The Case for a New Metallurgy for Meteorites

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1813

For nearly 200 years, the meteoritic Widmanstätten Structure has been used to:

- **Understand the fundamentals of irons and steels 1800s to 1930s**
  - **Invar effect 1900s to Present**
  - **Martensite 1920s to 1930s**

- **Develop metallurgical tools and techniques**
  - **Metallograph - 1850s**
  - **X-ray 1920s to 1930s**
  - **Microprobe - 1950s**

- **Develop the Fe-Ni phase diagram - 1904 to Present**

- **Calculate "Metallographic Cooling Rates" - Serve as the "thermometer" (geo-speedometer) for the study of small planetary bodies and asteroids - 1960s - Present**

Assumptions made long ago about nickel-iron meteorite formation conditions must be re-evaluated in the light of modern metallurgical understanding.

The 1904 Fe-Ni Phase Diagram

Taenite
Face-centered cubic iron
Gamma (Austenite)

Kamacite
Body-centered cubic iron
Alpha ferrite

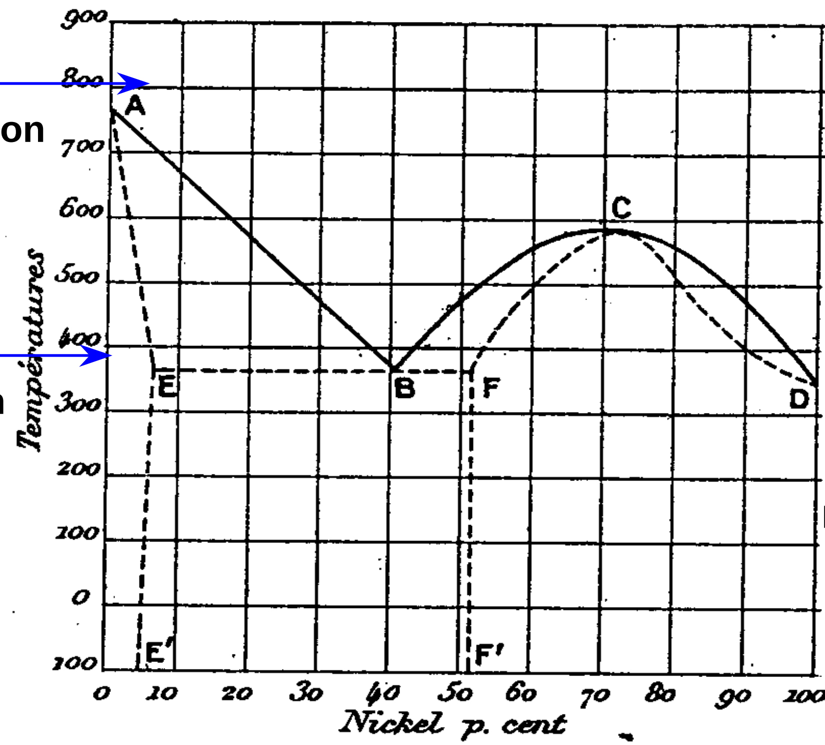
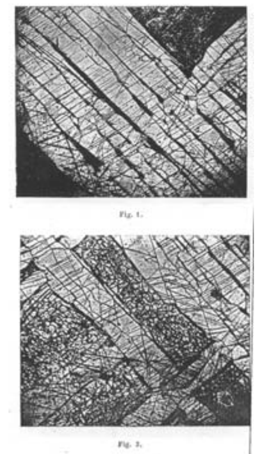


Fig. 8.



Meteoritic Widmanstätten Structure
Tombouctou 25 diameters

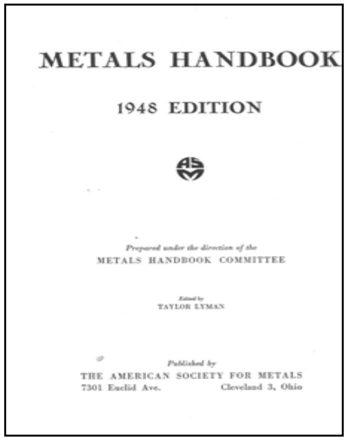
Osmond and Cartaud
1904

Assumptions - 1904

- **The meteoritic Widmanstätten structure is an equilibrium structure formed on slow cooling.**
- **The meteoritic Widmanstätten structure is formed by a solid state phase transformation below 800C.**
- **Meteoritic irons are similar to terrestrial irons except that meteoritic irons are in equilibrium, whereas terrestrial irons are metastable.**

