

# INTRODUCTION

- Characterize MV-1 biogenic magnetite
- Characterize ALH84001 Martian magnetite
- MV-1 and ALH84001 magnetite populations are physically and chemically indistinguishable
- We suggest a common formation mechanism
- Summary of latest results, >4 years of work
  - Thomas-Keprta *et al.*, GCA, December 2000
  - Thomas-Keprta *et al.*, PNAS, submitted

# Terrestrial Magnetite



**Inorganic  
(natural and synthetic)**

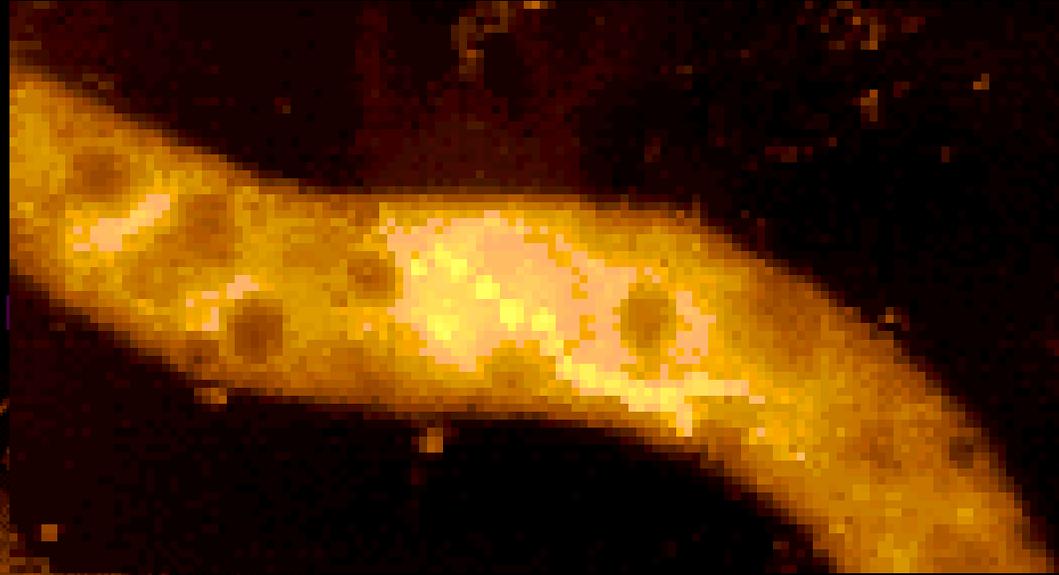
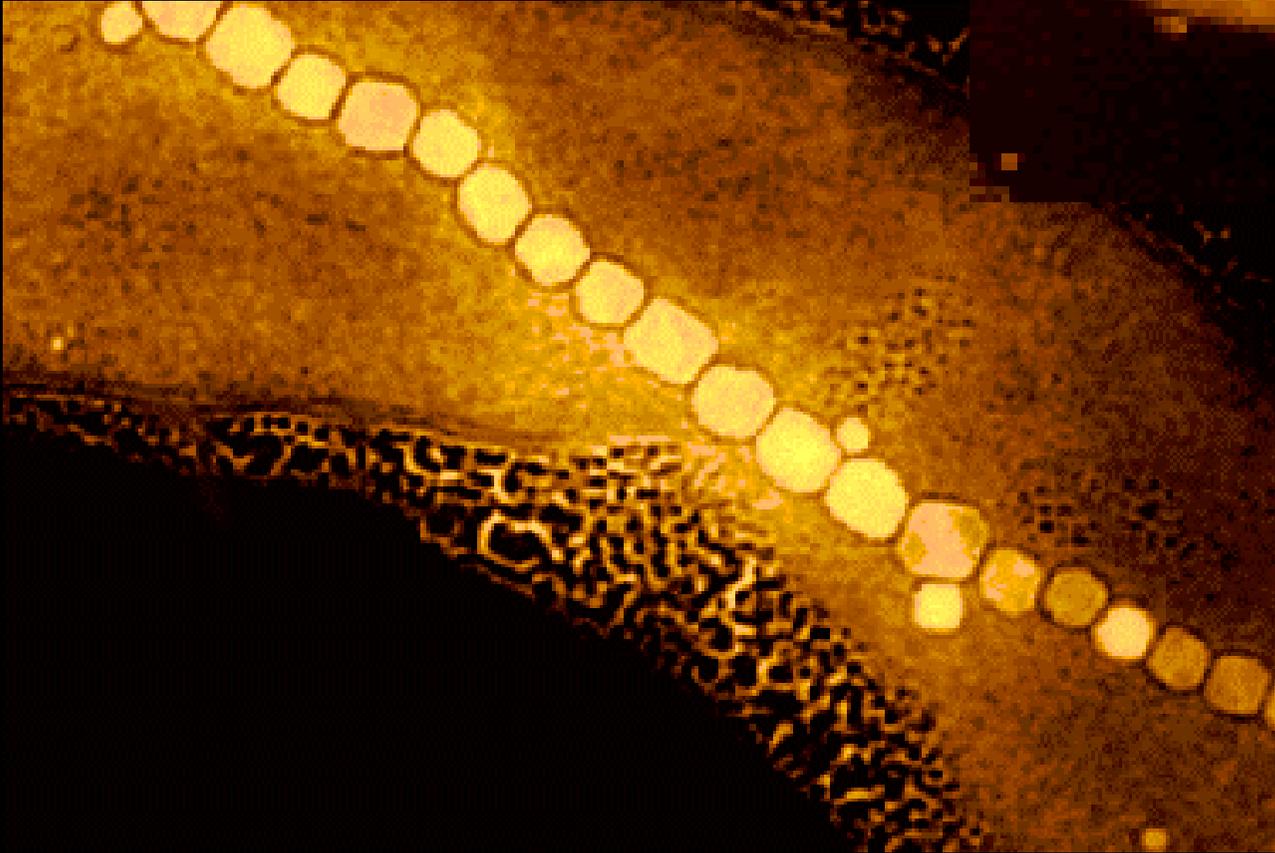
**Biogenic**

# WHY DO MAGNETOTACTIC BACTERIA PRODUCE MAGNETITE?



- **Act as a compass to help bacteria orient and navigate**
- **Combined with bacteria's ability to sense oxygen concentration, presence of magnetite improves survival rate**
- **Biogenic magnetites are perfect bar magnets (Natural Selection optimizes magnetic moment) = better survival rate**

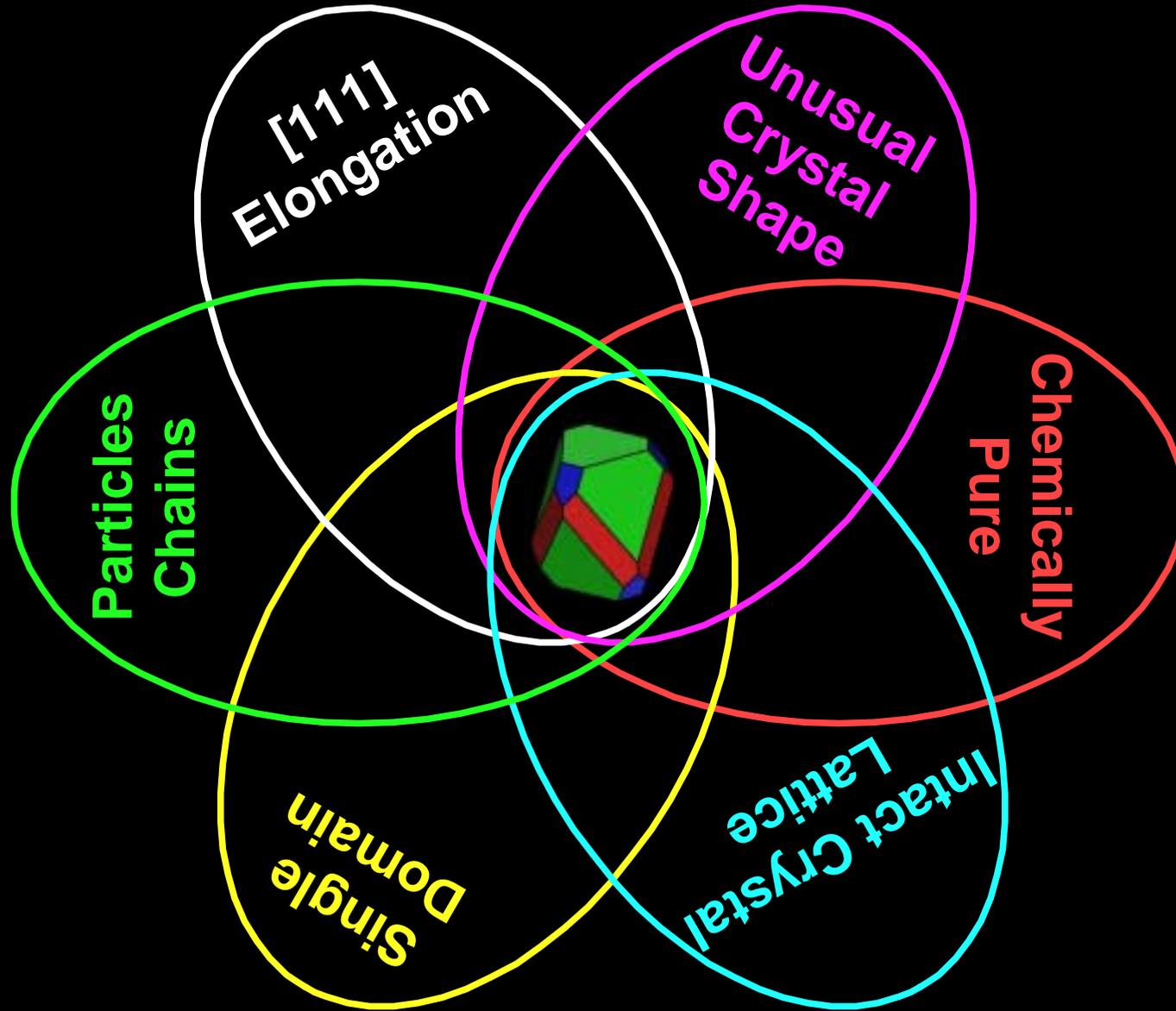
# Magnetite Crystals Produced by Magnetotactic Bacteria



