RIGHT AND LEFT: Geochemical Origins Of Life's Homochirality

United States Naval Observatory
February 28, 2008

Robert Hazen, Geophysical Laboratory

Research Collaborators

Carnegie Institution
- Hugh Churchill
- H. James Cleaves
- George Cody
- Gözen Ertem
- Tim Filley
- Rebecca Martin
- Jake Maule
- Andrew Steele

George Washington Univ.
- Glenn Goodfriend
- Henry Teng

Univ. of Delaware
- Donald Sparks

Univ. of Arizona
- Robert T. Downs

George Mason University
- Harold Morowitz

Johns Hopkins University
- Dimitri Sverjensky
- Caroline Jonsson
- Christopher Jonsson

Carnegie-Mellon University
- Aravind Asthagiri
- David Sholl

Smithsonian Institution
- Ed Vicenzi

Spanish Astrobiology Inst.
- Antonio Salgado-Serrano

Two Questions (Possibly Related)

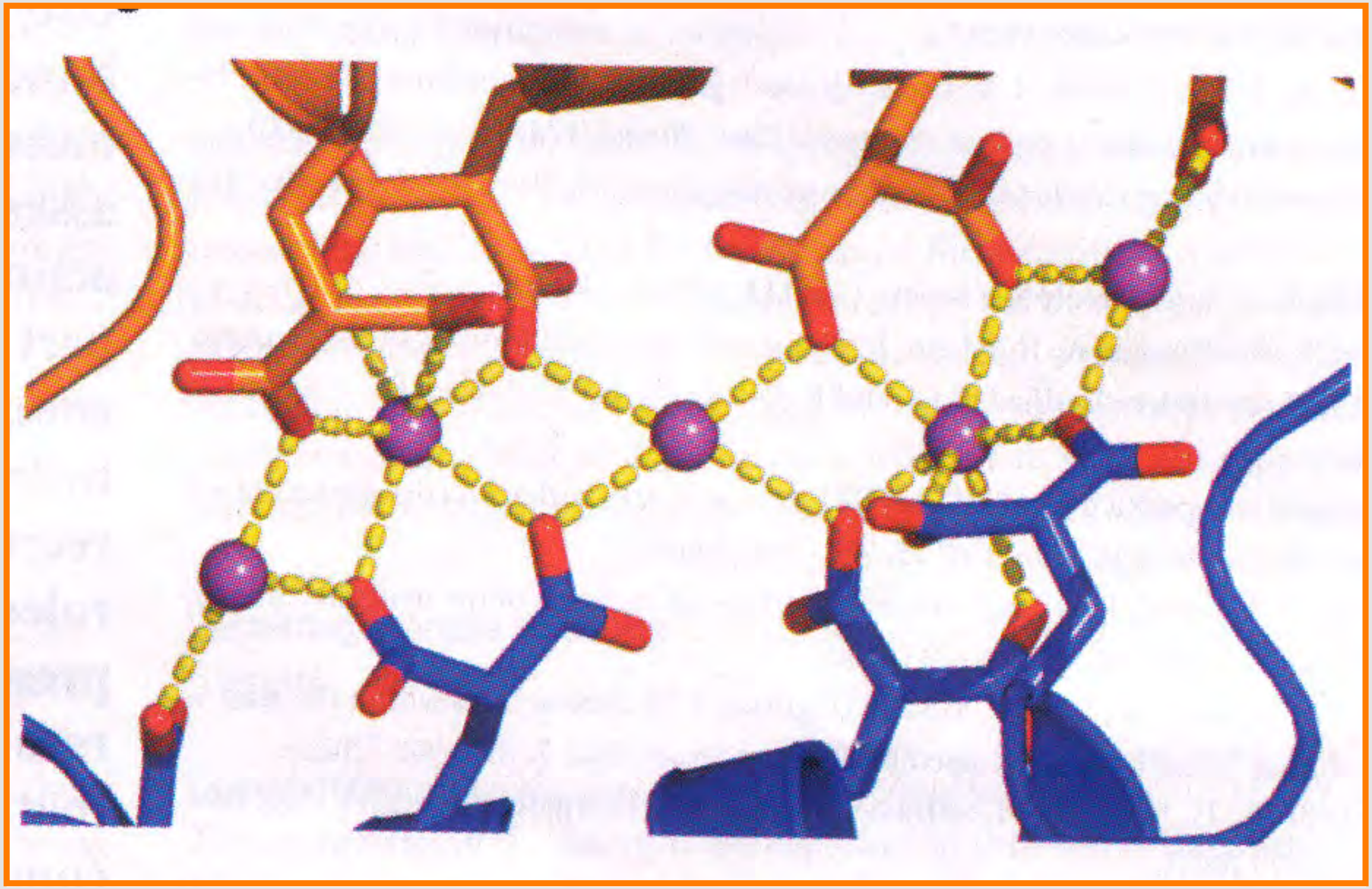
1. How do crystals interact with organic molecules?

2. What processes selected life’s idiosyncratic molecules?

Crystal-Molecule Interactions

- Formation of teeth and bones
- Biomineralization and biofilms
- Fossilization
- Weathering and soil formation
- Paints, glues, dyes
- Environmental monitoring and clean-up
- Nanotechnology
- Drug synthesis and purification
- Origins of life

Crystal-Molecule Interactions



Huong et al. (2003) "Bone recognition mechanism of porcine osteocalcin from crystal structure" Nature 425:977-980.

Central Assumptions of Origin-of-Life Research

The first life forms were carbon-based.

Life's origin was a chemical process that relied on water, air, and rock.

The origin of life required a sequence of emergent steps of increasing complexity.

Life's Origins: Four Emergent Steps

1. Emergence of biomolecules
2. Emergence of organized molecular systems
3. Emergence of self-replicating molecular systems
4. Emergence of natural selection

Origin of Biomolecules: The Problem

A fundamental attribute of life is a high degree of molecular selectivity and organization, but prebiotic synthesis processes are indiscriminate.

What prebiotic processes might have contributed to such selection and organization?

Biomolecular Selectivity: Amino Acids

- Only 20 biological amino acids compared to >90 in Murchison meteorite
- Only α-H amino acids (i.e., no α-methyl amino acids)
- Homochirality – L>>R

Biological Homochirality

Many of life's essential molecules are chiral.

(L)-enantiomer   (R)-enantiomer

How did life on Earth become homochiral?

Annual sales of chiral pharmaceuticals approaches $200 billion.

Basic Vocabulary

Chiral = Enantiomeric = Handed

“D” = “R” = Right-handed

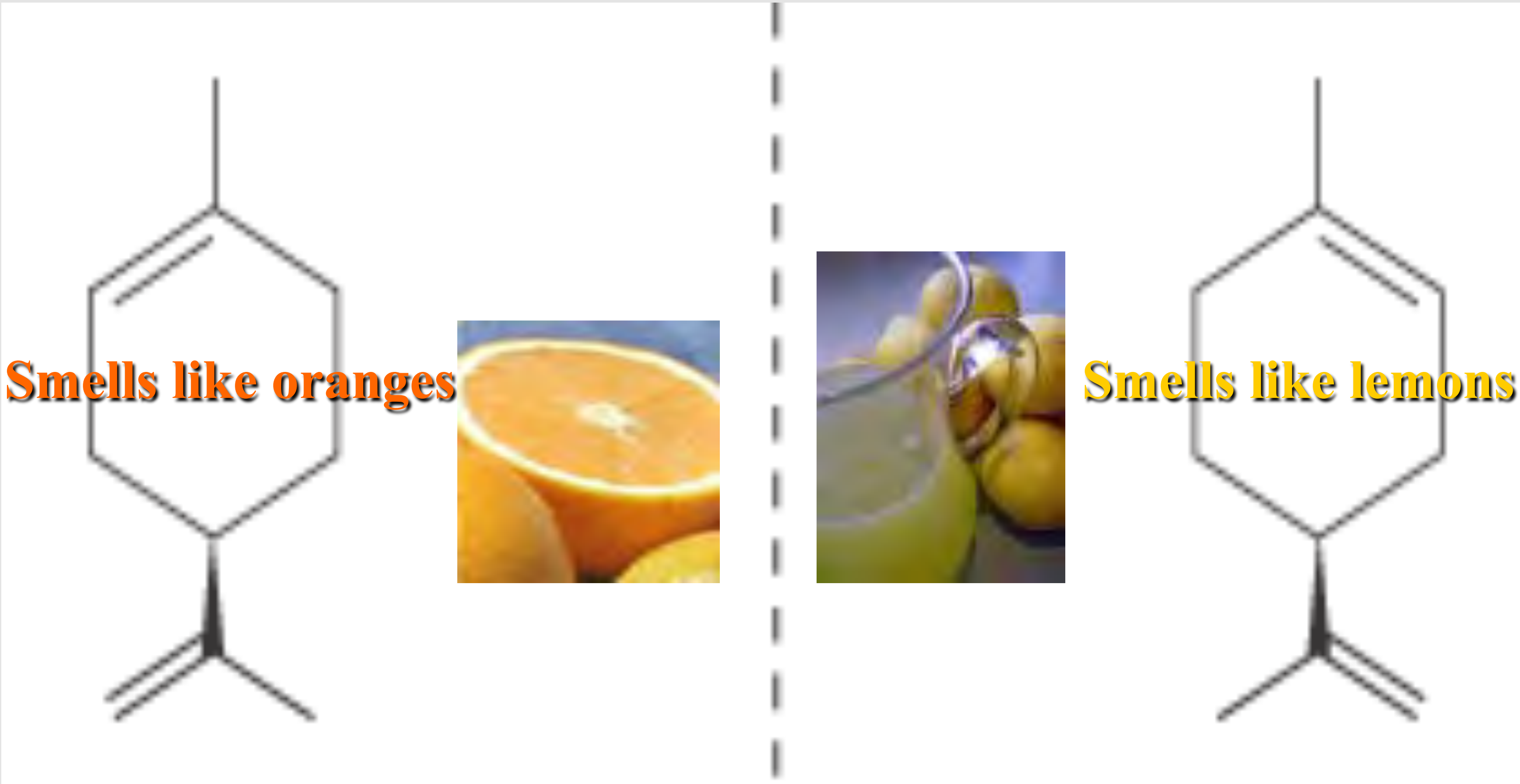
“L” = “S” = Left-handed

Homochiral versus heterochiral

Racemic = mixture of left and right

Symmetry Breaking = separate D/L

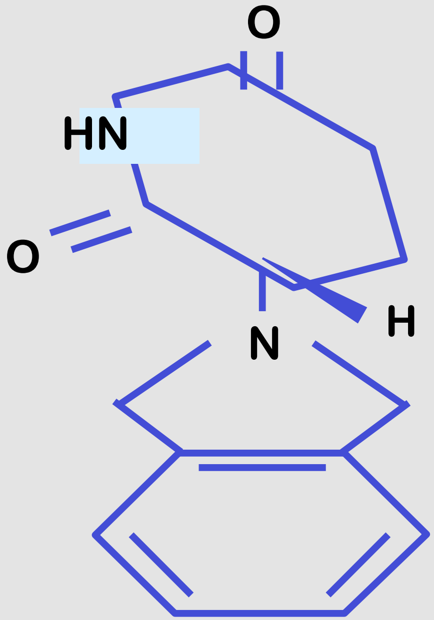
Chiral Purity is Important



R-Limonene Mirror L-Limonene

Chiral Purity is Important

Thalidomide

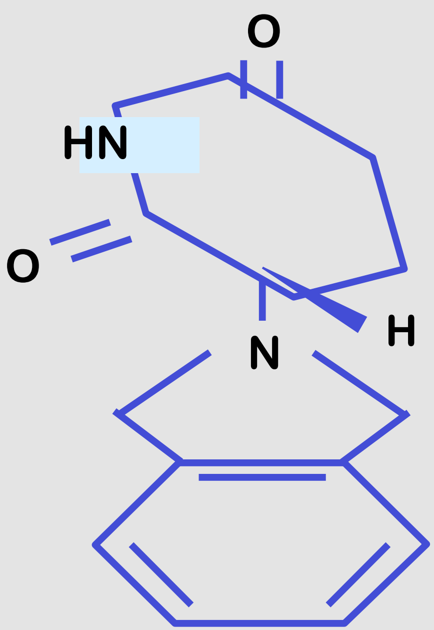


R-enantiomer

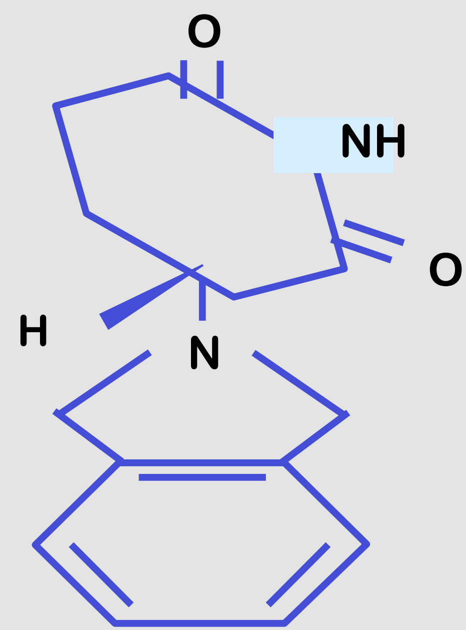
Analgesic (Good)

Chiral Purity is Important

Thalidomide



R-enantiomer
Analgesic (Good)



S-enantiomer
Teratogen (Bad)

Enantioselective Chemistry

1. Enantioselective separation

Racemic Mixture → Chiral reagent → Enantiomerically Pure Product

2. Enantioselective synthesis

Prochiral Reactants → Chiral catalyst → Enantiomerically Pure Products

Prebiotic Chiral Selection

- Prebiotic synthesis processes produce mixtures of left and right molecules.

- But life demonstrates a remarkable degree of chiral selectivity.

What is the mechanism of symmetry breaking?

Previous Hypotheses

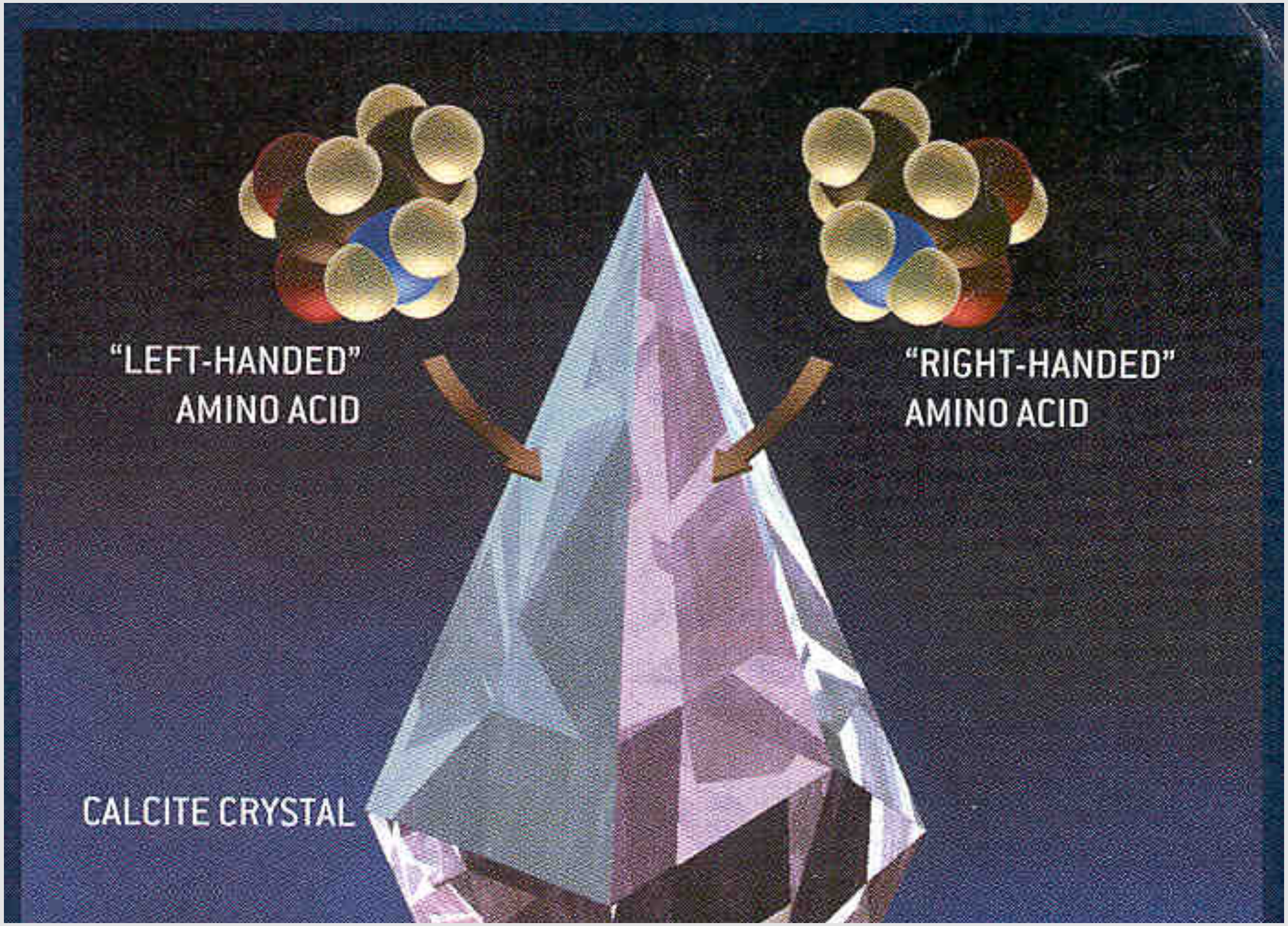
Global Mechanisms:

- **Selective synthesis or photolysis by CPR**
- **Parity violations in ß decay**

Local Chiral Microenvironments:

- **Chiral molecules, themselves**
- **Mineral surfaces**

Our Hypothesis: Minerals Work



Our Hypothesis: Minerals Work

Aspartic acid on calcite

Lysine on quartz

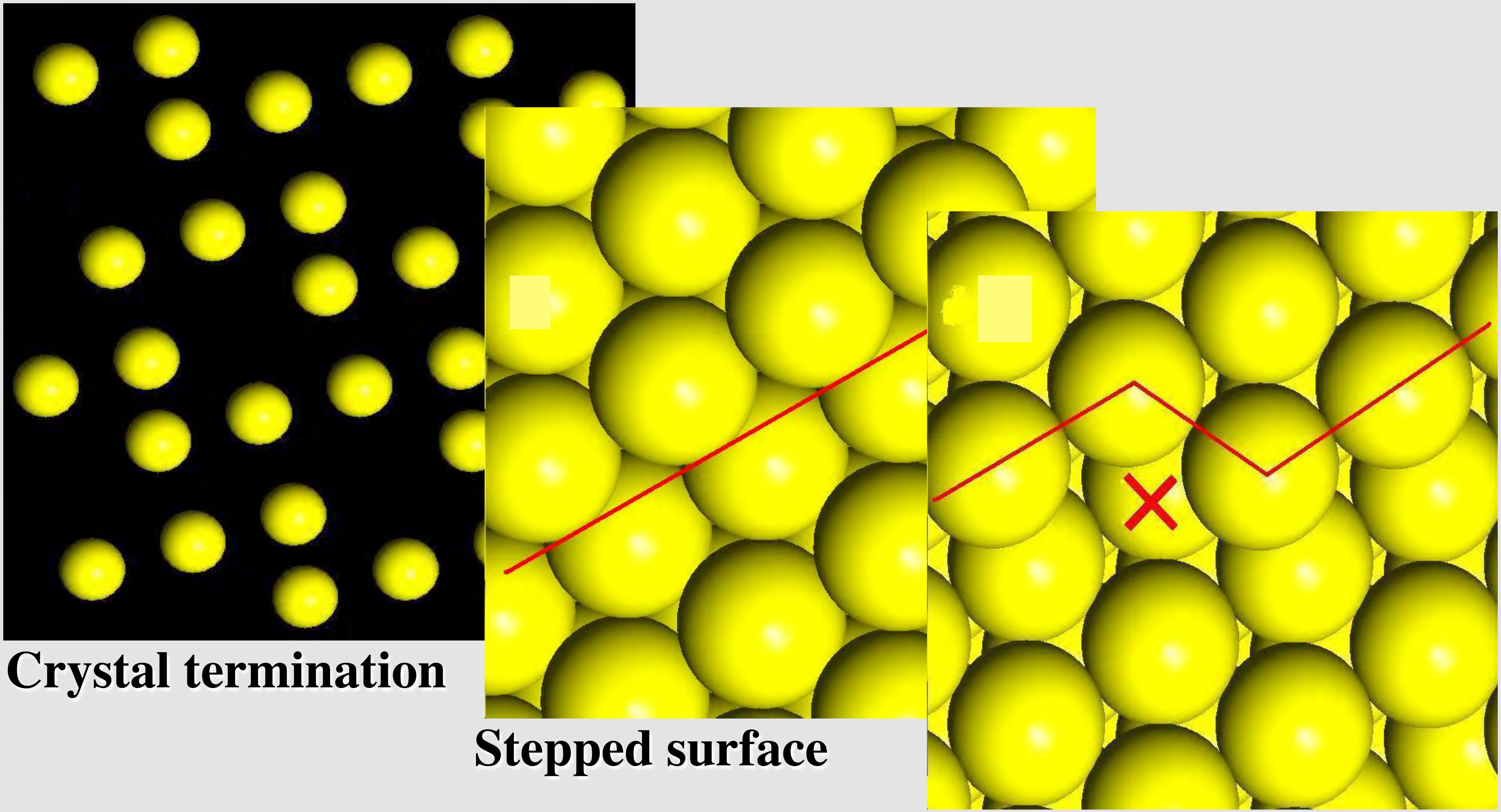
TCA on calcite

TCA on feldspar

Objectives

1. **Examine the occurrence of chiral mineral surfaces in nature** (Hazen 2004; Downs & Hazen 2004).
2. **Demonstrate chiral selectivity by mineral surfaces** (Hazen et al. 2001; Castro-Puyana et al. 2008).
3. **Deduce mineral-molecule interactions** (Asthagiri & Hazen 2006; 2007).
4. **Propose a general experimental research strategy** (Hazen, Steele et al. 2005; Hazen 2006).