1948 Metals Handbook Fe-Ni Phase Diagram includes region above 1300 ^{o}C

Body Centered Cubic
Delta Ferrite

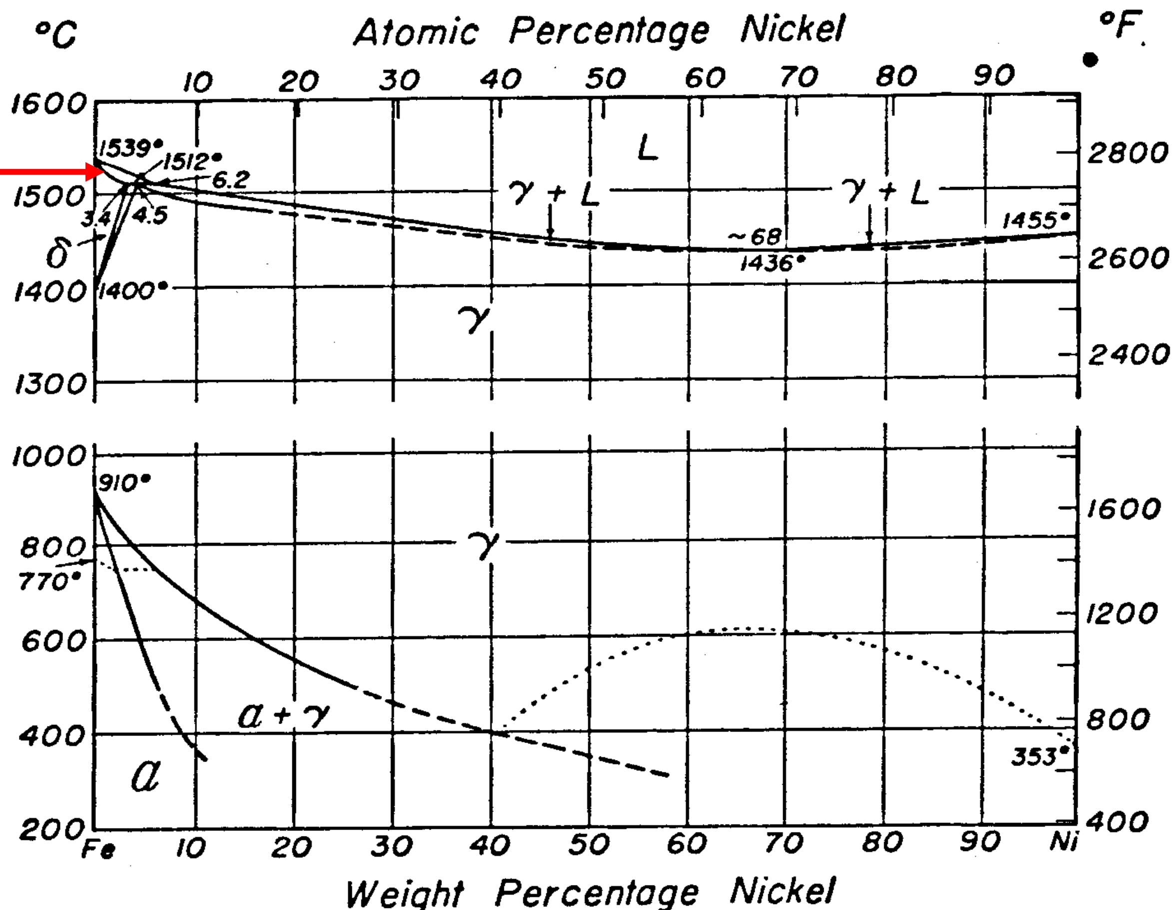

METALS HANDBOOK

1948 EDITION

Prepared under the direction of the
METALS HANDBOOK COMMITTEE

Edited by
TAYLOR LYMAN

Published by
THE AMERICAN SOCIETY FOR METALS
7301 Euclid Ave. Cleveland 3, Ohio



Body-centered cubic Delta Ferrite:

- **A primary crystallization structure formed above ~1500 ^{o}C.**
- **Can be retained at room temperature.**
- **Cannot be distinguished metallographically from body-centered cubic alpha iron.**

Kamacite can also be interpreted as Delta Ferrite, formed by solidification from a melt.