# HOW DO MAGNETOTACTIC BACTERIA PRODUCE MAGNETITE CRYSTALS?

- **Strict cellular control at the atomic level to produce magnetite crystals with specific properties:**
- **Physical control —magnetosome membrane**
- **Chemical control —ions/molecules at membrane boundary**
- **Genetic control —enzymes/proteins within membrane**

# SIX PROPERTIES OF BIOGENIC MAGNETITE



**We have identified six properties  
(independent variables) of biogenic  
magnetite influenced by  
natural selection**



**Single domain?** no → **Unlikely Biogenic**  
↓ **yes**



**Chemically pure?** no → **Unlikely Biogenic**  
↓ **yes**



**Defect free?** no → **Unlikely Biogenic**  
↓ **yes**



**Unusual geometry?** no → **Unlikely Biogenic**  
↓ **yes**



**[111] elongation?** no → **Unlikely Biogenic**  
↓ **yes**



**In chains?** no → **Unlikely Biogenic**  
↓ **yes** → **Biogenic**  
↓ **Inorganic**

# BIOGENIC MAGNETITE AS A BIOSIGNATURE

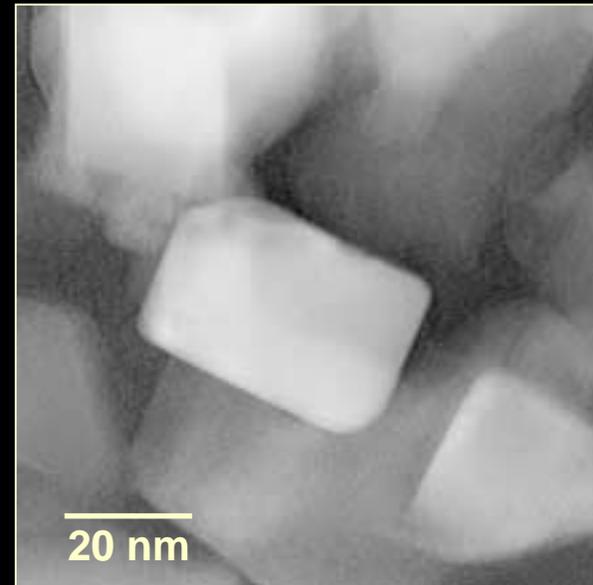
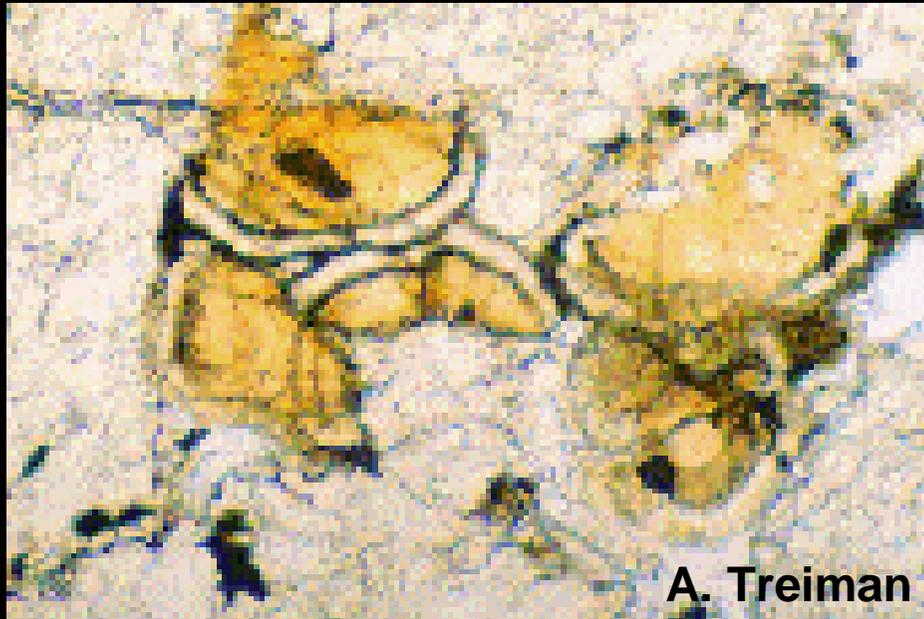


**The probability that an inorganic magnetite will, by chance, meet all these criteria is virtually zero**

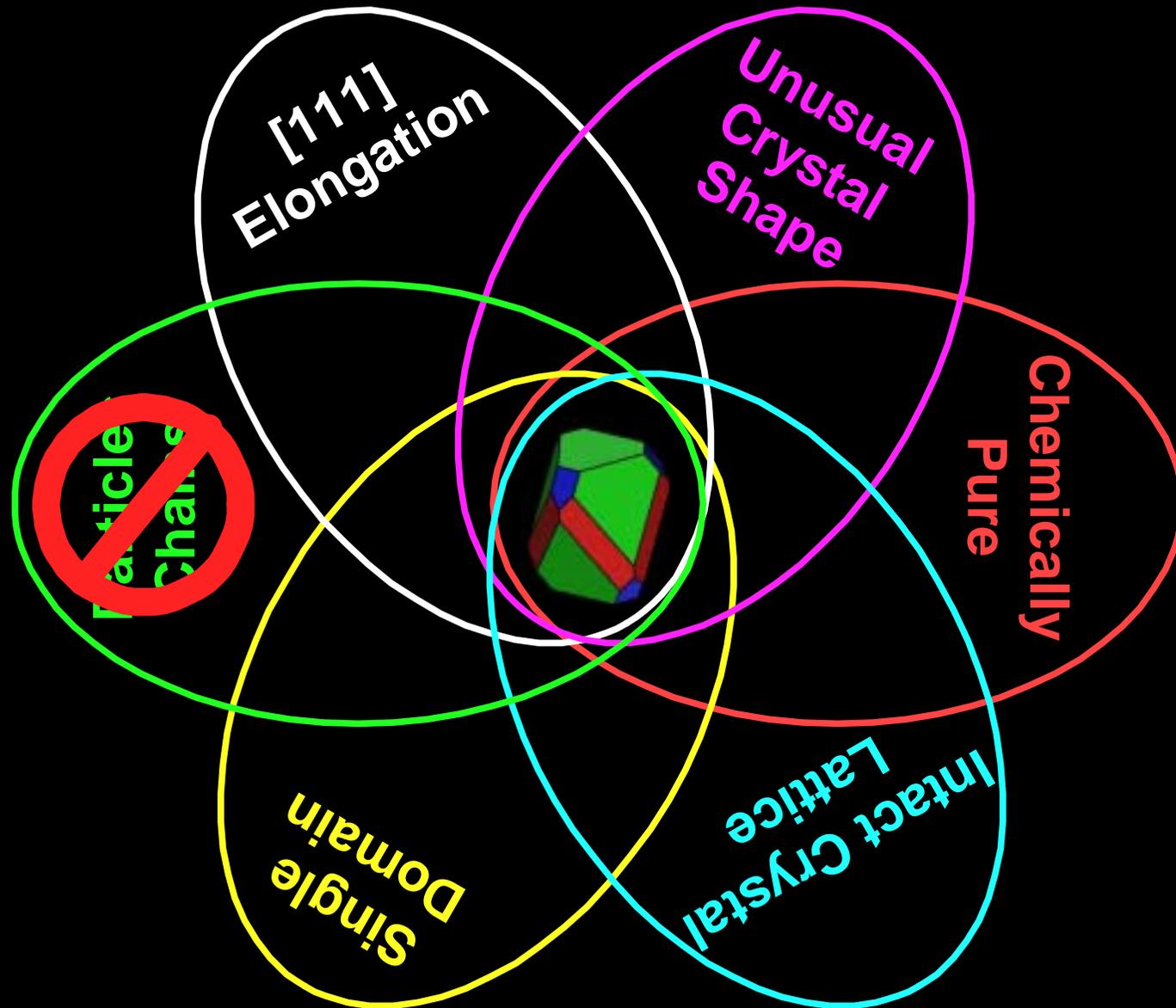
**Biogenic magnetite *can* be distinguished  
from inorganic magnetite**