1. Natural Chiral Surfaces

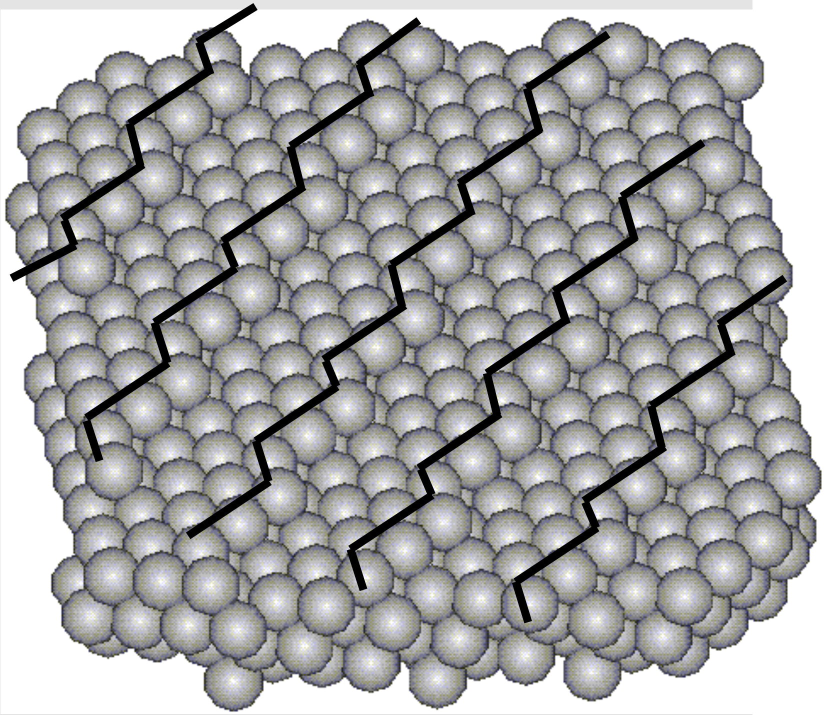


Crystal termination

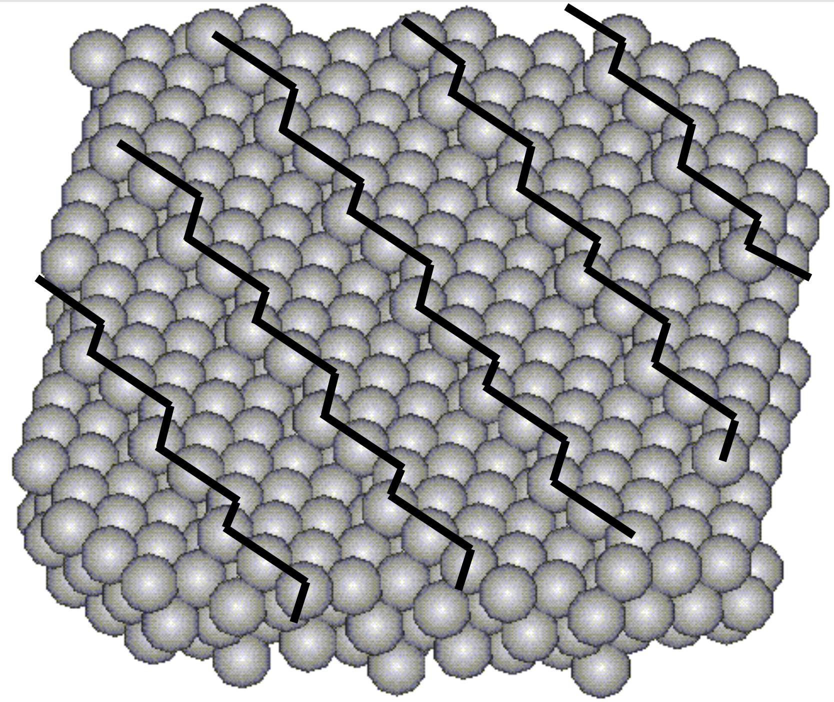
Stepped surface

Kink site

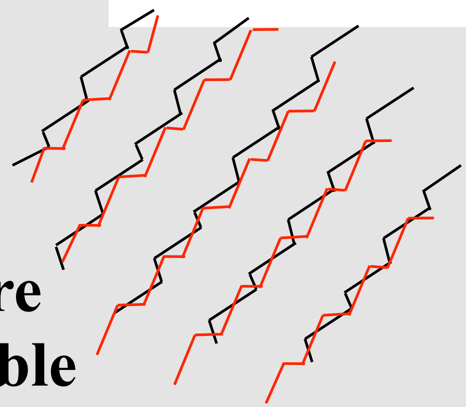
Chiral Single-Crystal Metal Surfaces



FCC(643)



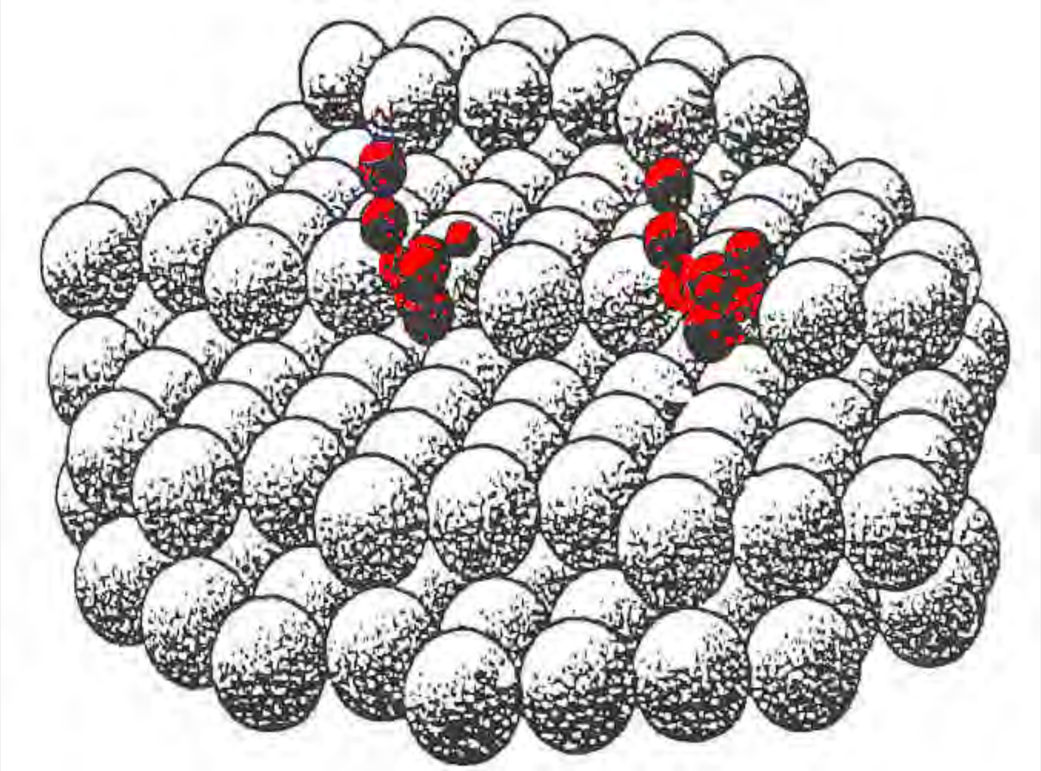
FCC$(\bar{6}\,\bar{4}\,\bar{3})$



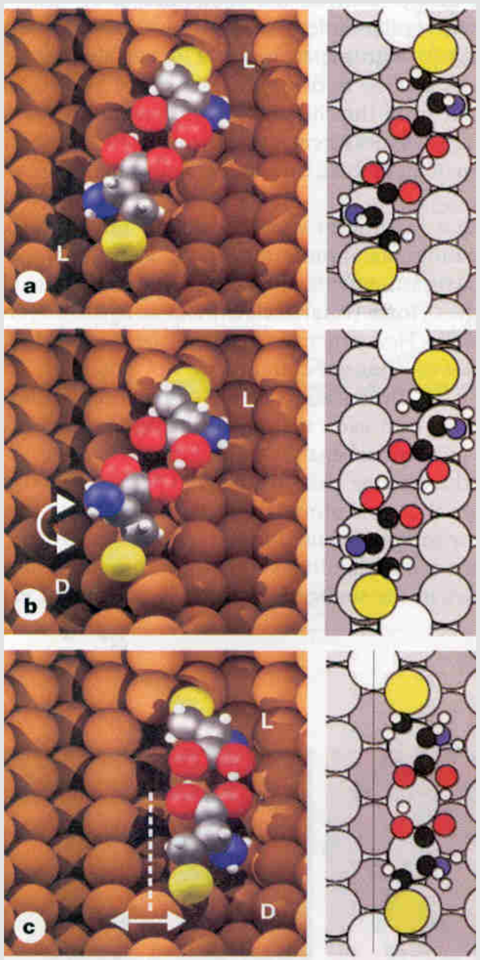
Mirror images are non-superimposable

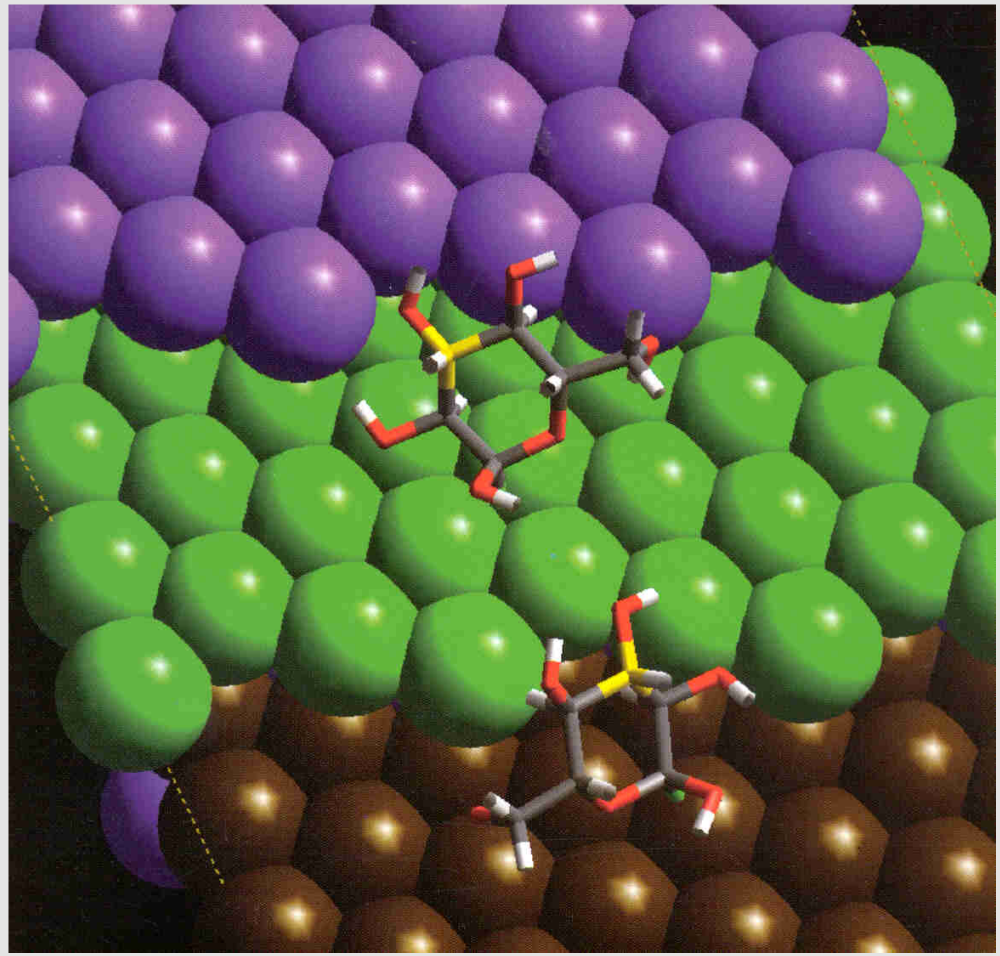
Chiral Surfaces Can Select Chiral Molecules

McFadden et al. (1996) "Adsorption of chiral alcohols on 'chiral' metal surfaces." *Langmuir* 12, 2483-2487.



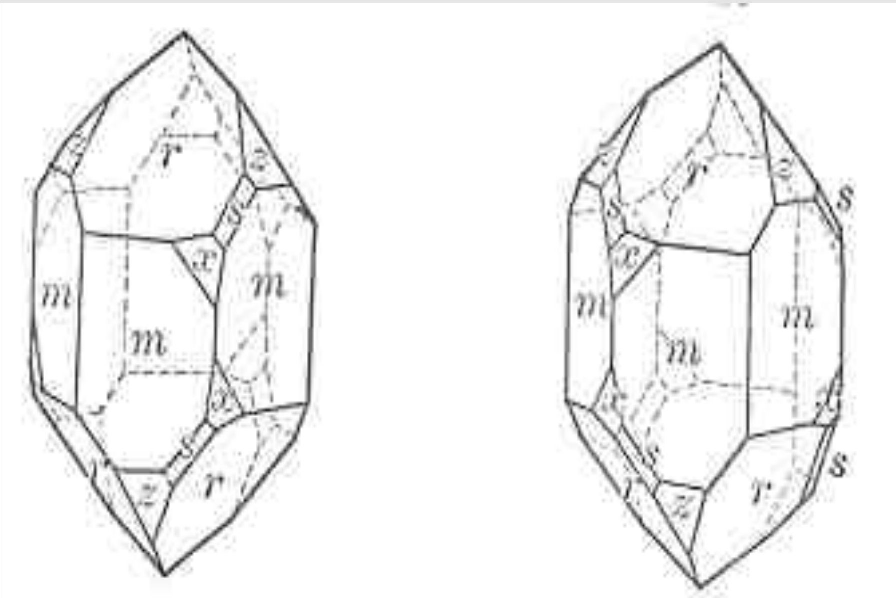
Chiral Adsorption



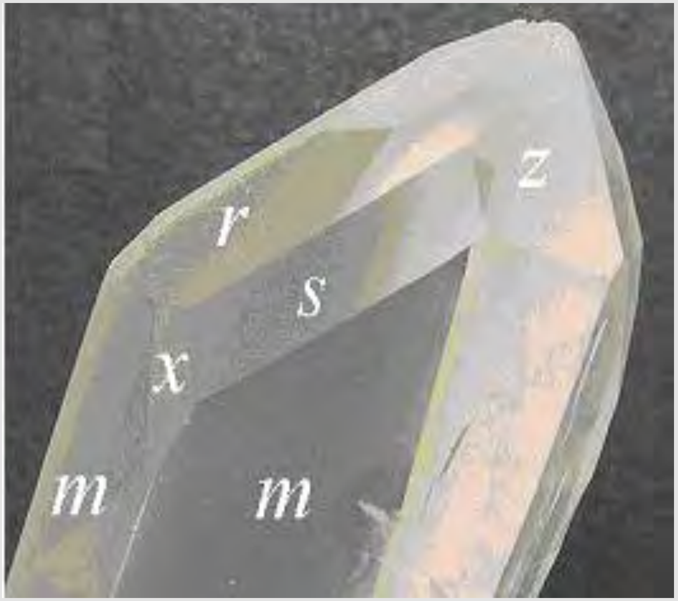


Quartz – SiO_2

Quartz is the only common chiral rock-forming mineral



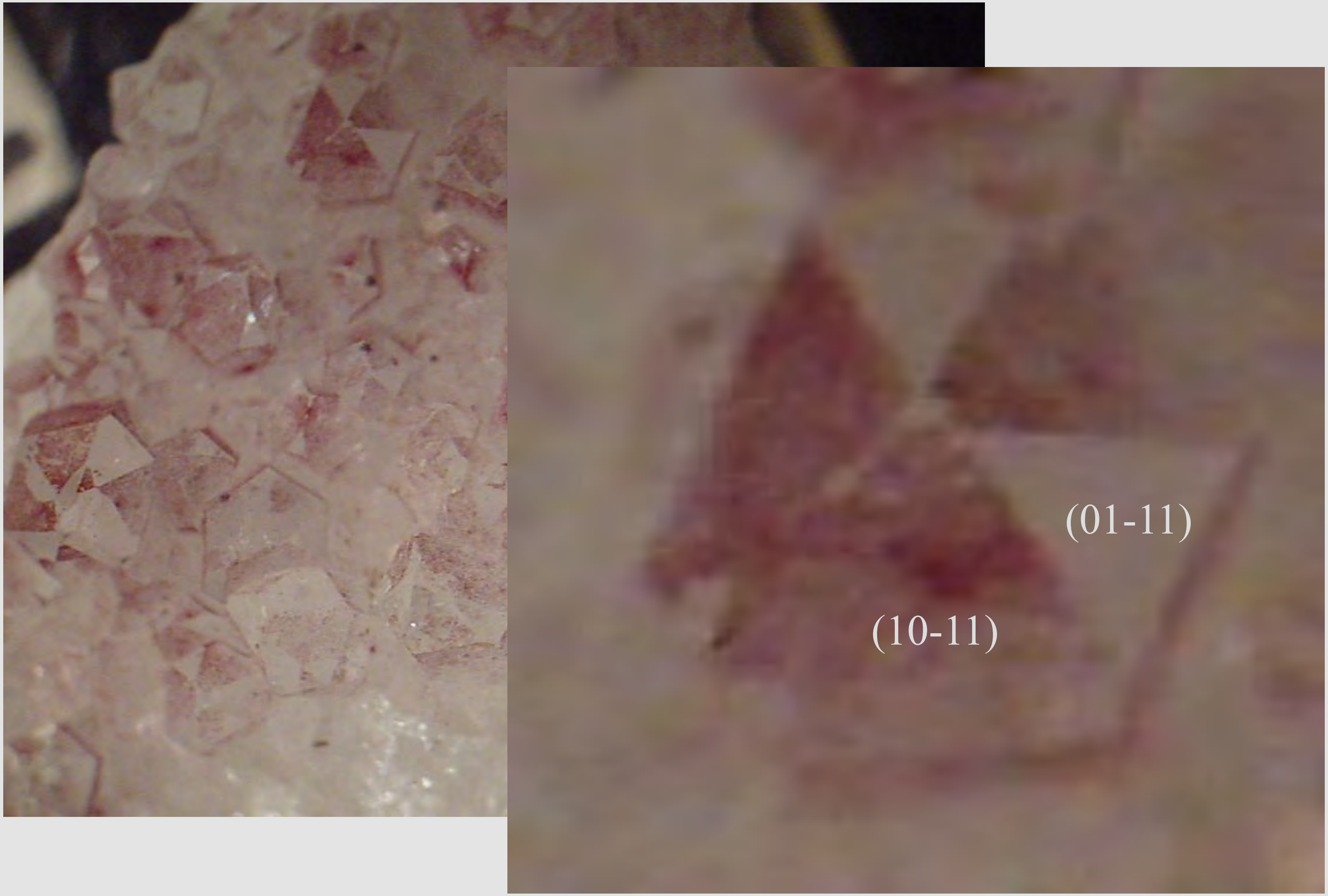
Right Left



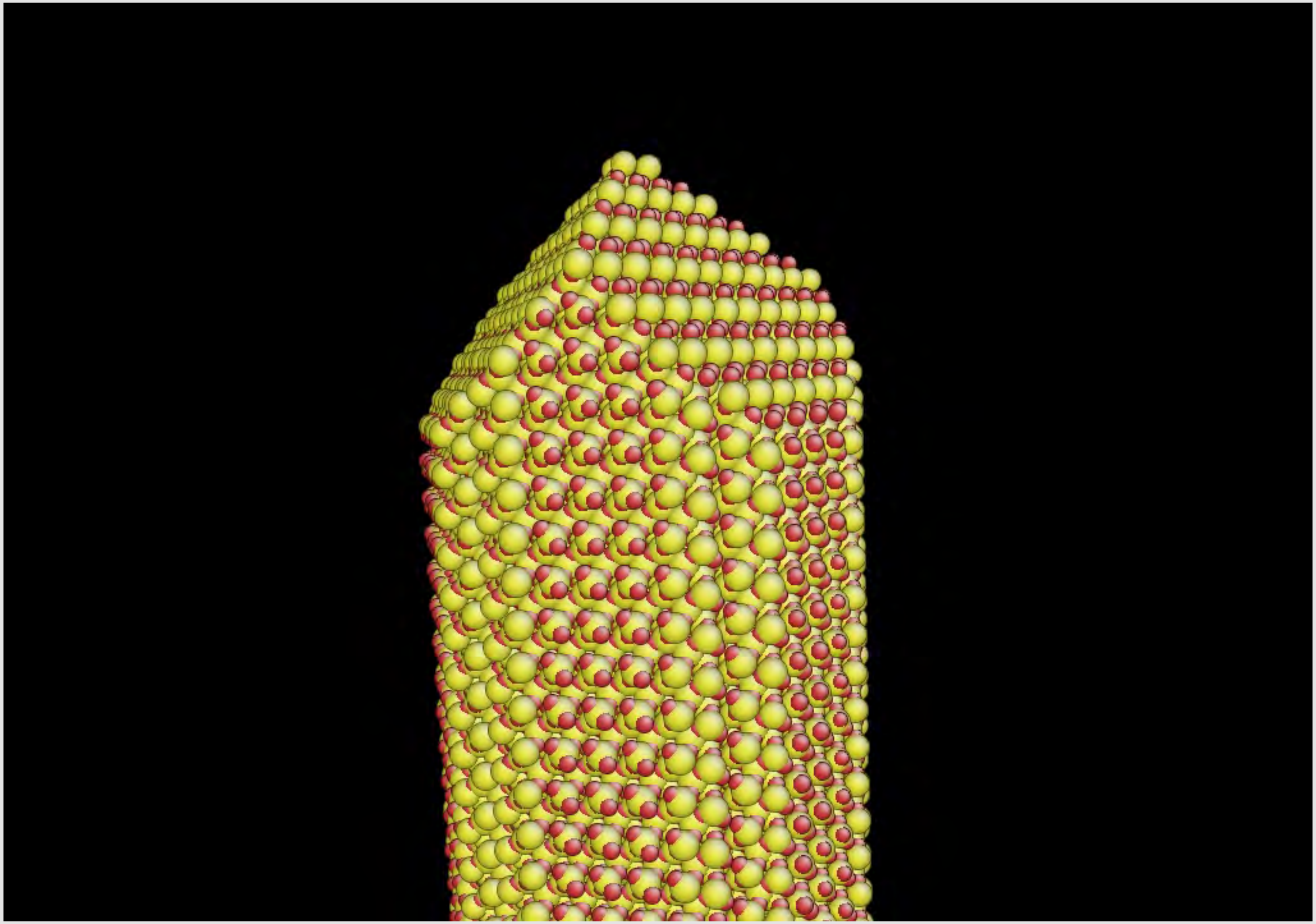
Reports of successful chiral selections as early as the 1930s.

