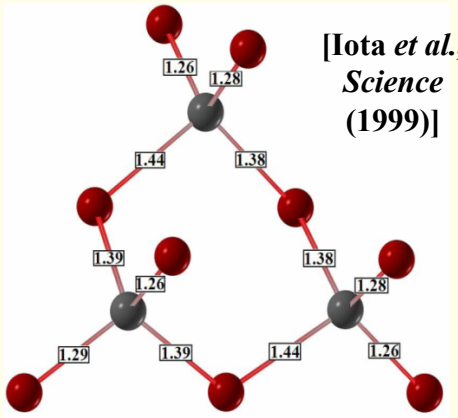
High-pressure studies reveal novel deep carbon phases: Polymeric CO_2

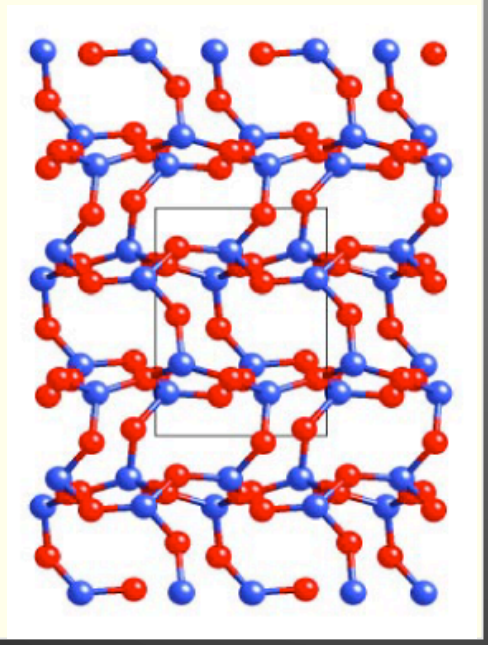
Low pressure: Molecular CO_2

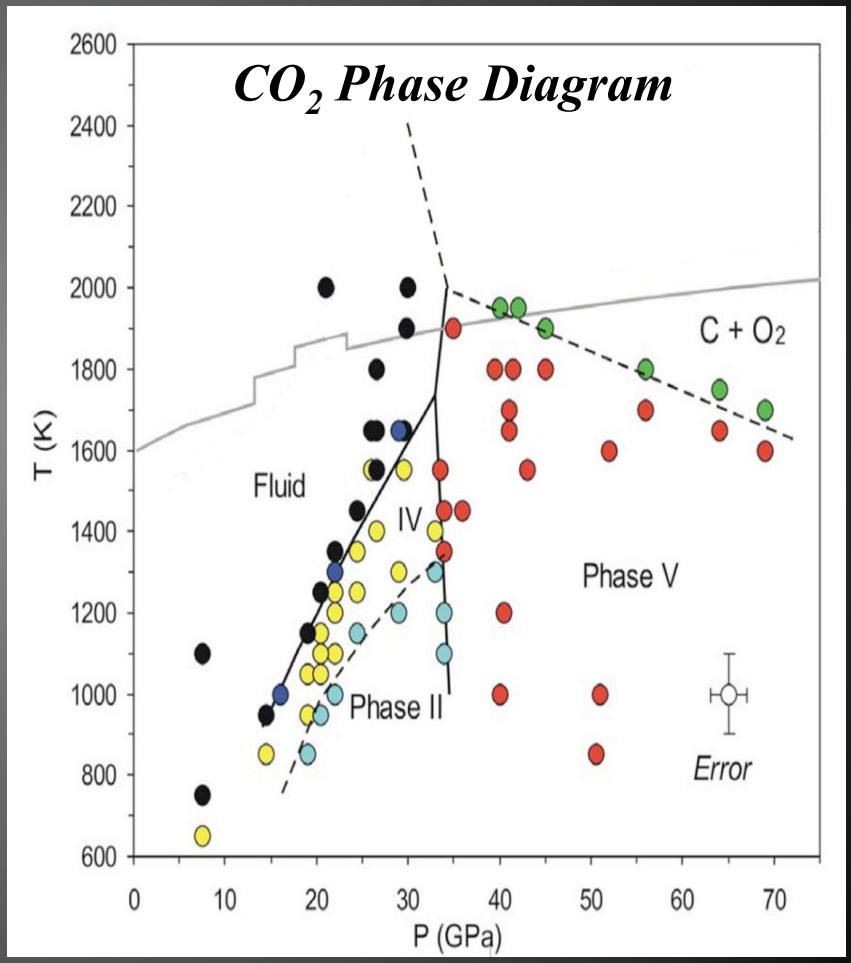


High pressure
Polymeric CO_2
silica-like structures



[Iota *et al.*, *Science* (1999)]





[Litasov et al., *submitted*]

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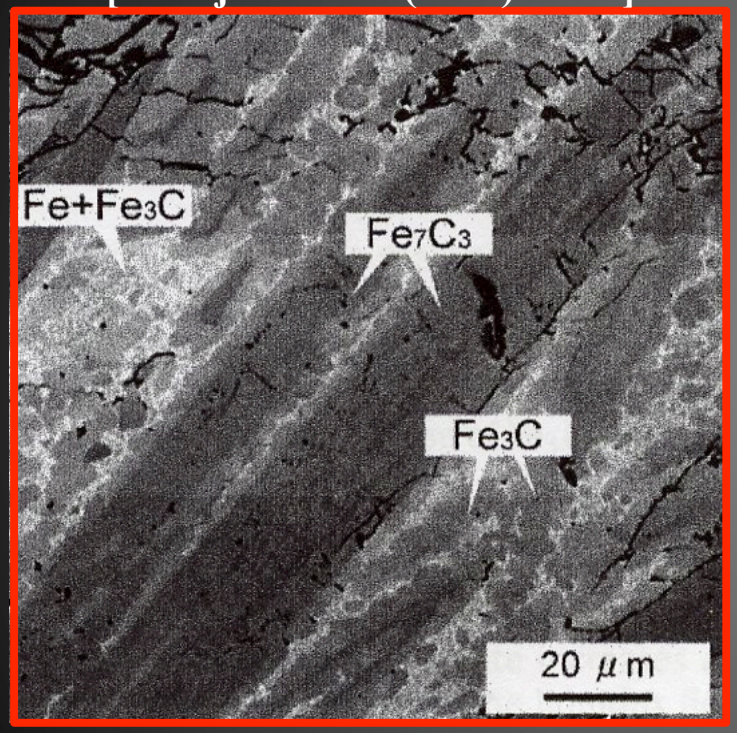
➢ ***The nature of these deep repositories is not known.***

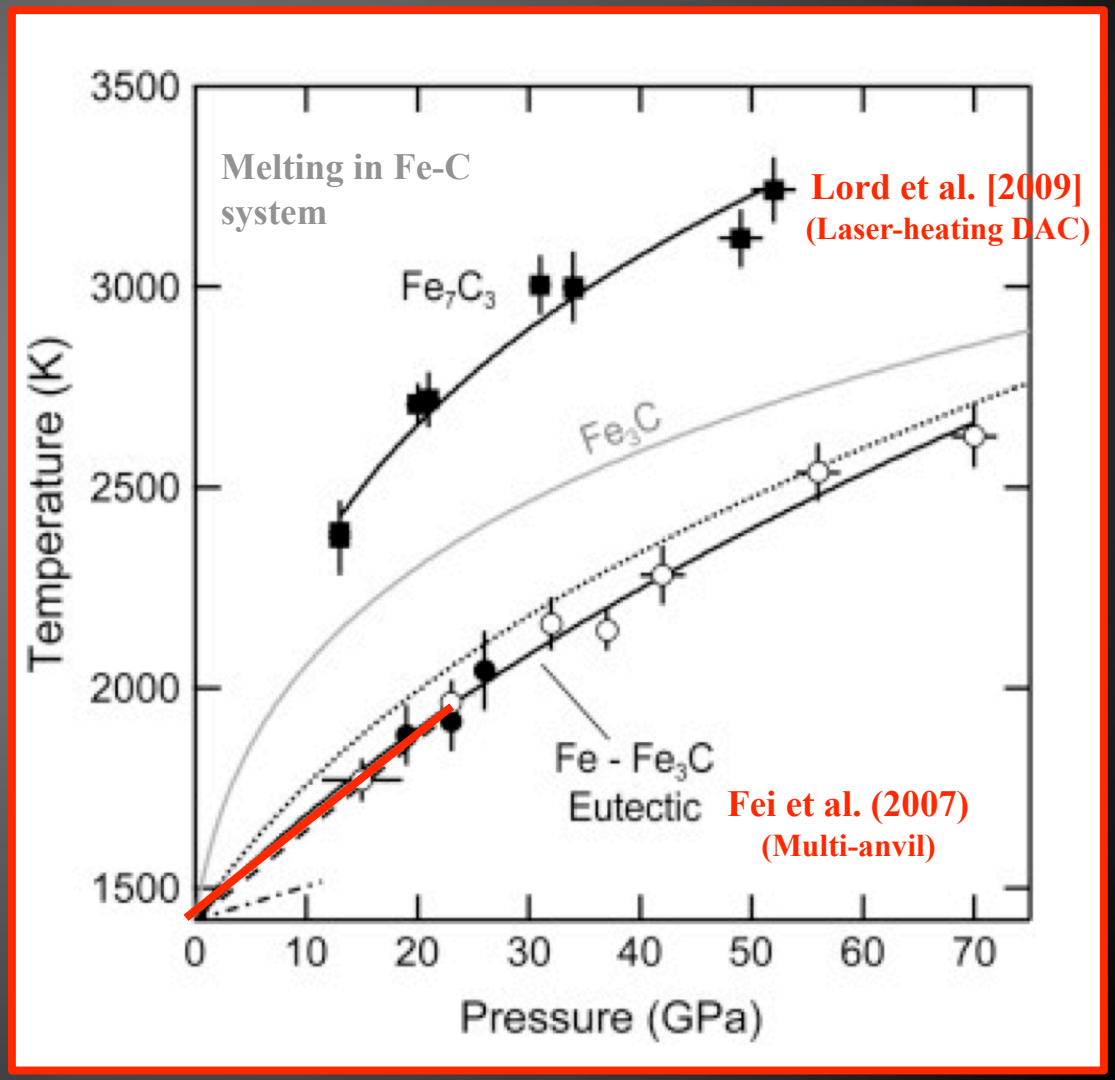
Is there carbon in Earth's core?

- 6-10% density deficit (outer core)
- ~2% density deficit (inner core)
- FeNi alloy + 8-12 wt% S, C, O, Si, H…?

[Nakajima *et al.* (2008) *PEPI*]



The search for new alloys and carbides is fundamental to understanding planetary interiors.



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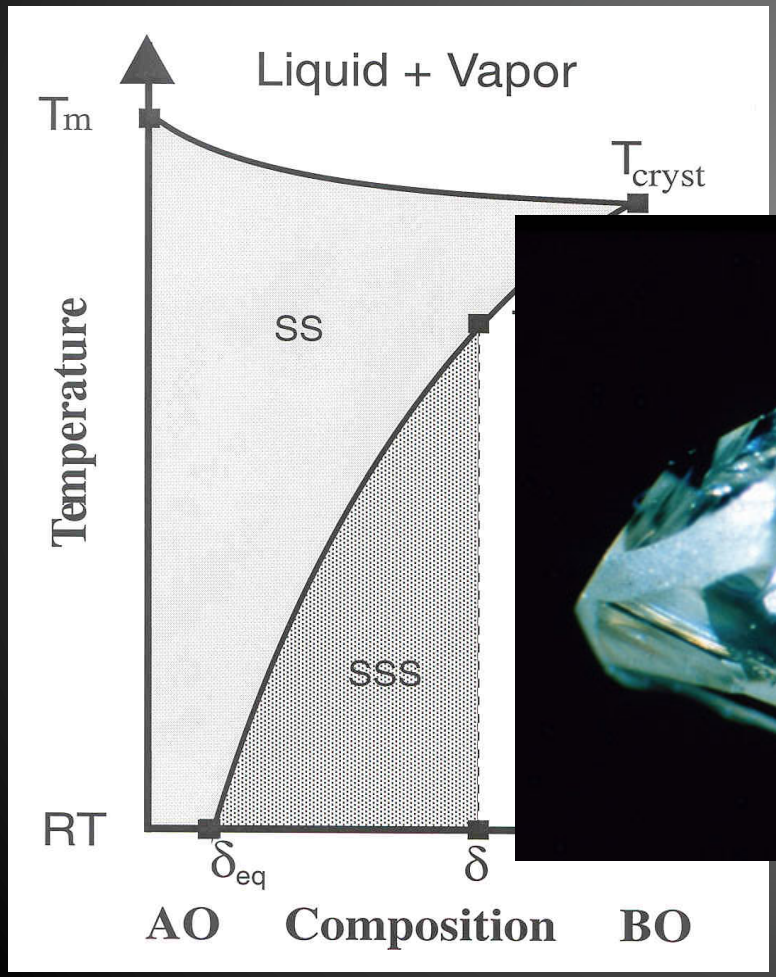
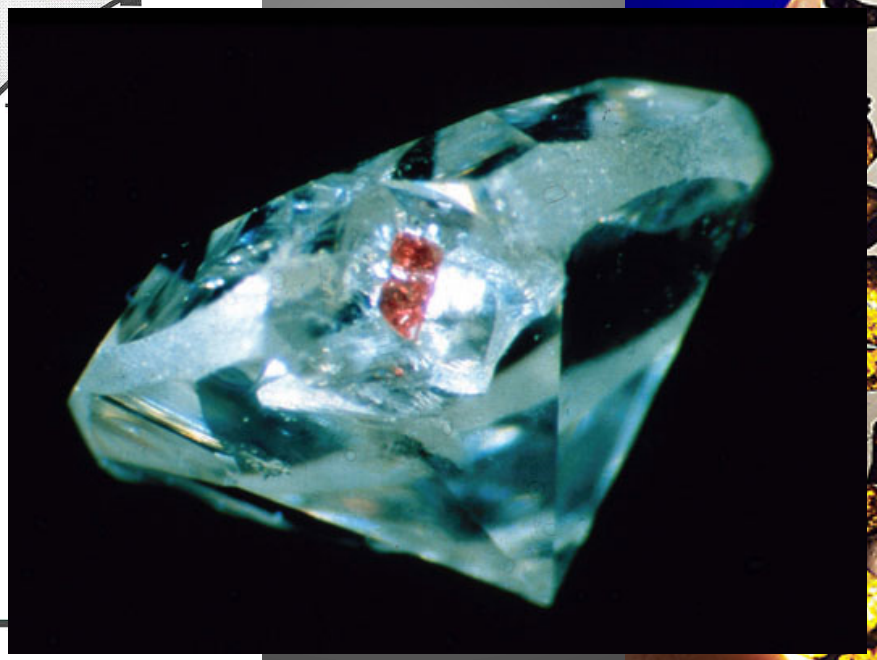
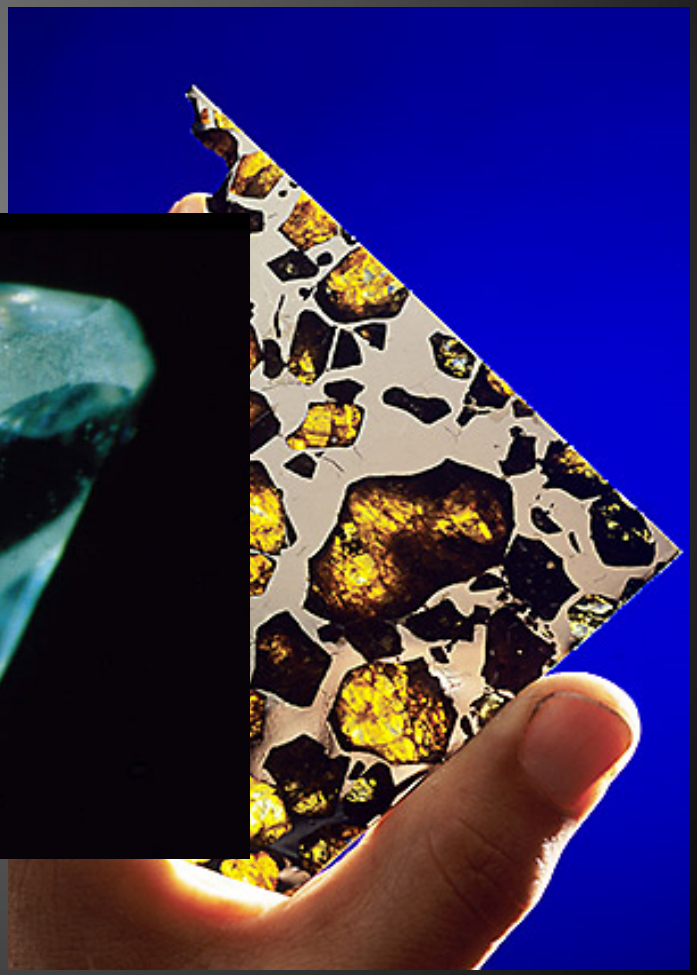
Deep Carbon Reservoirs

How much carbon can be incorporated into mantle oxides and silicates?