# MAGNETITES IN MARTIAN METEORITE ALH84001

**~25% of ALH84001 magnetite display 5 of the 6 properties that characterize biogenic magnetite -- are identical to magnetite produced by strain MV-1**

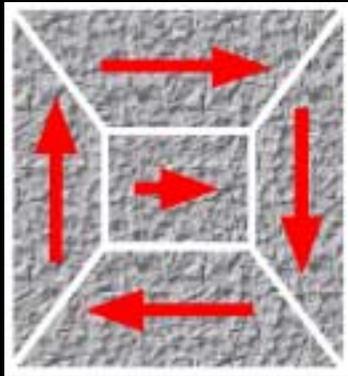


# PROPERTIES OF ALH84001 MAGNETITE



# NATURAL SELECTION YIELDS UNIFORMLY-MAGNETIZED MAGNETITE (SINGLE-DOMAIN)

**Too Big  
(Multi-Domain)**



Not very efficiently magnetized; a waste of metabolic iron.

**Just Right  
(Single-Domain)**



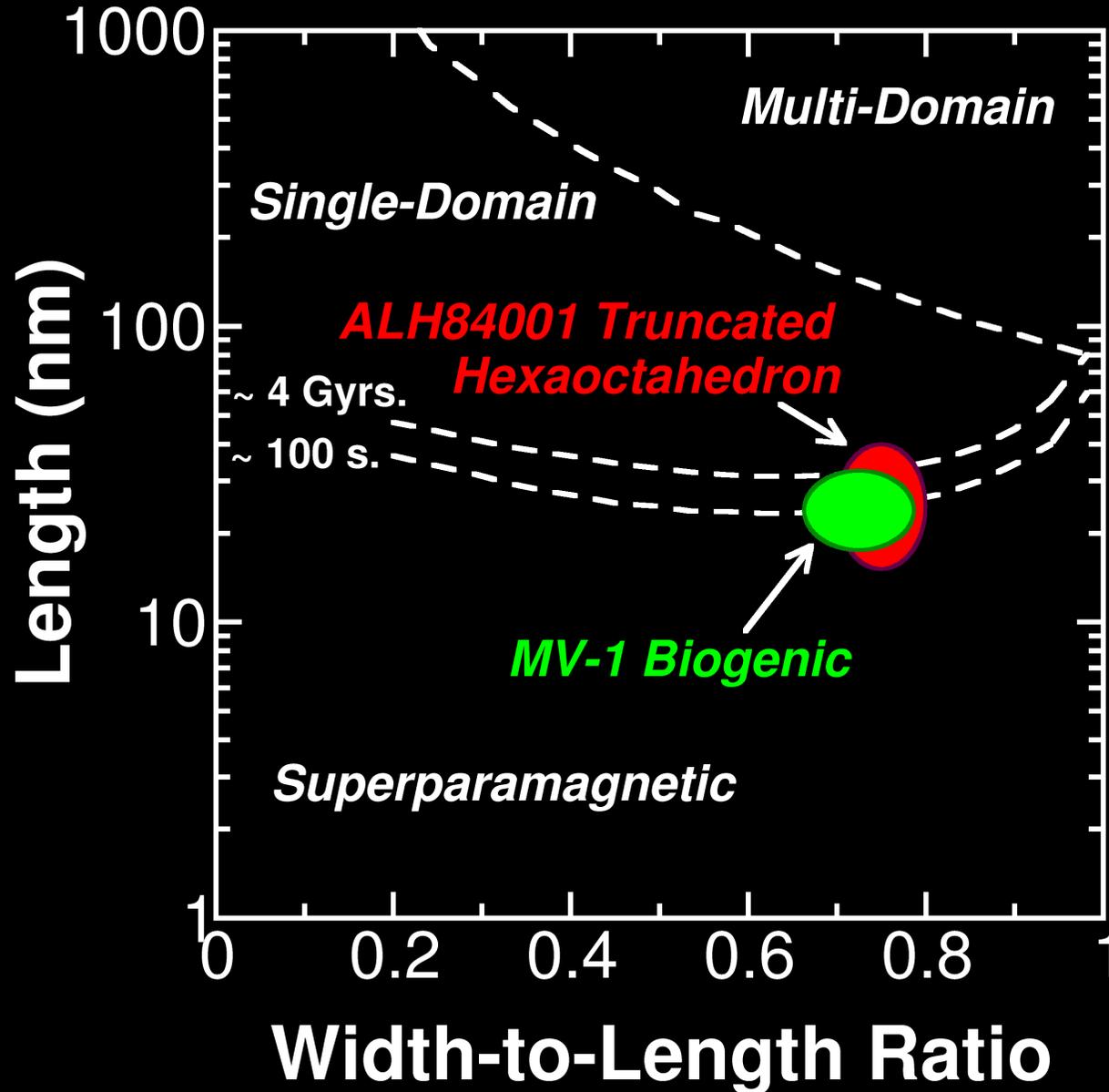
These particles are perfect bar magnets, very strong and stable.

**Too Small  
(Superpara-  
magnetic)**



The magnetic moment jumps around from thermal noise.