Yet all previous authors used <u>powdered</u> quartz!

Quartz: Face-Specific Adsorption

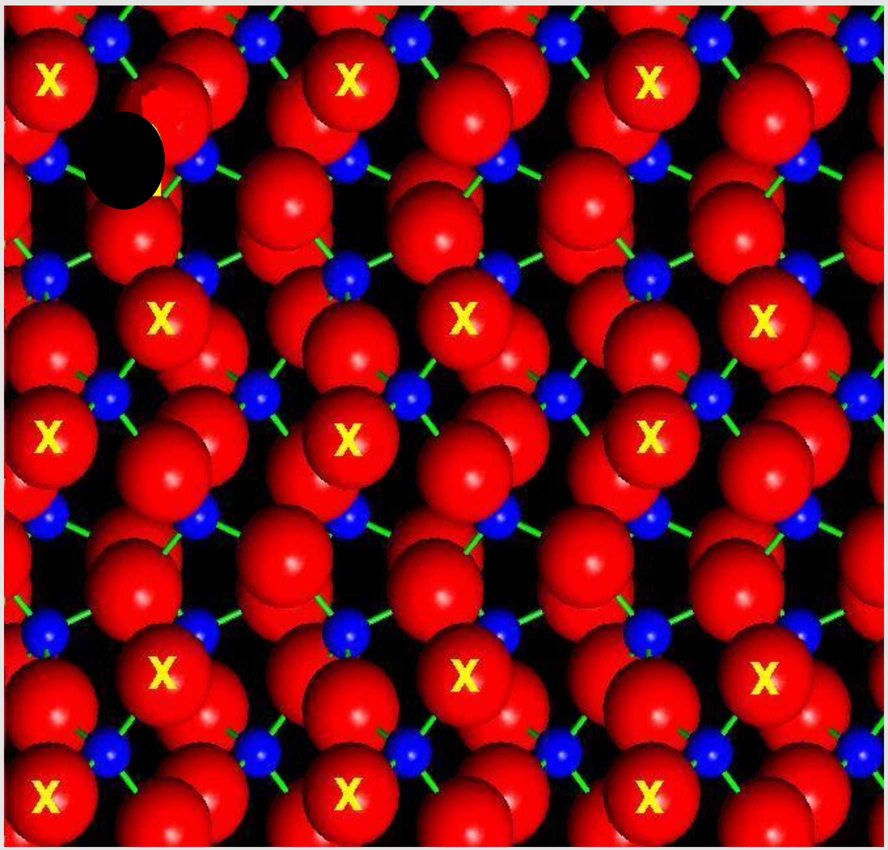


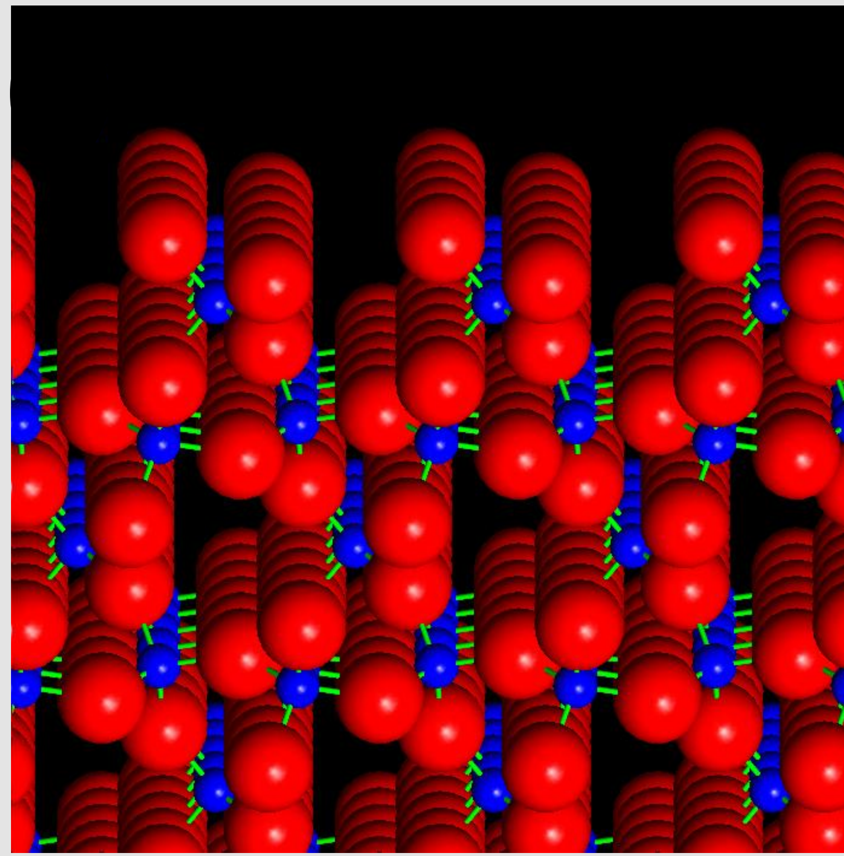
Quartz Crystal Faces



Courtesy of S. Parker

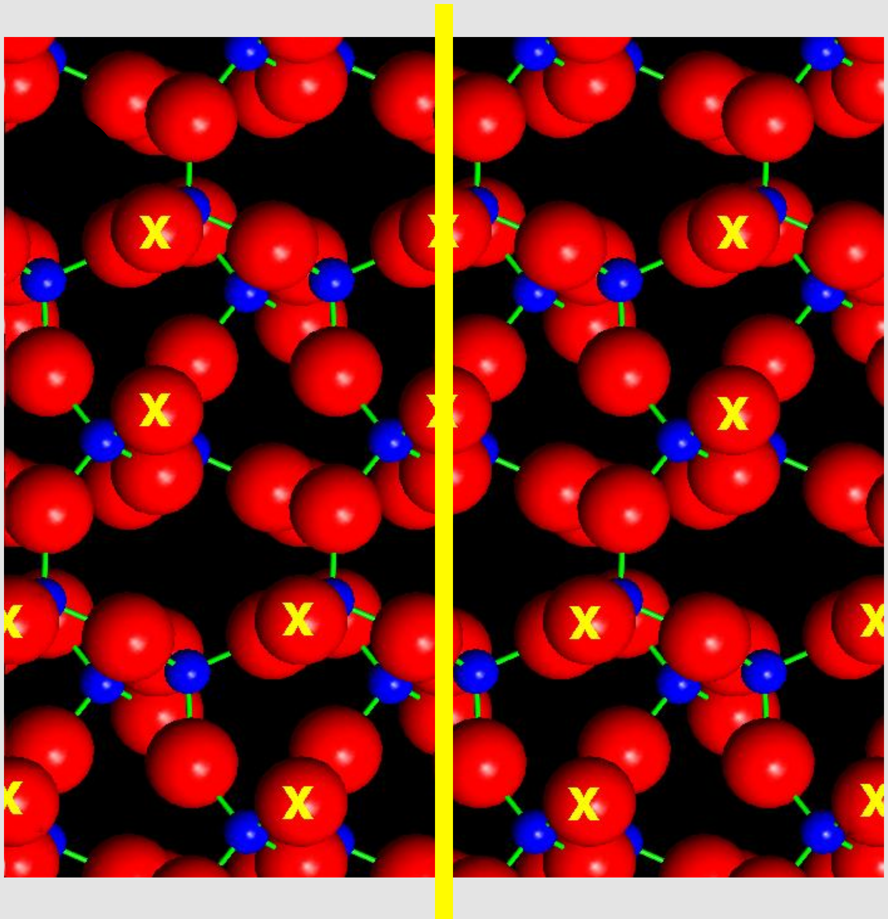
Quartz – (100) Face

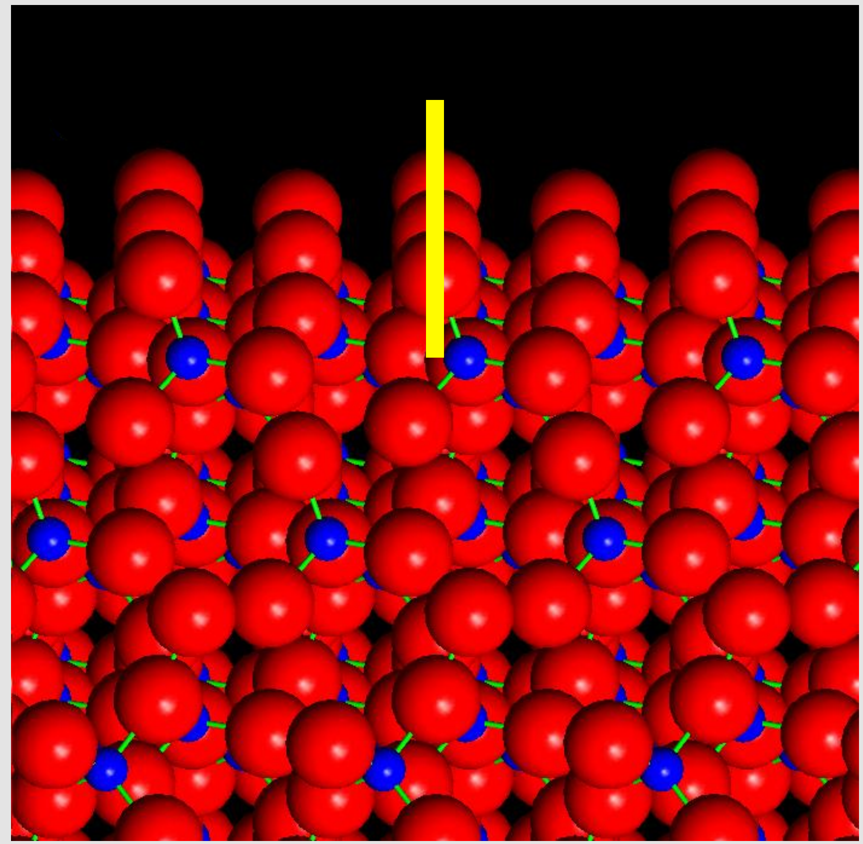




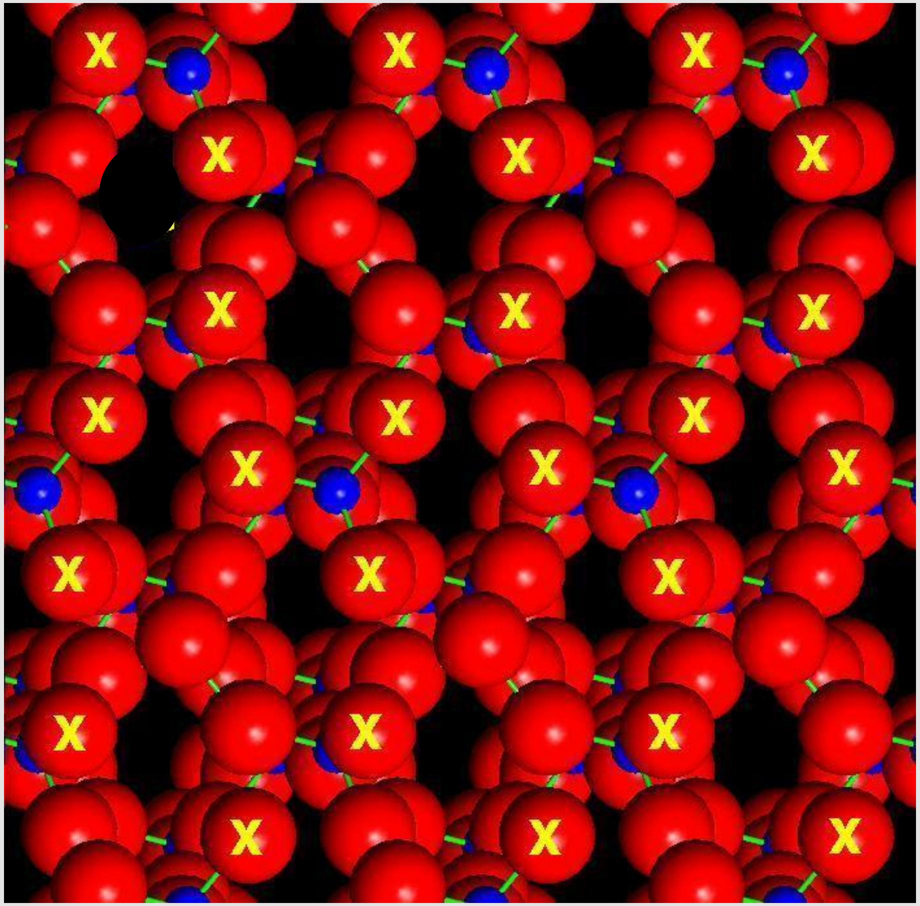
Quartz – (101) Face

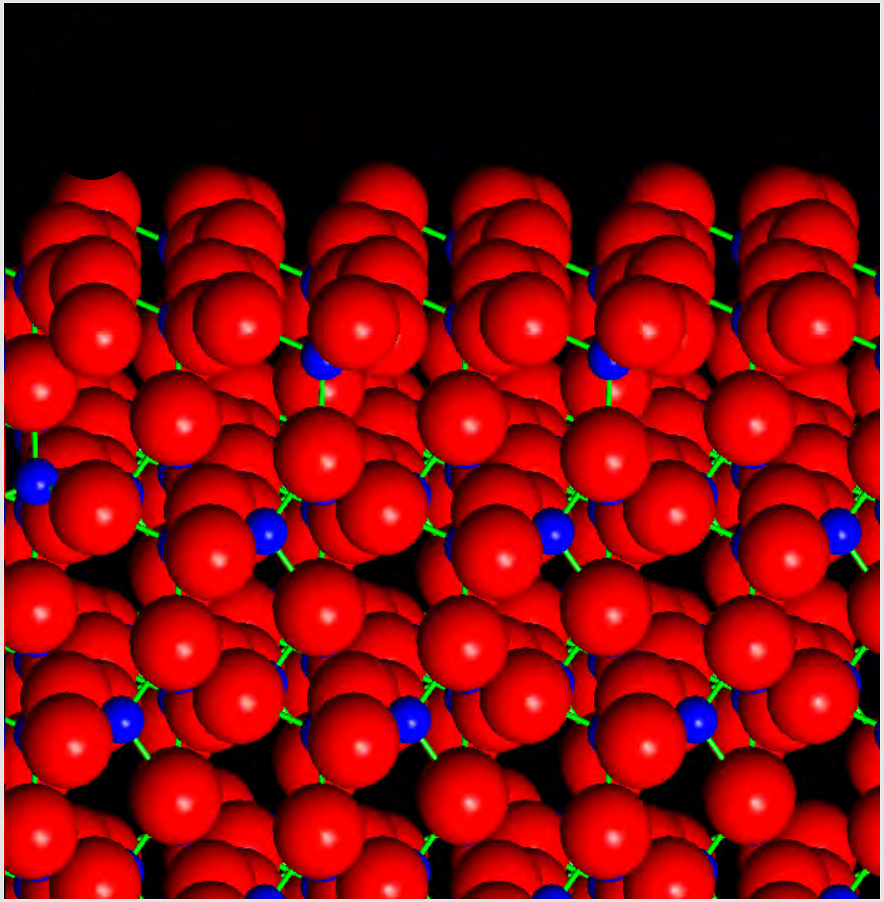
MIRROR



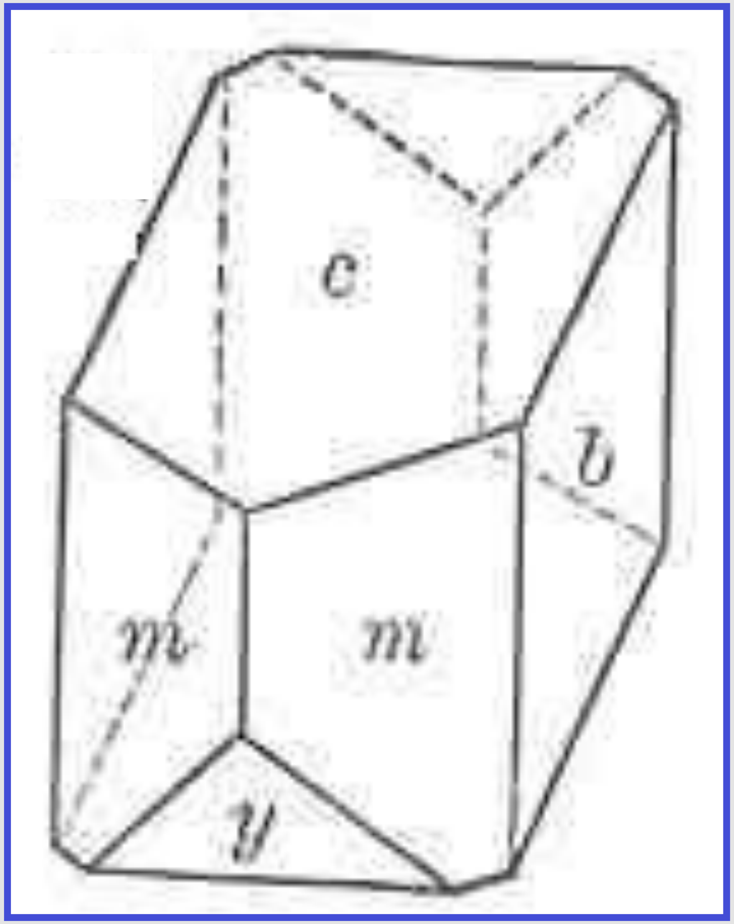


Quartz – (011) Face

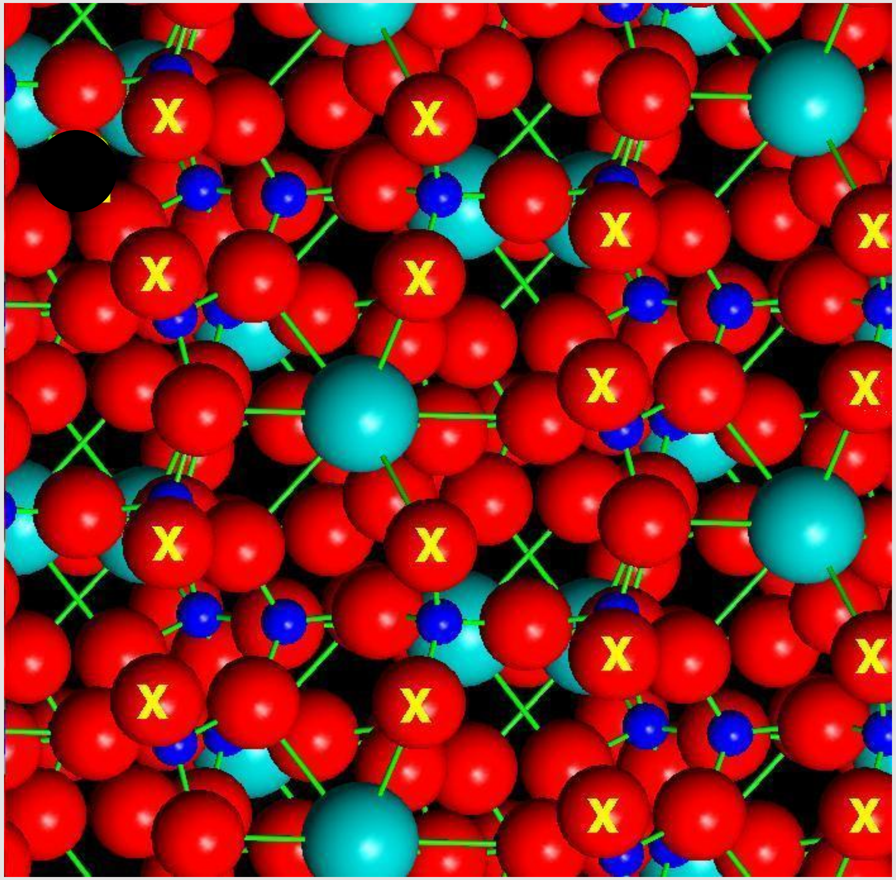


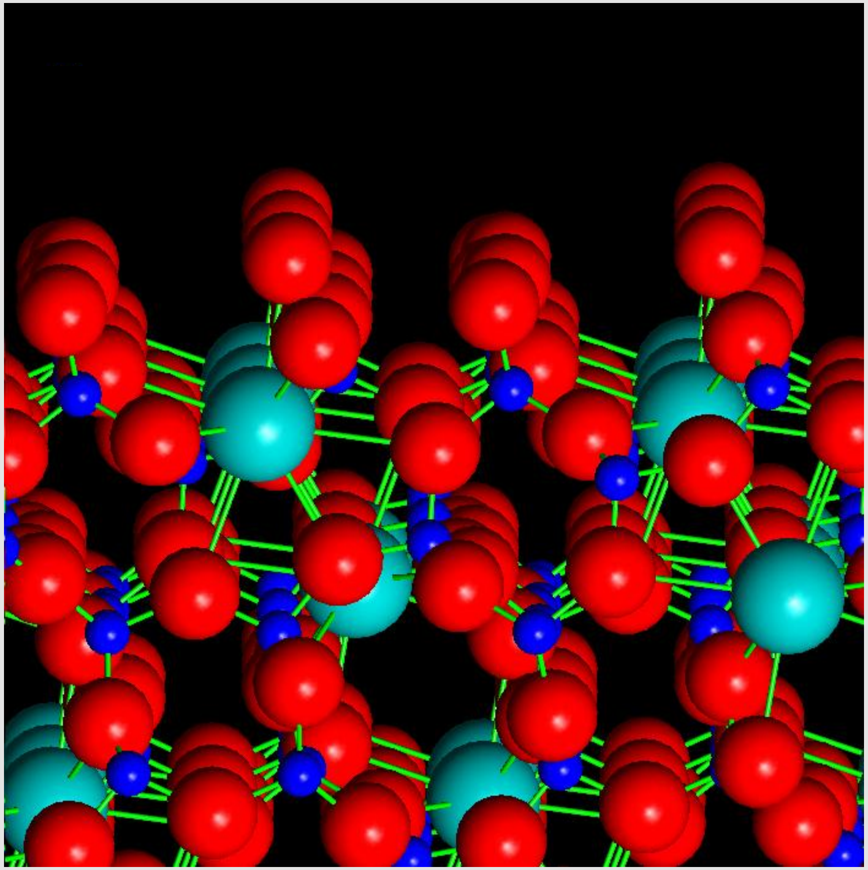


Feldspar (110)