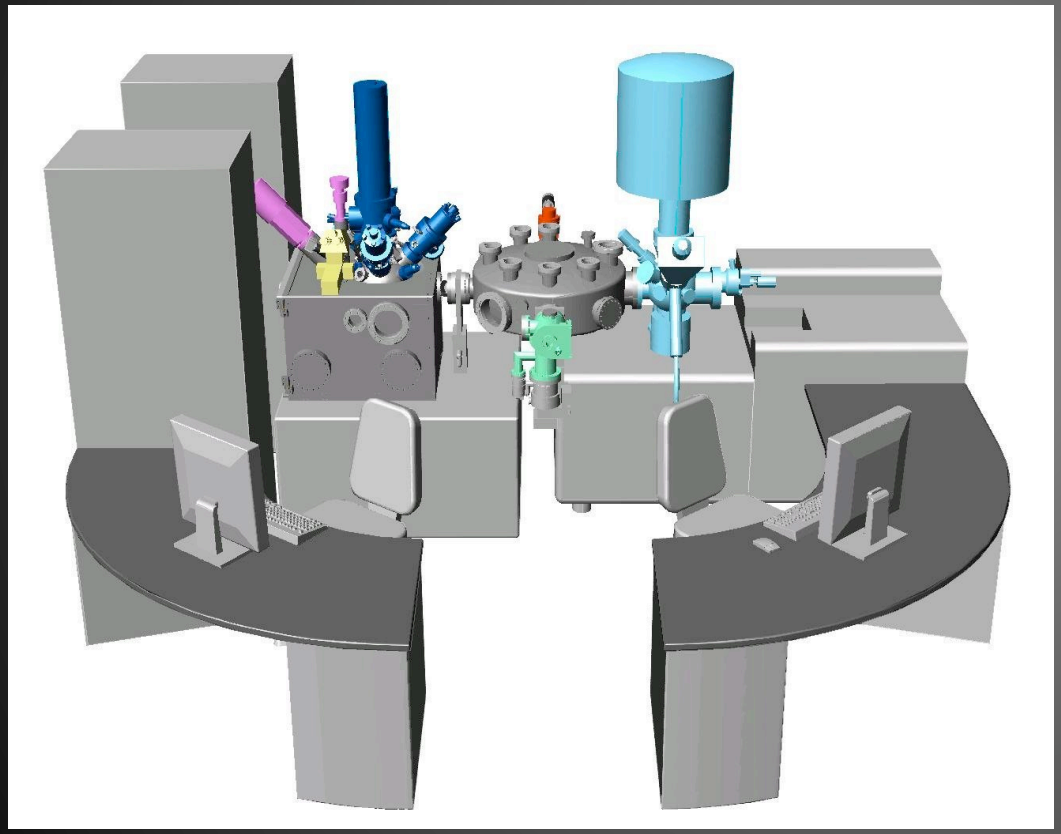






Deep Abiotic Organics – Hydrocarbons

Can we detect and characterize trace amounts of organic carbon in mantle samples and experimental runs?

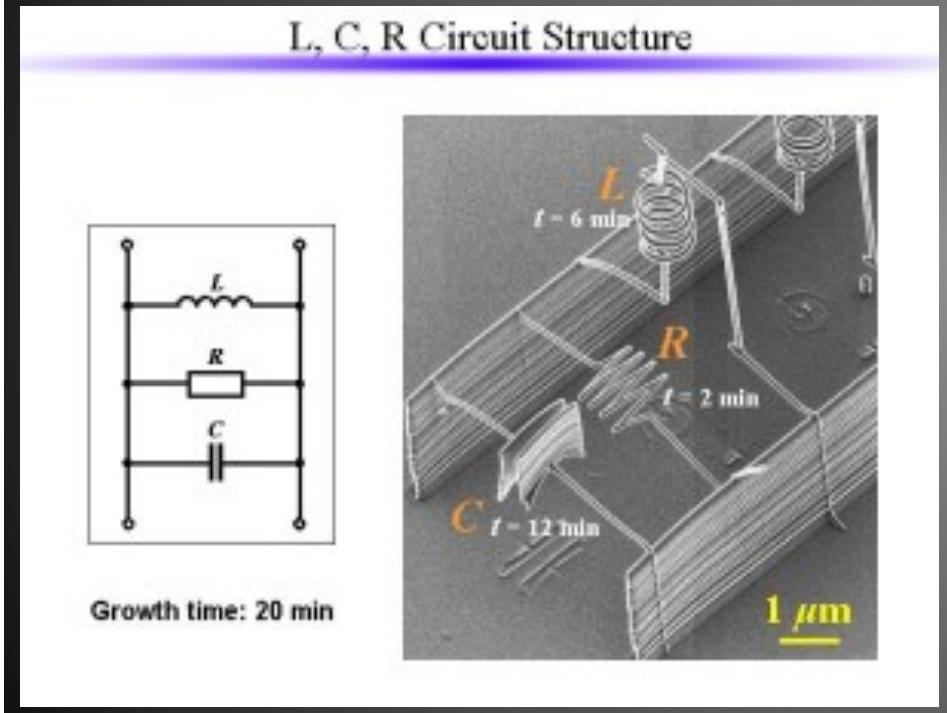


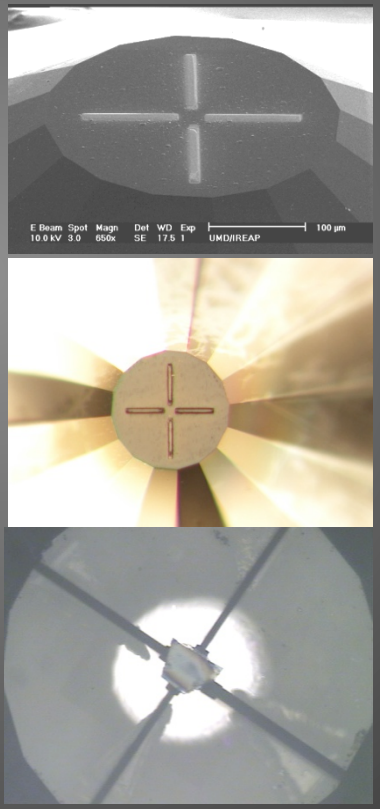
We plan to develop a nano-imaging ToF-SIMS to provide unprecedented resolution and sensitivity of minute C-bearing samples.

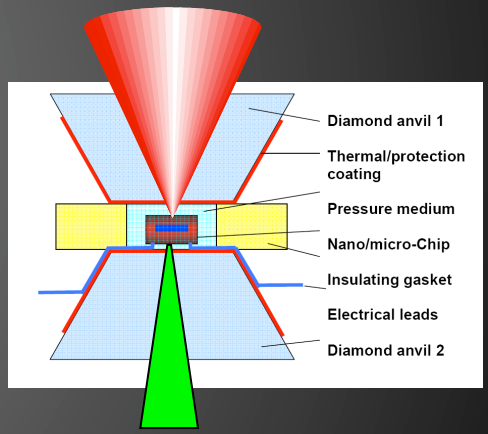
Andrew Steele et al.

Characterizing Deep Carbon Minerals

What are the properties of deep-Earth C-bearing minerals?



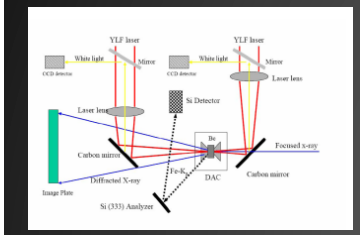




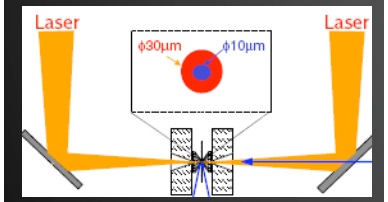
We need studies of thermochemical properties (micro- and nano-calorimetry) and transport properties

Characterizing Deep Carbon Minerals

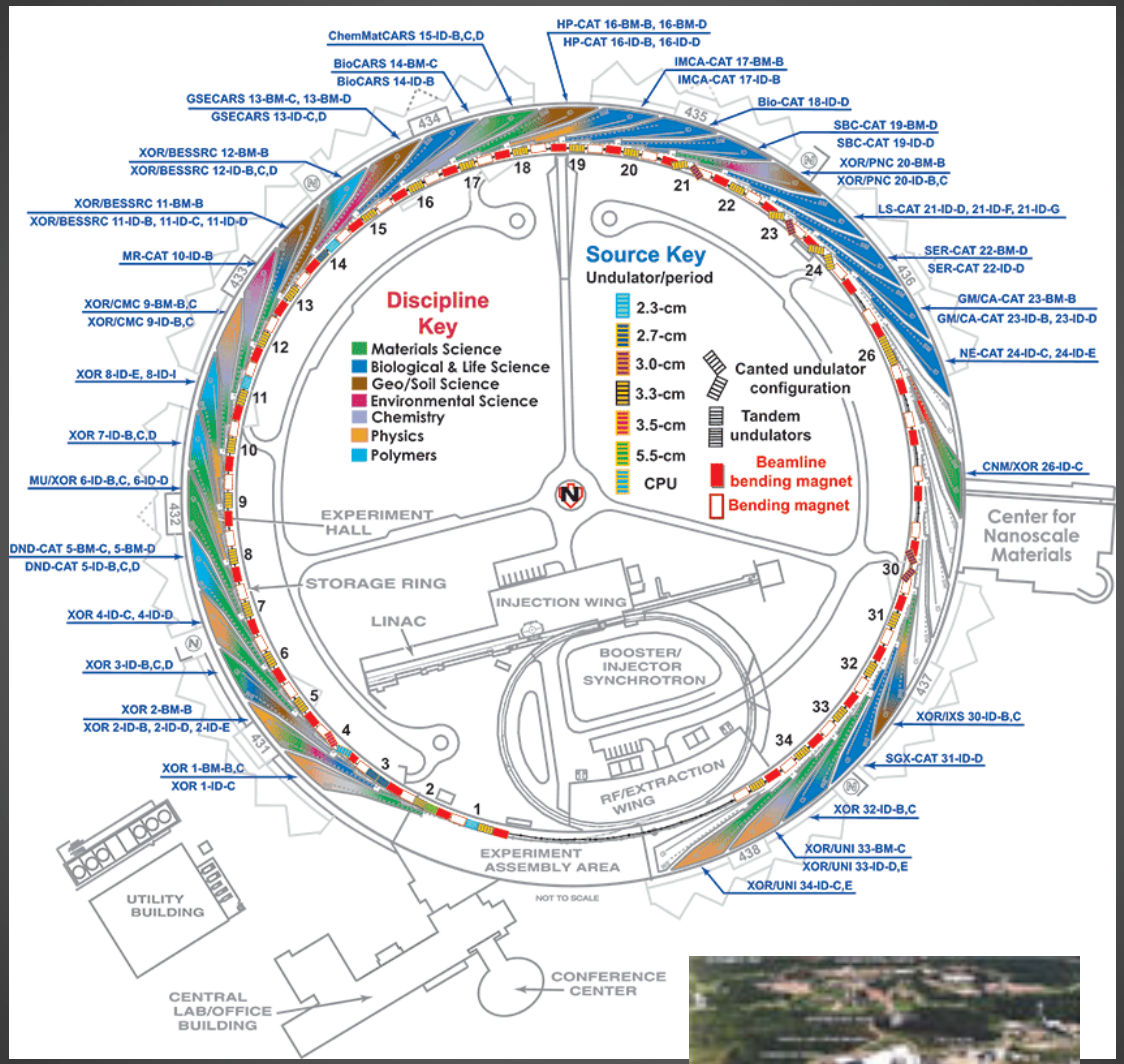
GSECARS
XES, Raman



Sector 3
NFS,
NRIXS



Sector 4
XMCD

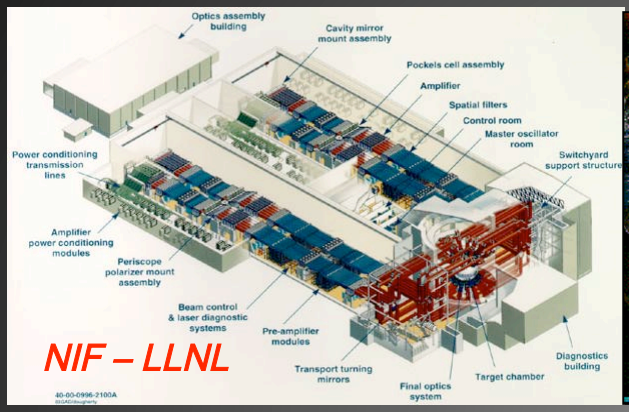


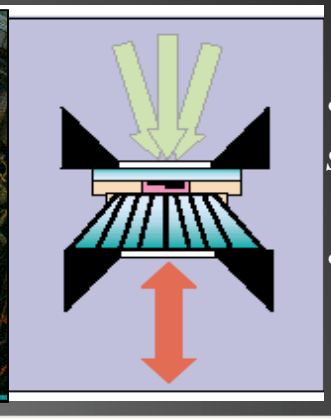
HPCAT
XES, Raman,
NFS, NRIXS

MERIX
RIXS

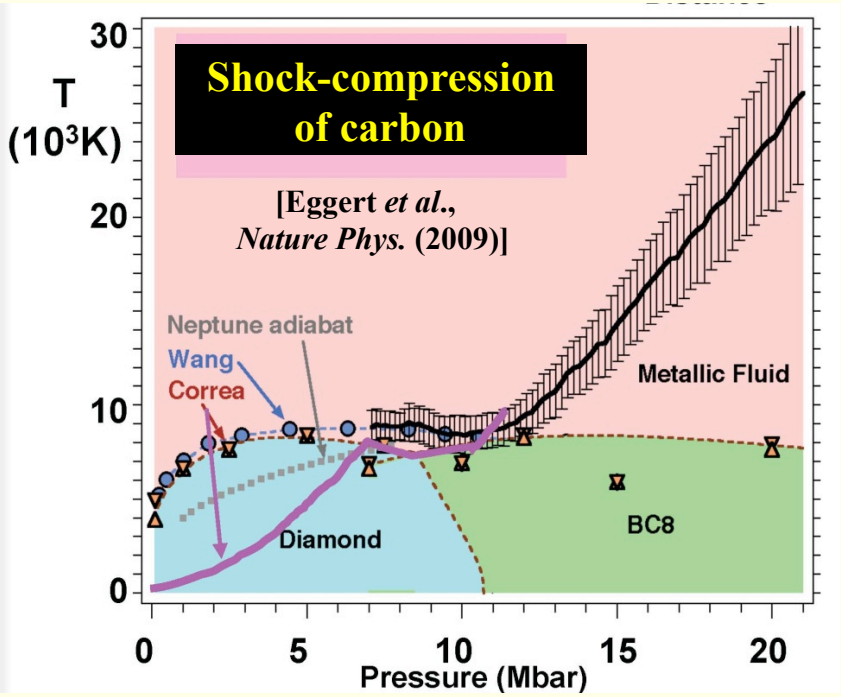
HERIX
Phonons,
quasielastic

Dynamic compression platforms will probe carbon in new regimes of stability and metastability.