# MV-1 & ALH84001 MAGNETITE SIZE RANGE

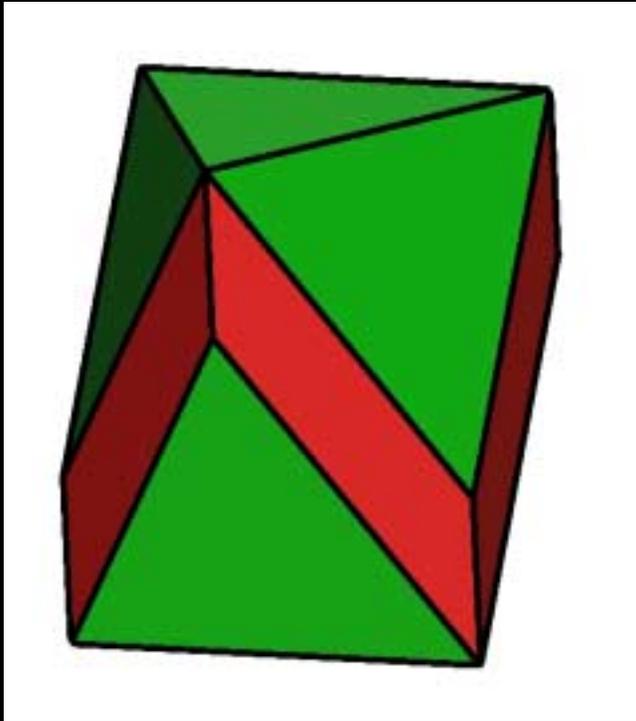


# DETERMINING CRYSTAL GEOMETRY OF SUBMICROMETER-SIZED CRYSTALS

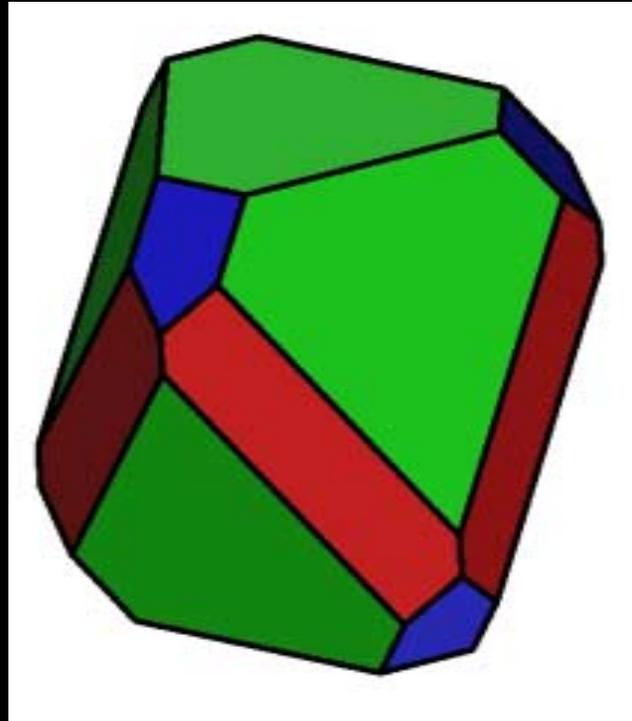


- TEM used to determine crystal geometry
  - Individual crystals imaged at different tilt angles ( $\pm 45^\circ$ )  
*combined with*
  - High resolution imaging and electron diffraction

# BIOGENIC MAGNETITE GEOMETRIES



Hexaooctahedron

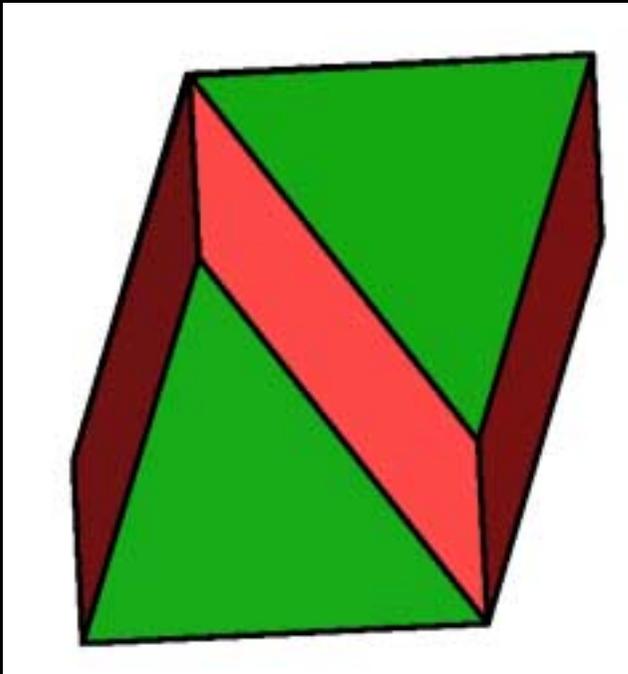


Truncated  
Hexaooctahedron

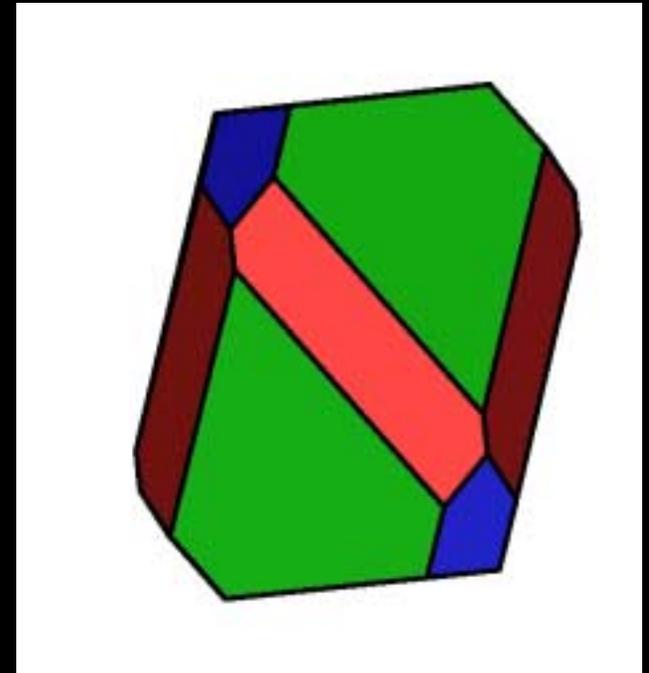
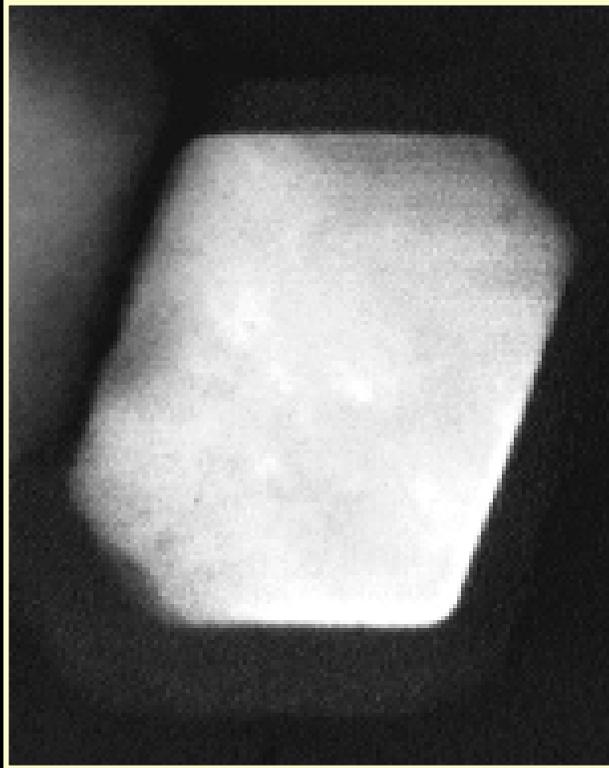
Blue = {100}  
Red = {110}  
Green = {111}

{111} ∨ {111} @ 109°  
{111} ∨ {100} @ 125°  
{111} ∨ {110} @ 145°  
{100} ∨ {110} @ 135°

