RIGHT AND LEFT:
Geochemical Origins
Of Life’s Homochirality

United States Naval Observatory
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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
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 $\alpha$-H amino acids (i.e., no $\alpha$-methyl amino acids)
- Homochirality – L$\gg$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

Smells like oranges
Smells like lemons

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)
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 β decay

Local Chiral Microenvironments:

• Chiral molecules, themselves
• Mineral surfaces
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).


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

Mirror images are non-superimposable
McFadden et al. (1996)
“Adsorption of chiral alcohols on ‘chiral’ metal surfaces.”
*Langmuir* 12, 2483-2487.
Chiral Adsorption
Quartz is the only common chiral rock-forming mineral

Reports of successful chiral selections as early as the 1930s. Yet all previous authors used powdered quartz!
Quartz: Face-Specific Adsorption
Quartz – (100) 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)
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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
Selective Adsorption on Calcite

- CaCO₃
- Rhombohedral
- Common (214) form
GC Analysis

Aspartic acid doublet
Aspartic acid doublet

~15 seconds
Separation →
Chiral Selection on Calcite

Chiral Separation of Amino Acids on Calcite

Hazen et al. (2001) PNAS
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

D-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.
D-Alanine-Calcite (214) Interactions

The stable converged configuration reveals surface relaxation and Ca-O and O-H interactions, but no strong third interaction.
Alanine-Calcite (214) Interactions

D-alanine

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

ChipWriter

• 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)

$m/\Delta m \sim 8000$ FWHM

43Ca$^+$ 42CaH$^+$

C$_2$H$_3$O$^+$

C$_2$H$_5$N$^+$

C$_3$H$_7^+$

43Ca$^+$ 42CaH$^+$

L lysine

calcite
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
DL-Xylose on Feldspar (010)
Mass vs. Intensity
for ~43 mass unit fragments

Key to Adsorbants

Pentose Sugars
- arabinose
- lyxose
- ribose
- xylose

Amino Acid
- lysine

$C_2H_3O$ (43.02)
$C_2H_5N$ (43.04)
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.
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