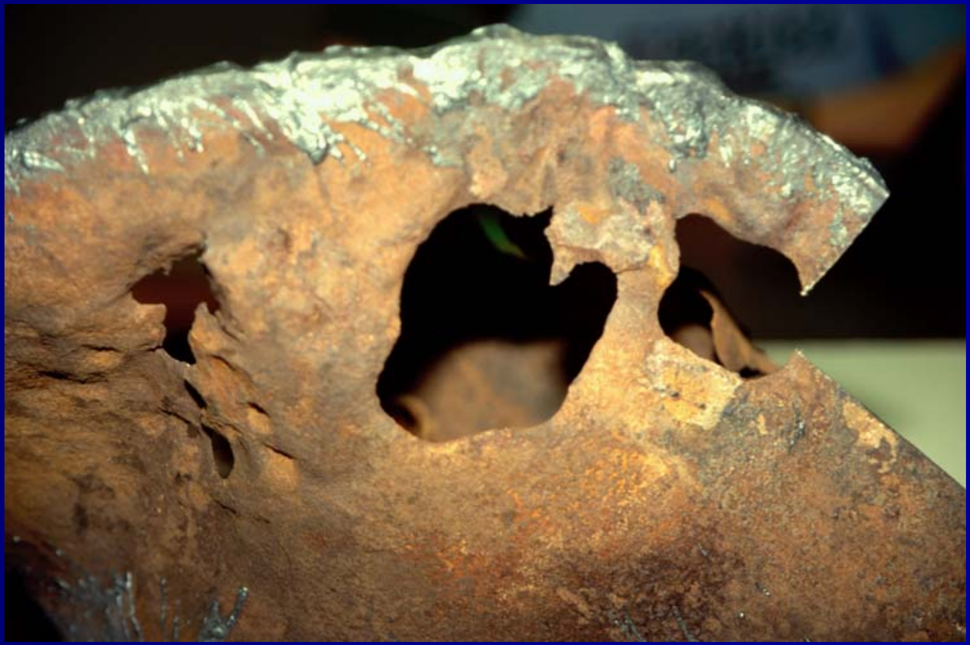
Microstructural Analysis of Steel from the World Trade Center Buildings 7, & 1 or 2