# TRUE GEOMETRY OF MV-1 MAGNETITE

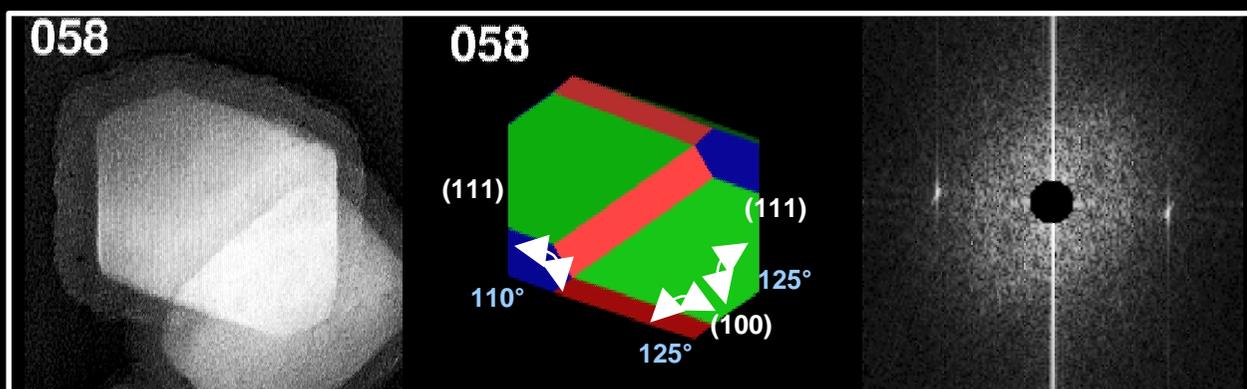
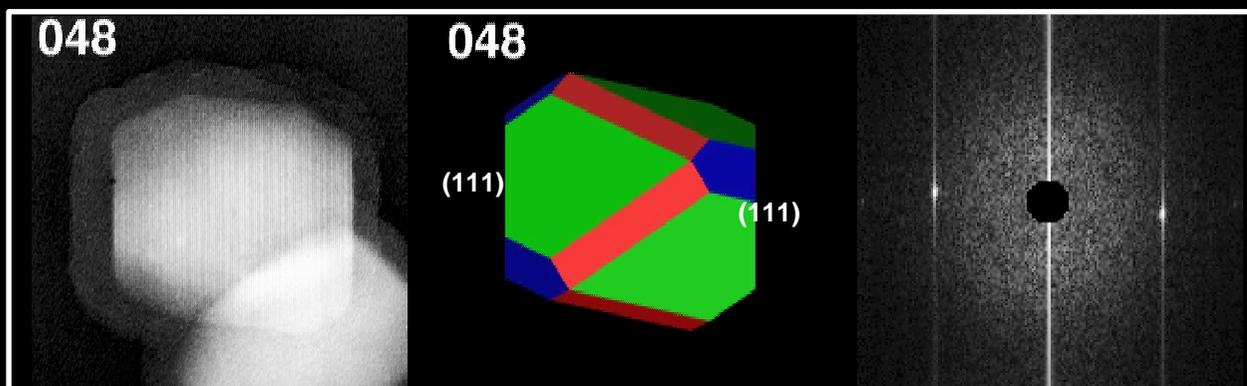
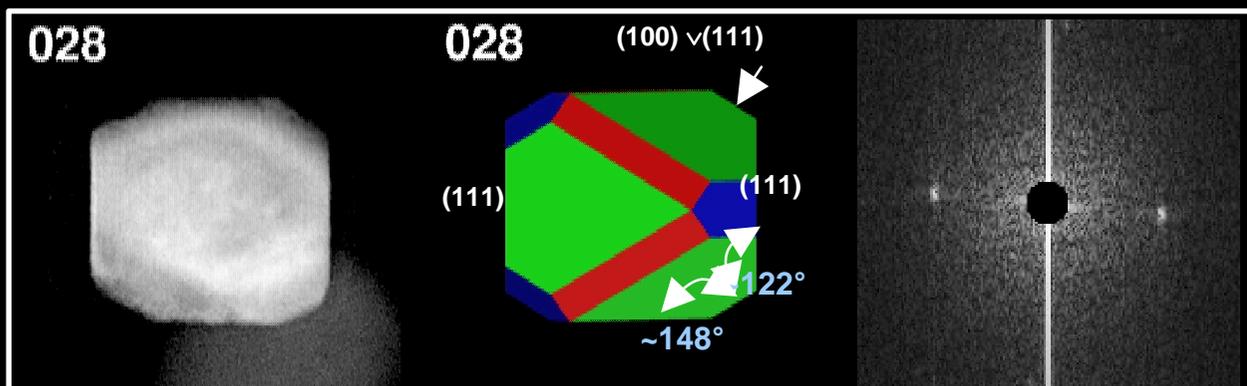
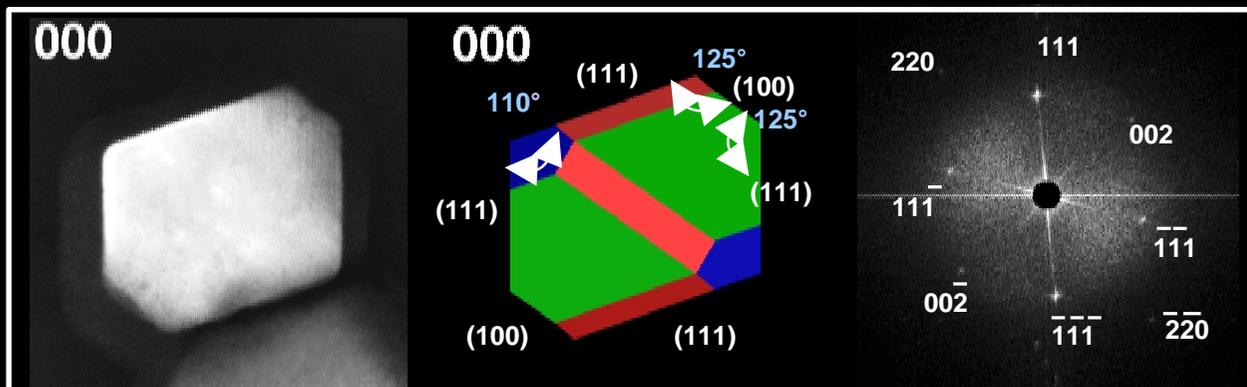


Hexaoctahedron

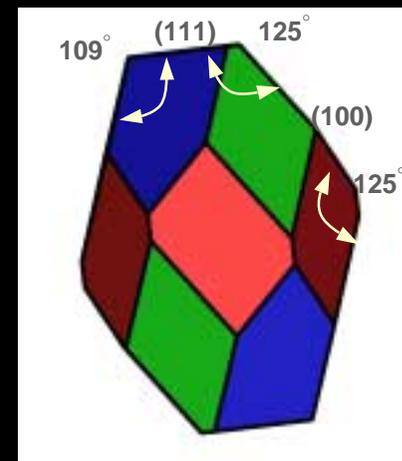
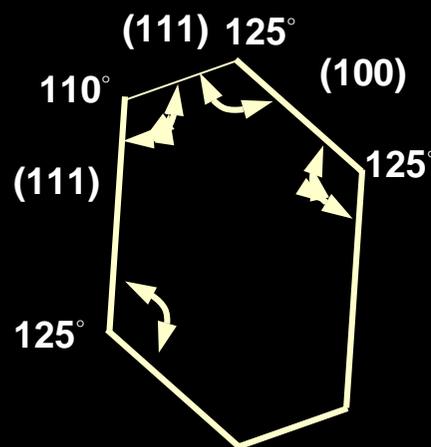
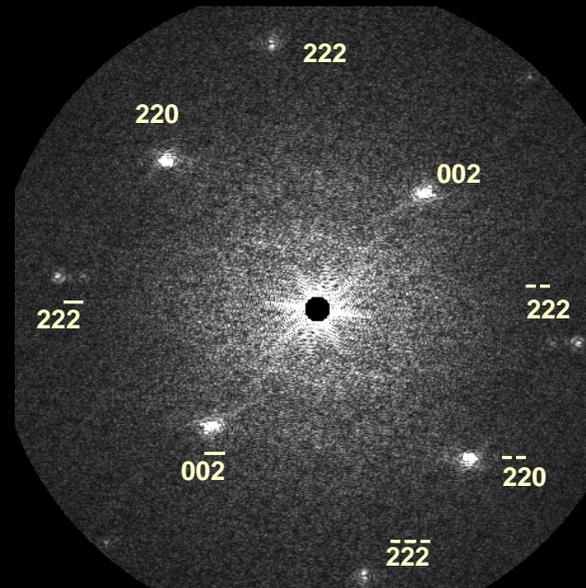
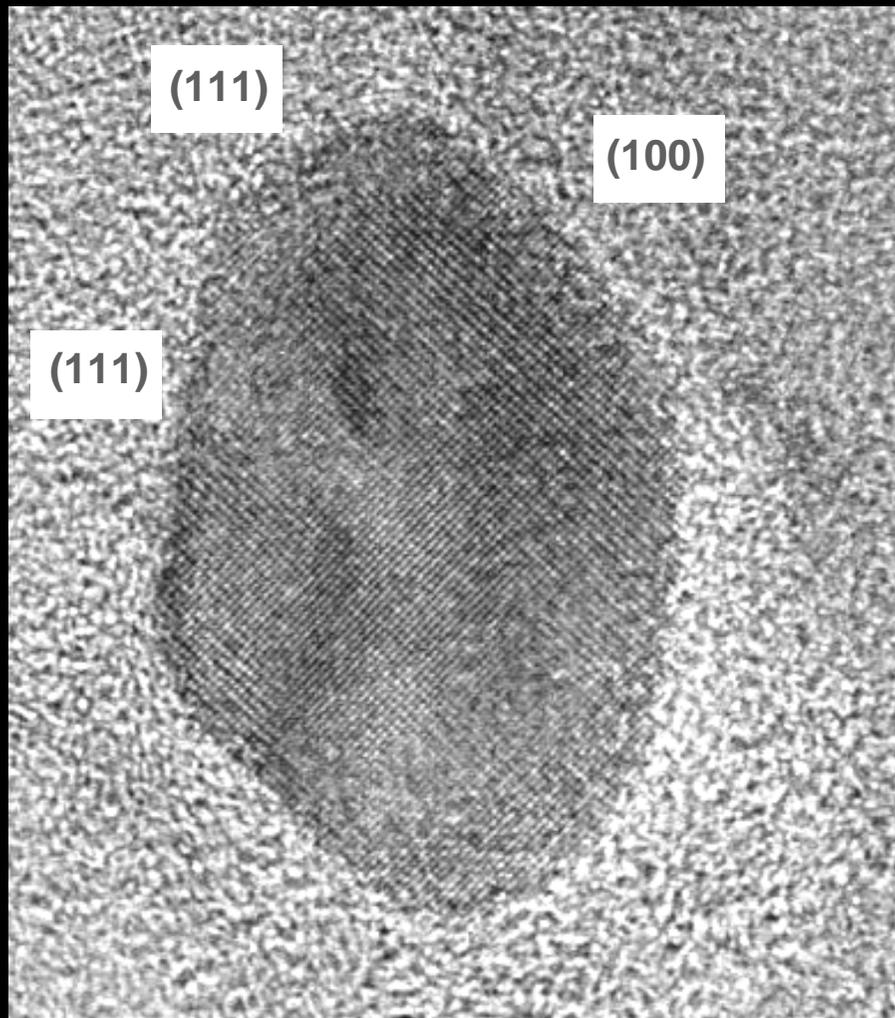