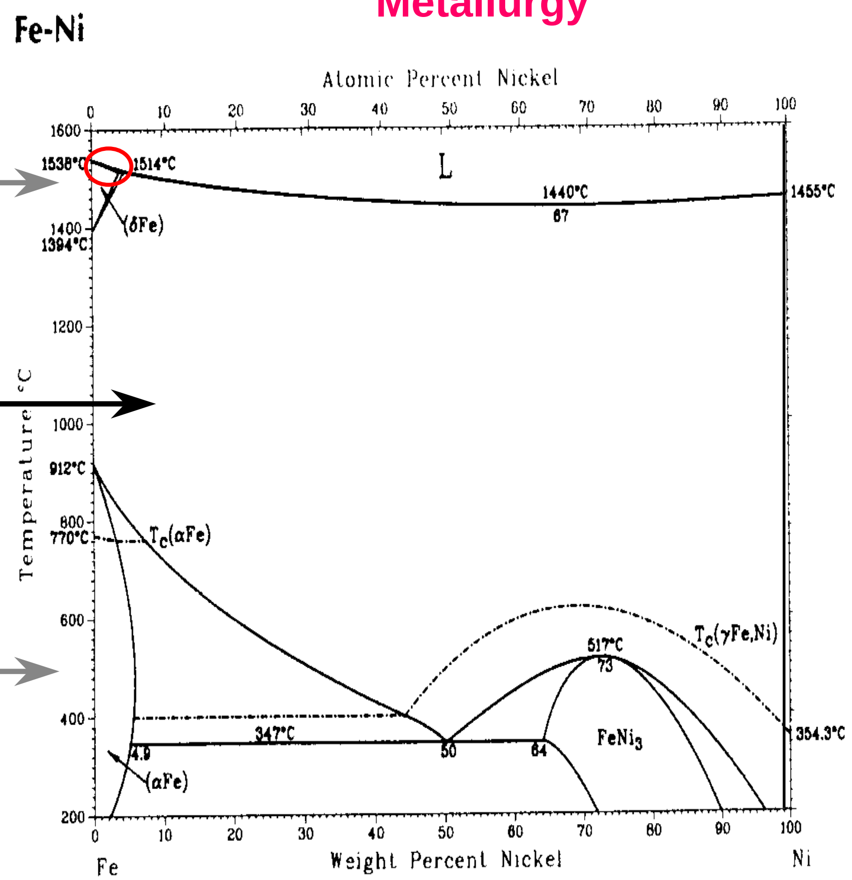
Today - Fe-Ni Phase Diagrams: Metallurgy vs Earth & Planetary Sciences

Metallurgy

Body Centered Cubic
Delta Ferrite

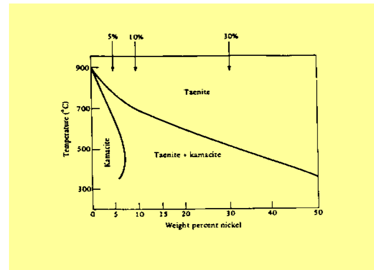
Face-centered cubic
Austenite

Body Centered Cubic
Alpha Ferrite



1992 ASM Handbook 1992

Meteoritics



1987 McSween

Metallurgical Equilibrium
Binary Phase Diagram Determination Today

Today, <u>equilibrium</u> metallurgical binary phase diagrams are determined in carefully controlled laboratory experiments.

Nickel-iron meteorites are “metallurgical garbage cans,” containing elements such as carbon, sulfur, phosphorus, etc. that impact phase formation.

Nickel-iron meteorites are completely inappropriate for metallurgical phase diagram determination.

Assumptions about meteoritic Widmanstätten Structure made in 1904 remain unchanged today in the Earth & Planetary Sciences.

Osmond & Cartaud 1904

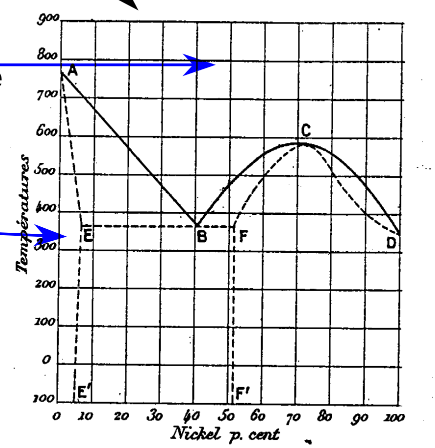
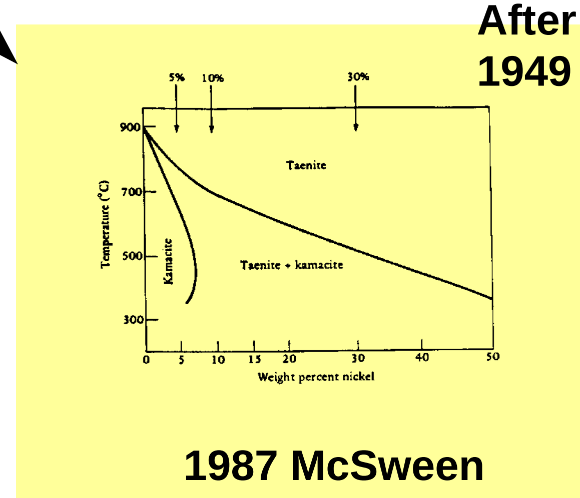


Fig. 8.



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- **The meteoritic Widmanstätten structure is an equilibrium structure formed on slow cooling.**
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Kamacite is not necessarily an equilibrium structure.