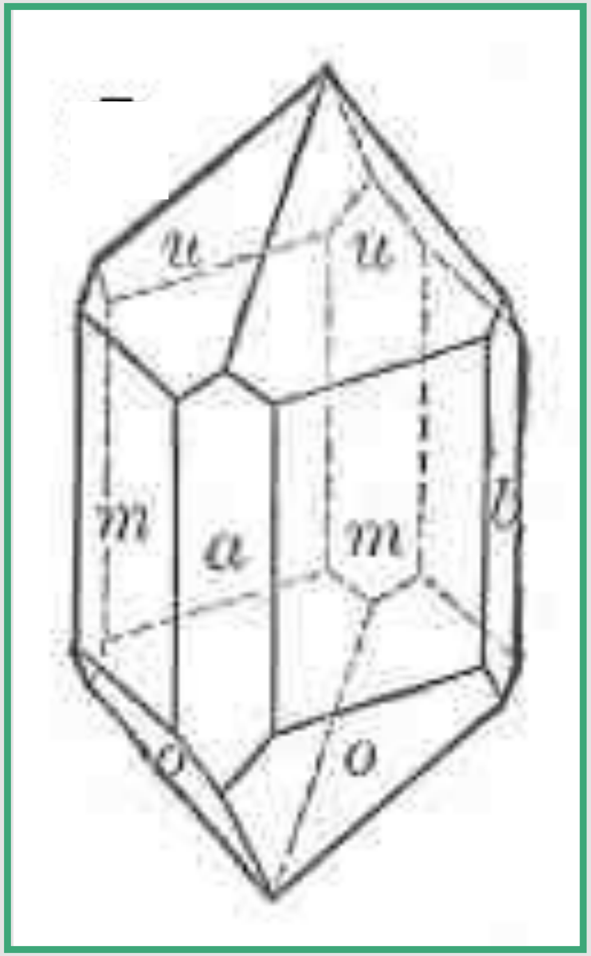


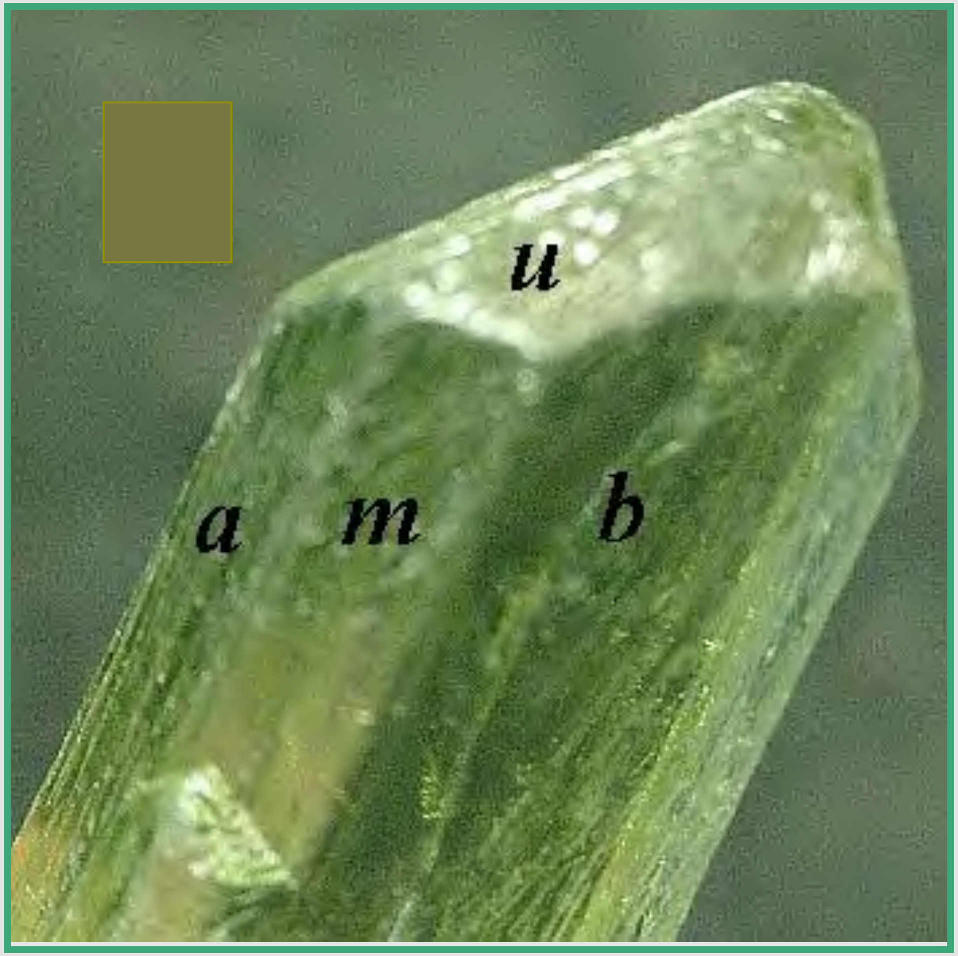
Feldspar (110)