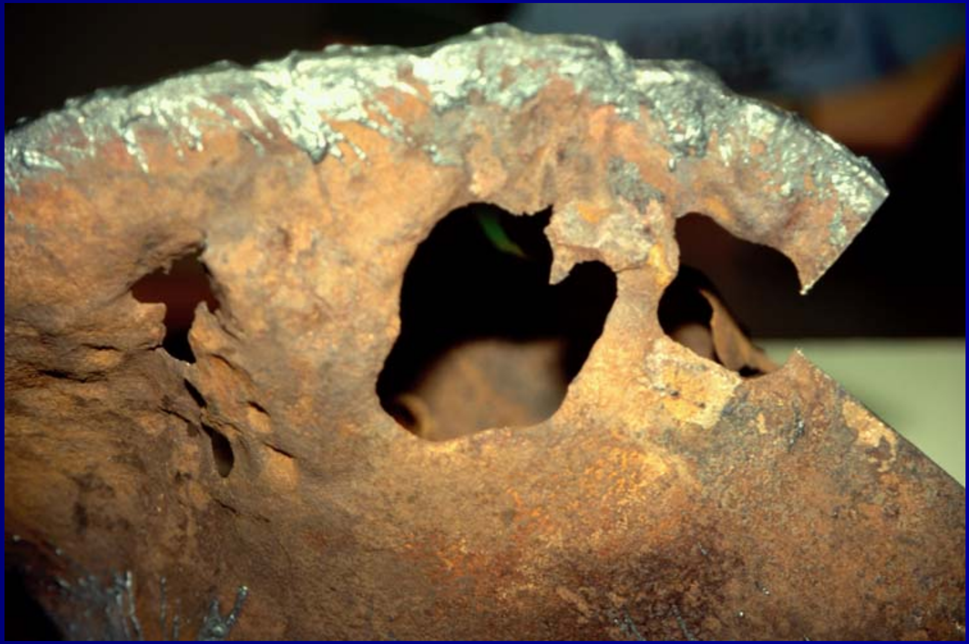


Ronald R. Biederman, WPI

Higgins Armory/WPI MCSI Symposium
June 5, 2006

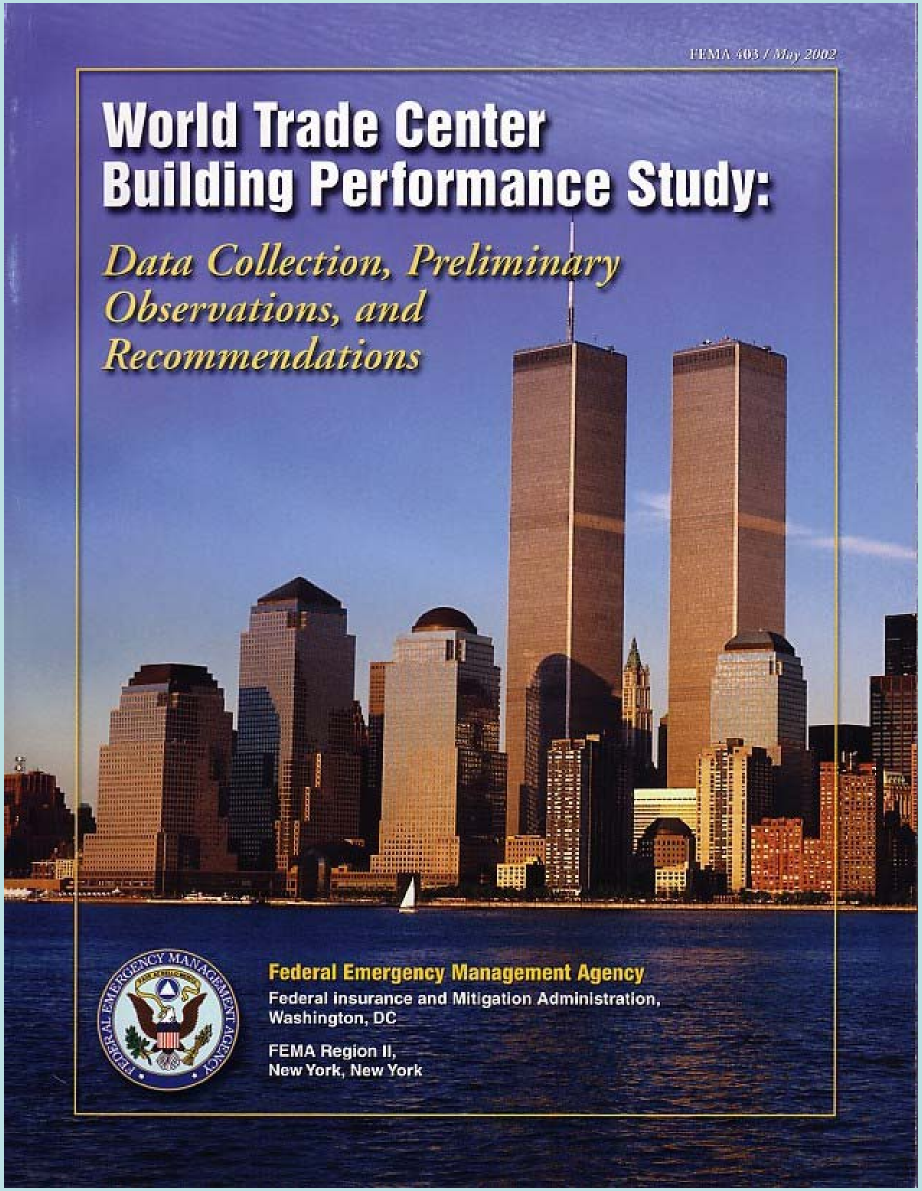
Microstructural Analysis of Steel from the World Trade Center Buildings 7, & 1 or 2