Truncated  
Hexaoctahedron

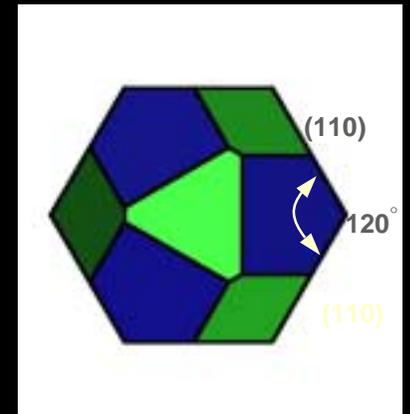
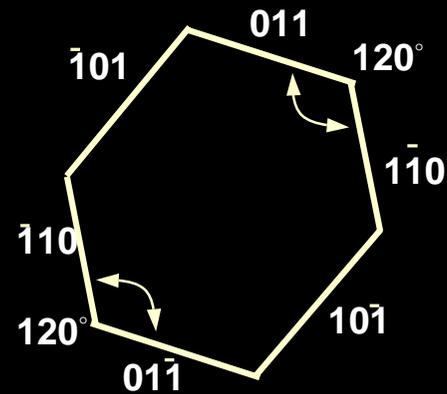
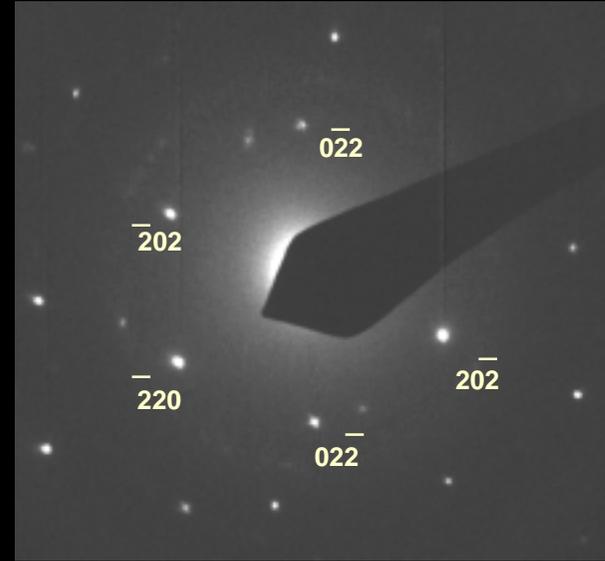
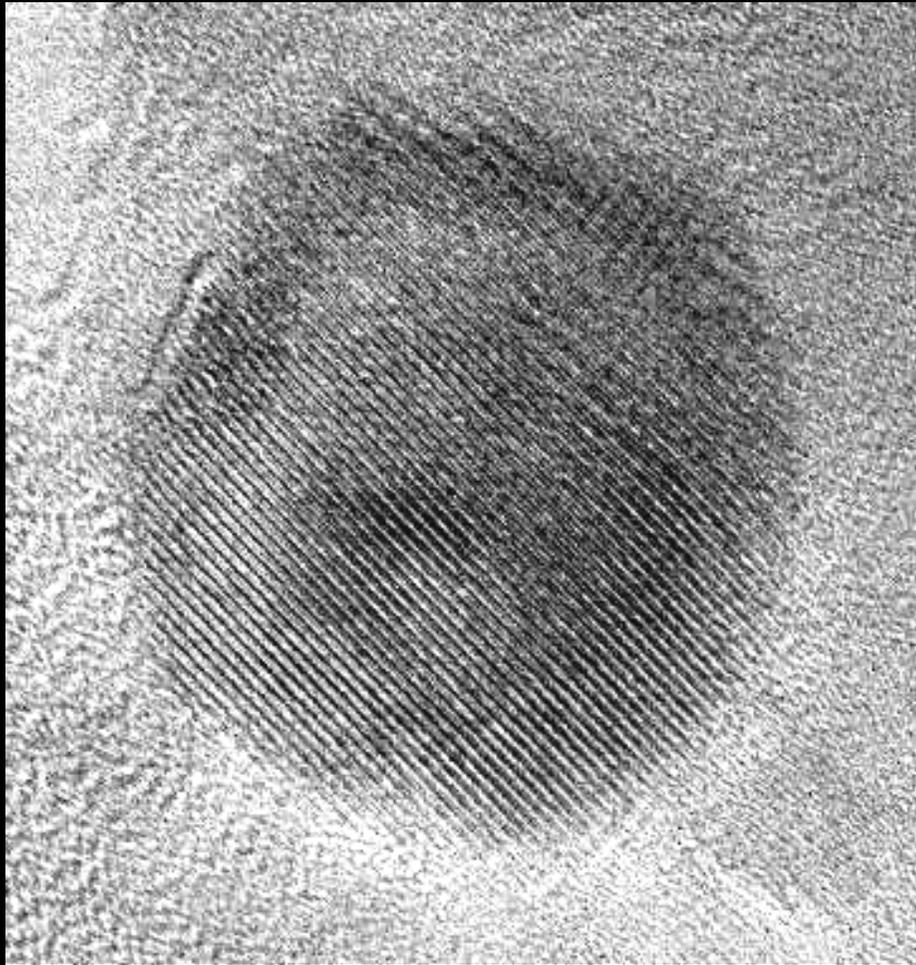
# MV-1 TRUNCATED HEXAOCTAHEDRAL MAGNETITE