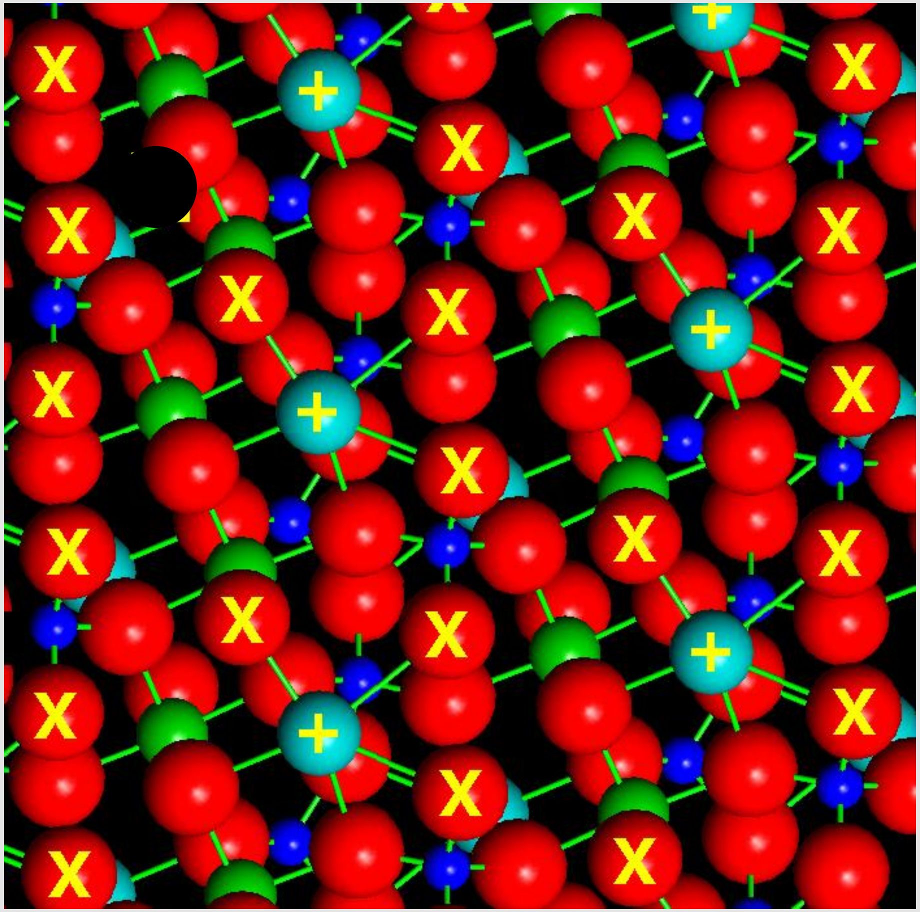


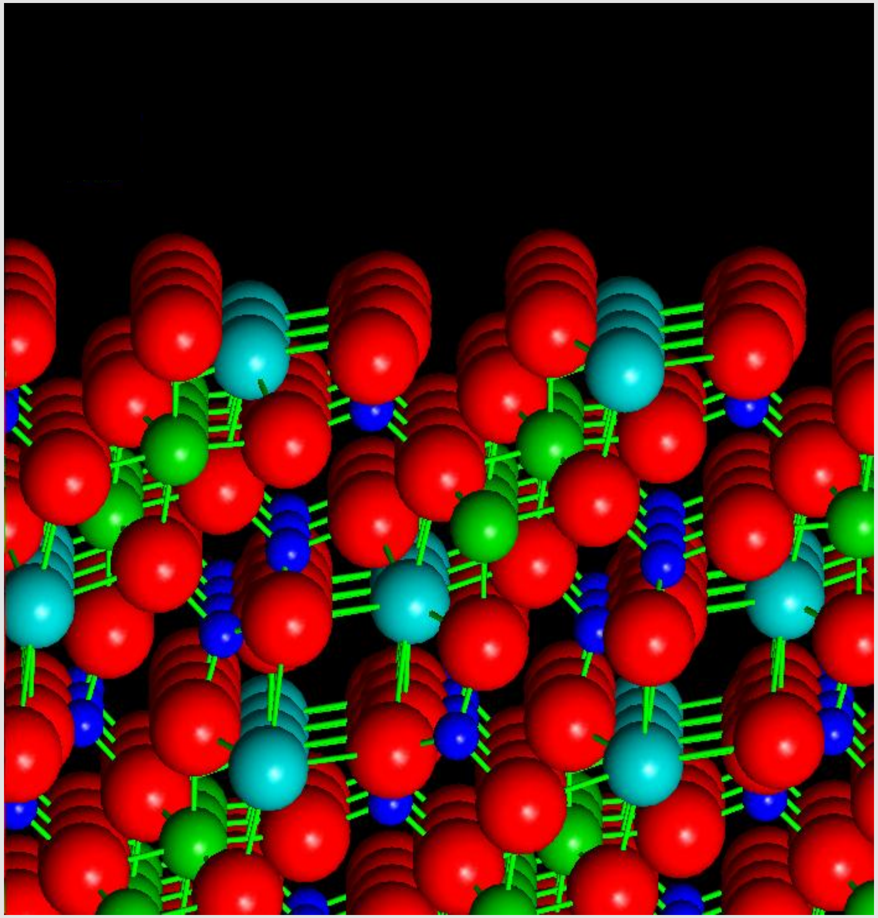
Diopside – (110) Face



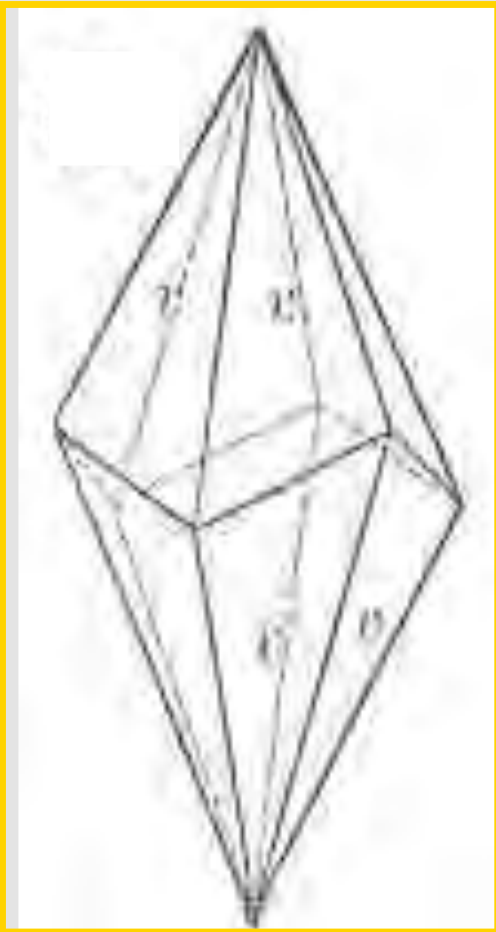


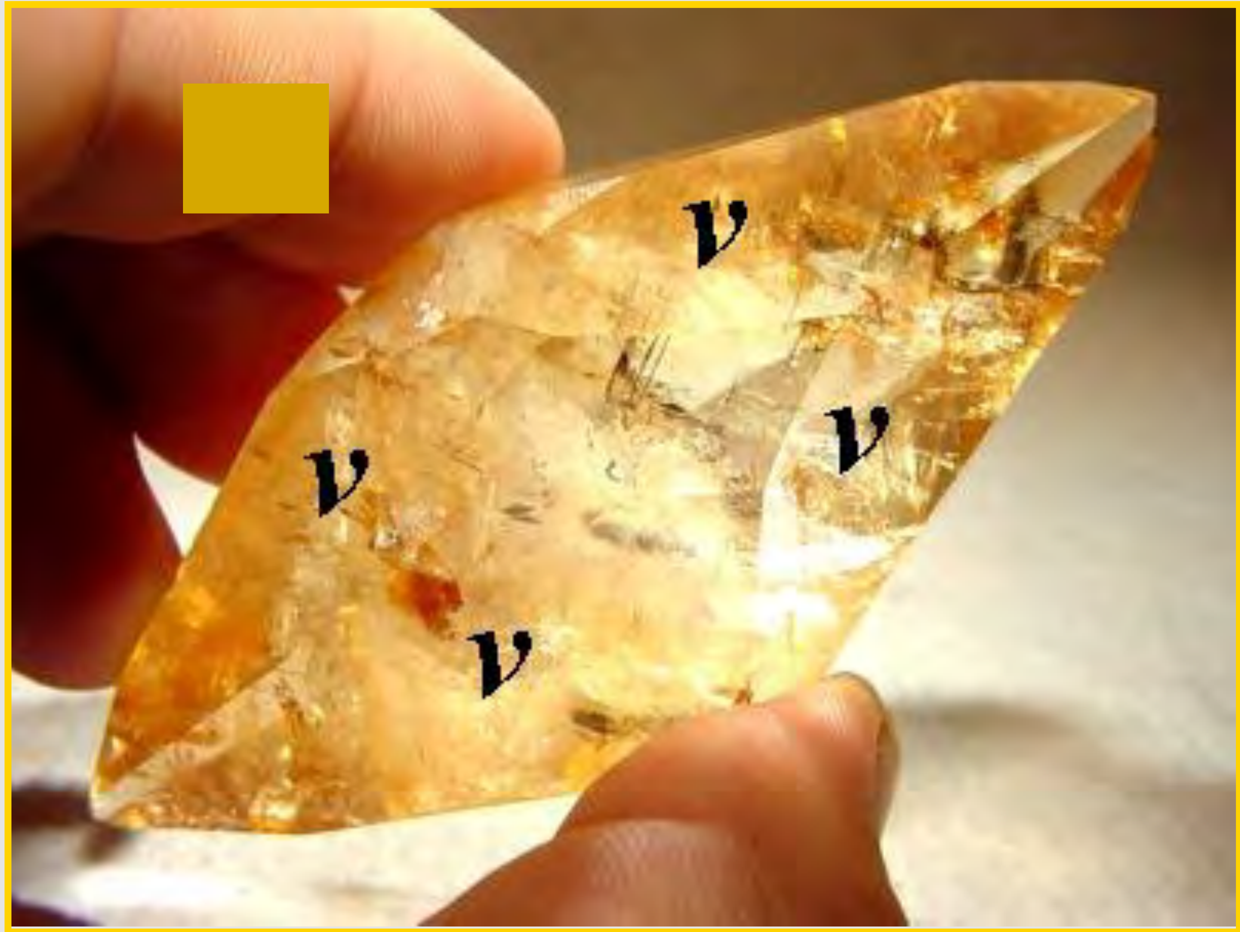
Diopside – (110) Face



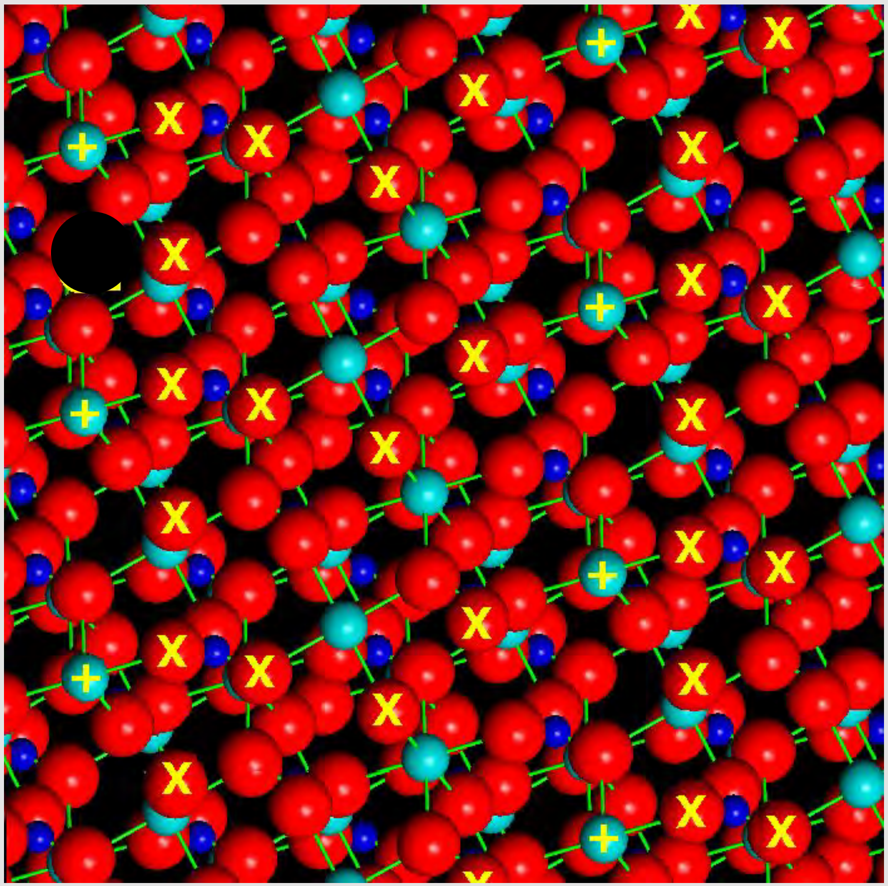


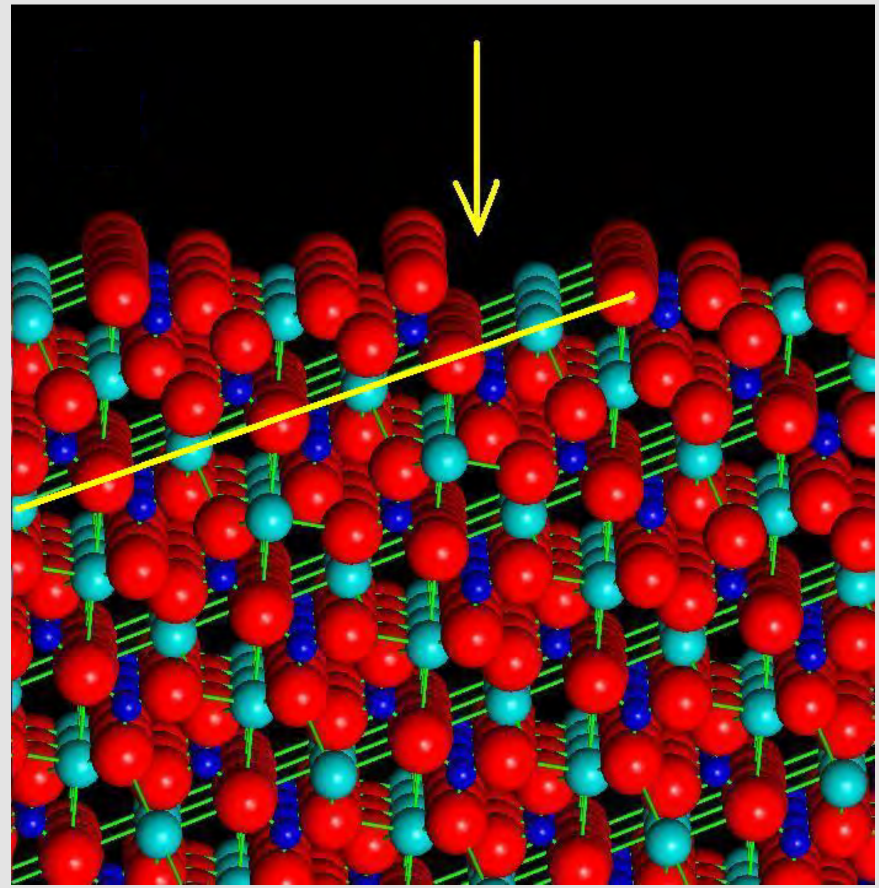
Calcite – $CaCO_3$



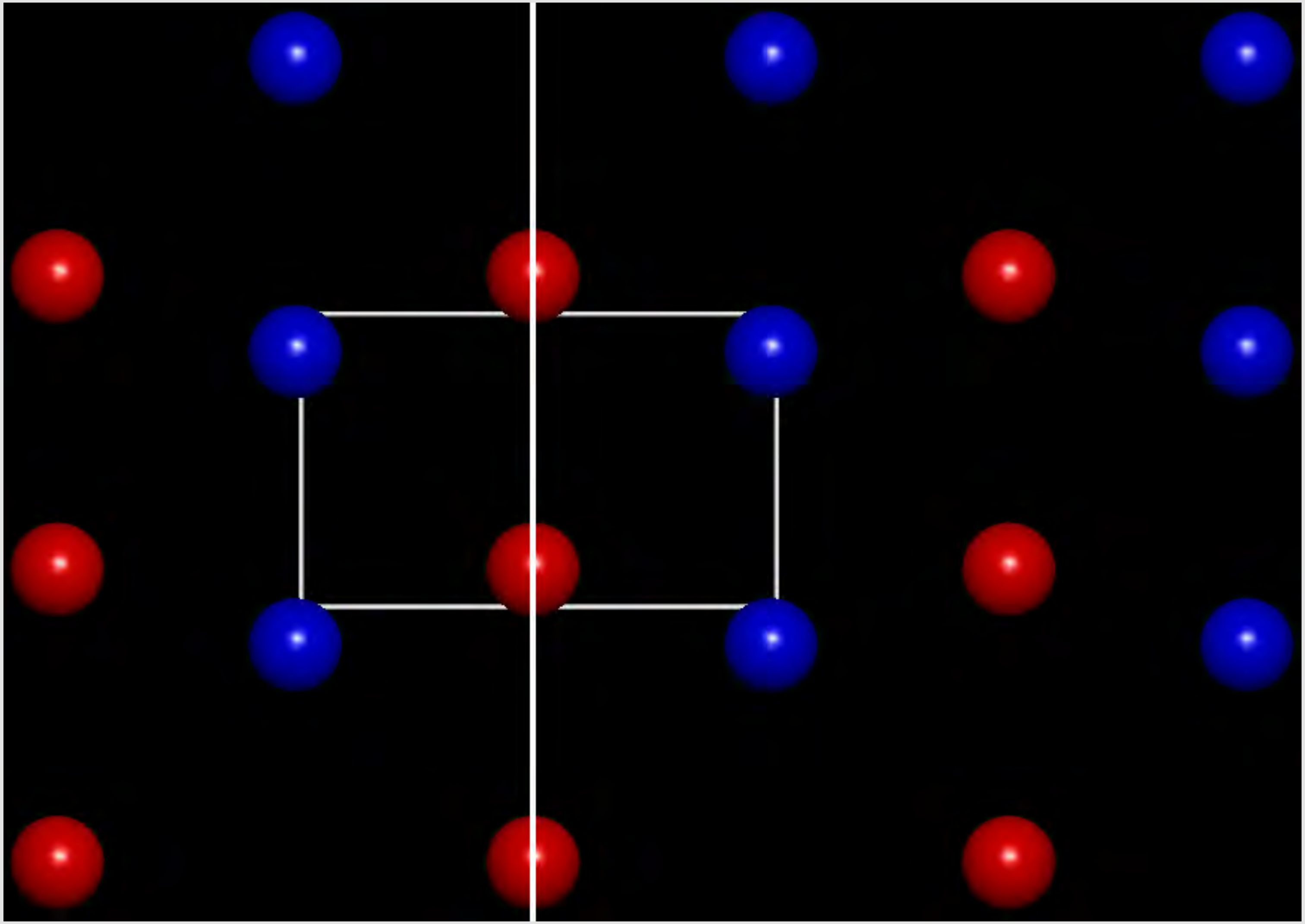


Calcite – (214) Face





Chiral Indices: Calcite (104)



Chiral Indices: Calcite (214)

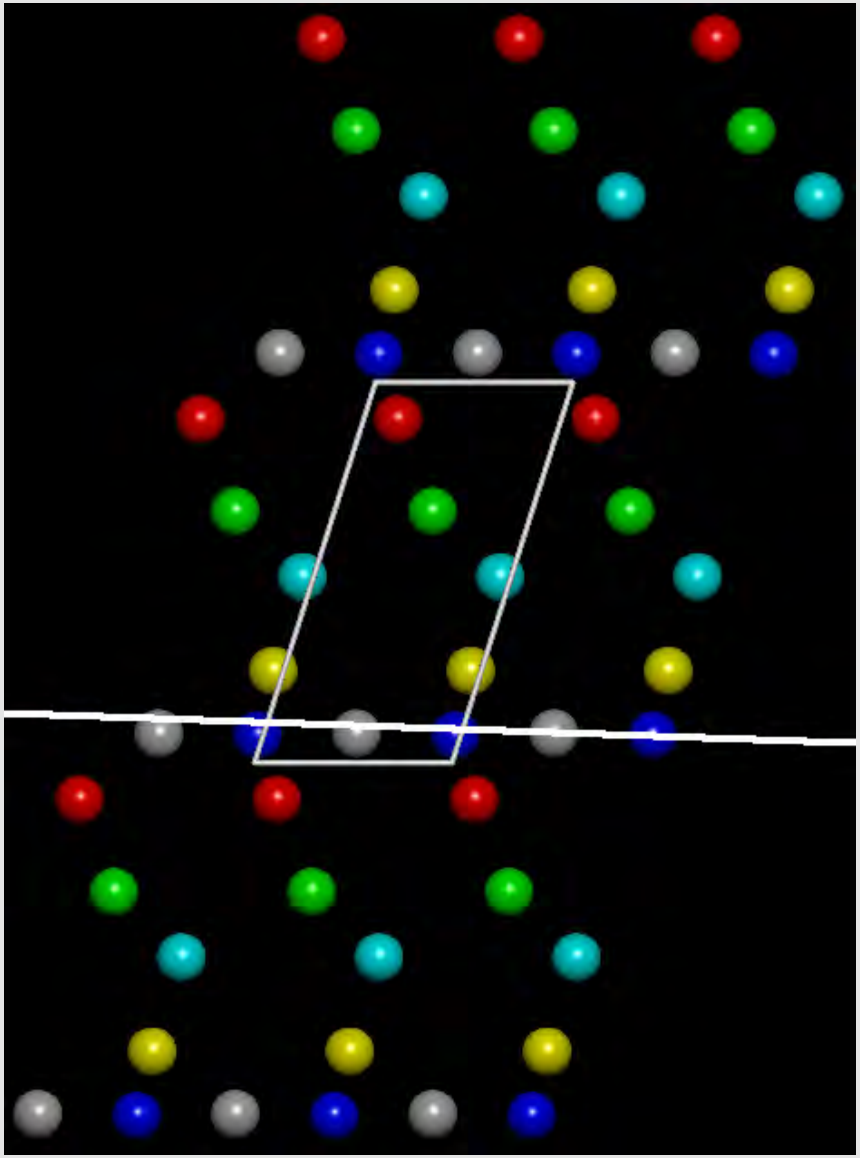


Table of Chiral Indices

Mineral	Face	Average Displ.	Max. Displ.
Calcite	(214)	0.93	1.81
Diopside	(110)-c	0.53	0.85
	(110)-e	0.72	1.54
Copper	(854)	0.84	1.29
Feldspar	(110)	0.52	1.01
Quartz	(100)	0.54	0.59
	(011)	0.36	0.46
	(101)	0	0

Downs & Hazen (2004) *J. Molec. Catal.*

Table of Chiral Indices

Mineral	Face	Average Displ.	Max. Displ.
Calcite	(214)	0.93	1.81
Diopside	(110)-c	0.53	0.85
	(110)-e	0.72	1.54
Copper	(854)	0.84	1.29
Feldspar	(110)	0.52	1.01
Quartz	(100)	0.54	0.59
	(011)	0.36	0.46
	(101)	0	0

Table of Chiral Indices

Mineral	Face	Average Displ.	Max. Displ.
Calcite	(214)	0.93	1.81
Diopside	(110)-c	0.53	0.85
	(110)-e	0.72	1.54
Copper	(854)	0.84	1.29
Feldspar	(110)	0.52	1.01
Quartz	(100)	0.54	0.59
	(011)	0.36	0.46
	(101)	0	0

Conclusions 1: Chiral Surfaces

Chiral mineral surfaces are common.

In oxides and silicates, larger chiral indices are often associated with the presence of both terminal cations and anions.

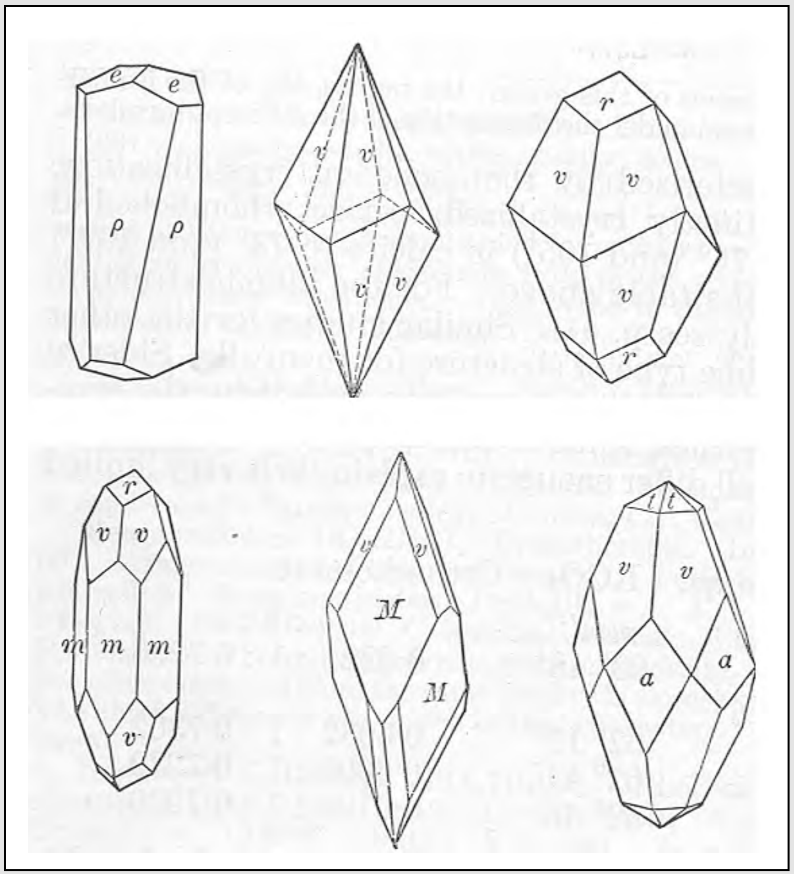
Relatively large chiral indices are often associated with stepped and kinked surfaces.

2. Mineral Chiral Selection

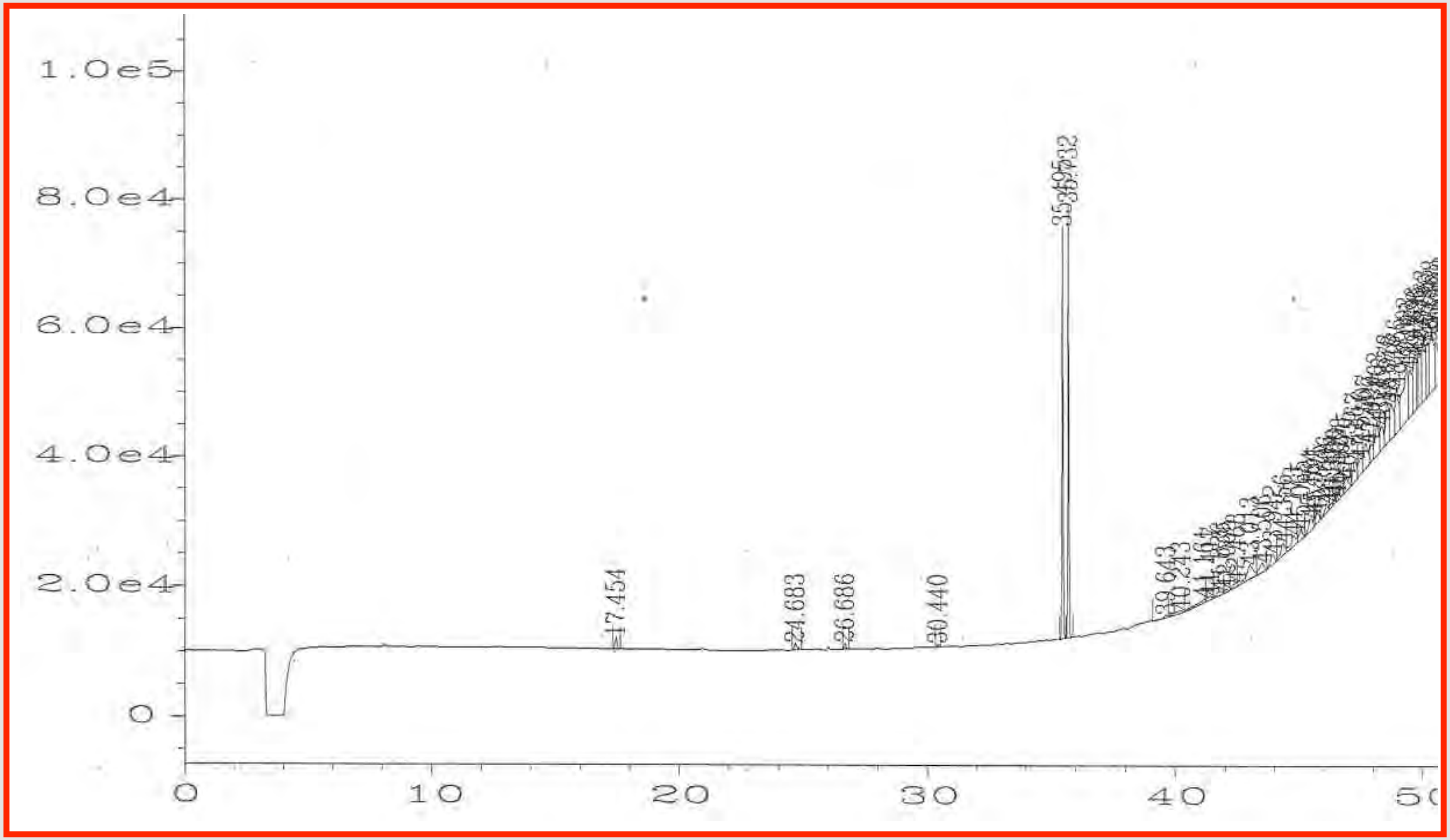
Glenn Goodfriend with Steve Gould

Selective Adsorption on Calcite

- $CaCO_3$
- Rhombohedral
- Common (214) form

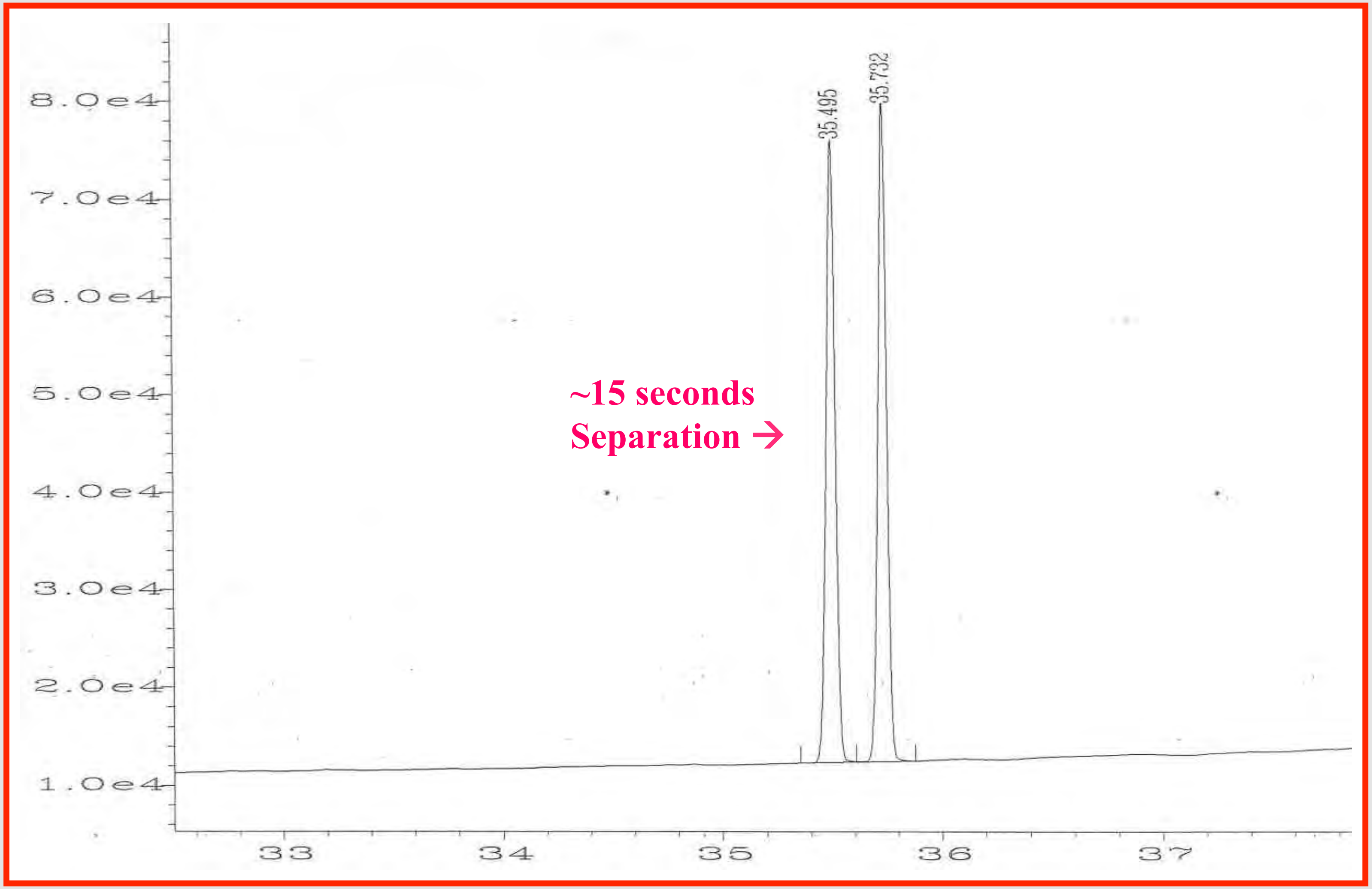


GC Analysis



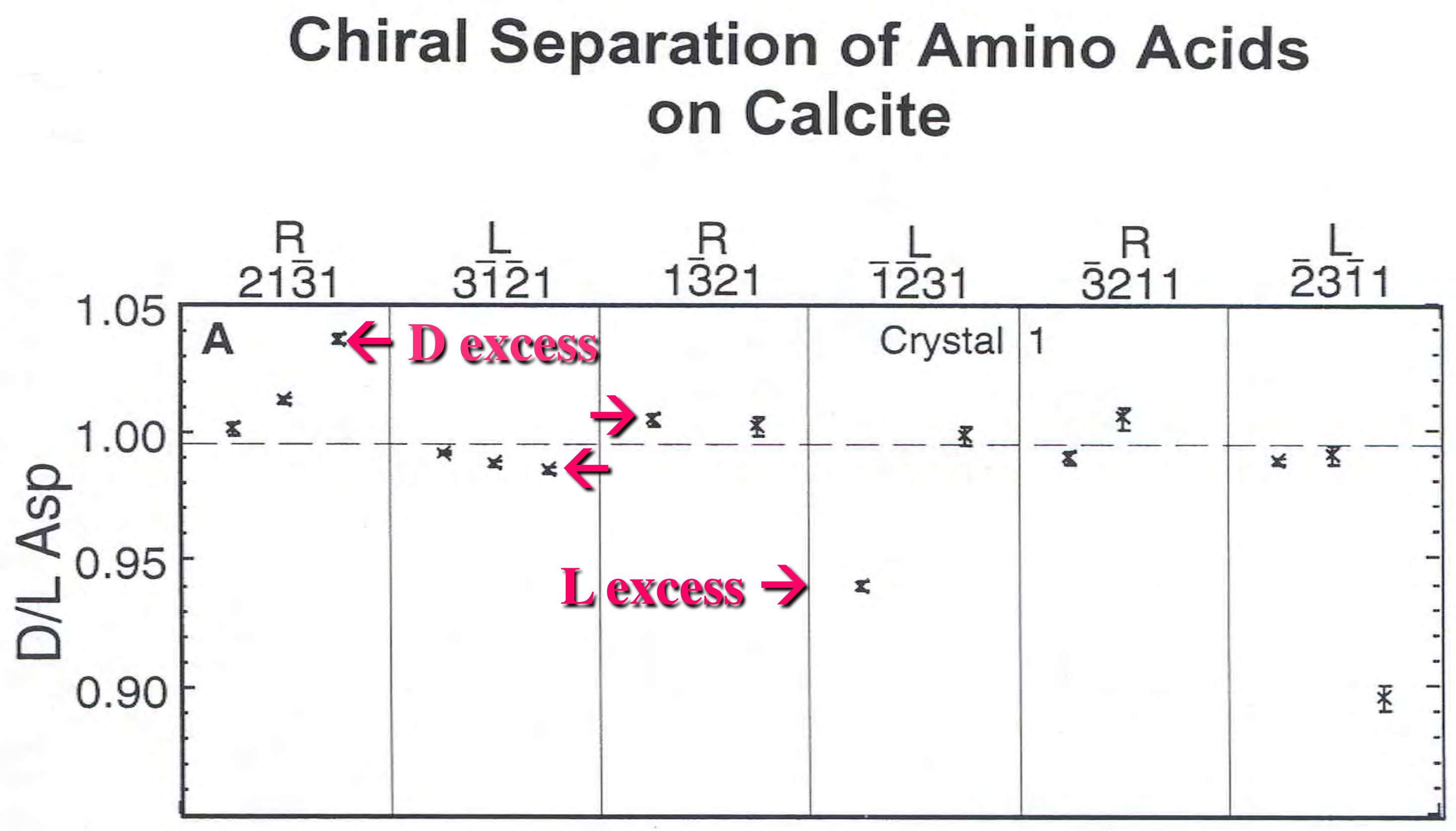
Aspartic acid doublet

GC Analysis



Aspartic acid doublet

Chiral Selection on Calcite



Hazen et al. (2001) *PNAS*

Conclusions 2: Mineral Chiral Selection

Calcite (214) crystal surfaces select D- and L-aspartic acid.