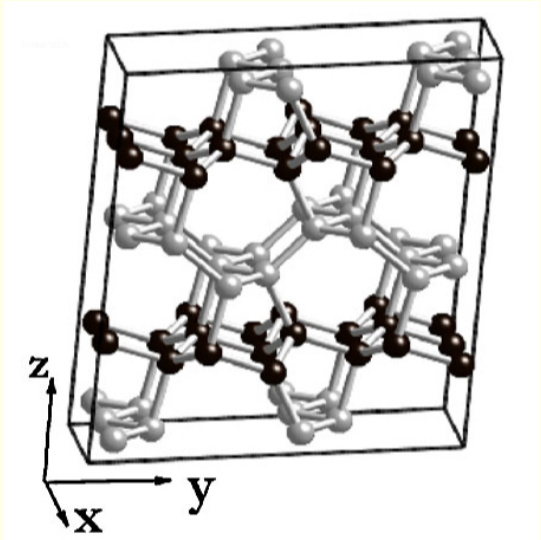


- *Combined static/dynamic*
- *Ramp compression*



- **Search for new carbon phases**

New structure at 16 GPa (theory)



[Li *et al.*, *Phys. Rev. Lett.* (2009)]

Revisit Project Mohole

Reaching Earth's mantle and recovering a pristine sample is a major scientific and technological objective of the IODP.

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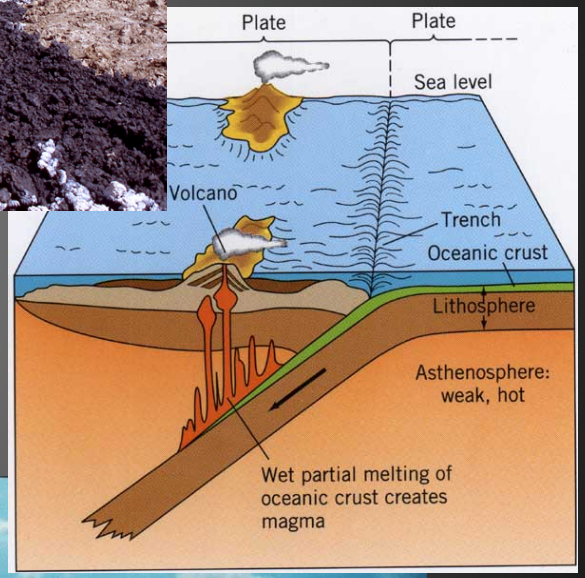
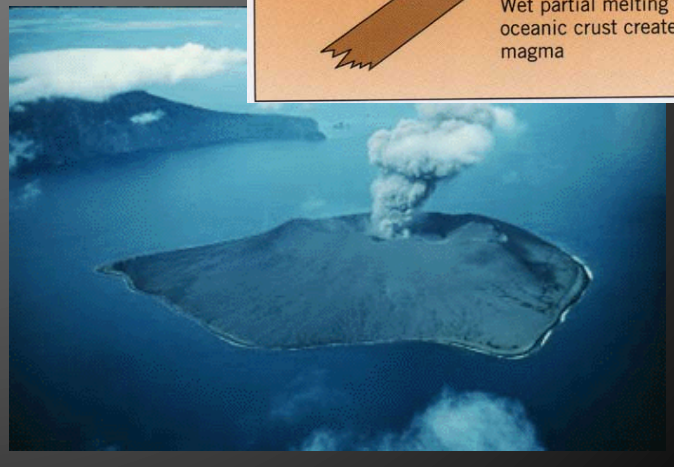
Deep Life	C-H-O-N-P-S	--	variable	< 15 km	???

➢ ***The nature of these deep repositories is not known.***

The extent to which carbon moves to and from Earth's surface at subduction zones is not known.

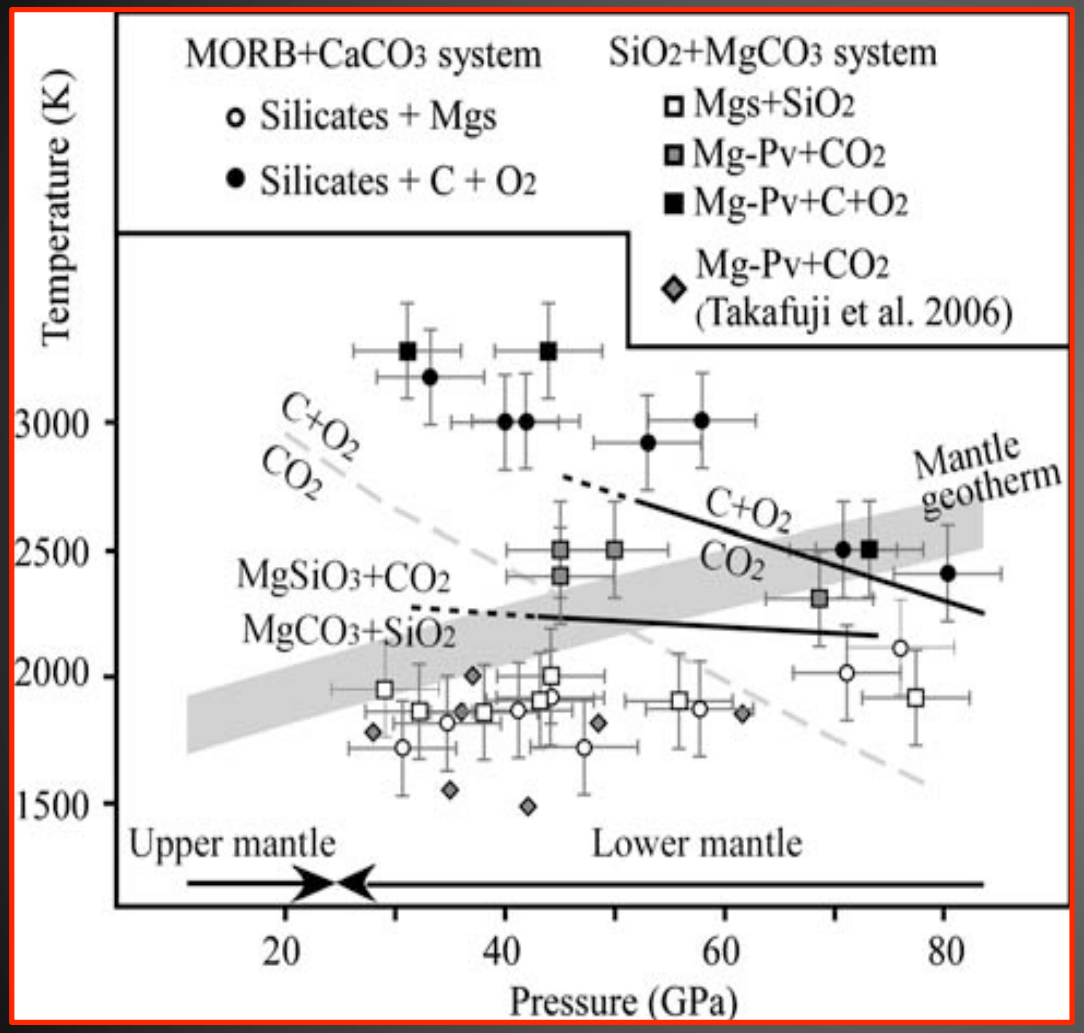


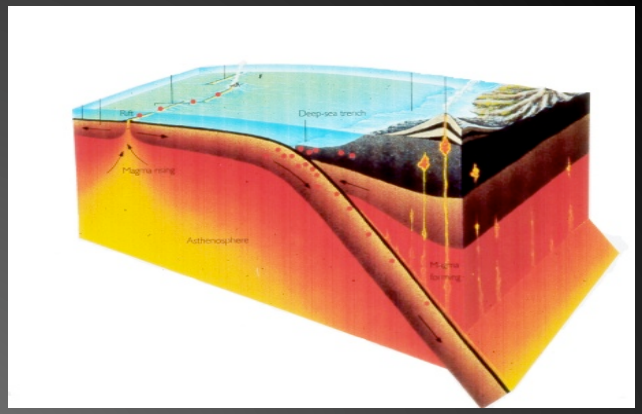


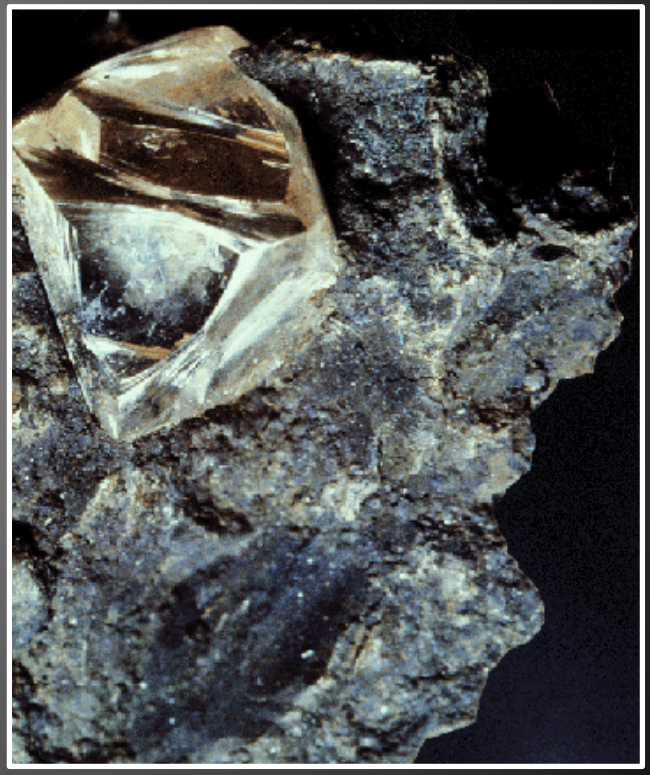
Estimates of the % subducted carbon flux returning to the surface ranged from 2% to 75%

[*Sloan Deep Carbon Workshop Report* (2008)]

High *P-T* experiments reveal that carbonates may not decompose in subducting slabs.







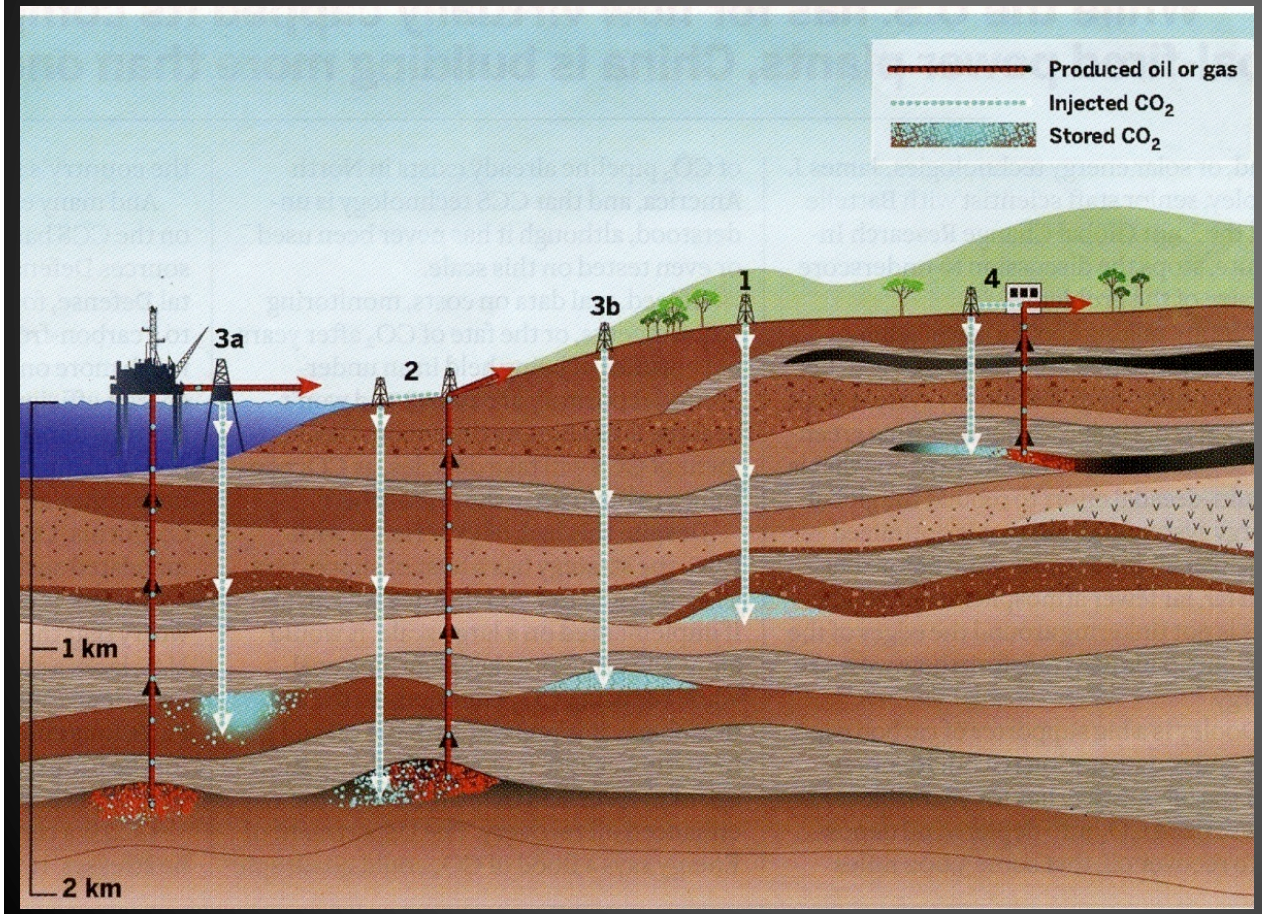
CO_2 may persist in the subducted slab.

[Seto et al. *Phys Chem. Minerals* (2008)]

This CO_2 may be a source of diamonds

Deep CO_2 Sequestration

What is the mechanism and rate of carbonate formation?

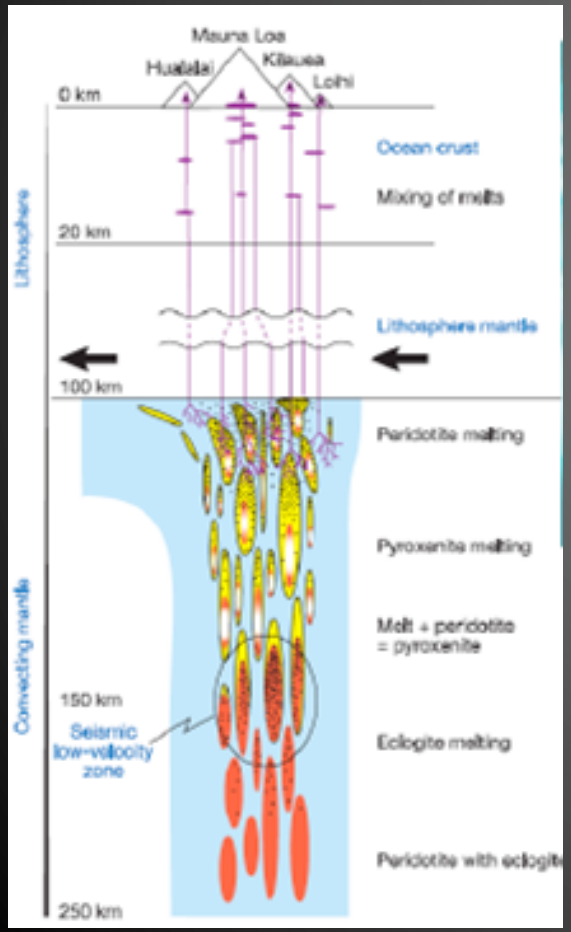


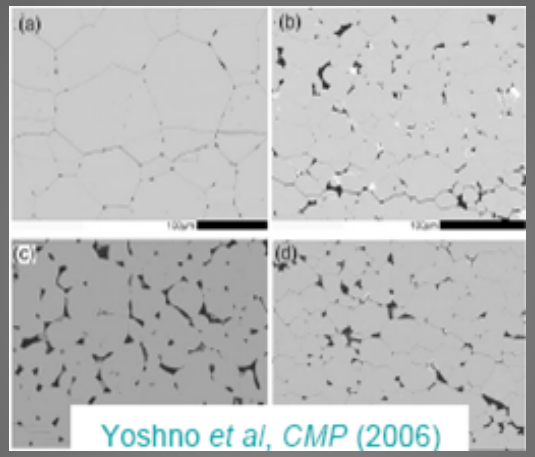
DRIVING CO_2 UNDERGROUND

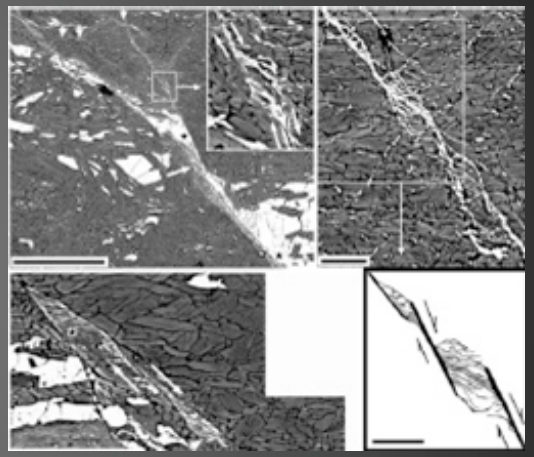
Current capacity = 10^4 gigatons CO_2

Deep Carbon Fluxes

How do methane, CO_2 and other volatiles move through Earth's deep interior?