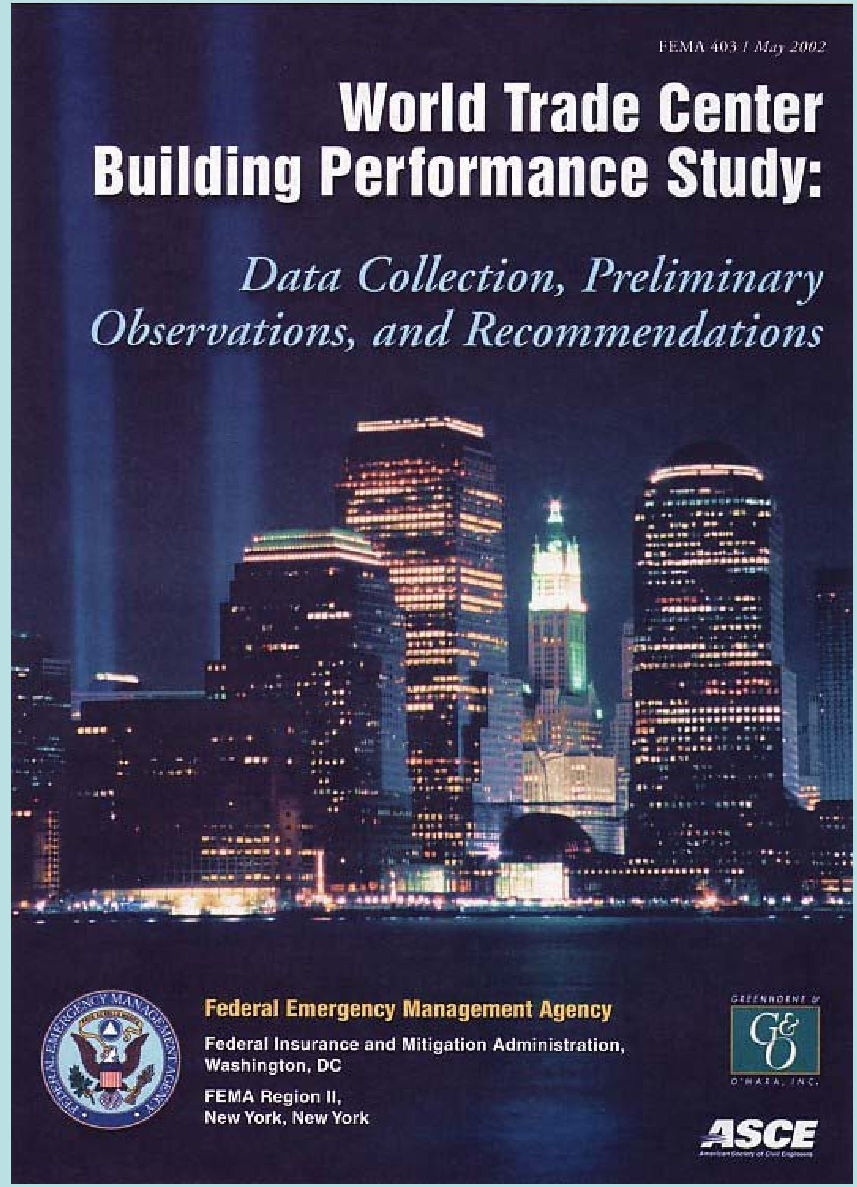
-The Role of Heat and Hot Corrosion in the Failure