We do not observe selective adsorption of glutamic acid or alanine on calcite.

Maximum selective adsorption occurs on terraced crystal faces. This fact suggests that chiral selection may occur along linear features.

The alignment of chiral amino acids on calcite may lead to homochiral polymerization.

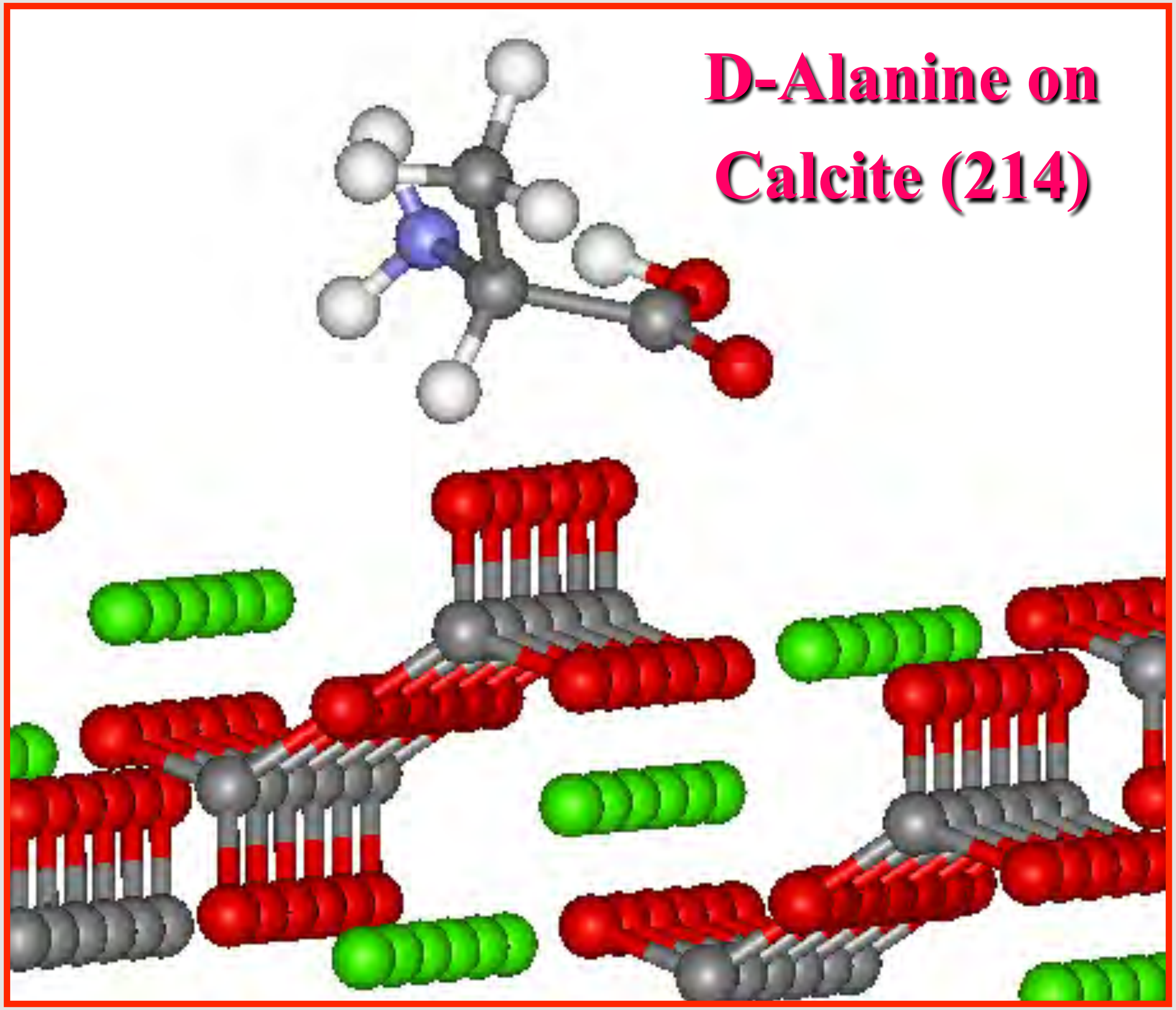
3. Modeling Mineral-Molecule Interactions

Why do D- and L-amino acids bind differently (aspartic acid versus alanine on calcite)?

Experiments do not tell us much except that there may be an electrostatic contribution.

Can modeling shed light on specific atomic-scale interactions?

Modeling Mineral-Molecule Interactions



Modeling Alanine on Calcite (214)

Use density functional theory (an accurate 1st principles method) to model interactions.

As a first approximation ignore water (i.e., gas phase model).

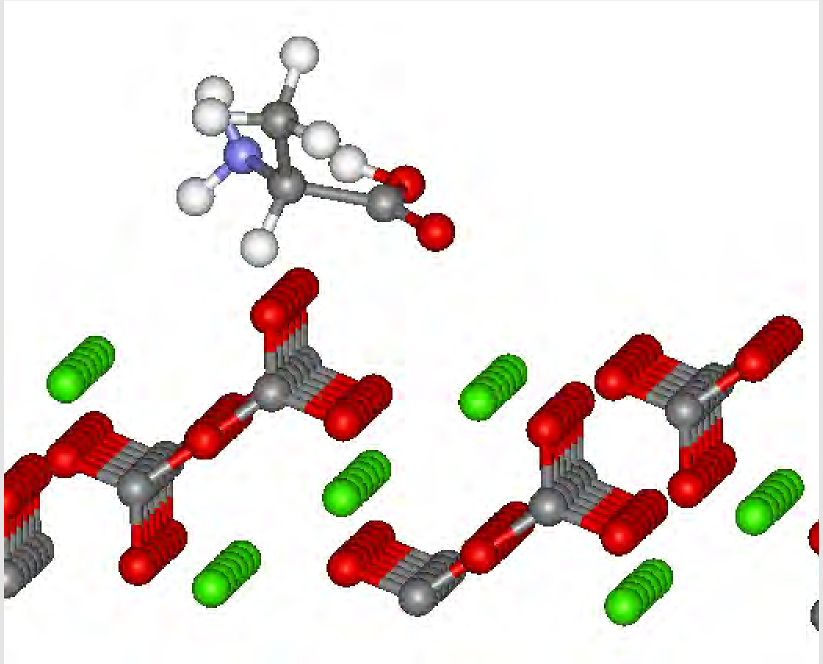
Examine numerous plausible configurations.

The most stable configurations involve Ca-O bonding between calcite and carboxyl groups.

D-Alanine-Calcite (214) Interactions

Begin by bringing a D-alanine molecule close to an unrelaxed calcite surface.

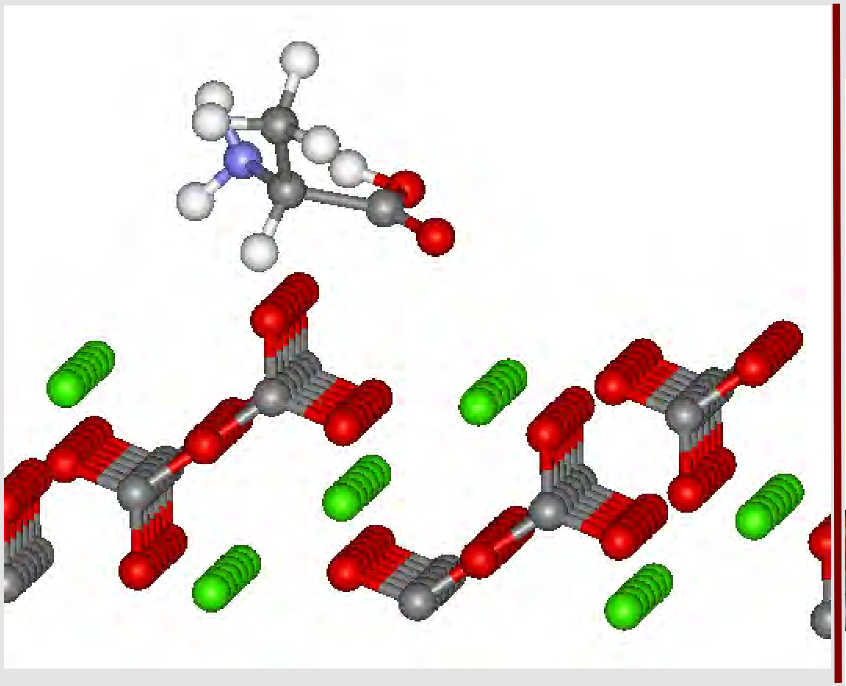
initial



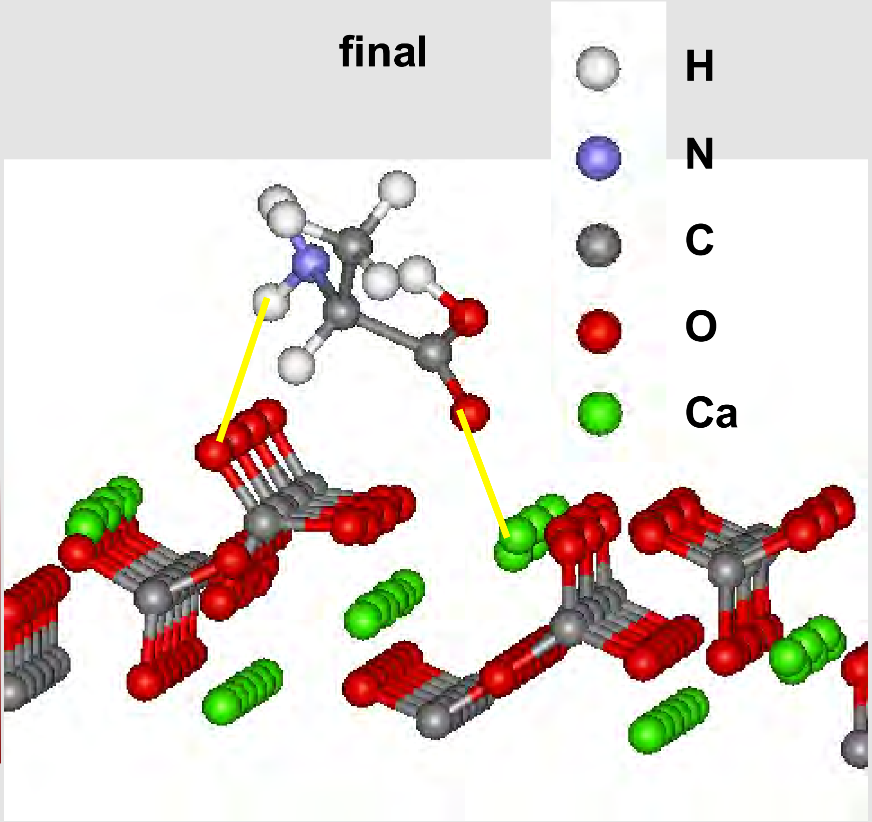
D-Alanine-Calcite (214) Interactions

The stable converged configuration reveals surface relaxation and Ca-O and O-H interactions, but no strong third interaction.

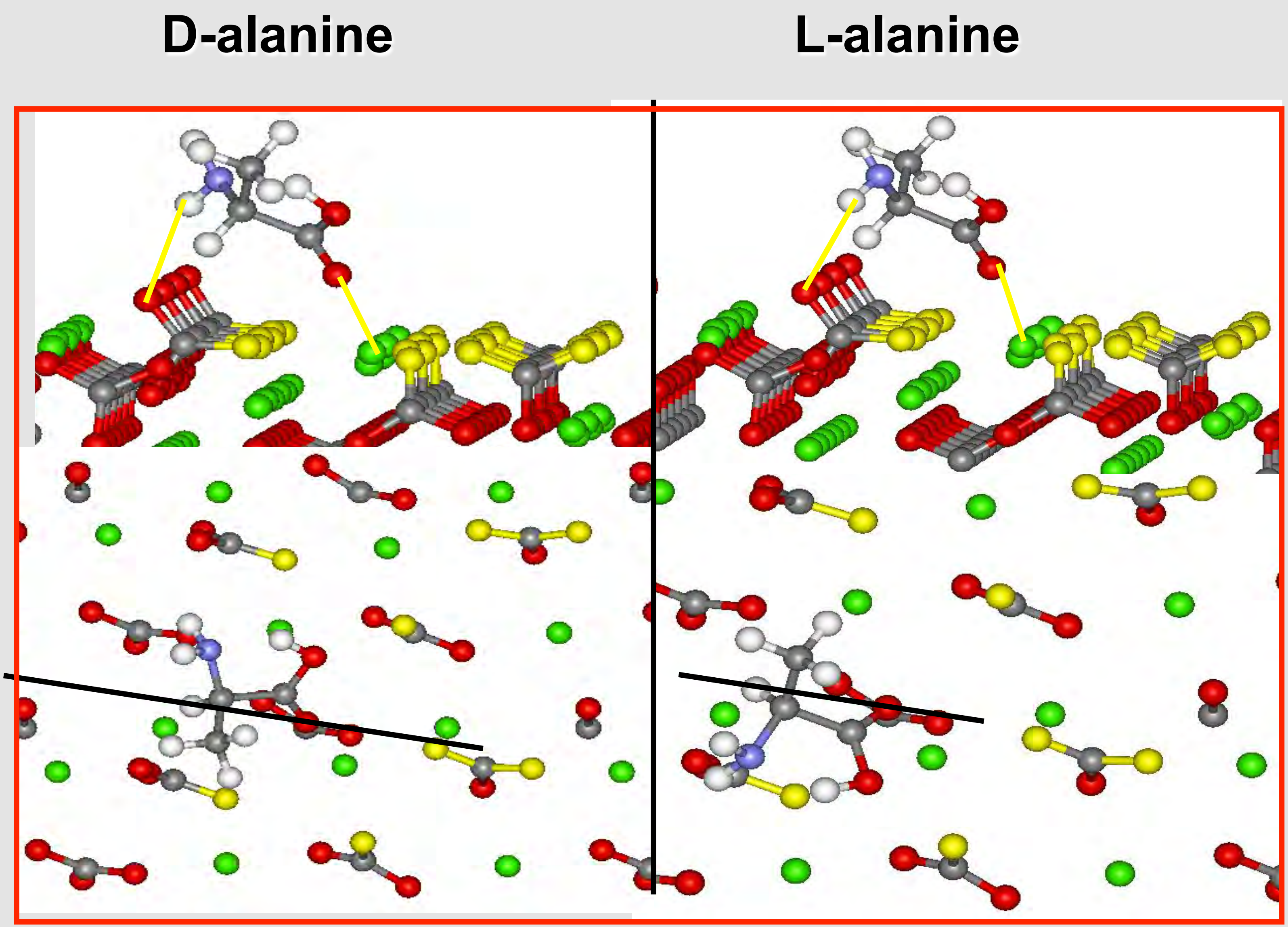
initial



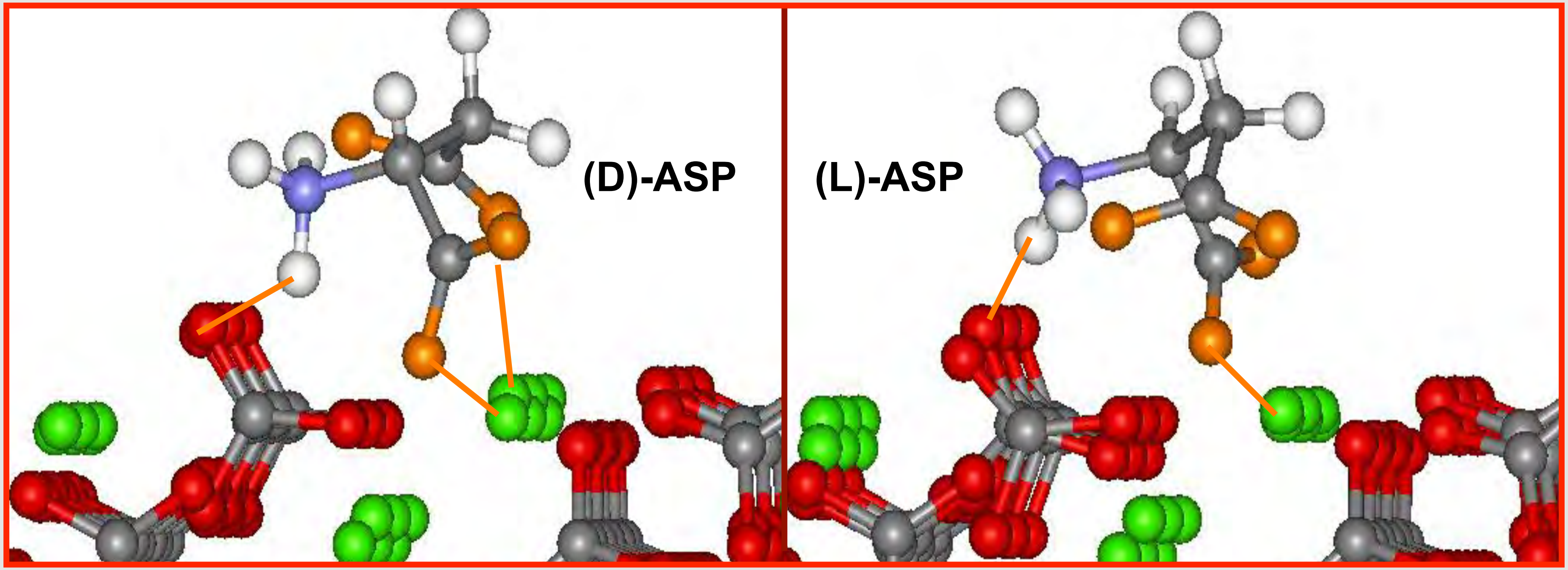
final



Alanine-Calcite (214) Interactions



Aspartic Acid-Calcite (214) Interactions



The most stable configuration found for D- and L-aspartic acid on calcite (214) surface. The D enantiomer is favored by 8 Kcal/mol.

Conclusions 3: Modeling Mineral-Molecule Interactions

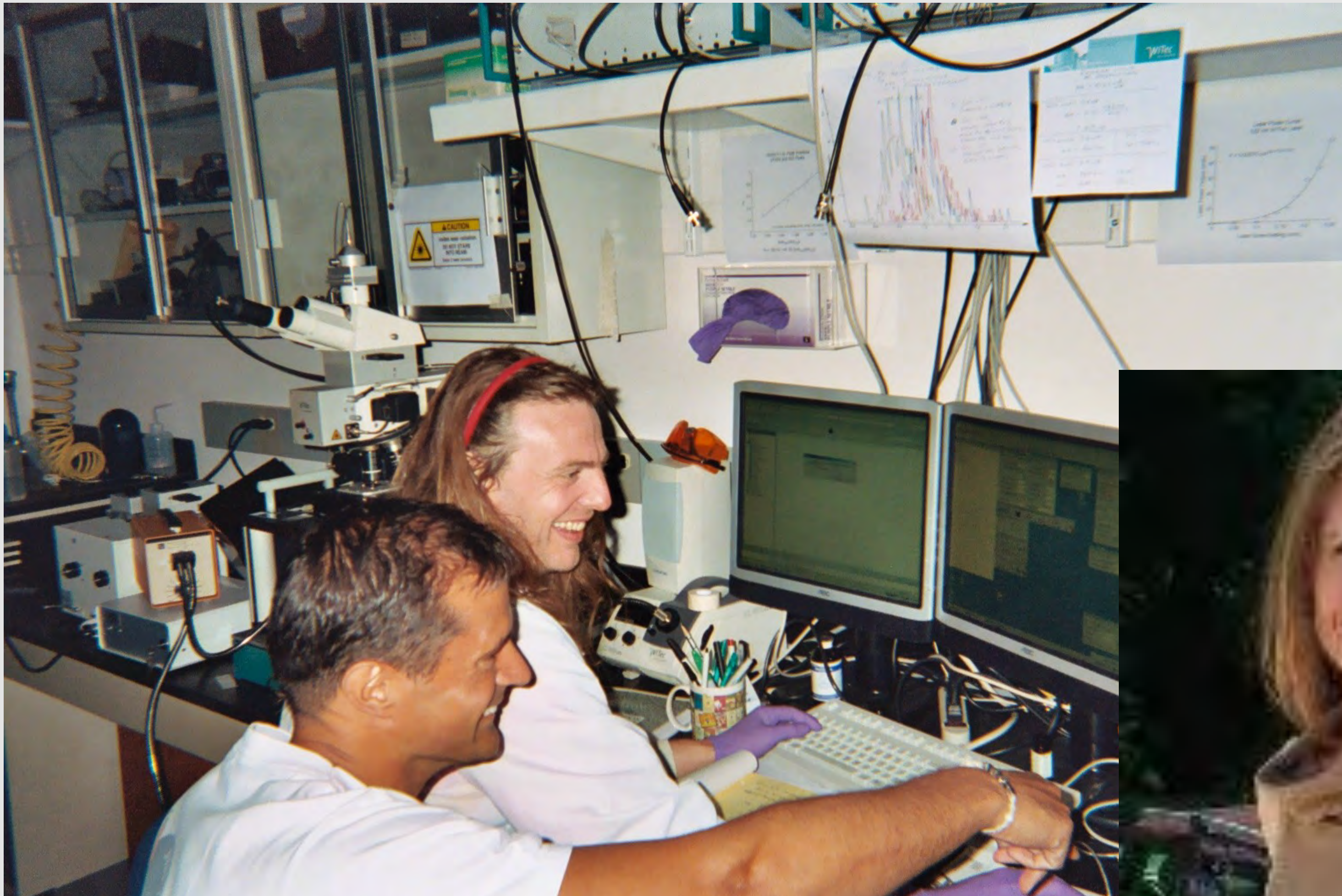
Chiral interactions require three points of interaction.