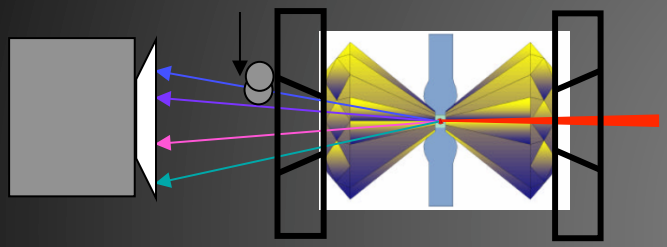




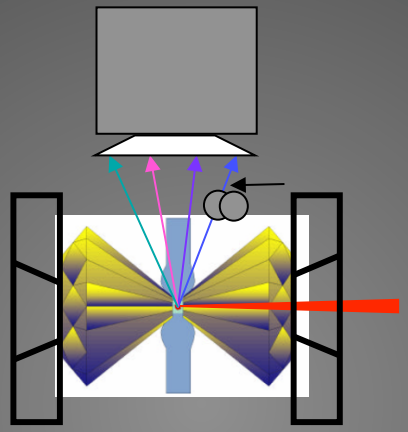
We hope to develop an X-ray nanoscope to explore 3D tomography with 30-nm resolution for exploring fluid-rock interactions in Earth's deep interior.

Nanoscale imaging of hetereogeneous materials

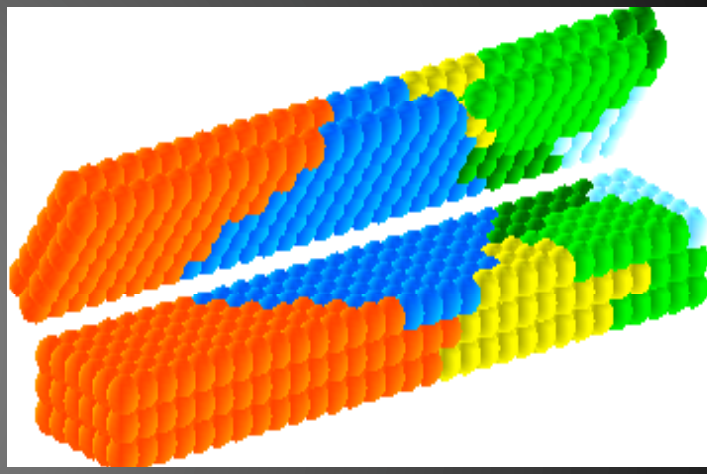
3-D grain boundary mapping



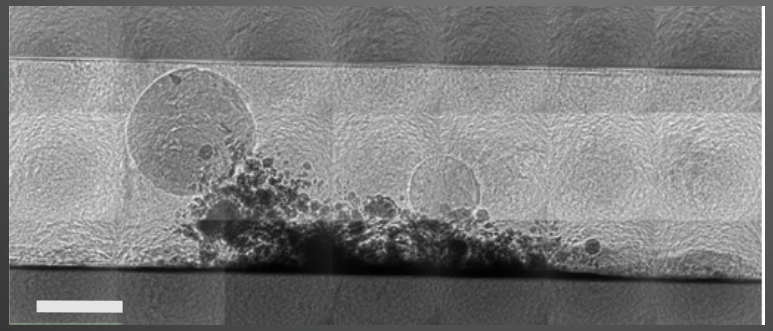
Forward x-ray diffraction with high energy x-ray beams



High resolution with medium energy x-ray beams



Example of 3-D grain boundary mapping at ambient condition



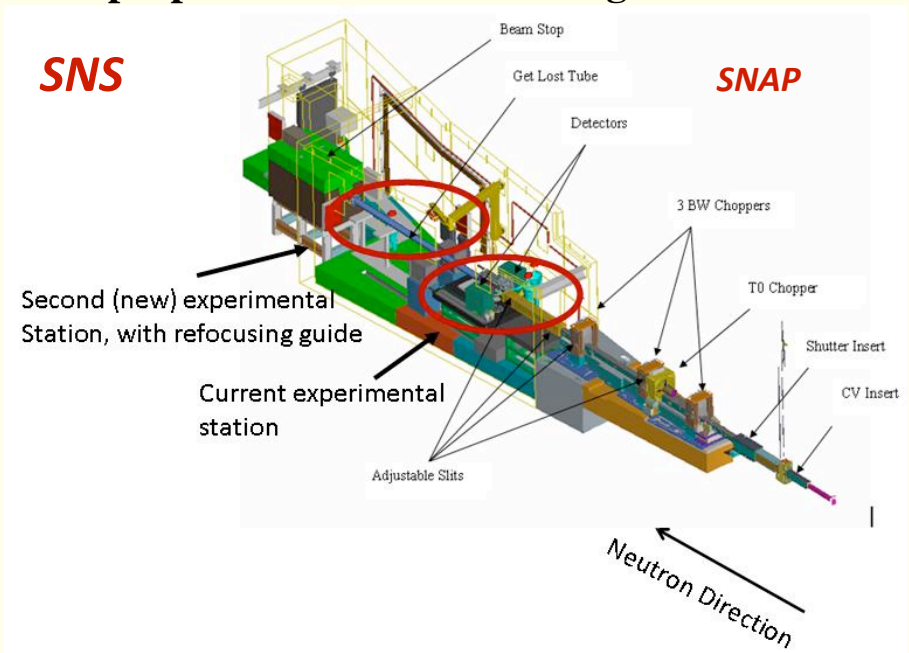
20um

Nano-imaging (TXM)

- 30 nm in 3-D
- Individual grains
- EoS of amorphous, liquid, crystals
- interaction under P

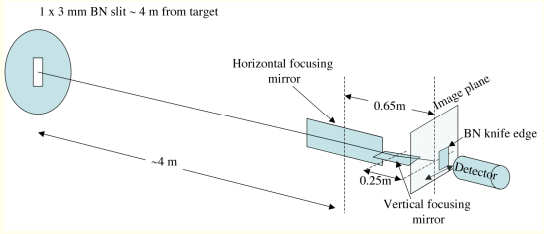
Understanding high *P-T* fluids and fluid-rock interactions requires advanced neutron scattering techniques.

- **Direct measurements of high *P-T* structure and properties of carbon-bearing fluids**



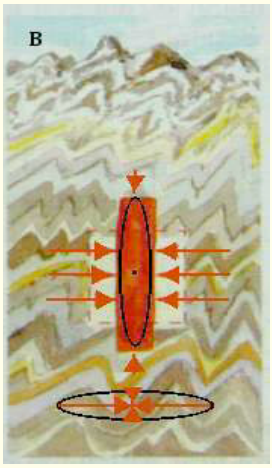
A second experimental station is ideally suited to accommodate a large 1500 tonne multi-anvil press or a dedicated liquids and amorphous extreme environment diffractometer

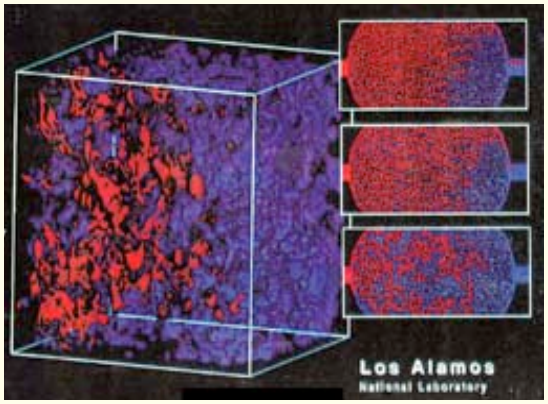
Extend focusing <100 μm



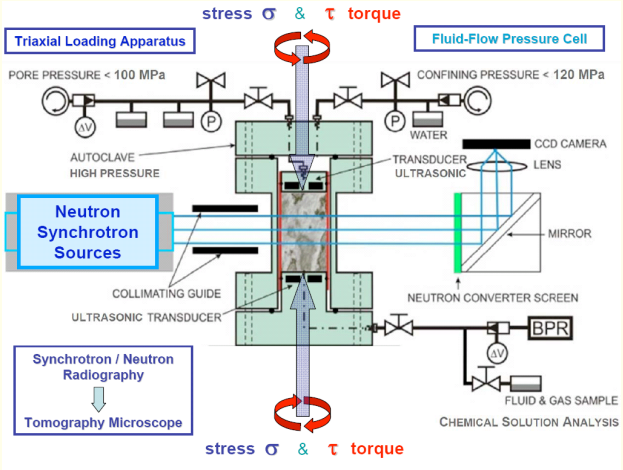
OAK RIDGE National Laboratory

- **Imaging C-O-H fluid-rock systems under extreme conditions**





Proposed Integrated Experimental Setup for Neutron Tomography and Ancillary Measurements (LANL)



Monitor Every Volcano on Earth

A combination of *in situ*, real time, web accessible measurements and satellite observations.

We do not know how much carbon is stored within the Earth

Reservoir	Composition	Structure	Atom % C	Depth	Abundance
Diamond	C	diamond	100	> 150 km	<< 1%
Graphite	C	graphite	100	< 150 km	<< 1%
Carbonates	$(Ca,Mg,Fe)CO_3$	unknown	20	0 to ???	???
Carbides	SiC, FeC, Fe_3C	moissanite, cohenite	50 ???	???	
Metal	Fe,Ni	kamecite/awaurite	minor ???	???	???
Silicates	Mg-Si-O	various	trace ???	???	???
Oxides	Mg-Fe-O	various	trace ???	???	???
Sulfides	Fe-S	various	trace ???	???	???
Silicate melts	Mg-Si-O	--	trace ???	???	???
CHON fluids	C-H-O-N	--	variable	???	???
Methane	CH_4	--	20	???	???
Clathrates	*e.g.*, $[H_2O+CH_4]$	clathrate	variable	???	???
Hydrocarbons	C_nH_{2n+2}	--	variable	???	???
Organic Species	C-H-O-N	--	variable	???	???
Deep Life	C-H-O-N-P-S	--	variable	< 15 km	???

➢ ***The nature of these deep repositories is also not known.***

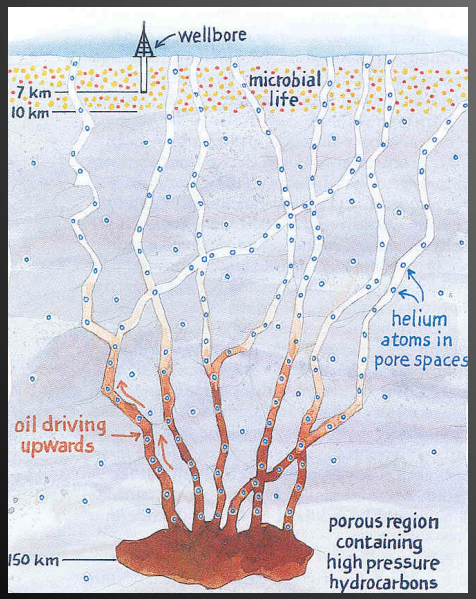
The extent of deep abiotic organic synthesis is an open question

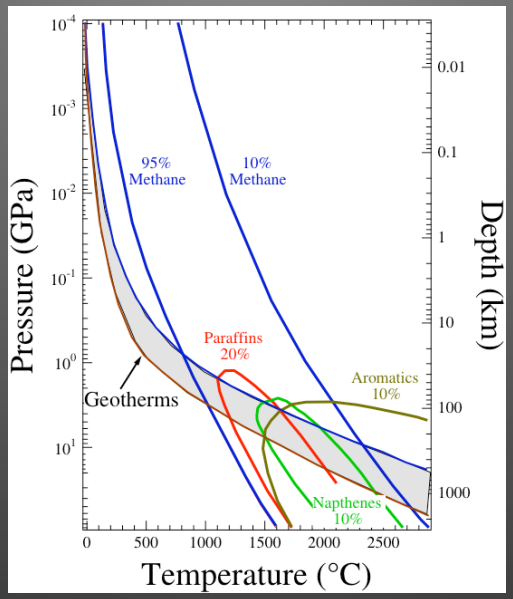
Conventional wisdom points to a predominantly biological source for the origins of deep hydrocarbons.

Nevertheless, many fundamental experiments to assess the role of deep abiotic organic synthesis have yet to be undertaken.

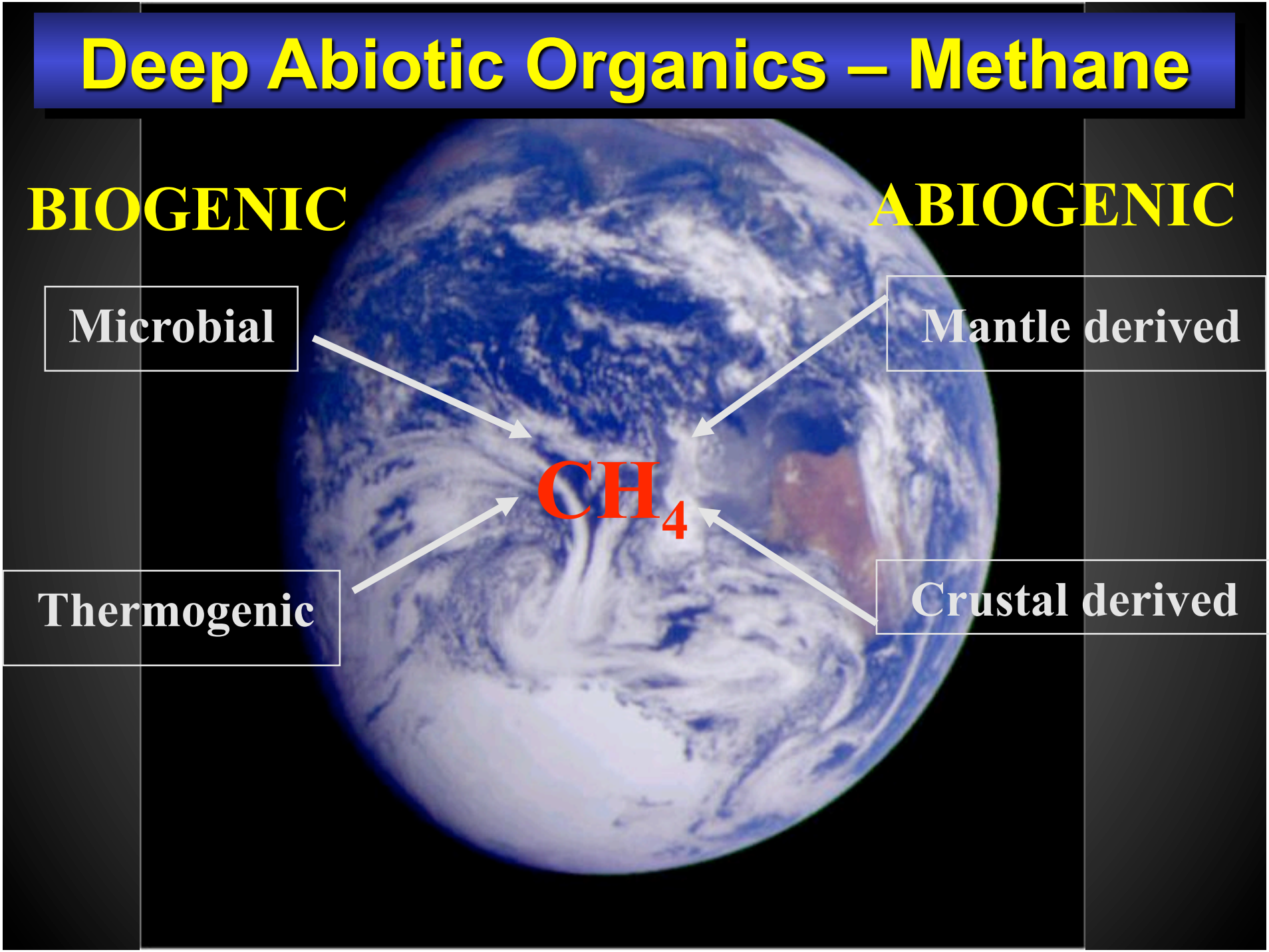
Is there a mantle source of methane and higher hydrocarbons?