Definition of Widmanstätten Structure:
Change in meaning from Morphology to Mechanism over Time

1948 ASM Metals Handbook

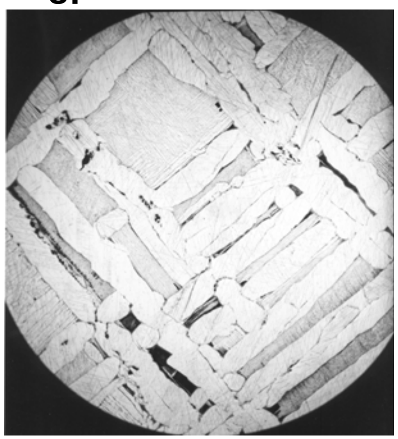
Between 6 and 25% Ni, the alloys are martensitic after fast cooling; after slow cooling or reheating, they decompose into alpha + gamma. The structure varies from the martensitic to the Widmanstätten type observed in meteorites.

1985 ASM Metals Handbook

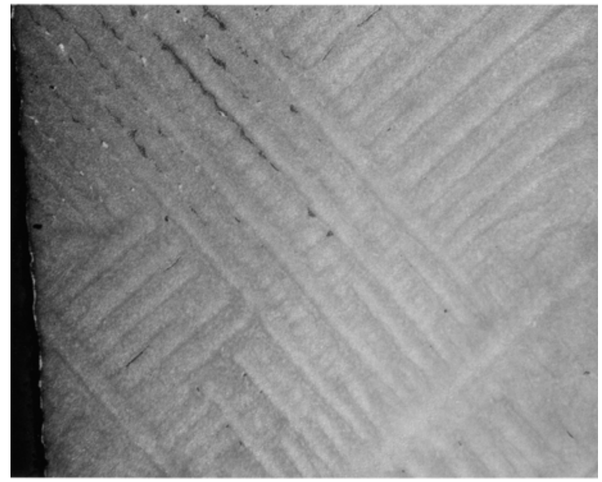
Widmanstätten structure. A structure characterized by a geometrical pattern resulting from the formation of a new phase along certain crystallographic planes of the parent solid solution. The orientation of the lattice in the new phase is related crystallographically to the orientation of the lattice in the parent phase. This structure was originally observed in meteorites, but is readily produced in many other alloys, such as titanium by appropriate heat treatment.

Widmanstätten Structure: 1813 - Today
A change in meaning over time: From Morphology to Mechanism