Which molecule sticks to which surface is idiosyncratic.

4. A General Research Strategy

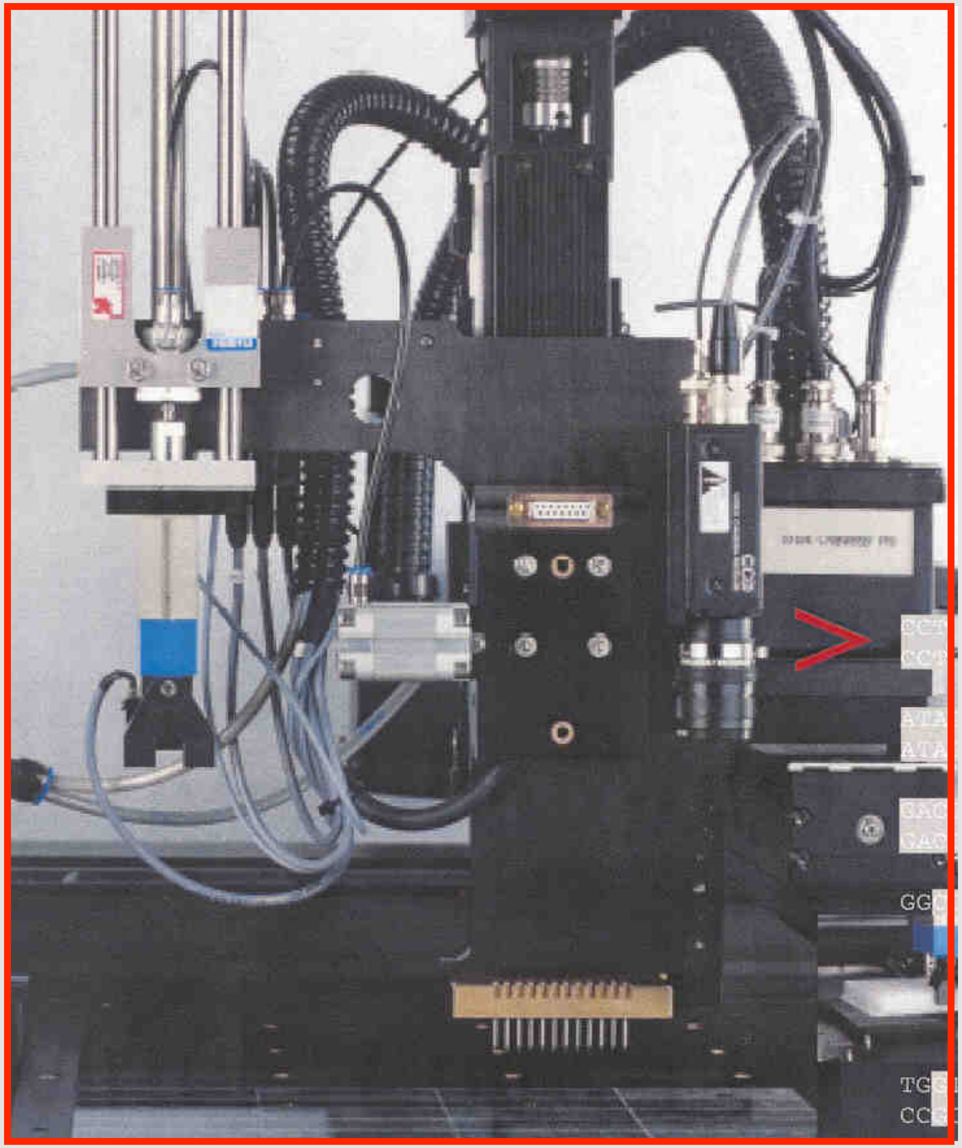
How do we evaluate interactions among the numerous possible mineral-molecule pairs?

We need a combinatoric approach.



Jake Maule, Andrew Steele and Rebecca Martin

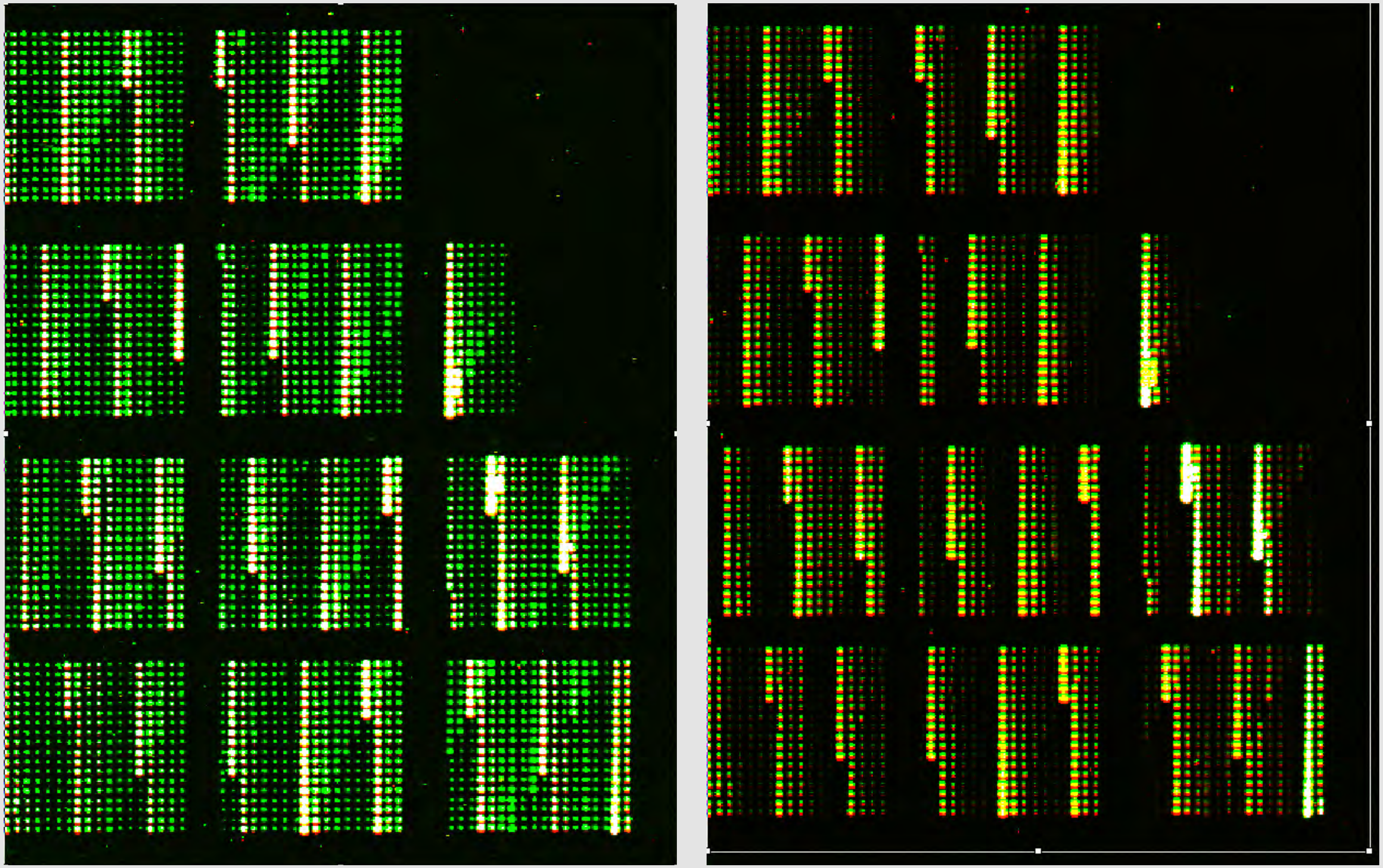
A Combinatoric Strategy



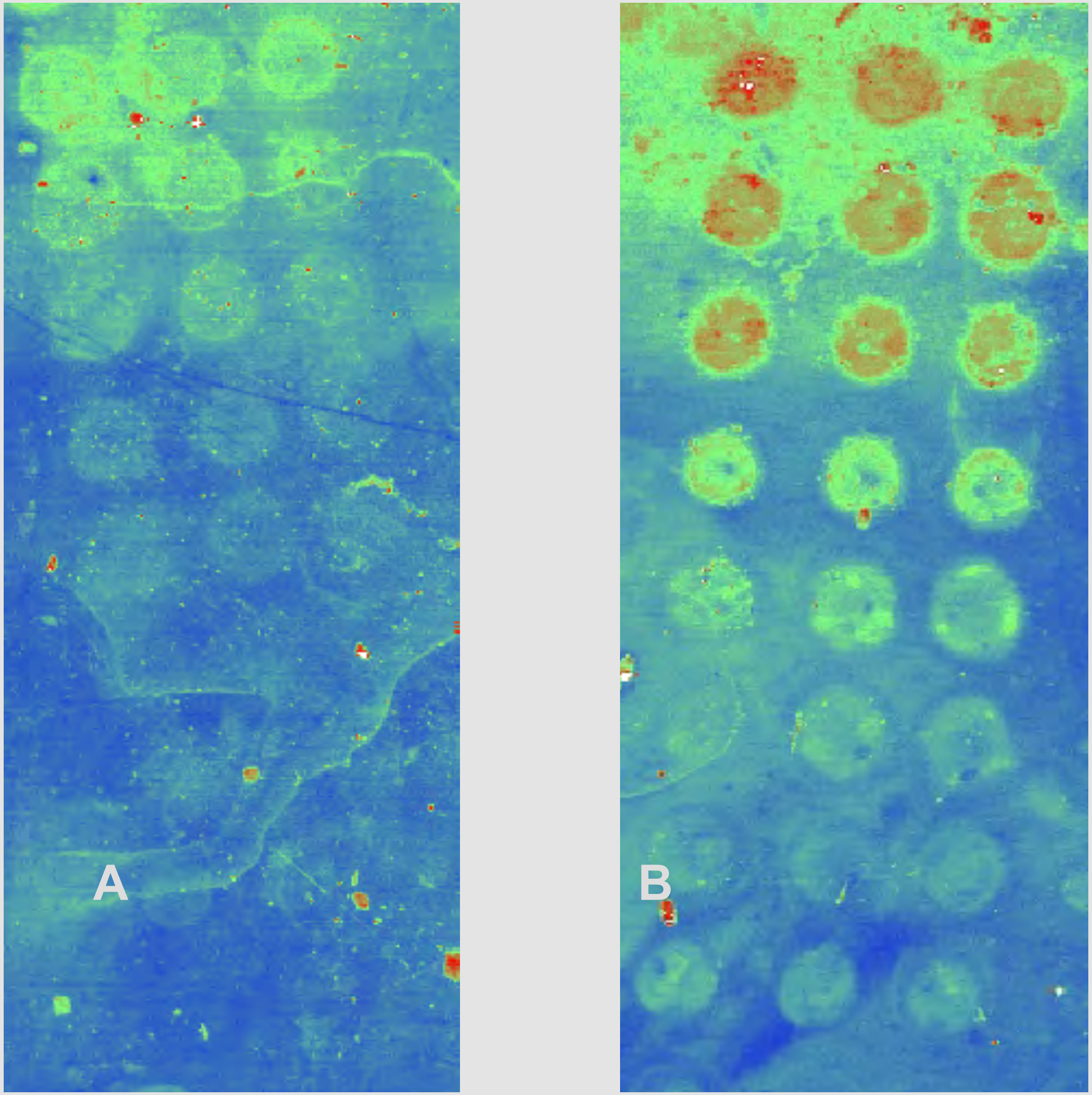
<u>**ChipWriter**</u>

- **Up to 126 minerals**
- **Up to 49,152 spots per mineral**
- **Up to 96 different wells**
- **100-micron spots**

Microarrays of Cy3-labeled asparagine, glutamine and tyrosine on glass at 20 serial dilutions.



Each microarray was scanned simultaneously with 532nm/635nm lasers and the fluorescence emission was captured at the wavelength bands of 557-592nm (Cy3) and 650-690nm (Cy5). Each image shows the intensity of Cy3/Cy5 fluorescent bands at a focal distance of 60µm (left) and 120µm (right).

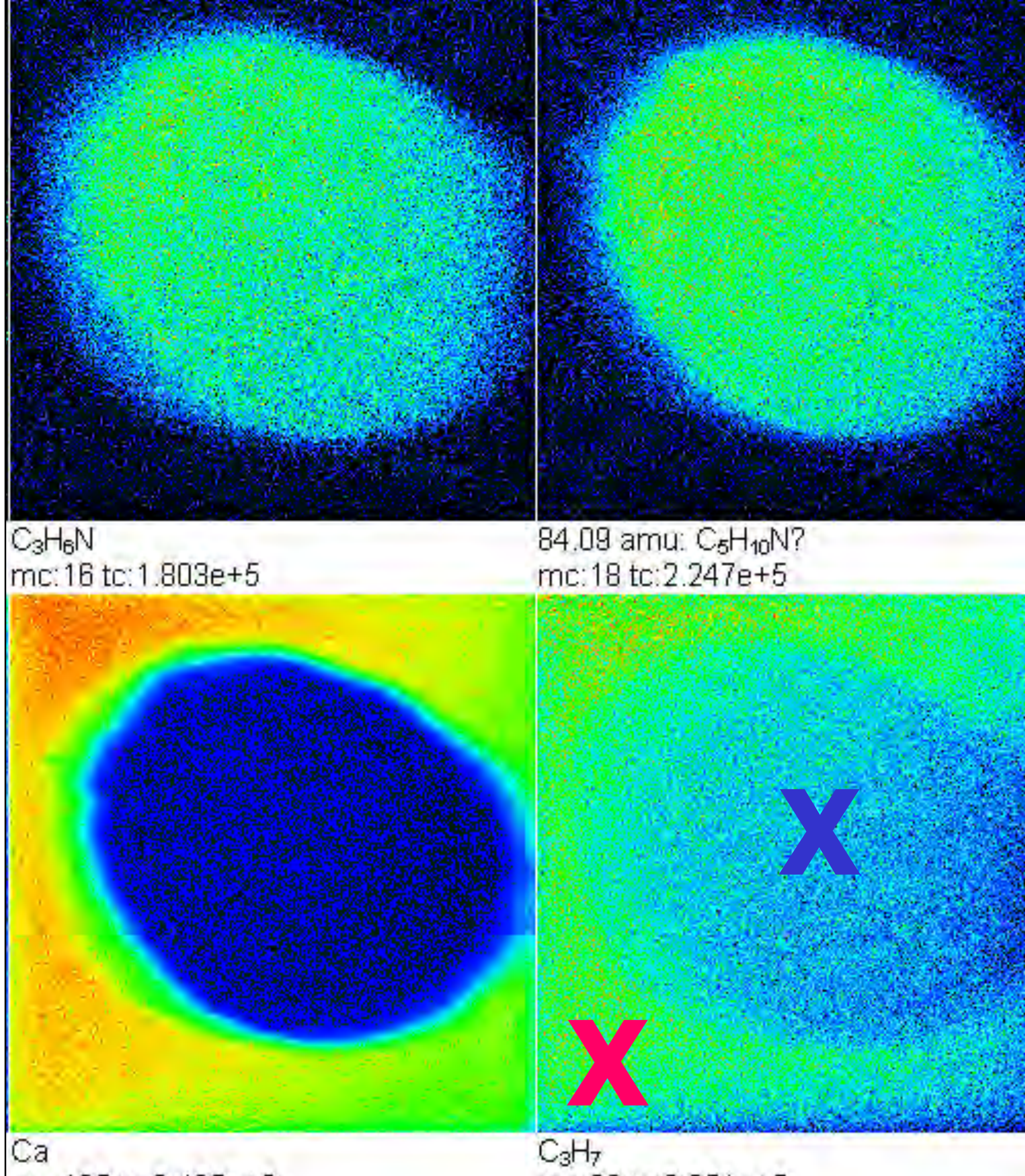


Microarrays of Cy3-labeled L-lysine on left- and right-handed quartz (100) faces at 8 serial dilutions. 150-micron spots.

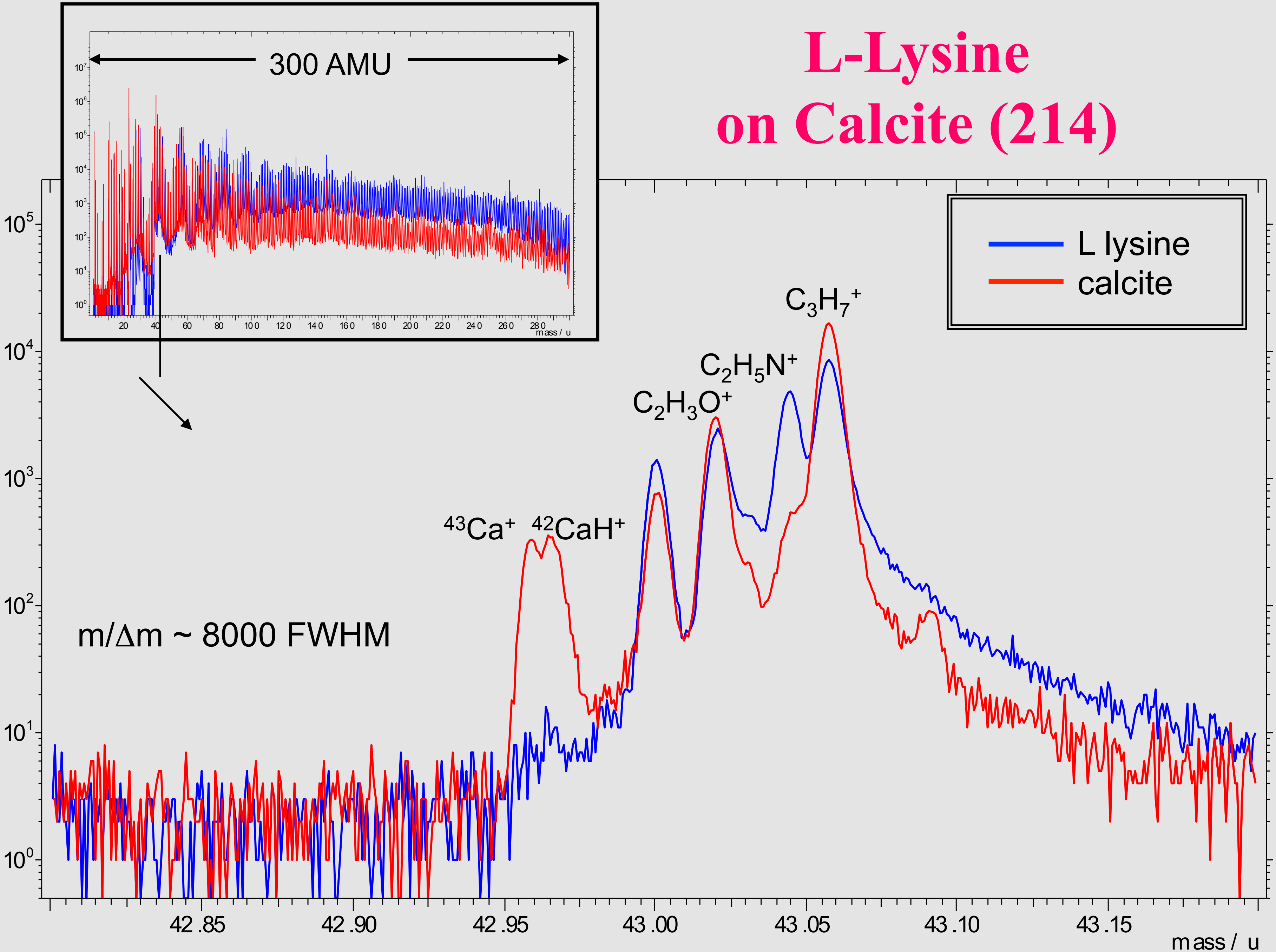
Edward Vicenzi and Detlef Rost
ToF-SIMS Lab, Smithsonian Institution

ToF-SIMS

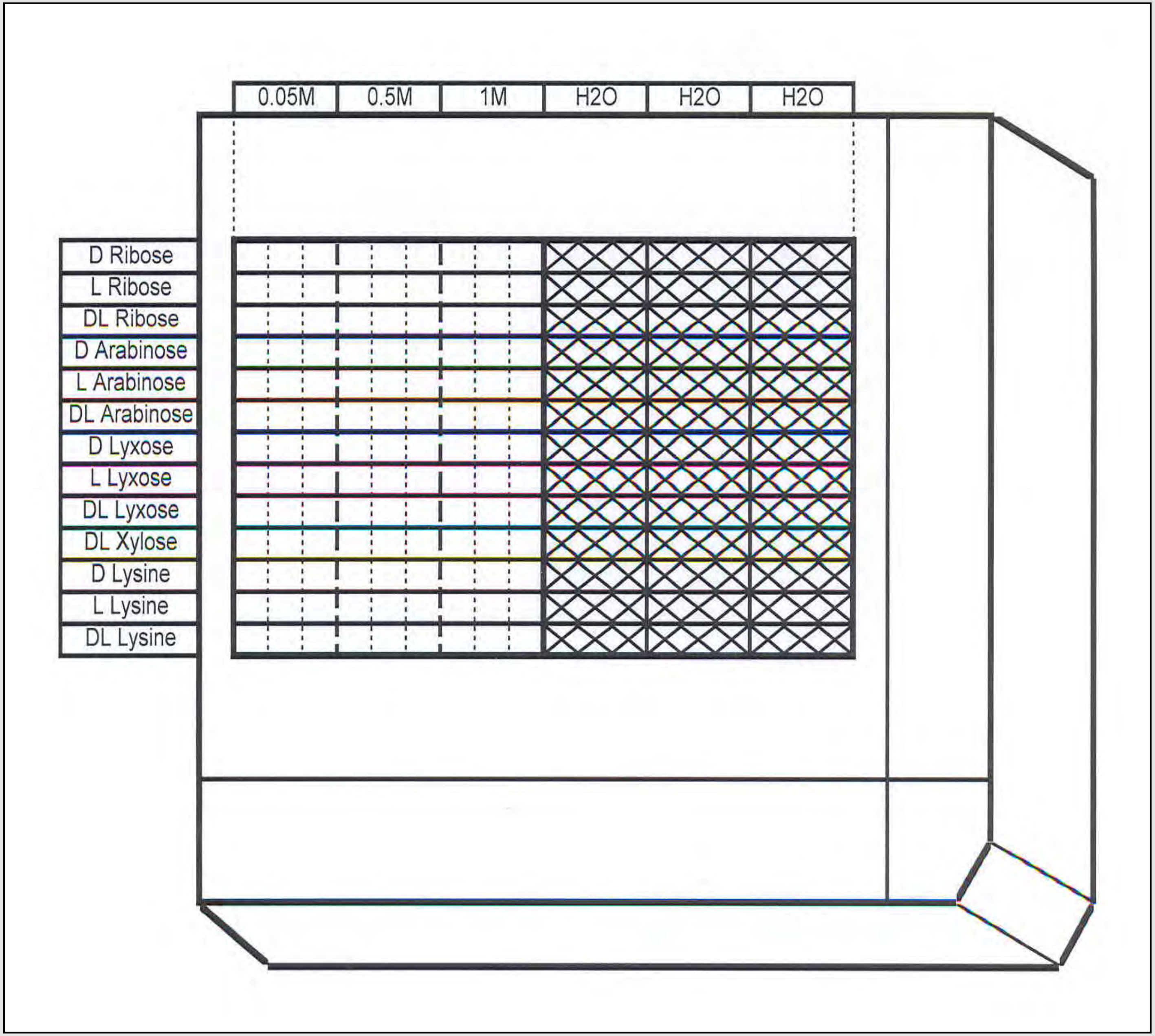
High-resolution ion fragment maps of 150-micron L-lysine spots on calcite (214).