Did deep organic synthesis play a role in life's origins?

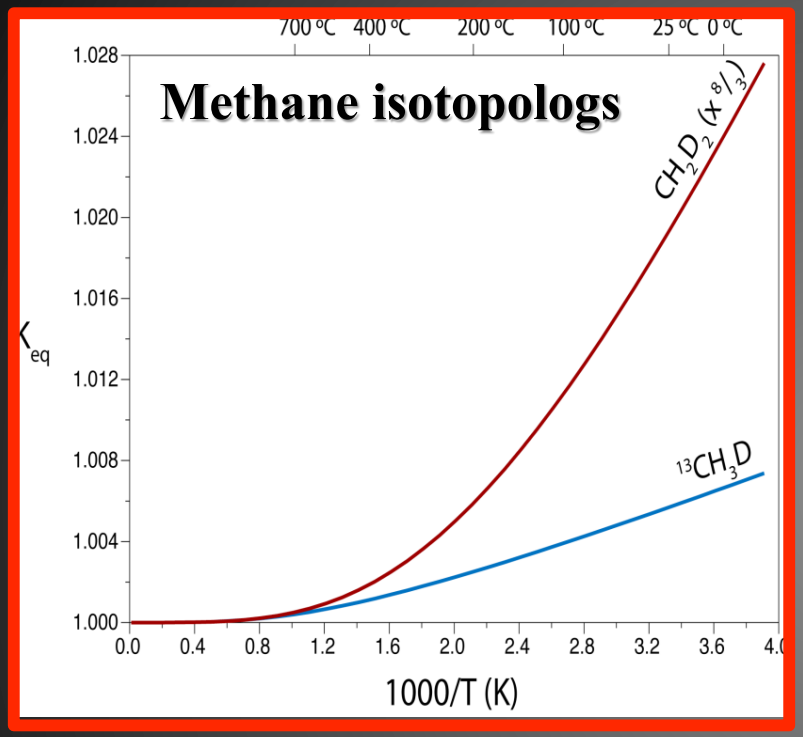




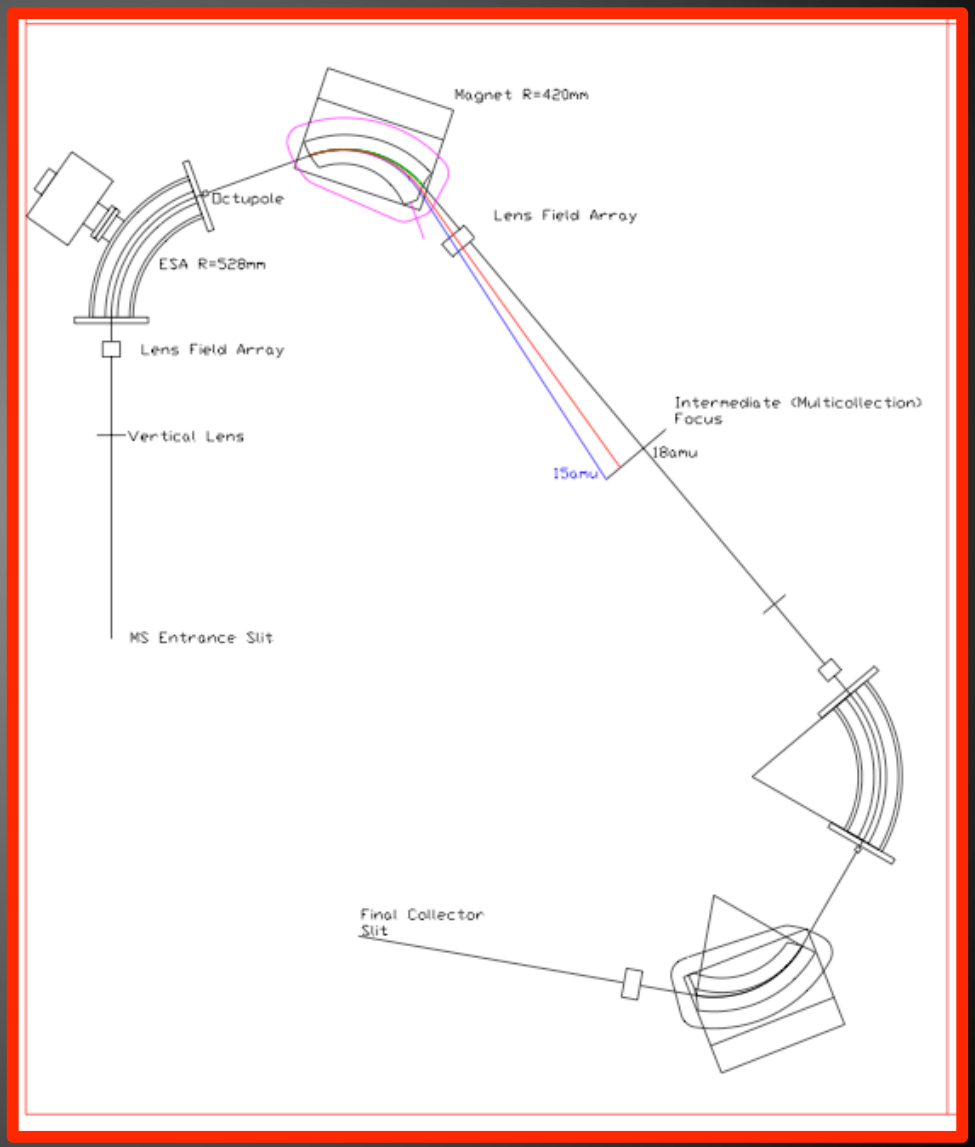
Deep Abiotic Organics – Methane



Deep Abiotic Organics – Methane

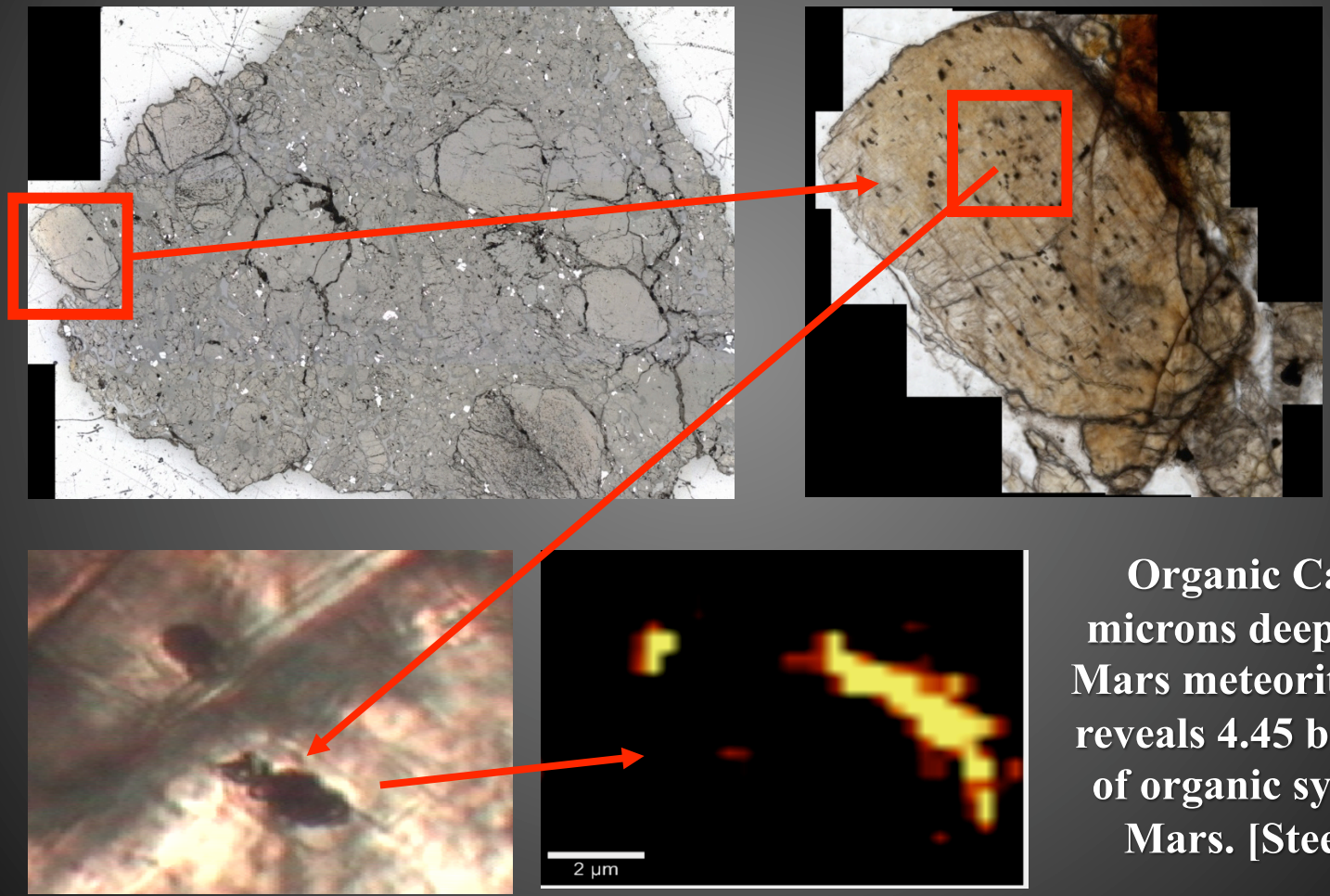


Sloan and Shell are helping to fund a high-resolution tandem mass spectrometer to measure CH_4 isotopolog ratios. This instrument is designed to distinguish biotic and abiotic methane. (Young & Rumble)



Deep Abiotic Organics – Hydrocarbons

Can we detect and characterize trace amounts of organic carbon in mantle samples and experimental runs?



Organic Carbon 4-microns deep within an Mars meteorite inclusion reveals 4.45 billion years of organic synthesis on Mars. [Steele et al.]

Confocal micro-Raman

We do not know how much carbon is stored in Earth's deep interior.

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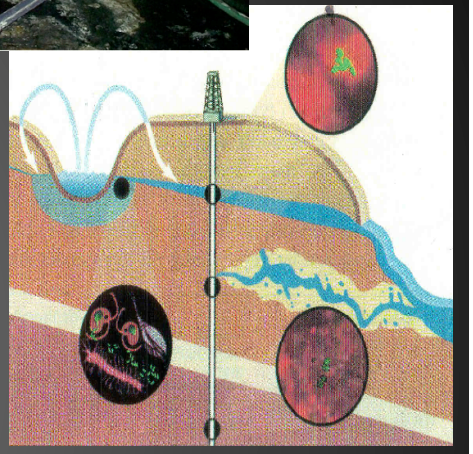
➢ ***The nature of these deep repositories is not known.***

The nature and extent of the deep microbial biosphere is unknown.

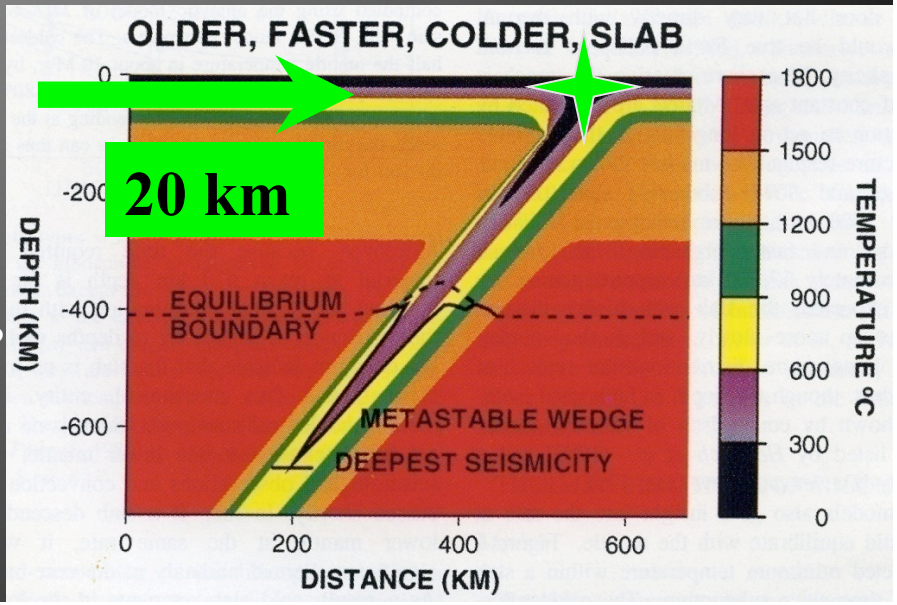
- What are the *P-T* limits of deep life?
  - *Most estimates suggest T < 130°C*
    [Kashefi & Lovley *Science*, (2003)]
  - *Recent reports hint at biological activity at T > 200°C*
    [Kelley et al. *AGU Fall Meeting*, (2004); Dong et al. (2010) China DCO meeting]



- What is the extent (biomass) of deep life?
  - *Some recent estimates exceed 50%*
    [Pfiffner et al. *Geomicrobiol J* (2006)]

- How do deep microbes survive?

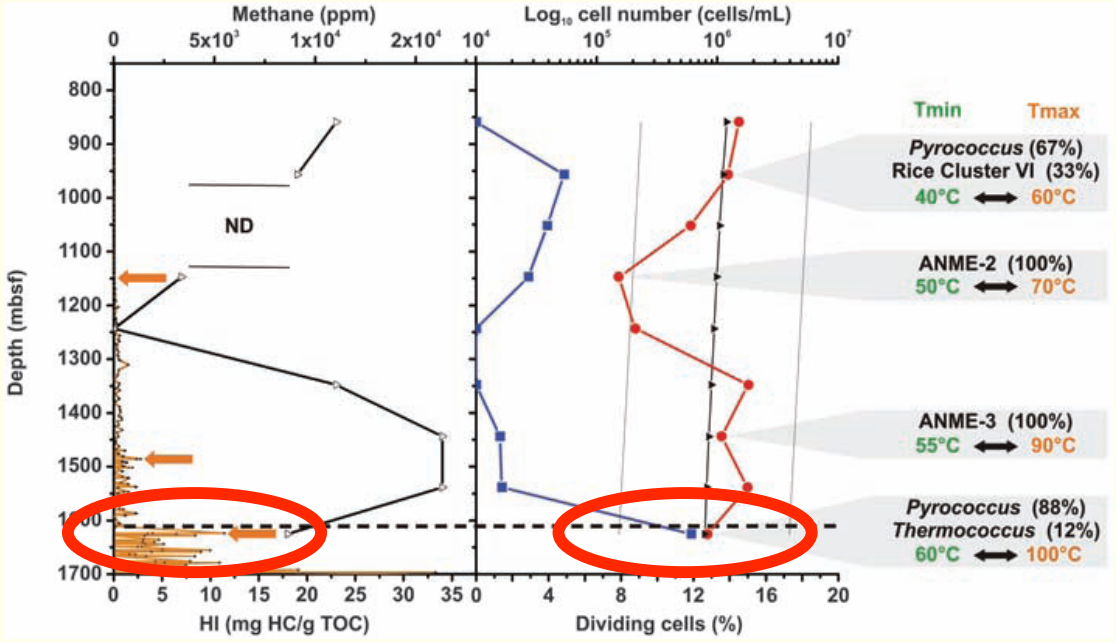
- Can we take advantage of deep life's unique biochemistry for technological applications: i.e., sequestration, remediation, or prospecting?



Ocean drilling is revealing an extremophile microbial biosphere in ancient sediments at depths greater than 1 km.