Ronald R. Biederman, WPI

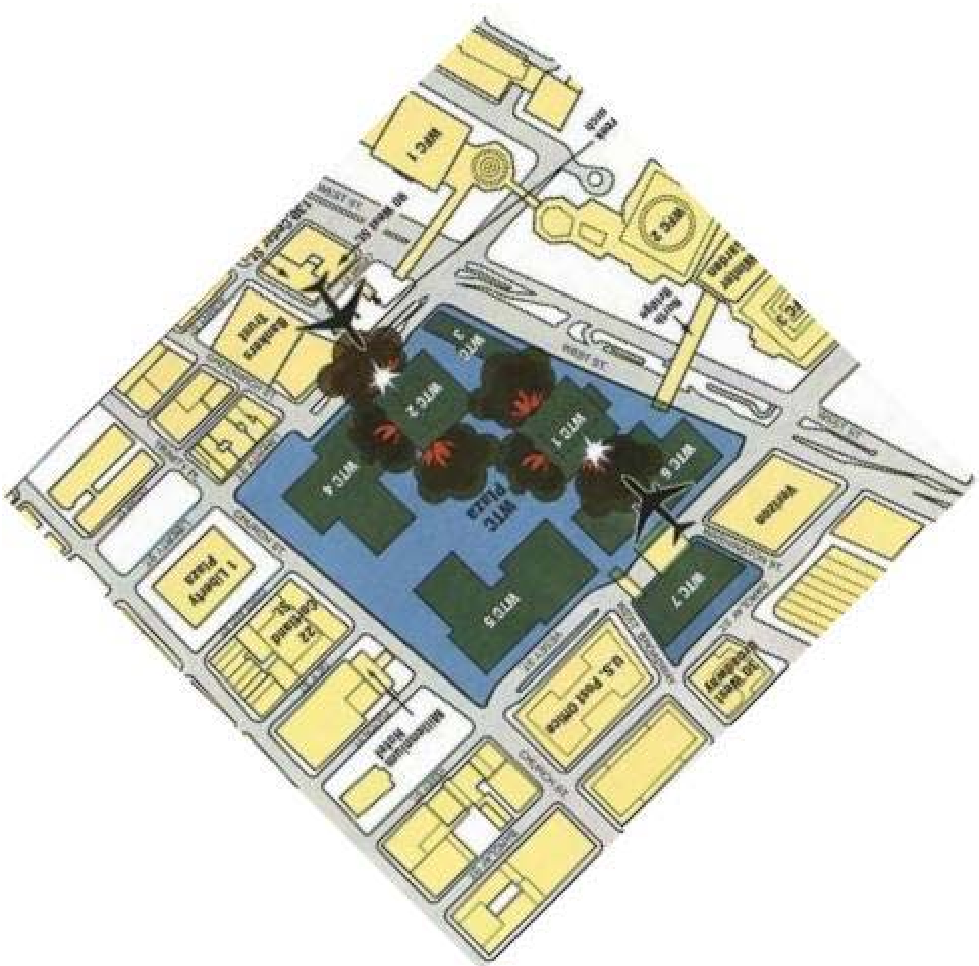
Higgins Armory/WPI MCSI Symposium
June 8, 2005