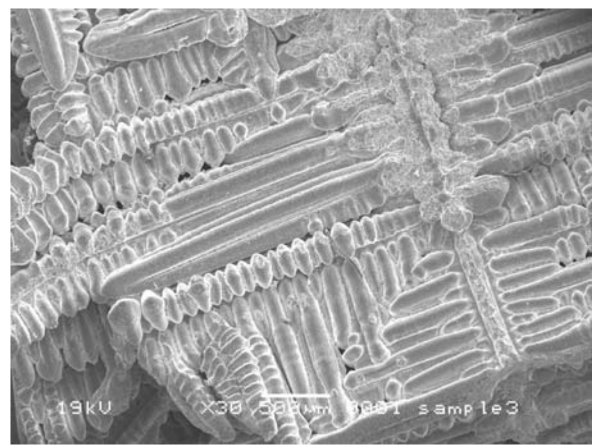
Agpalilik Nickel-Iron



Specimen courtesy of Dr. V. Buchwald



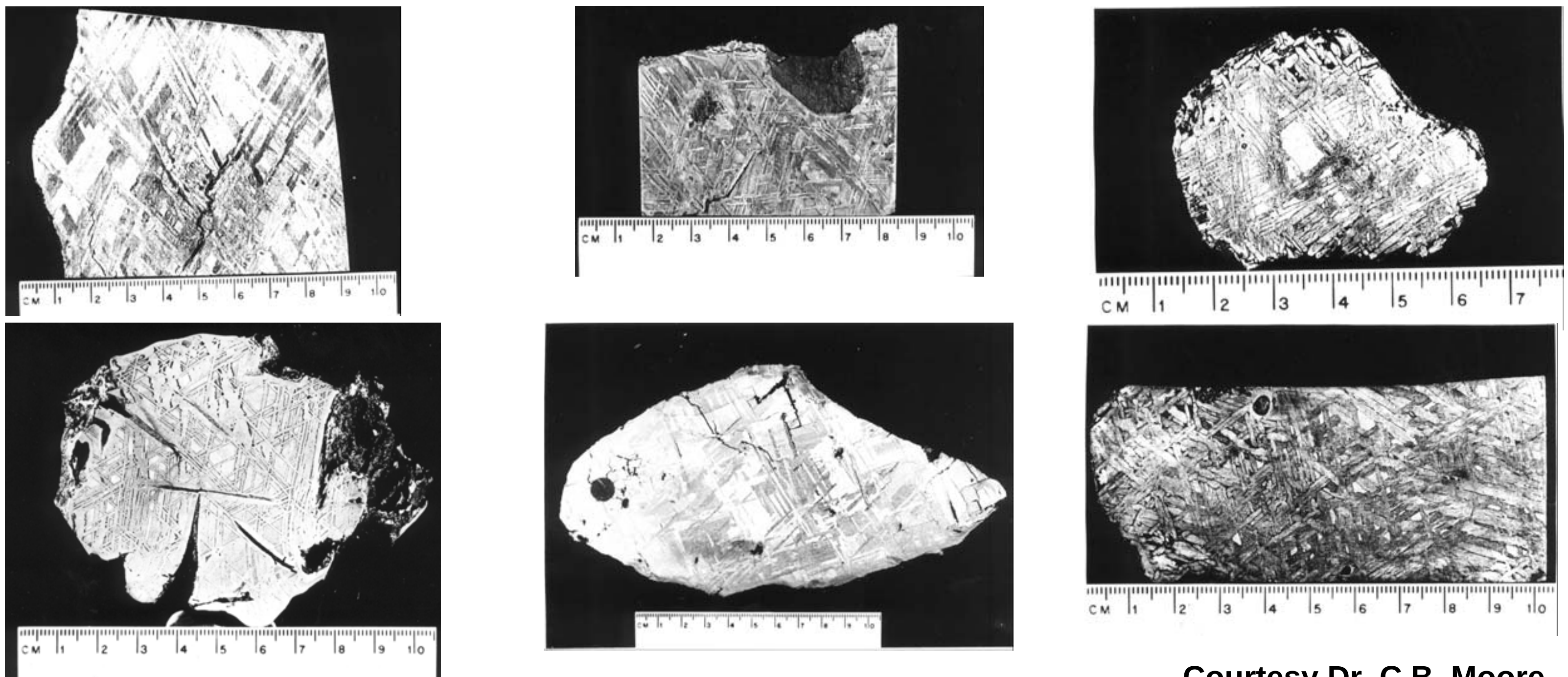
Cast single crystal nickel superalloy



Vacuum deposited nickel superalloy

Morphology does not imply mechanism.

<u>Equilibrium Assumption</u> **Microstructures are considered to be <u>unchanged</u> from their structure inside the meteorite parent body, except for a 10 mm heat-affected zone.**