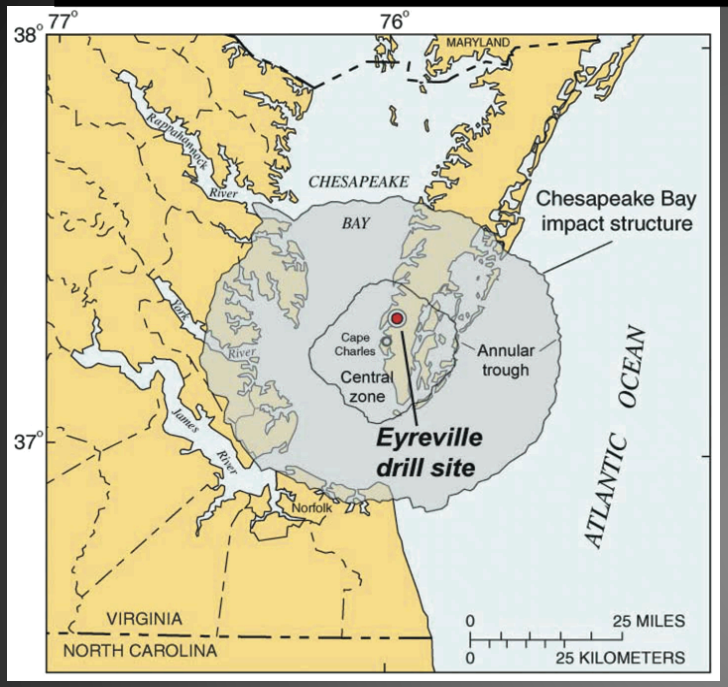
Extending the deep sub-seafloor biosphere

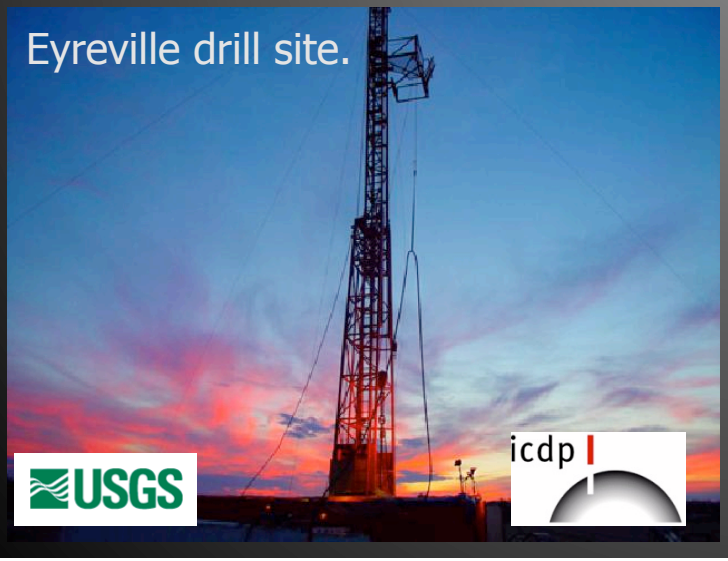
[Roussel *et al.*, *Science* (2008)]

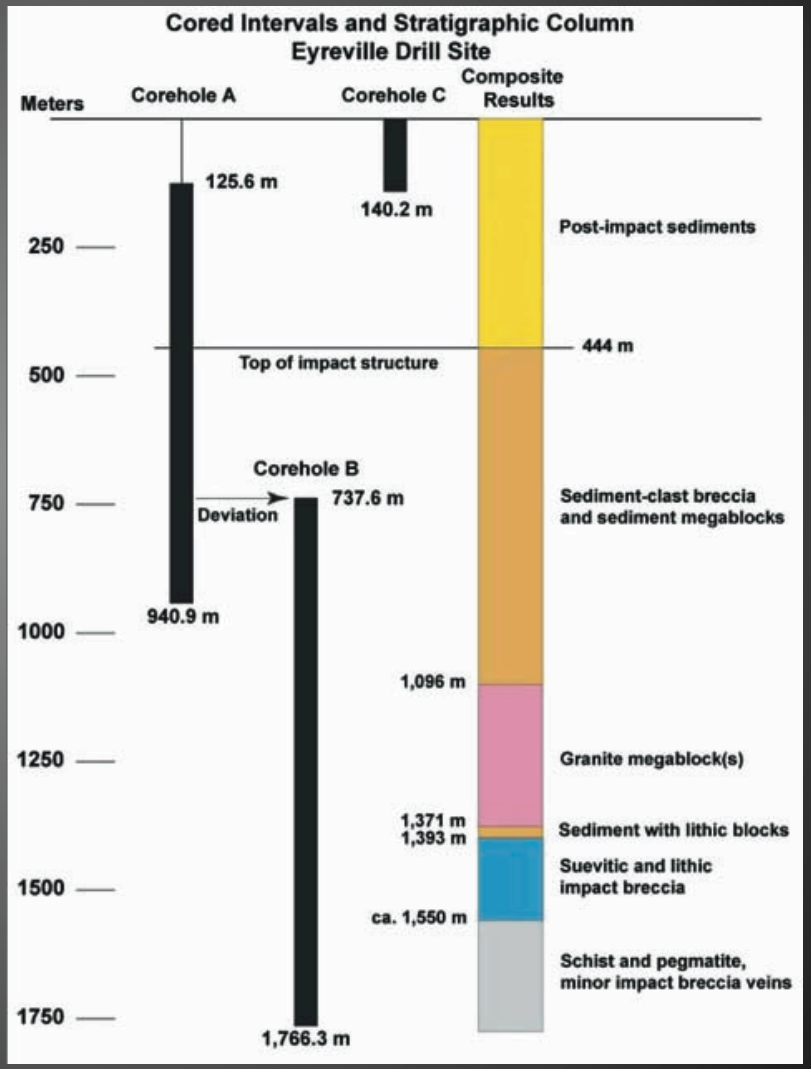


Low diversity of Archaea, dominated by *Thermococcus* and *Pyrococcus*
Anaerobic CH_4 oxidizers
111 My sediments

Deep Microbial Life – Drilling

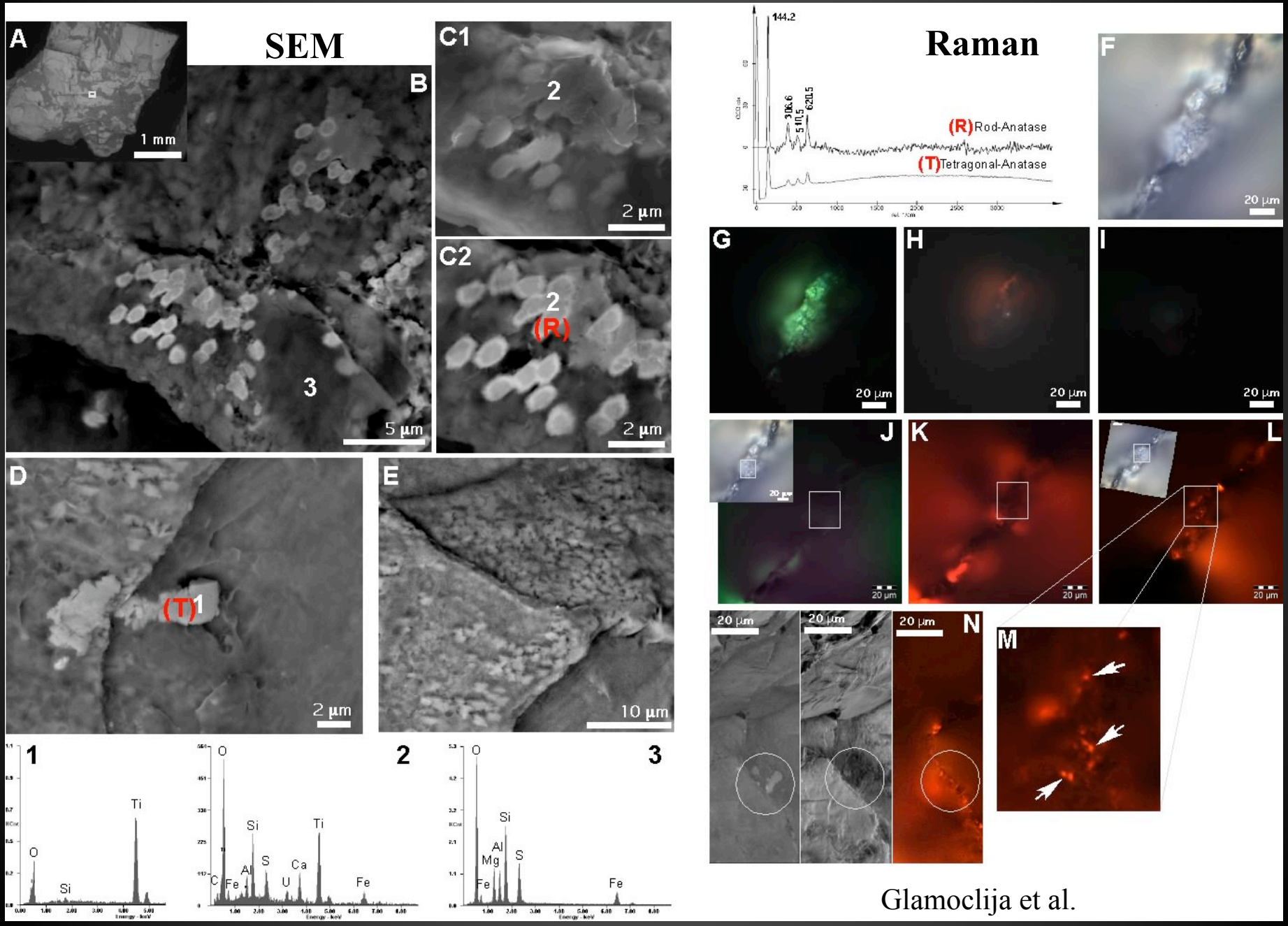






Gohn et al. 2006

Microbes from a pyrite vein within the biotite granite mega block from 1,353m depth.



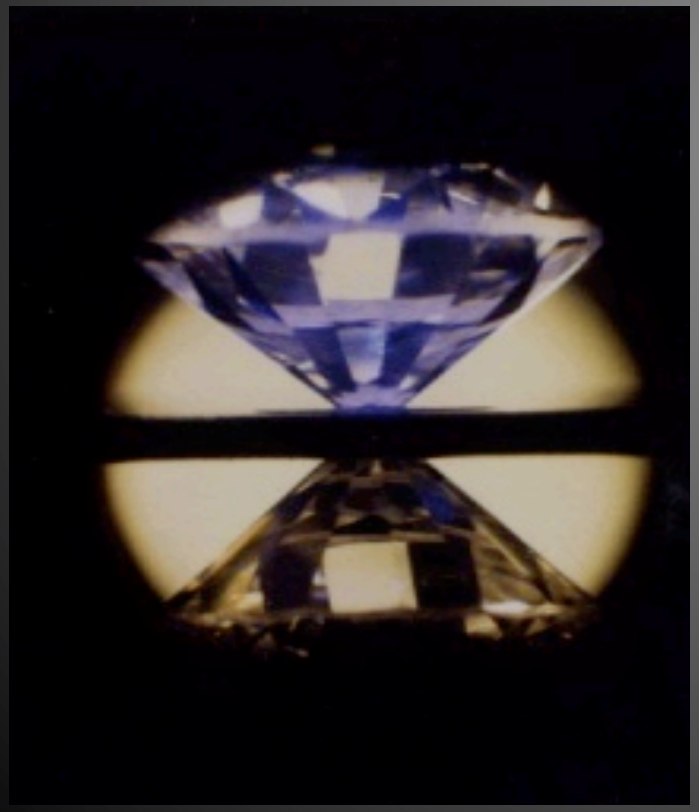
Glamoclija et al.

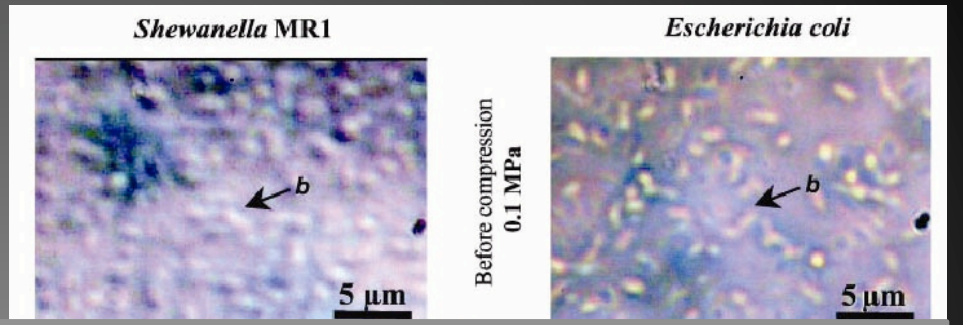
In situ experiments reveal that life can persist to pressures > 14,000 atmospheres

22 FEBRUARY 2002 VOL 295 SCIENCE

Microbial Activity at Gigapascal Pressures

Anurag Sharma,* James H. Scott,* George D. Cody, Marilyn L. Fogel, Robert M. Hazen, Russell J. Hemley, Wesley T. Huntress





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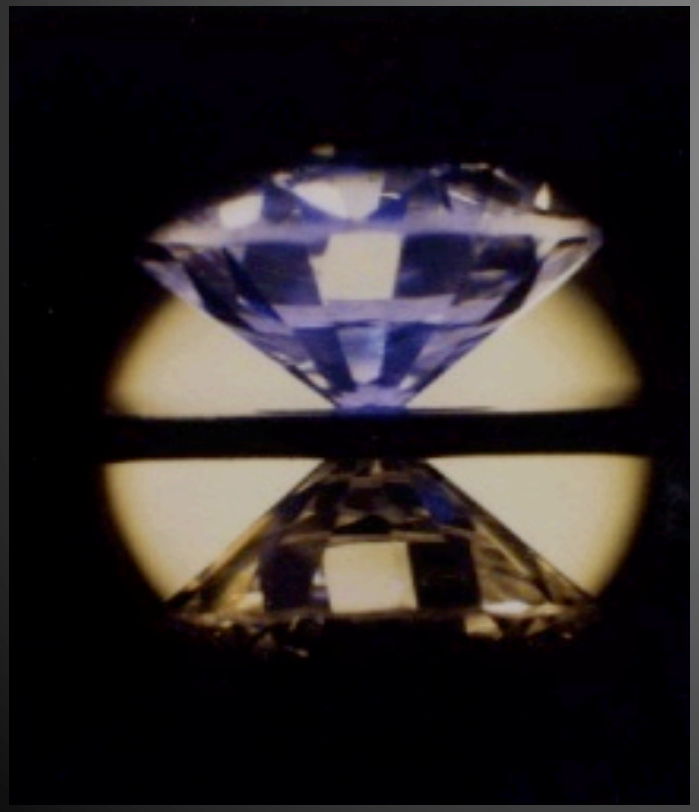