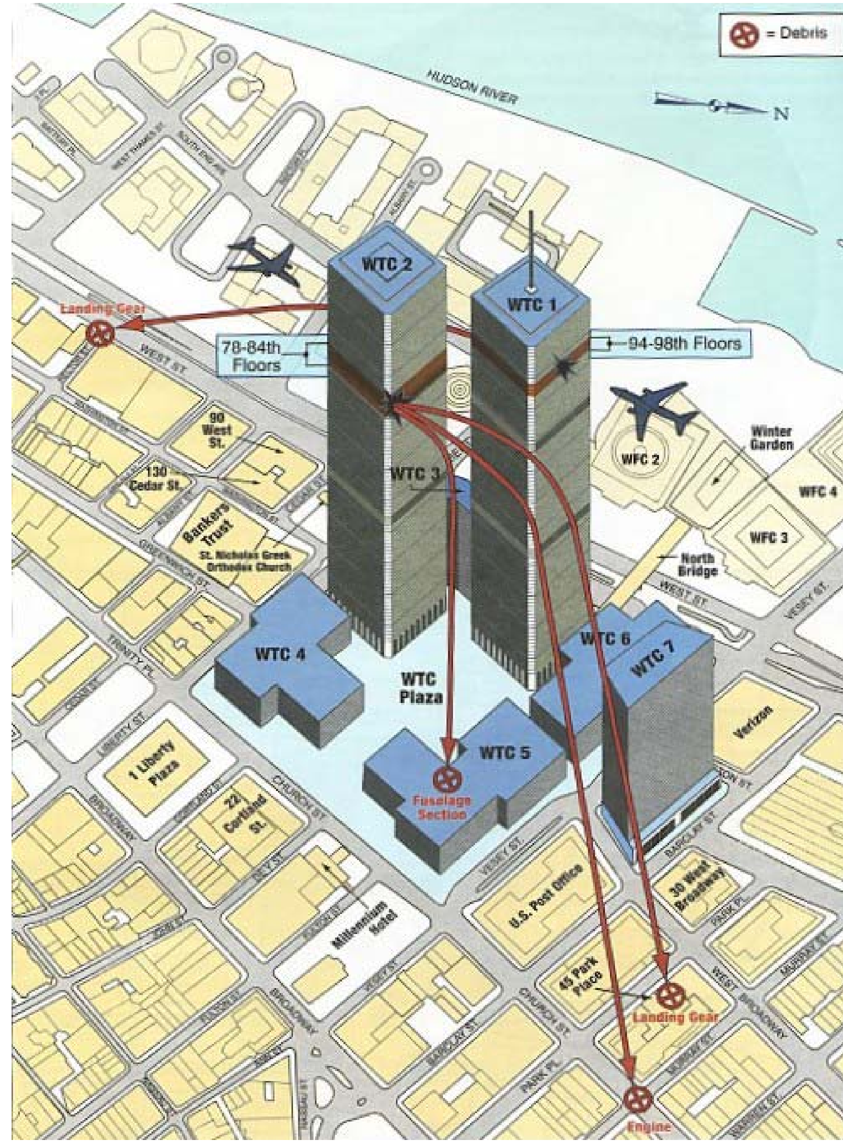


FEMA 403 /May 2002

Geography of the World Trade Center Complex

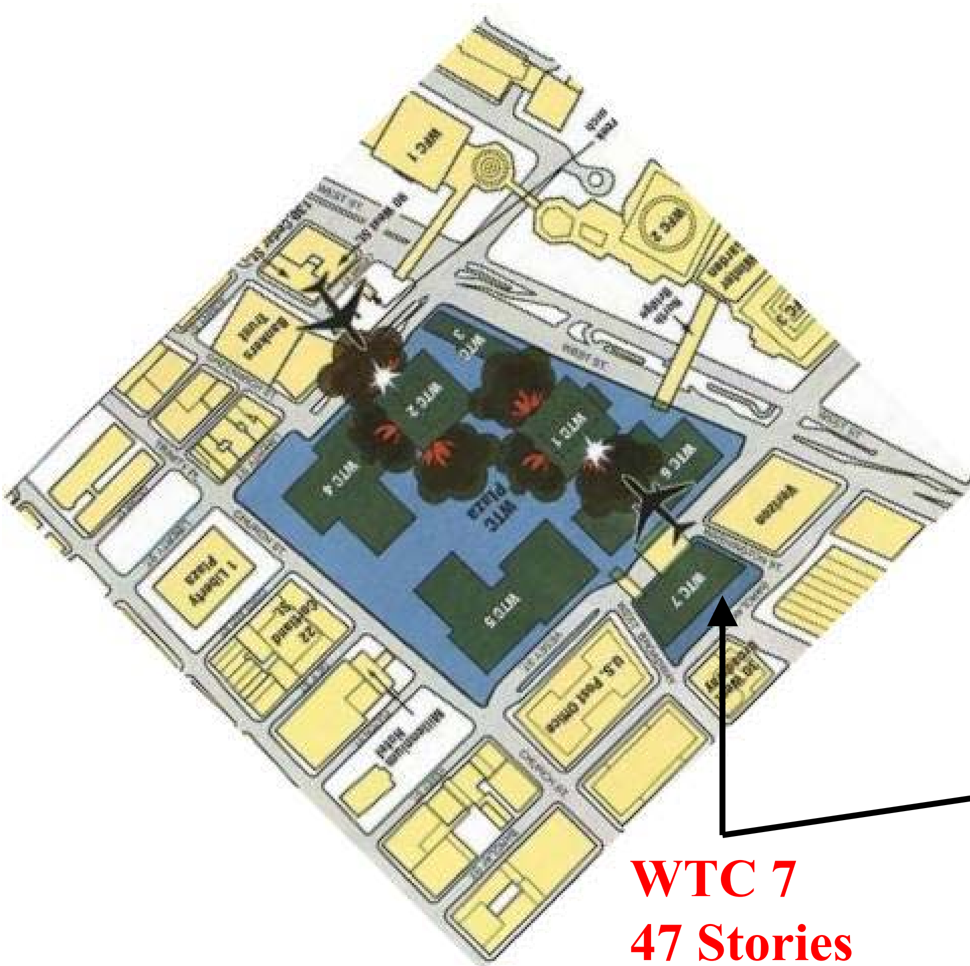


September 11, 2001



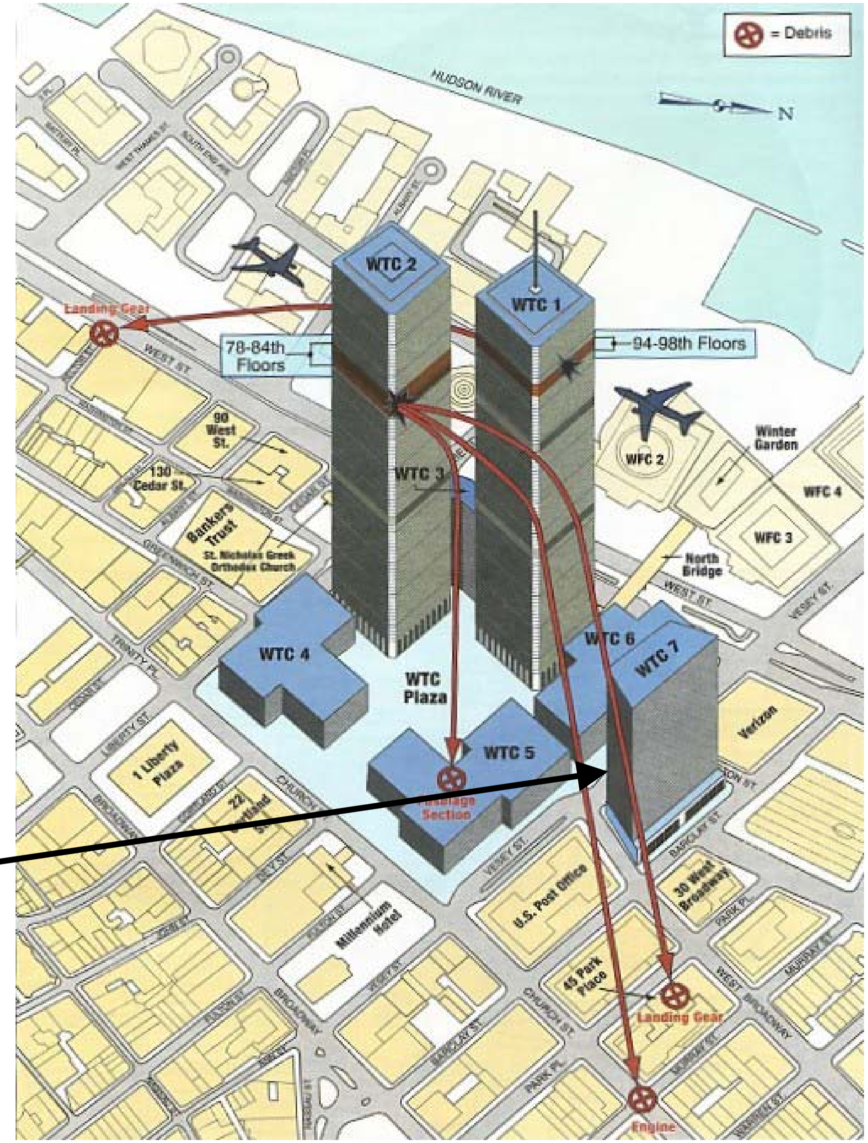
From FEMA 403 /May 2002

Geography of the World Trade Center Complex



September 11, 2001

WTC 7
47 Stories
Built 1987
Modified After
1993 Attack



From FEMA 403 /May 2002

Table 1.1 Timeline of Major Events[1]