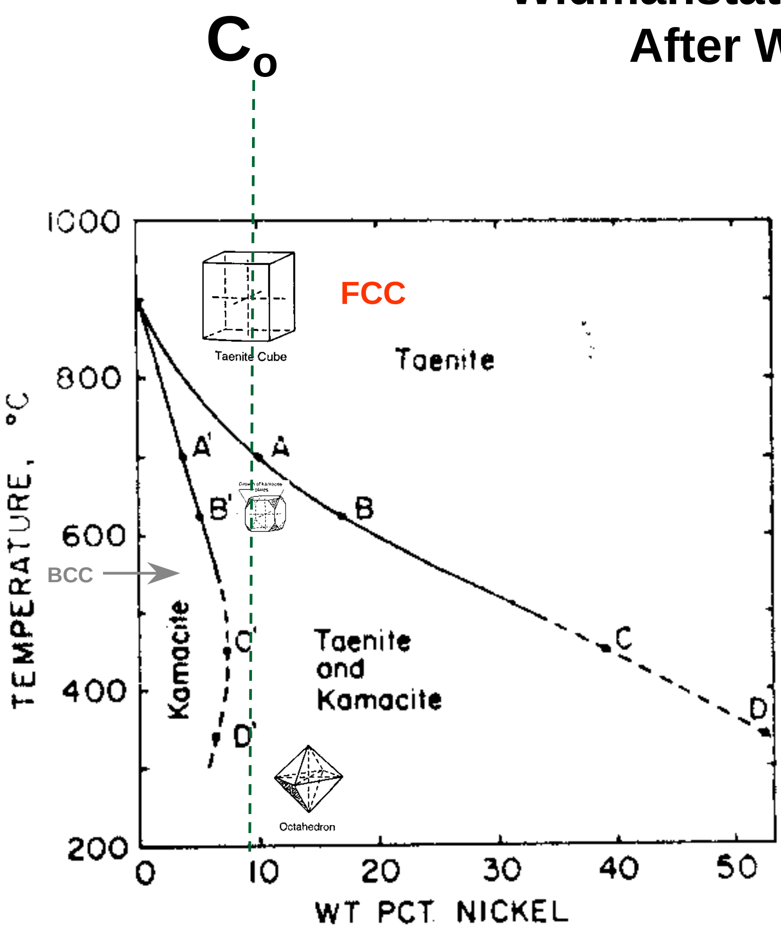
Courtesy Dr. C.B. Moore

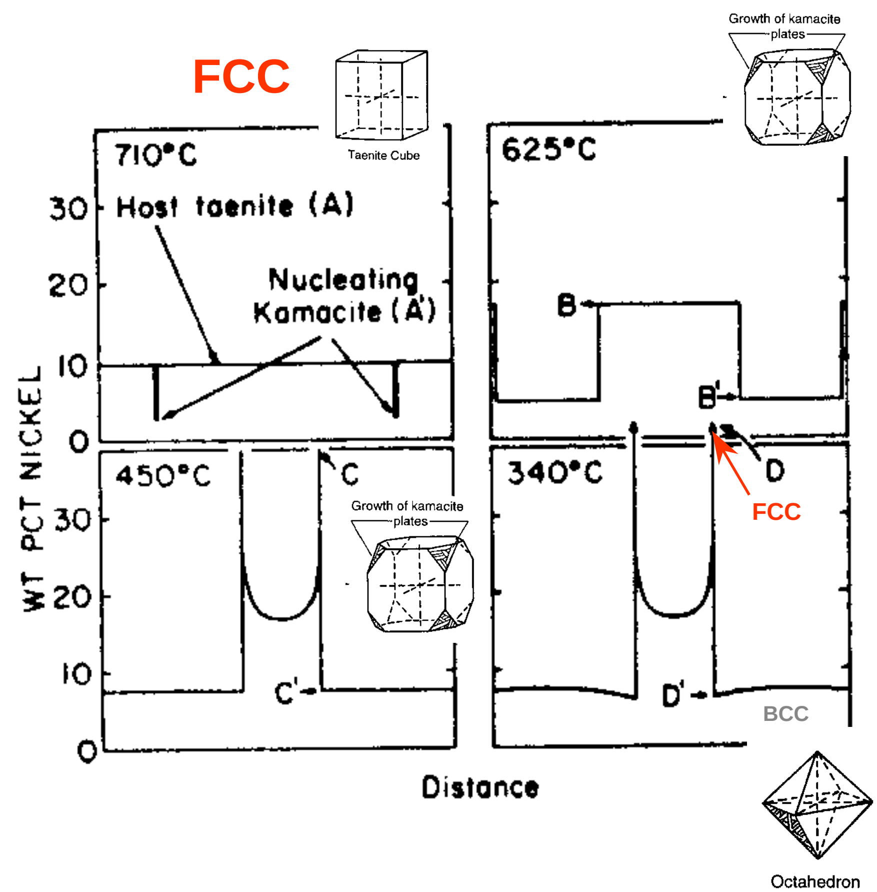
Meteoritic Widmanstätten Structures

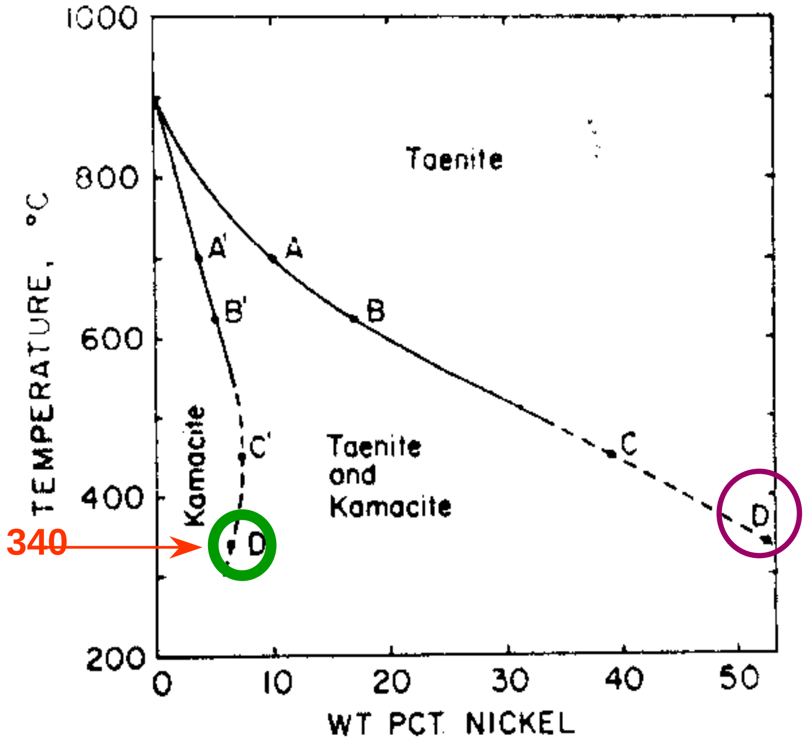
Implication: In the transition from inside the meteorite parent body to Earth arrival, these materials never reached their melting point.

The melting point of pure iron is 1538 ^{o}C.