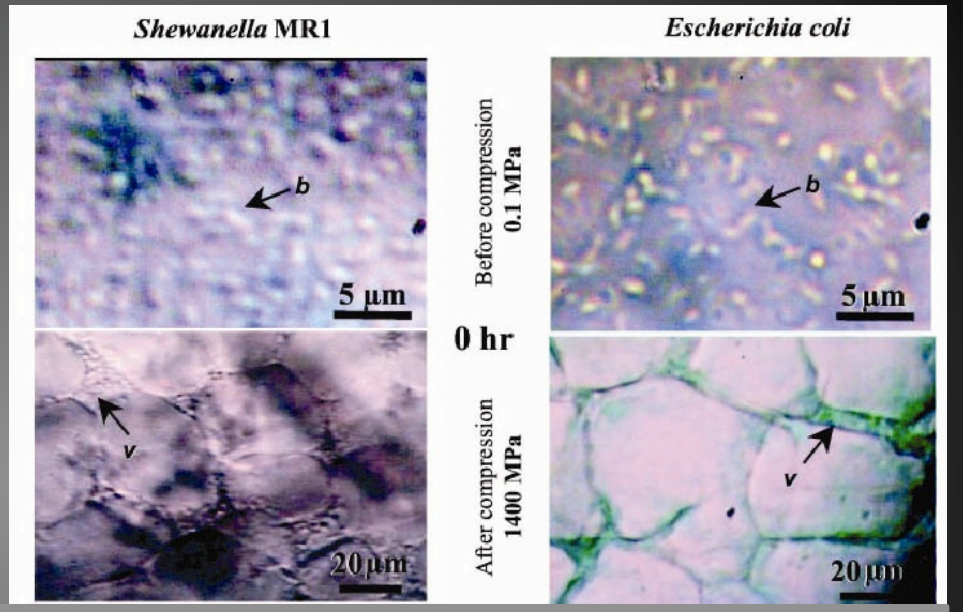

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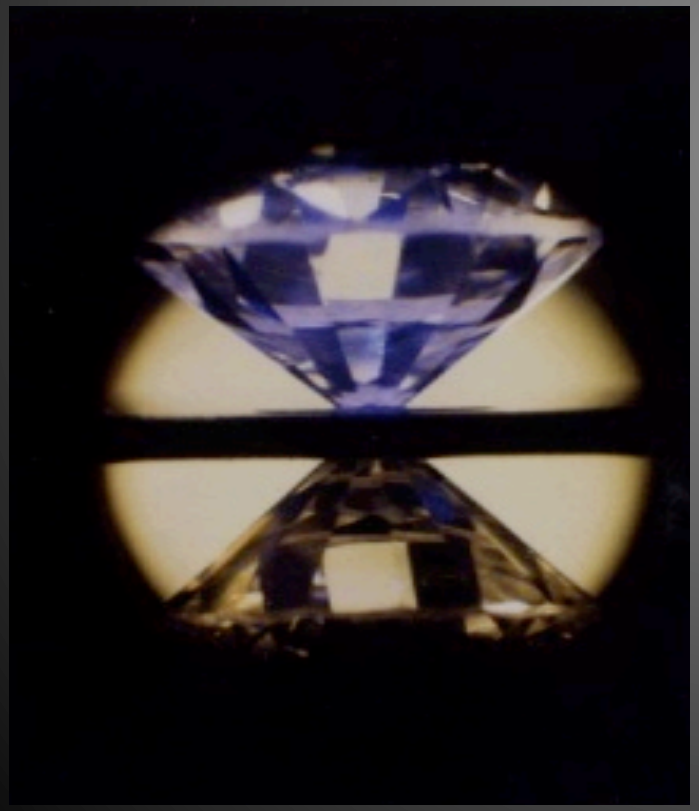

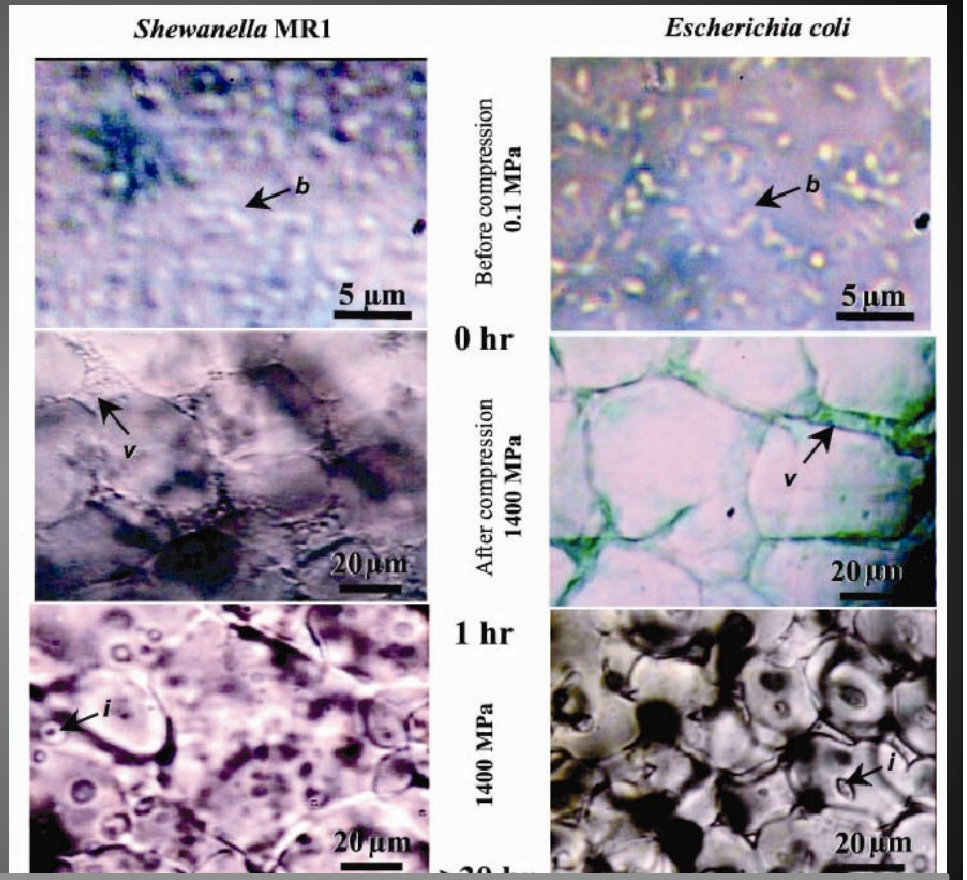

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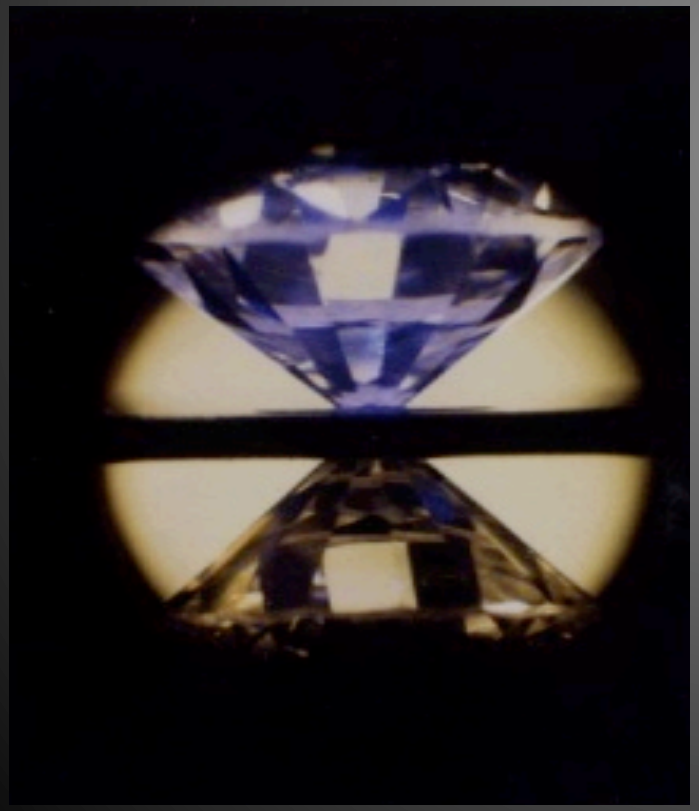

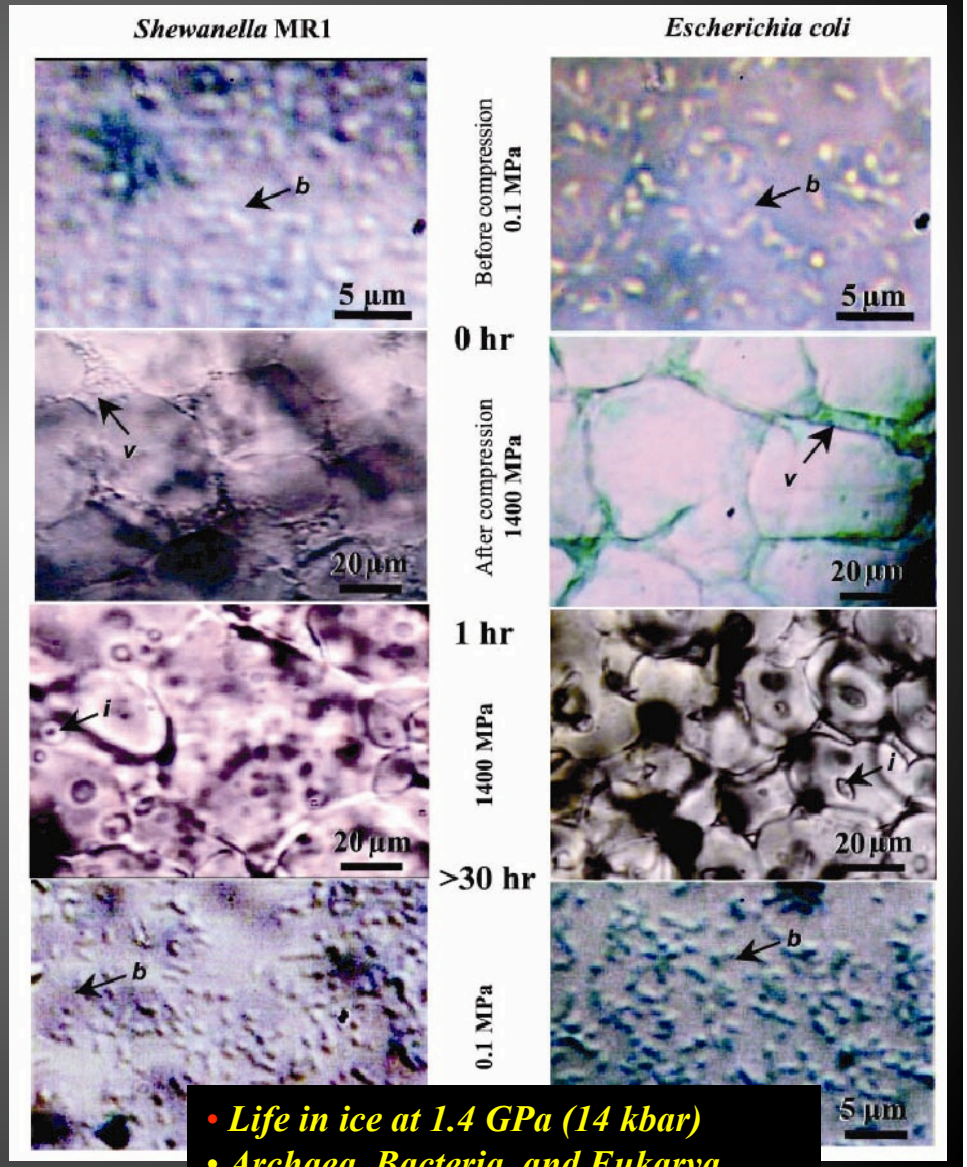

- *Life in ice at 1.4 GPa (14 kbar)*
- *Archaea, Bacteria, and Eukarya*

In situ experiments reveal that life can persist to pressures > 14,000 atmospheres

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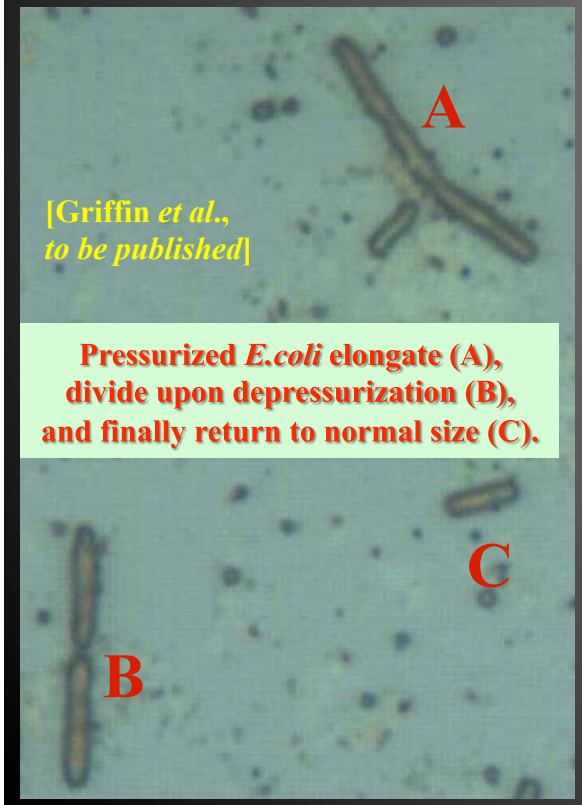
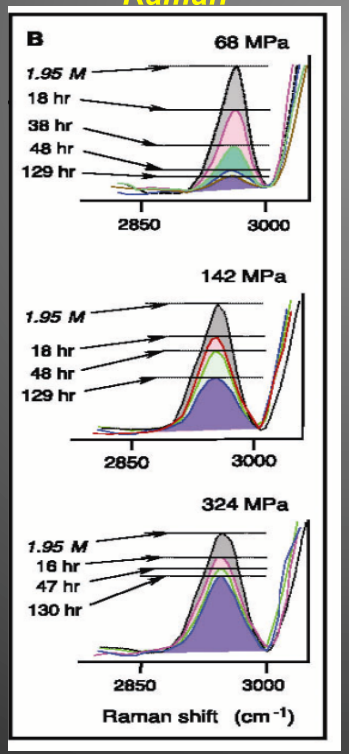
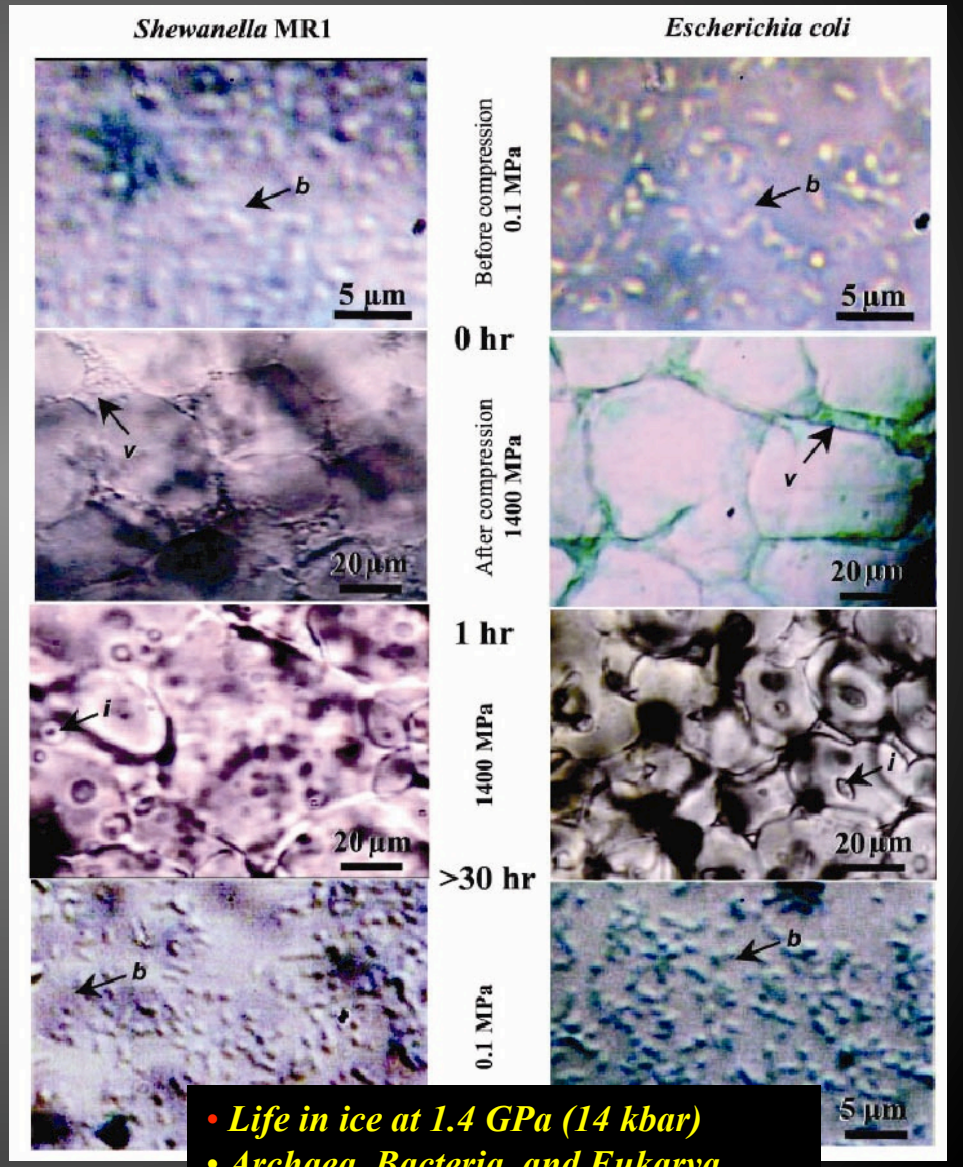


[Griffin *et al.*, *to be published*]

Pressurized *E.coli* elongate (A), divide upon depressurization (B), and finally return to normal size (C).