Start Time[2]	Signal Duration	Magnitude (Richter Scale)	Event
8:46:26 EDT (12:46 UTC)	**12 seconds**	**0.9**	WTC 1 (the north tower) was hit by American Airlines Flight 11, a hijacked 767-200ER commercial jet airliner.
9:02:54 EDT (13:02 UTC)	**6 seconds**	**0.7**	WTC 2 (the south tower) was hit by United Airlines Flight 175, also a hijacked 767-200ER jet.
9:59:04 EDT (13:59 UTC)	**10 seconds**	**2.1**	WTC 2 began collapsing after 56 minutes, 10 seconds. Large debris from the collapse fell on WTC 3 and WTC 4, 130 Cedar Street, 90 West Street, and Bankers Trust. WTC 3 suffered a partial collapse. Fire was initiated in WTC 4 and 90 West Street.
10:28:31 EDT (14:28 UTC)	**8 seconds**	**2.3**	WTC 1 began collapsing after 102 minutes, 5 seconds. Large debris from the collapse fell on WTC 3, 5, 6, and 7; the Winter Garden; and the American Express (World Financial Center 2) building. WTC 3 collapsed to the 3rd floor, and fires were initiated in WTC 5, 6, and 7.
17:20:33 EDT (21:20 UTC)	**18 seconds**	**0.6**	WTC 7 began collapsing. **~8.5hrs after initial incident**

1 Based on seismic recordings made by the Lamont-Doherty Earth Observatory of Columbia University, 34 kilometers north of the WTC site.

2 EDT = Eastern Daylight Time; UTC = Coordinated Universal Time. Times cited in this report are based on these times, rounded to the nearest minute.

Important Observations by FEMA Concerning WTC 7

1. The collapse of WTC 7 is of significant interest because it appears that the collapse was due primarily to fire, rather than any impact damage from the collapsing WTC 1 tower. There is no history or record of a fire induced collapse in a fire protected steel building prior to this event.

Important Observations by FEMA Concerning WTC 7

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2. Collapse is consistent with an initial failure that occurred internally in the lower floors toward the east side of the building. Fire ignition likely started as a result of falling debris from WTC 1 damaging the south face of WTC 7 (Floors 6,7, 8, 10, 11, 19). The building main structural support members are located in the 5th to the 7th floors.

Important Observations by FEMA Concerning WTC 7

1. The collapse of WTC 7 is of significant interest because it appears that the collapse was due primarily to fire, rather than any impact damage from the collapsing WTC 1 tower. There is no history or record of a fire induced collapse in a fire protected steel building prior to this event.

2. Collapse is consistent with an initial failure that occurred internally in the lower floors toward the east side of the building. Fire ignition likely started as a result of falling debris from WTC 1 damaging the south face of WTC 7 (Floors 6,7, 8, 10, 11, 19). The building main structural support members are located in the 5th to the 7th floors.

3. The fire progressed throughout the day, virtually unimpeded by manual or automatic fire suppression systems. The fire got hotter as time progressed. There is no physical, photographic or other evidence to either substantiate or refute the discharge of fuel oil from the piping system. “Although the total diesel fuel on the premises contained massive potential energy, the best hypothesis has only a low probability of occurrence”