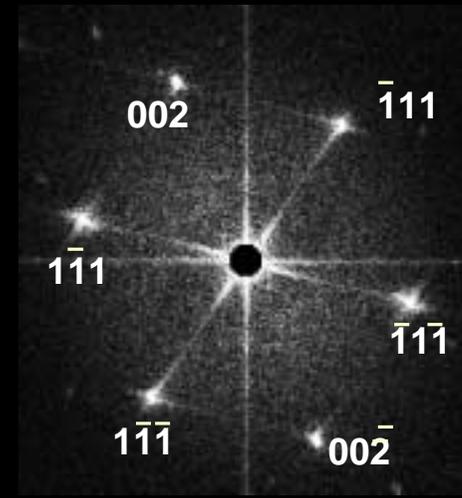
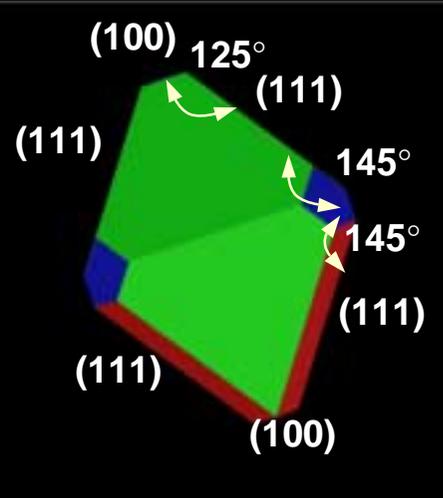
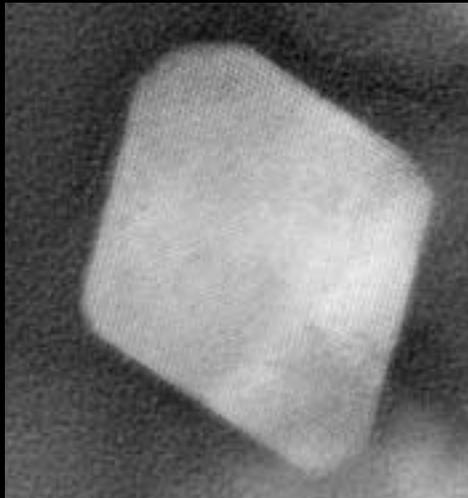
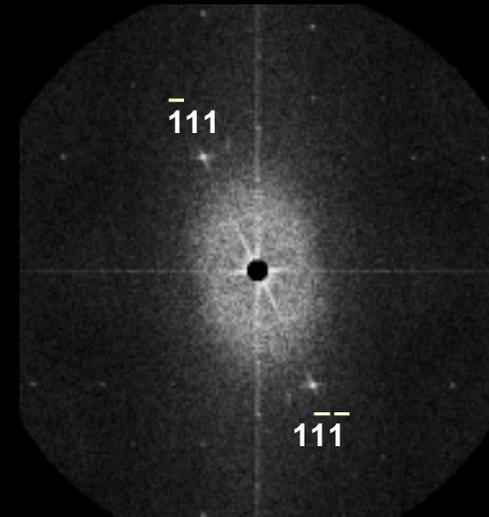
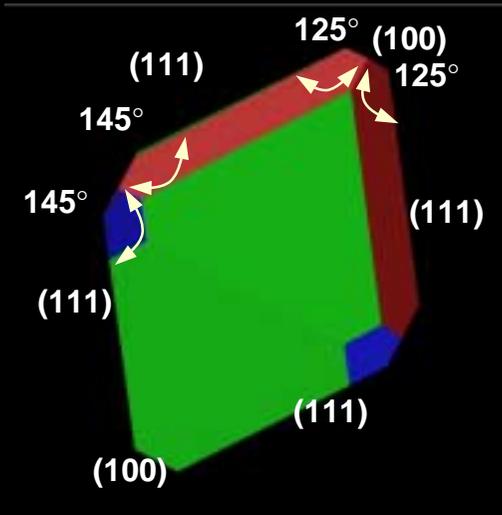
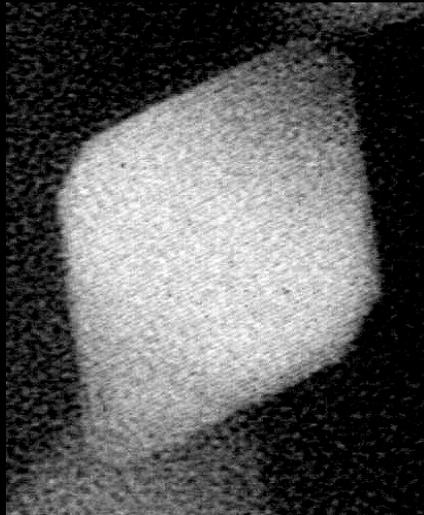
# ~3.9 Ga OLD MAGNETITE IN ALH84001 CARBONATE



# ~3.9 Ga OLD MAGNETITE IN ALH84001 CARBONATE



# MV-1 or ALH84001 MAGNETITE?



# CONCLUSIONS



**ALH84001 truncated hexaoctahedral magnetites are chemically and physically identical to biogenic magnetite produced by magnetotactic bacteria**

*Martian Truncated  
Hexaoctahedral Magnetite*

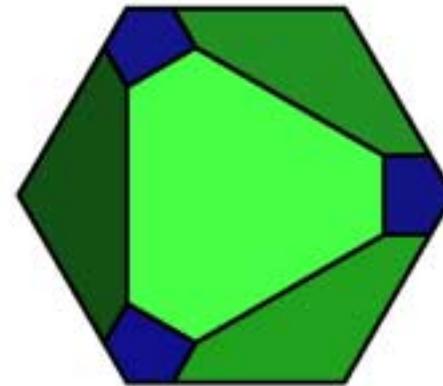
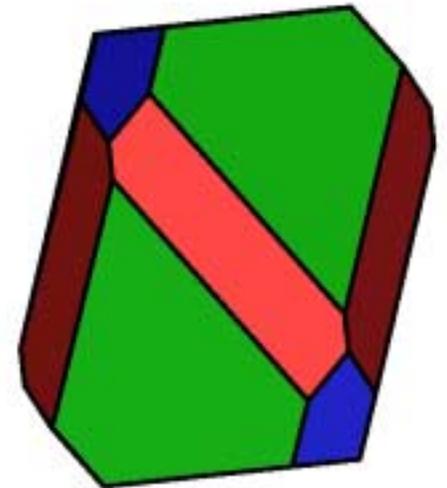
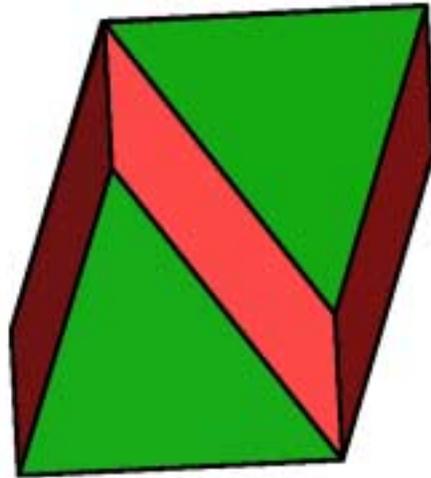
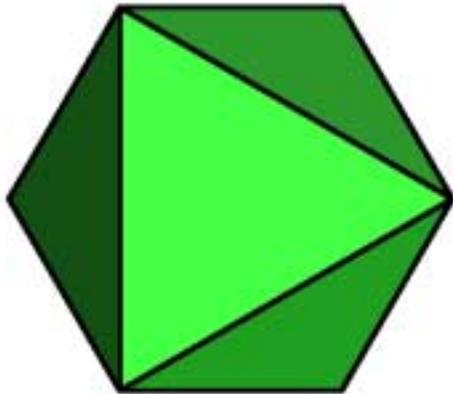
Origin ?

*Biogenic*  
Abundant on the Earth

*Inorganic*  
Not observed naturally on Earth  
Yet to be synthesized in the Lab

# BIOGENIC MAGNETITE GEOMETRIES: SIDE AND TOP VIEWS

Hexaoctahedron



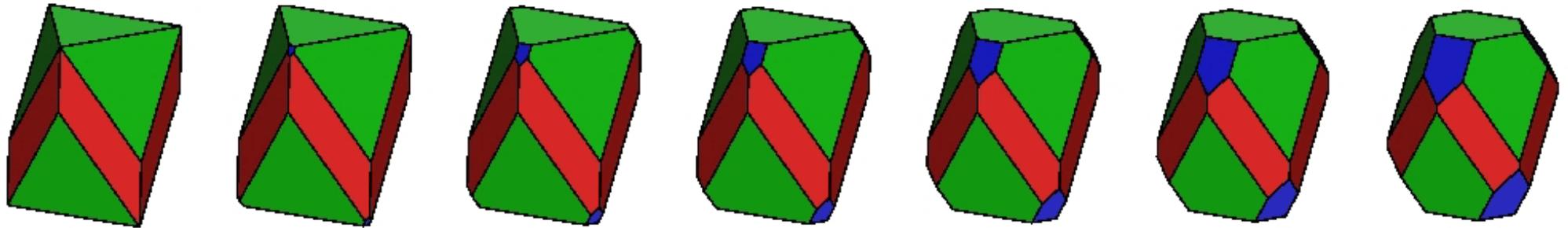
Truncated  
Hexa-  
octahedron

# MV-1 MAGNETITE AS A BIOSIGNATURE

- **Populations of magnetite in rocks and sediments that display these 5 or 6 properties are identical to biogenic magnetite—they are considered to have formed by similar biogenic mechanisms**
- **Populations of inorganic magnetite display at most 2 or 3 of these properties**
- **Confidence of a biogenic origin for a magnetite population grows as more characteristics are expressed**