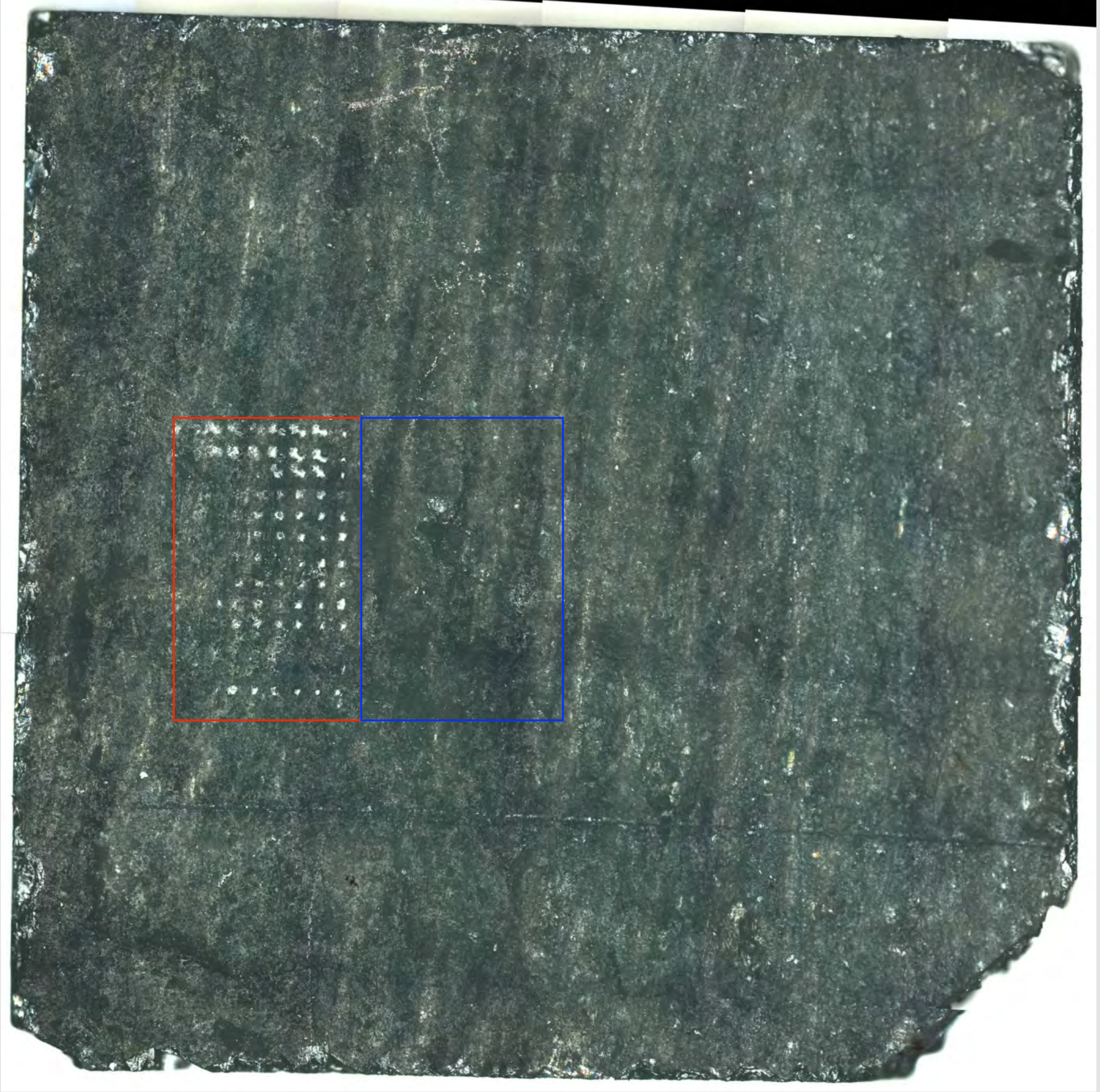


L-Lysine on Calcite (214)



9 x 13 Array on 1 x 1 x 0.3 cm feldspar plate.

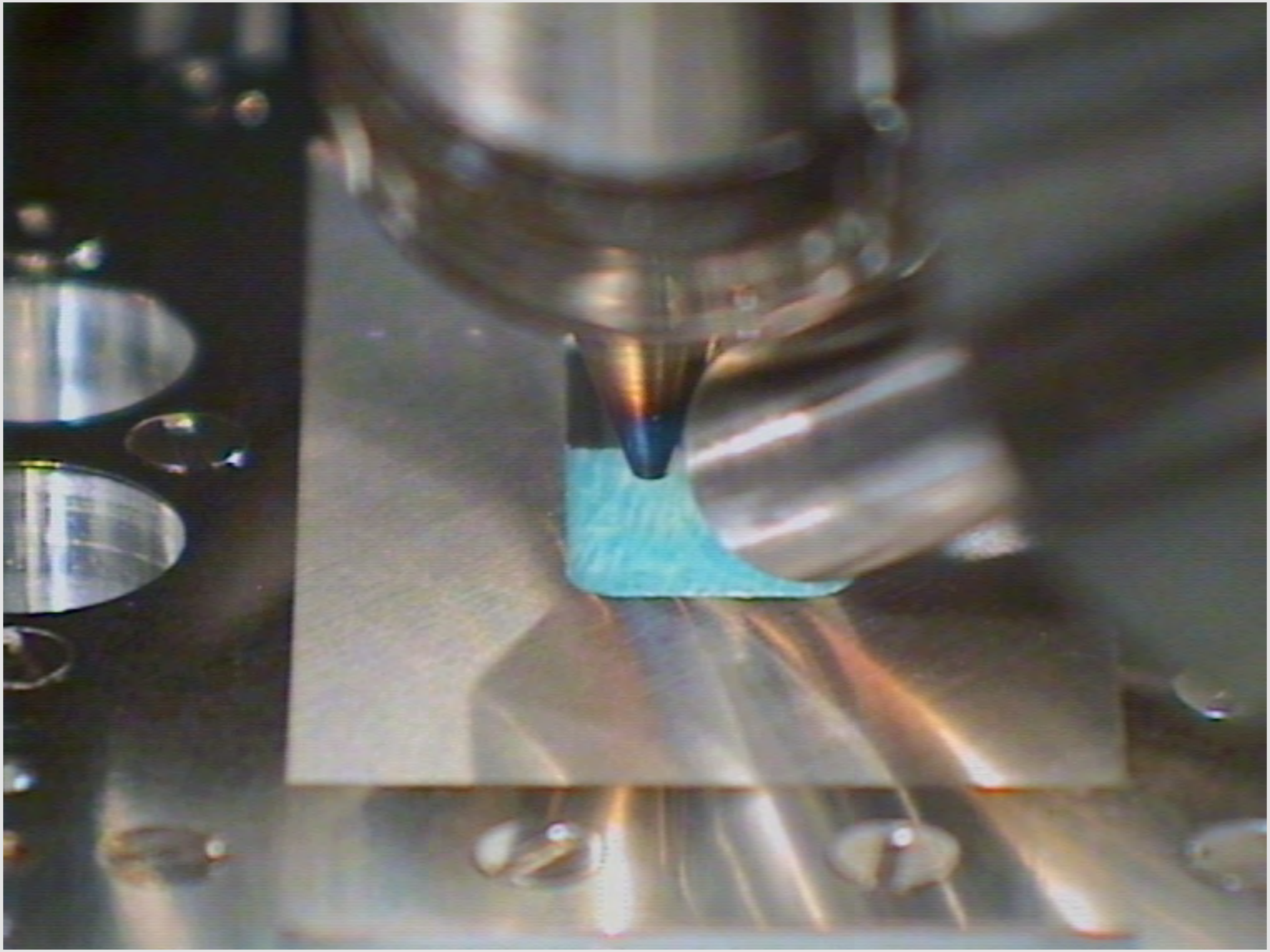




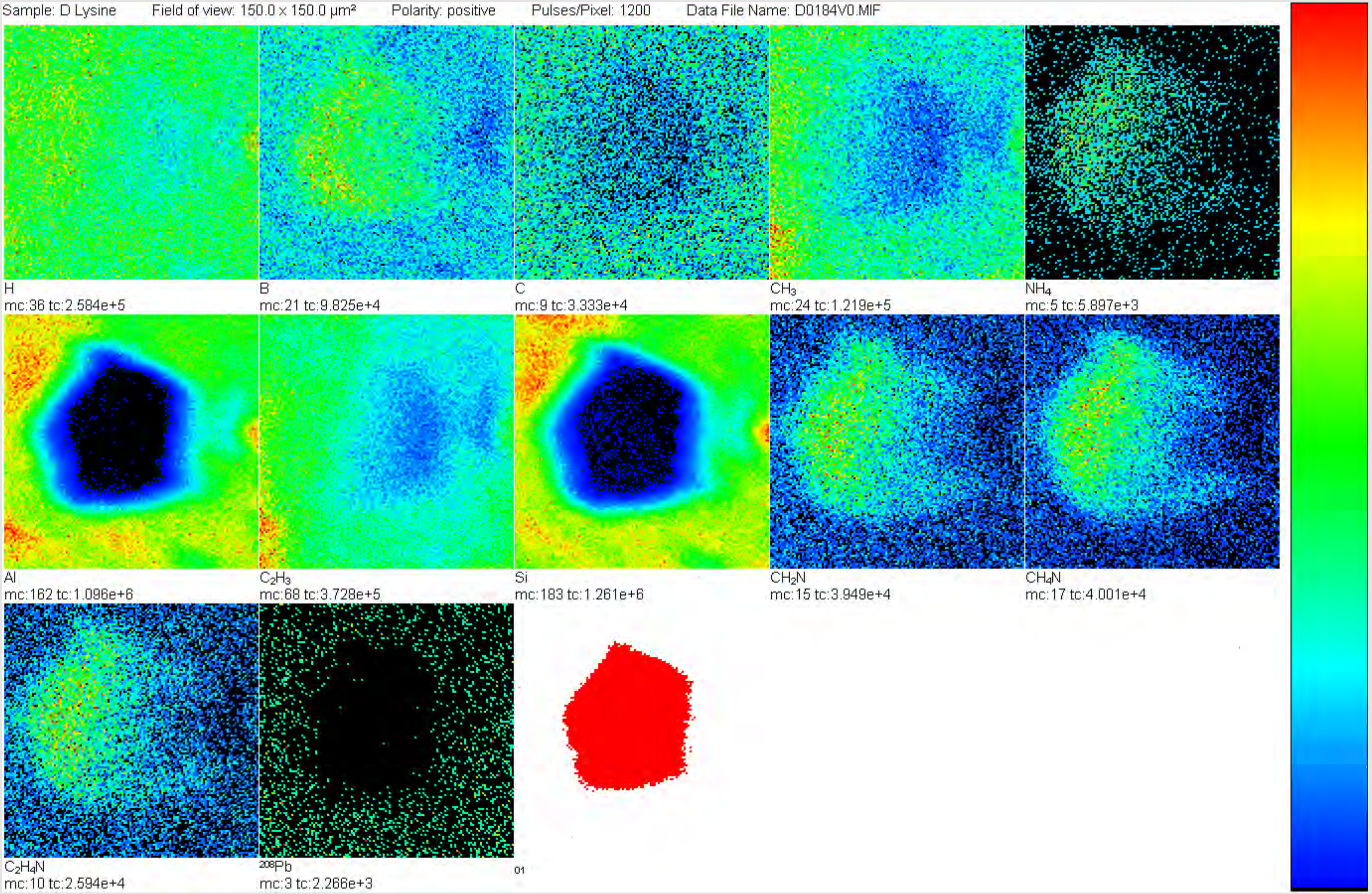
AMINO ACIDS AND SUGARS ON FELDSPAR

(010) Face – 1 x 1 cm plate

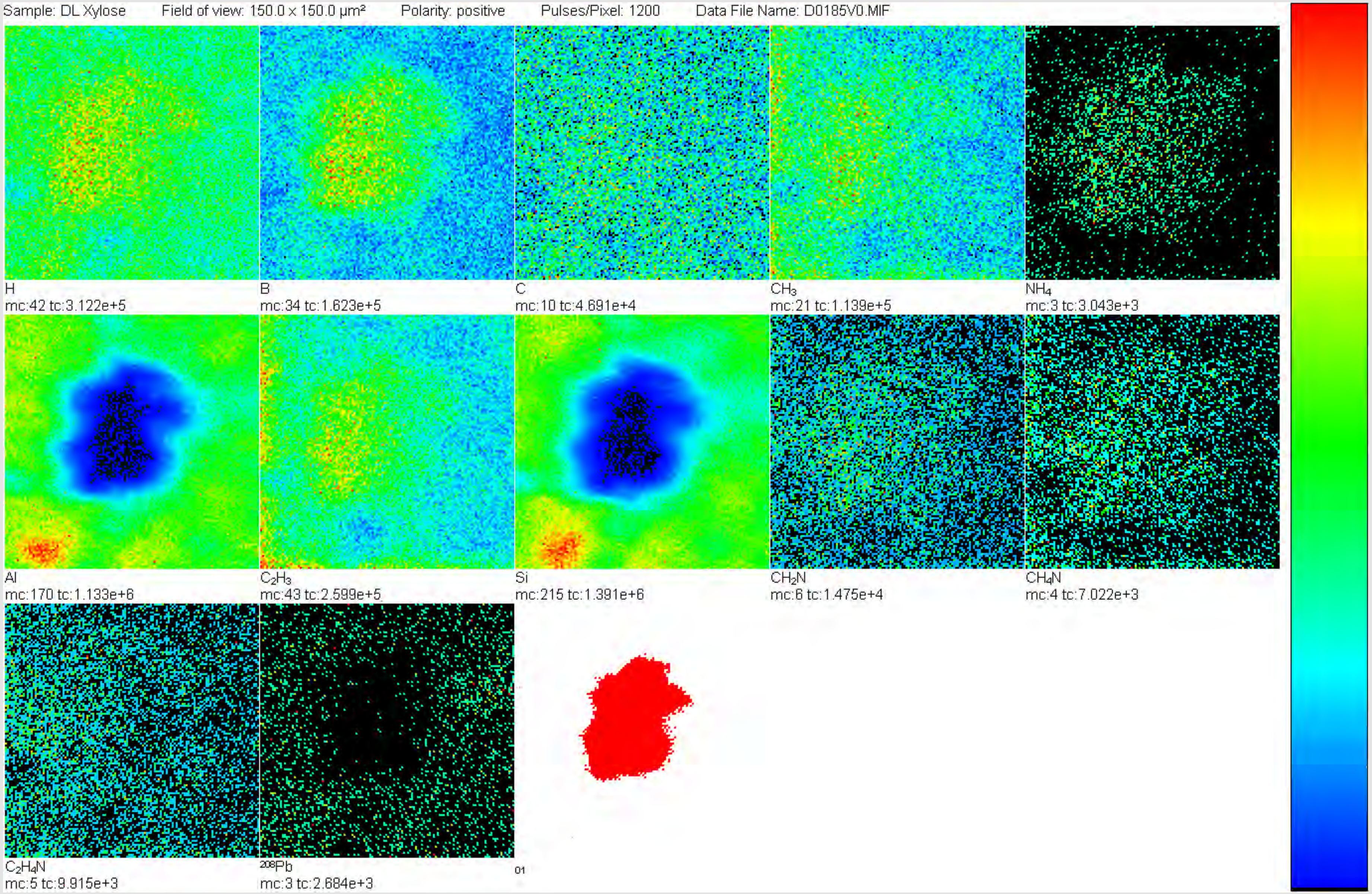
Feldspar (010) in ToF-SIMS Sample Holder



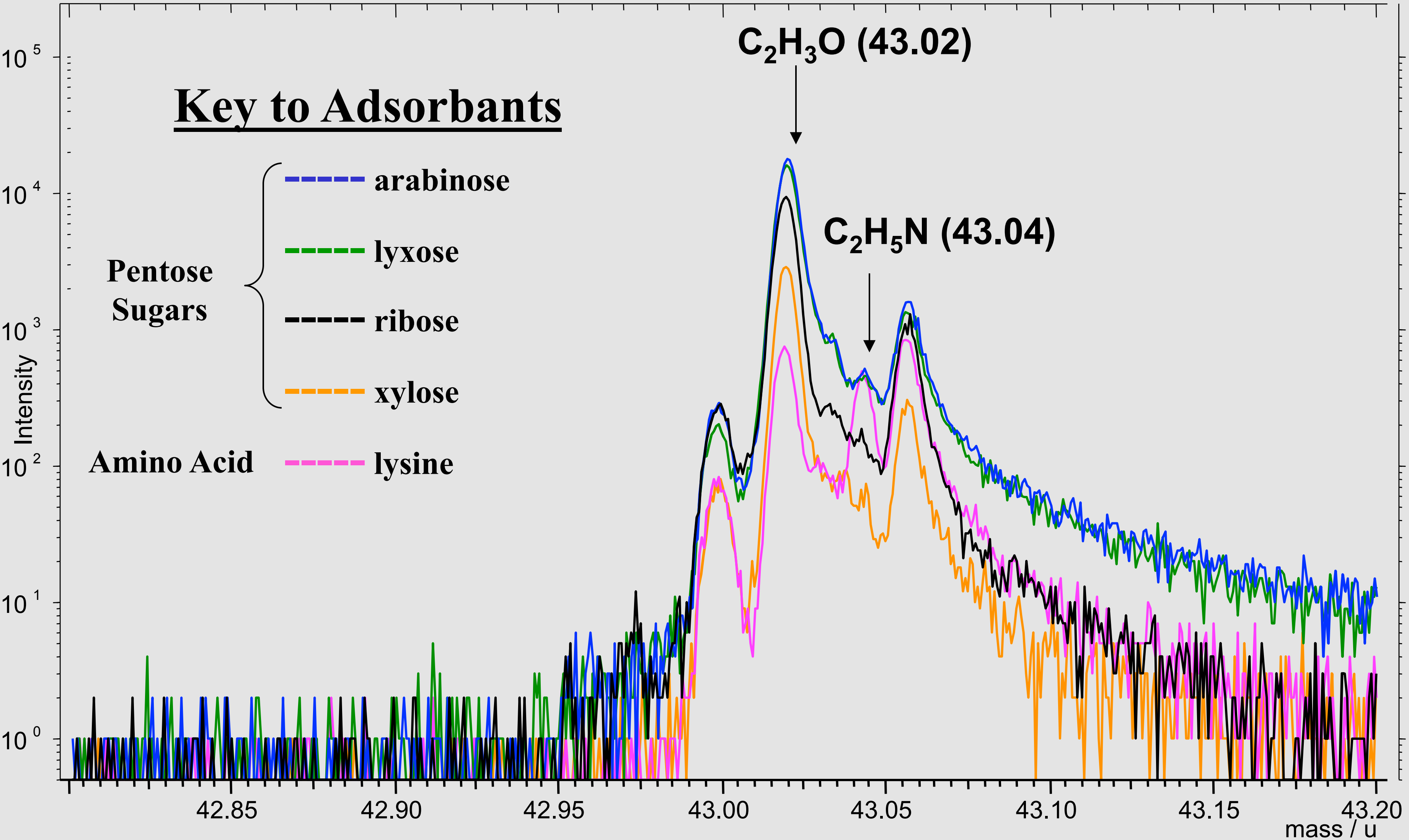
D-Lysine on Feldspar (010)



DL-Xylose on Feldspar (010)



Mass vs. Intensity for ~43 mass unit fragments



CONCLUSIONS

- **Many mineral surfaces have the potential for chiral selection of plausible prebiotic molecules.**

- **Microarray technology coupled with ToF-SIMS provides a powerful experimental means for combinatoric studies of mineral-molecule interactions.**

With thanks to:

NASA Astrobiology Institute
National Science Foundation
Carnegie Institution of Washington