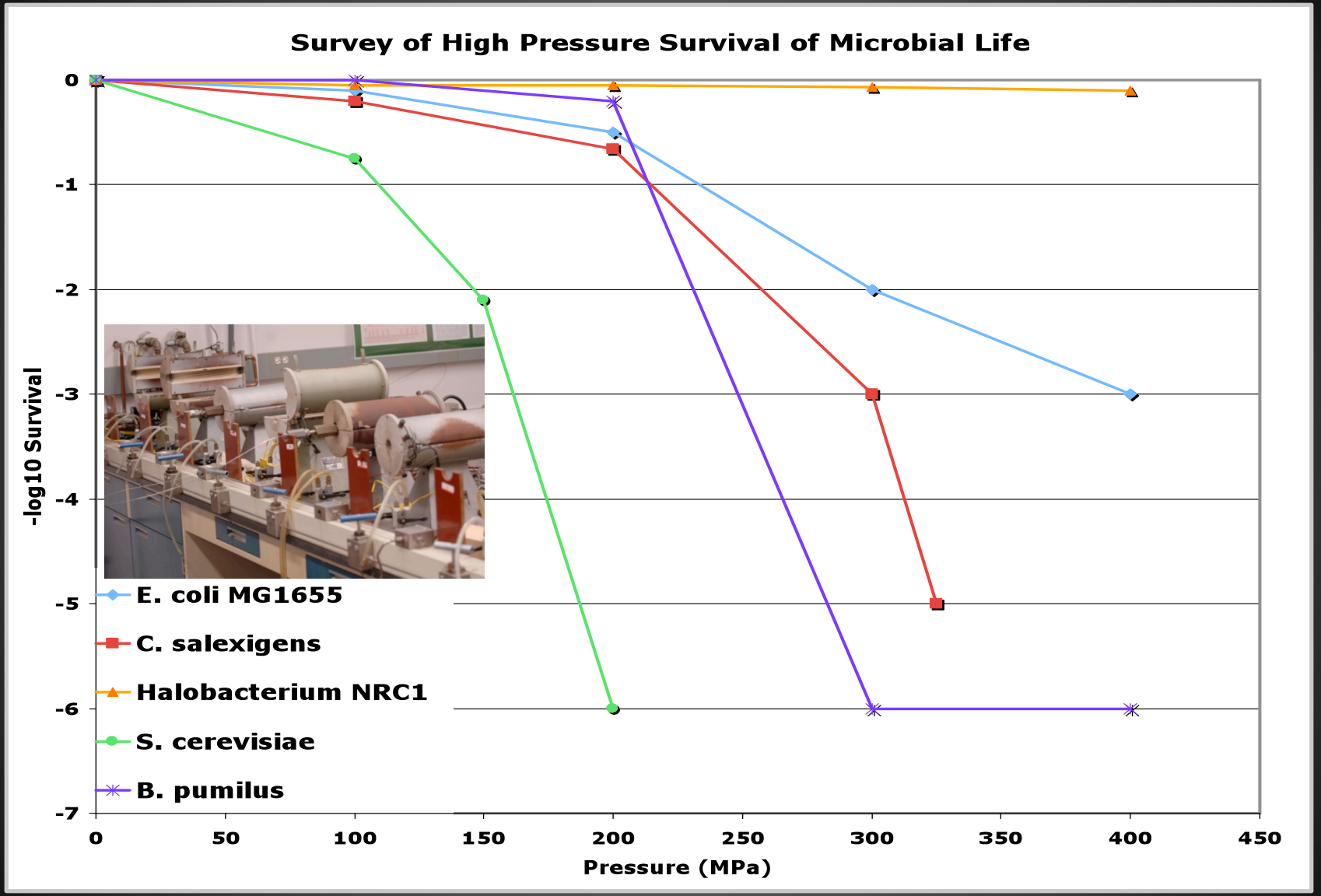
Nutrient Uptake Raman





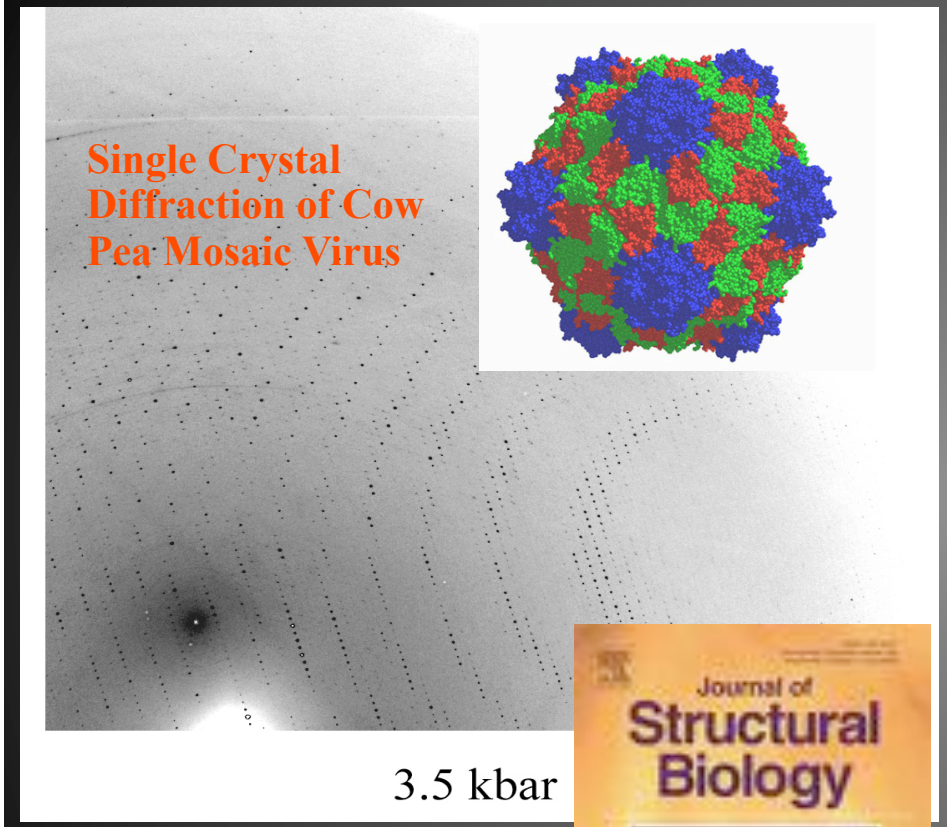
- *Life in ice at 1.4 GPa (14 kbar)*
- *Archaea, Bacteria, and Eukarya*

Surveys demonstrate high-pressure viability.

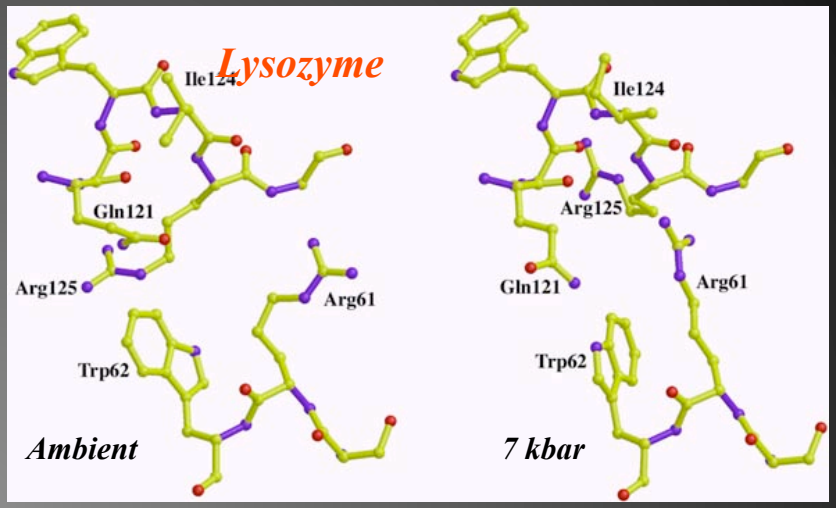


[Kish *et al.*, *to be published*]

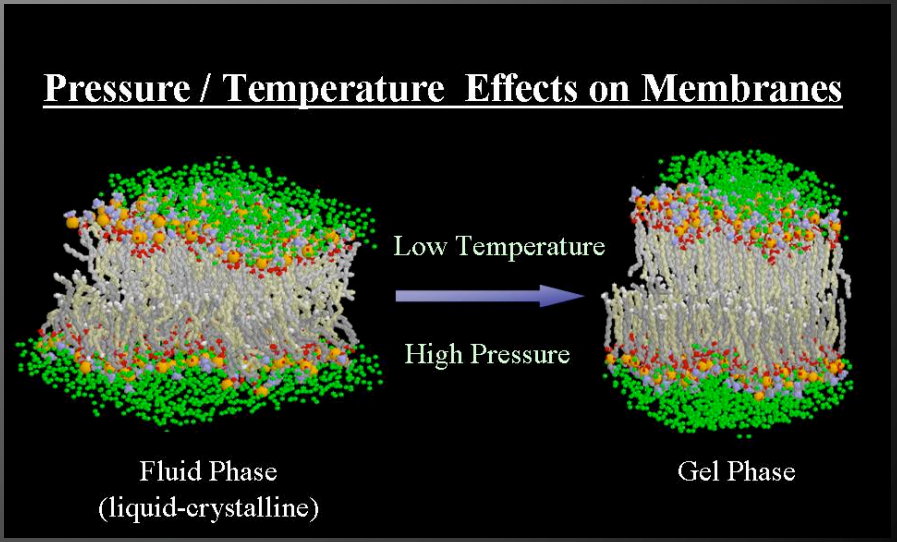
These findings require new probes of structure-property relations in biomolecules



[Lin *et al.*, *Acta Cryst. D* (2005)]



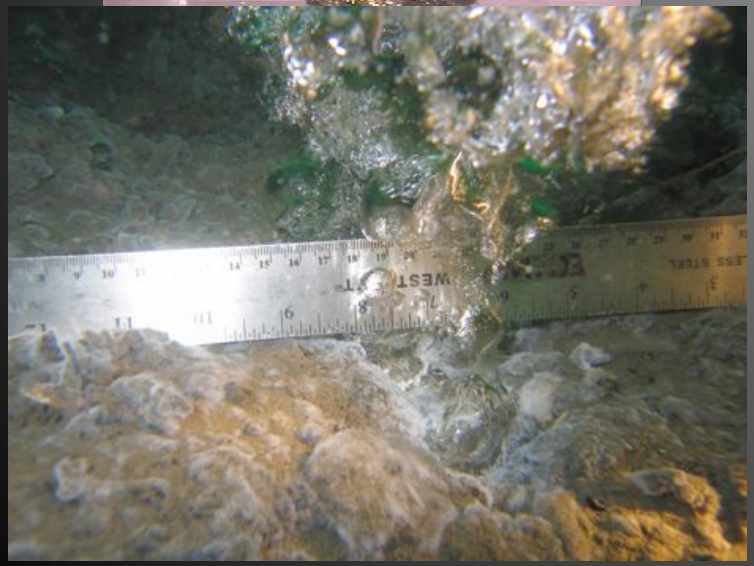
[Fourme *et al.* (2002)]

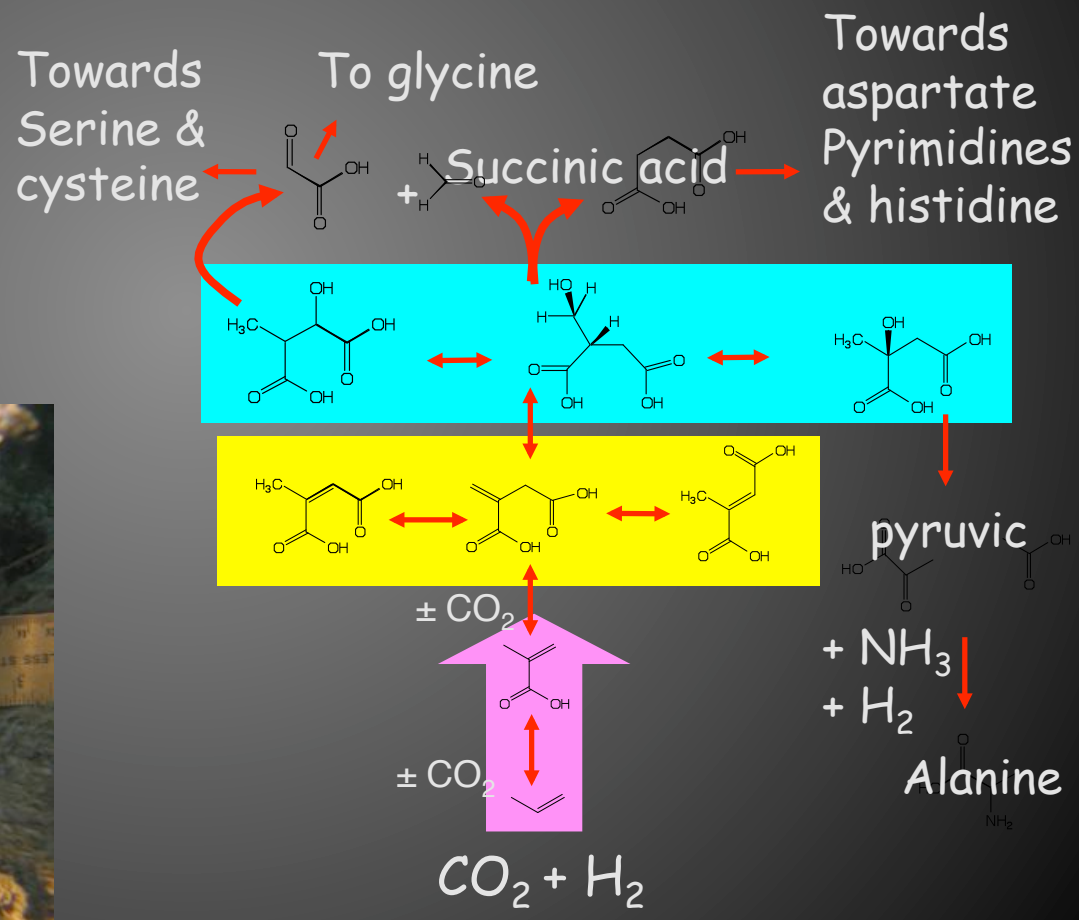


[*after* Bartlett, *Sloan Workshop* (2008)]

Deep Organic Synthesis and Life

Did deep organic synthesis contribute to the origins of life?

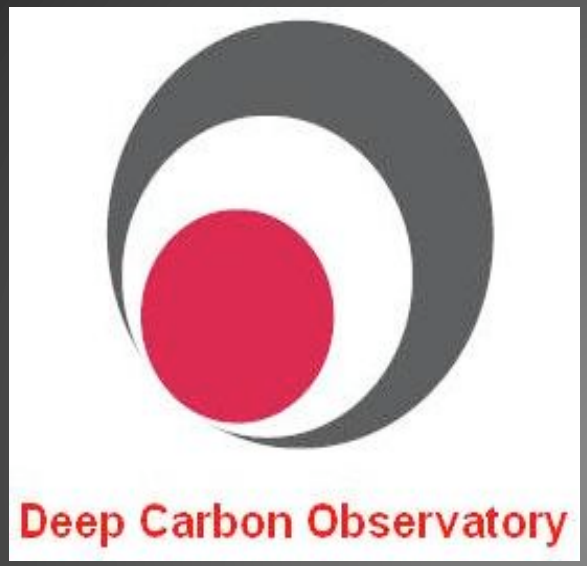




(Cody et al. 2001, 2004)

There are fundamental gaps in our understanding of deep carbon.

1. *We do not know how much carbon is stored within the Earth, nor do we know the nature of those deep repositories.*
2. *We do not know how carbon moves from one deep repository to another, nor do we know the extent to which carbon moves to and from Earth's surface.*
3. *We do not know the physical and thermochemical properties of deep carbon-bearing fluids, nor do we know how these fluids migrate within the deep interior and to the surface.*
4. *We have only vague hints of a potentially vast deep microbial biosphere; we do not know the nature or extent of this deep ecosystem, nor do we know the potentially unique biochemical characteristics of deep life.*
5. *We do not know the nature of the deep carbon cycle, nor how it might impact societal issues concerning energy, environment and climate.*


Deep Carbon Observatory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1934

Thank You!


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