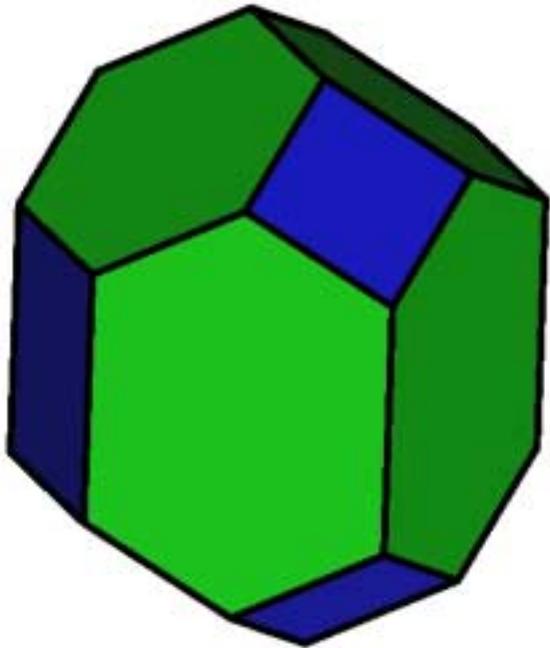
# Truncated Hexaoctahedral Magnetite

Hexaoctahedron

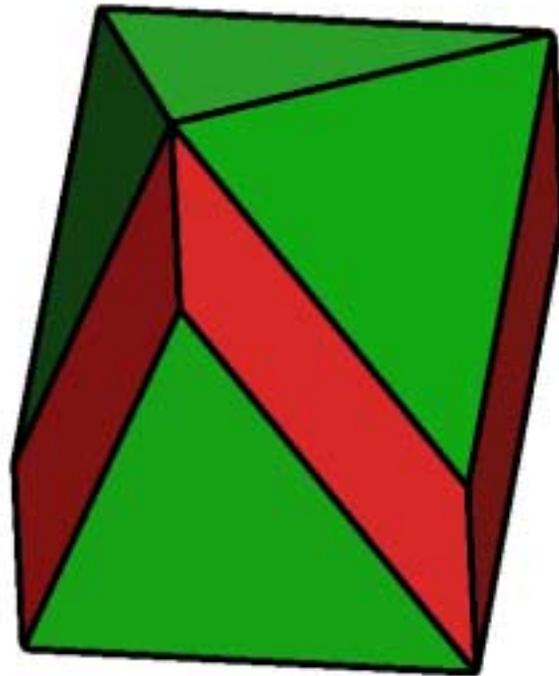


Truncated Hexaoctahedron

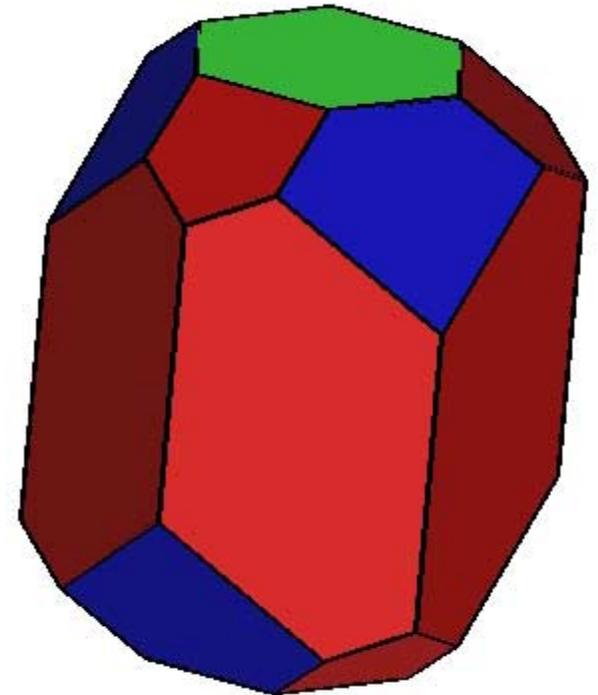
# Elongated Biogenic Magnetite Geometries



**Cubo-octahedral**

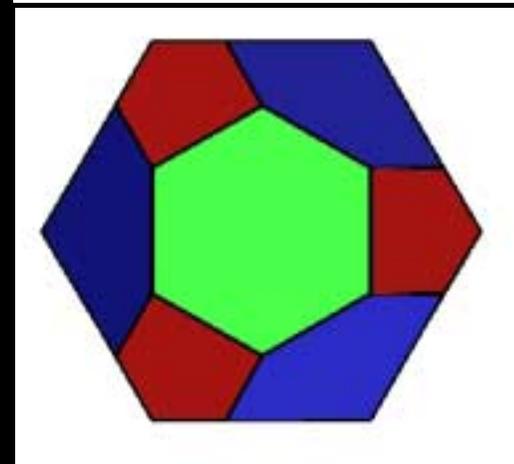
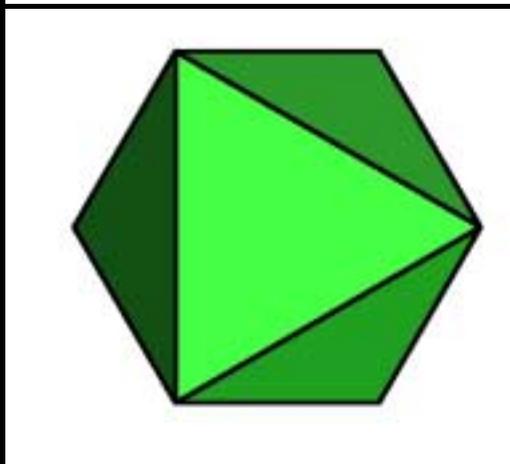
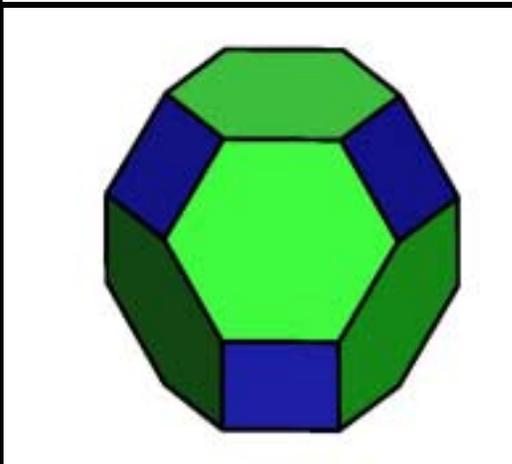
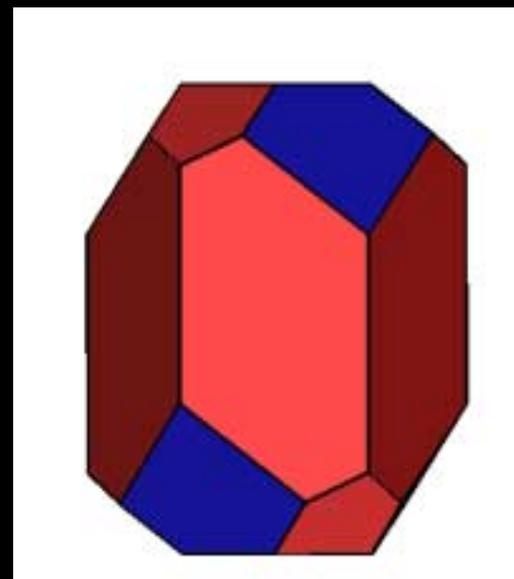
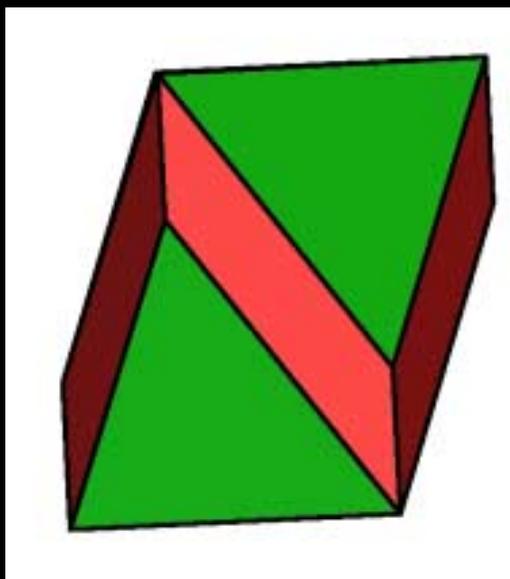
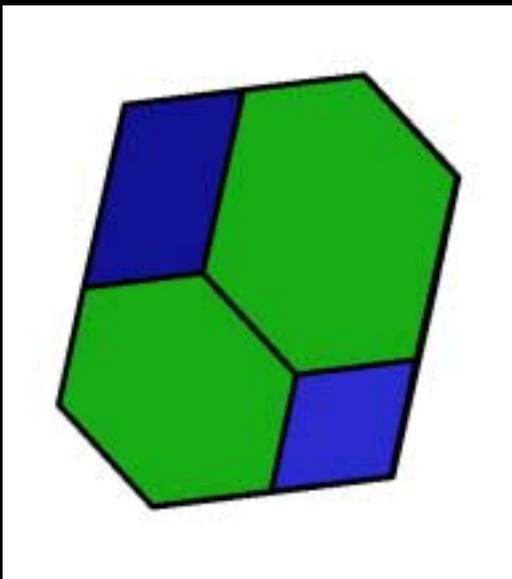


**Hexaoctahedral**



**Hexagonal Prisms**

# Side and Top Views of Elongated Biogenic Magnetites



**Cubo-octahedral**

**Hexaoctahedral**

**Hexagonal Prisms**