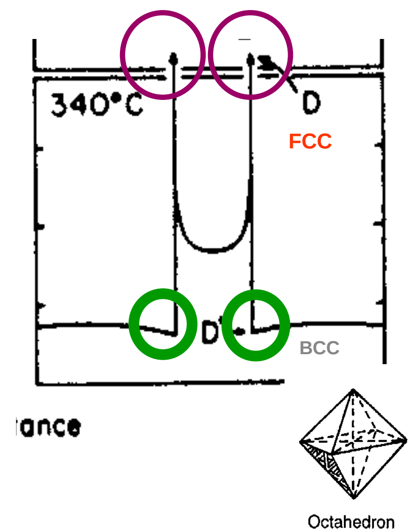
Metallographic Cooling Rate Theory and the "Widmanstätten Mechanism" After Wood 1967







Assumed equilibrium composition of FCC taenite *inside* the meteorite parent body.

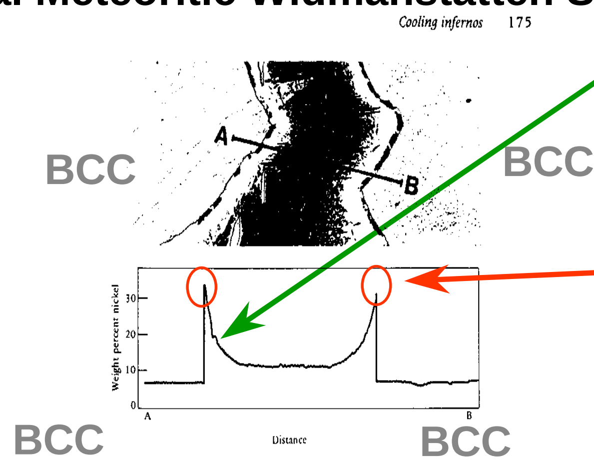


After Wood 1967

Metallographic Cooling Rates are derived from the slope of this line

through a mathematical model based on the assumption that this point is the equilibrium composition of taenite/"austenite" inside the meteorite parent body.

Typical Meteoritic Widmanstätten Structure

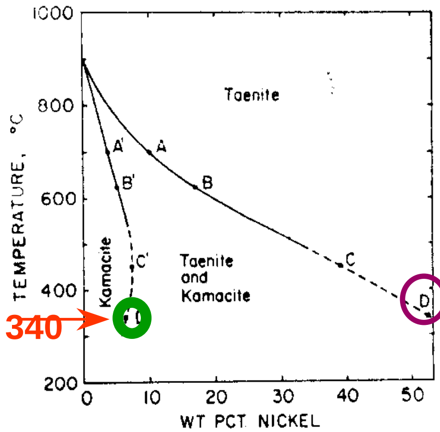


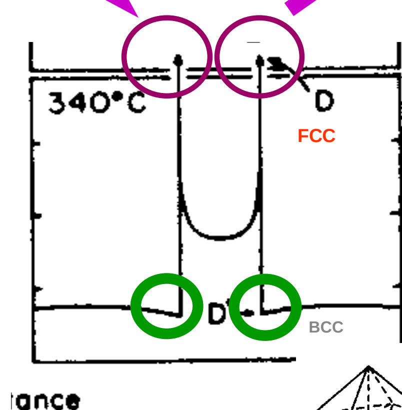
FCC

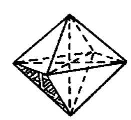
Typical microprobe trace

After Mc Sween 1987

Metallographic Cooling Rates

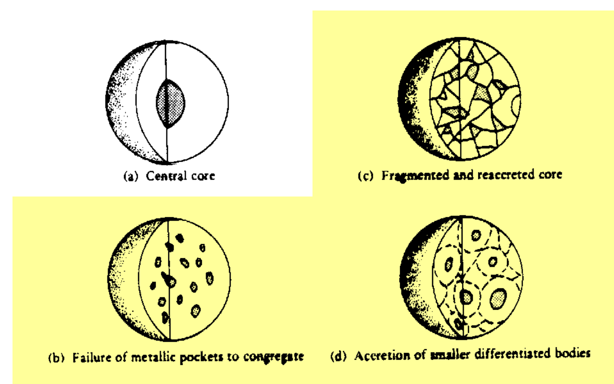






Octahedron

- **1985 Narayan and Goldstein: Major revision of iron meteorite cooling rates: 150 to 6000C per million years.**
- **1987 McSween: "Cooling rate data for iron meteorites favor the last 3 models, unless parent bodies with central cores were very small."**



McSween 1987

Meteorite Parent Body Models

Metallographic Cooling Rate Theory

The Metallographic Cooling Rate theory is founded on the 1904 assumption that kamacite (alpha ferrite) is formed from taenite (austenite) in a solid state phase transformation.

This is circular reasoning!

Potential Factors Influencing the Macro/Microstructural Development of the Meteoritic Widmanstätten Structure

- Solidification
  - Microgravity / Low Gravity / Free Fall
  - Undercooling
- Thermal and Compositional Gradients
  - Local Equilibrium
- Solid State Phase Transformations
- Other??

It is time for a New Metallurgy for Meteorites!

Budka Publications on Meteorite Metallurgy

Year	Author	Title	Journal	Vol., Pages
1982	P.Z. Budka	The Formation of Pallasitic Chondrules: Evidence for Rapid Solidification Under Microgravity Conditions	Meteoritics: The Journal of the Meteoritical Society	Vol. 17, No. 4
1984	P.Z. Budka	The Influence of Gravitational Body Force in Meteoritic Chondrule and Lunar Glass Formation	Meteoritics: The Journal of the Meteoritical Society	Vol. 19, No. 4, p. 201
1984	P.Z. Budka, F.F. Milillo	Speculations on the Formation of Metallic Meteorite Phases	Meteoritics: The Journal of the Meteoritical Society	Vol. 19, No. 4, pp. 201 - 202
1984	P.Z. Budka	The Formation of Chondrule-Containing Extraterrestrial Materials: Evidence for Rapid Solidification Under Microgravity Condditions	Journal of Non-Crystalline Solids	pp. 413 - 419
1986	P.Z. Budka, F.F. Milillo	The Inverse Peritectic Phase Transformation in the Fe-S System: Evidence for the Remelting of Troilite During Cooling	Meteoritics: The Journal of the Meteoritical Society	Vol. 24, No. 4, p.342
1986	P.Z. Budka, F.F. Milillo	Some Common Microstructural Features of Nickel-Iron Meteorites and Cast Ferrous Alloys	Meteoritics: The Journal of the Meteoritical Society	Vol. 24, No. 4, pp. 342 - 343
1986	P.Z. Budka, F.F. Milillo	Importance of Meteoritic Materials in Assessing the Influence of Microgravity on Solidification		
1988	P.Z. Budka	Meteorites as Specimens for Microgravity Research	Metallurgical Transactions A	Vol. 19A, August 1988 pp. 1919 - 1923
1993	P.Z. Budka & J.R.M. Viertl	Mundrabilla: A Microgravity Casting	Meteoritics	Vol. 28, No. 3, p. 333
1993	P.Z. Budka, J.R.M. Viertl, S.V. Thamboo	Meteorites and Microgravity Research	Advanced Materials & Processes	Vol. 144, No. 5, Nov. 1993, p. 4
1995	P.Z. Budka, J.R.M. Viertl, S.V. Thamboo	Gravity Independent Macro/Micro-structural Features: Lessons from Nickel-Iron Meteorites	7th International Symposium on Experimental Methods for Microgravity Materials Science, The Mineral, Metals & Materials Society	pp. 27 - 36
1996	P.Z. Budka, J.R.M. Viertl, S.V. Thamboo	Microgravity Solidification Microstructures as Illustrated by Nickel-Iron and Stony-Iron Meteorites	8th International Symposium on Experimental Methods for Microgravity Materials Science, The Mineral, Metals & Materials Society	pp. 49 - 57
1996	P.Z. Budka	Meteorites and the Iron-Nickel Phase Diagram	Advanced Materials & Processes	Vol. 150 No. 1, July 1996, pp. 27 - 30
1996	P.Z. Budka	The Evolution of Meteoritics and Metallurgy	Meteorite!	Vol. 2 No. 3, pp. 22 - 23
1997	P.Z. Budka, J.R.M. Viertl, S.V. Thamboo, R.E. LaRose	Mundrabilla's Anomalous Macrostructural Features Revealed as Microgravity Cast Structures Based on Classical Solidification Principles	28th Lunar and Planetary Science Conference	
1998	P.Z. Budka and J.R.M. Viertl	Metallography, Meteorites and the Fe-Ni Phase Diagram	28th Lunar and Planetary Science Conference	Feb. 1998, pp. 22 - 23
1998	P.Z. Budka, J.R.M. Viertl T. B Schumaker	Metallography, Meteorites and the Fe-Ni Phase Diagram	61st Meteoritical Society Meeting	
2001	P.Z. Budka and J.R.M. Viertl	Industrial X-Ray Technique Applied to Mundrabilla	64th Meteoritical Society Meeting	
2002	P.Z. Budka	Stony-Iron Meteorites (Pallasites) - A Study of Nature's Microgravity Specimens	14th International Symposium on Experimental Methods for Microgravity Materials Science	
2003	P.Z. Budka	Reconstructing Meteorite Microstructures	Advanced Materials & Processes	Vol. 161 No. 5, May 2003, www.asminternational.org/AMP, "Web Exclusives"
2003	P.Z. Budka	Stepping Back in Time: Digital Reconstruction of the Imilac Pallasite Formation,	Meteorite Nov. 2003 Vol. 9, No. 4, pp. 21 - 22	
2004	P.Z. Budka	Stepping Back in Time #2, Digital Reconstruction of the Gibeon Widmanstätten Structure,	Meteorite Nov. 2004 Vol. 10, No. 4, pp. 21 - 22	