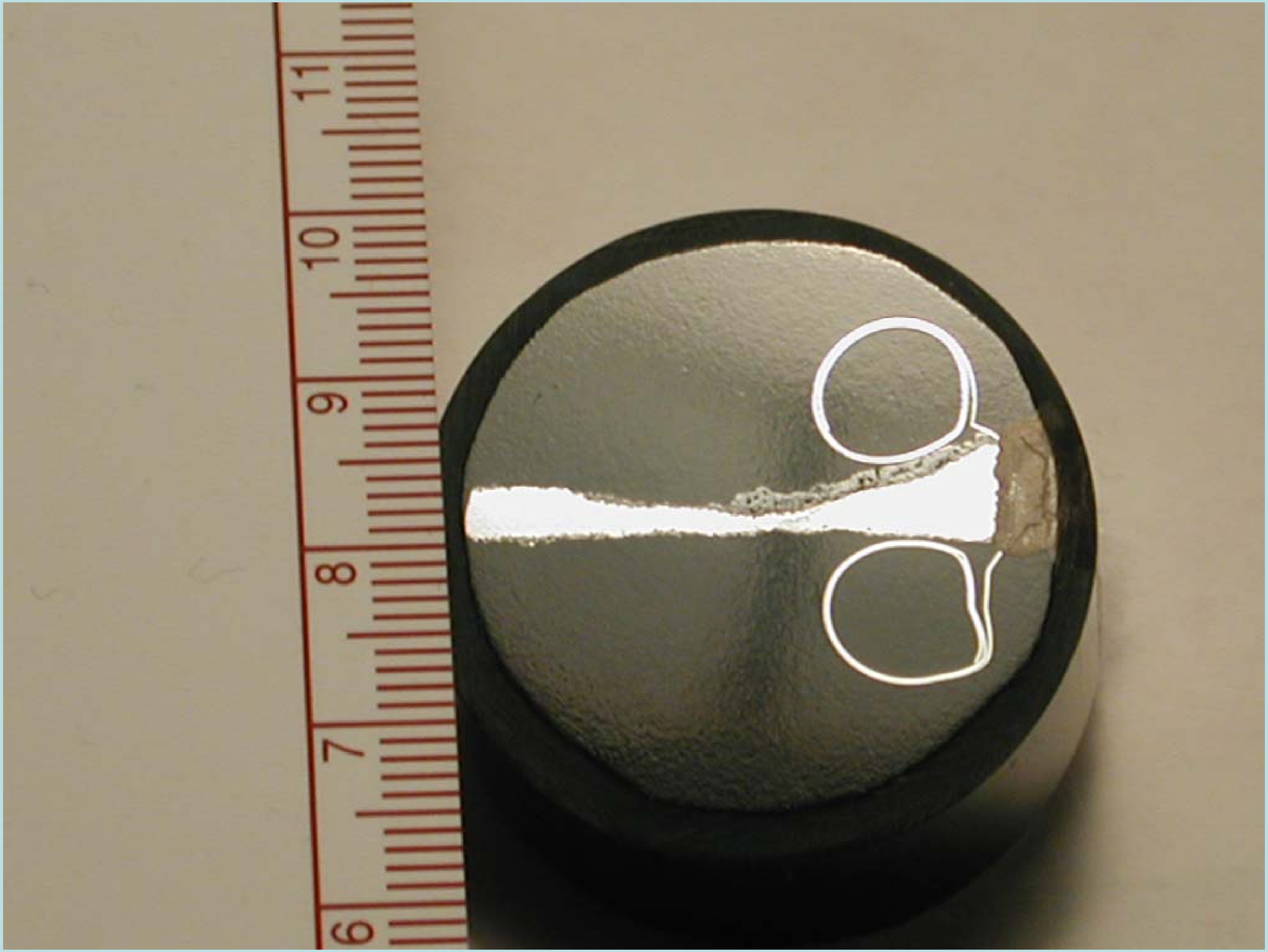
Can a microstructural examination of the steel give insight into why WTC 7 collapsed ?

First question ask by FEMA

Severely Eroded ½" Wide Flange Beam from WTC 7

Nominal Composition (%) of the A36 Steel Plate is:
(0.29C max, 0.80-1.2Mn, 0.04P, 0.05S, 0.15-0.3Si bal Fe)

Typical Cross Sectional Metallurgical Mount



FEMA’s Request:

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➊ Can we determine the maximum temperature that this A36 steel beam encountered?

FEMA's Request:

➊ Can we determine the maximum temperature that this A36 steel beam encountered?

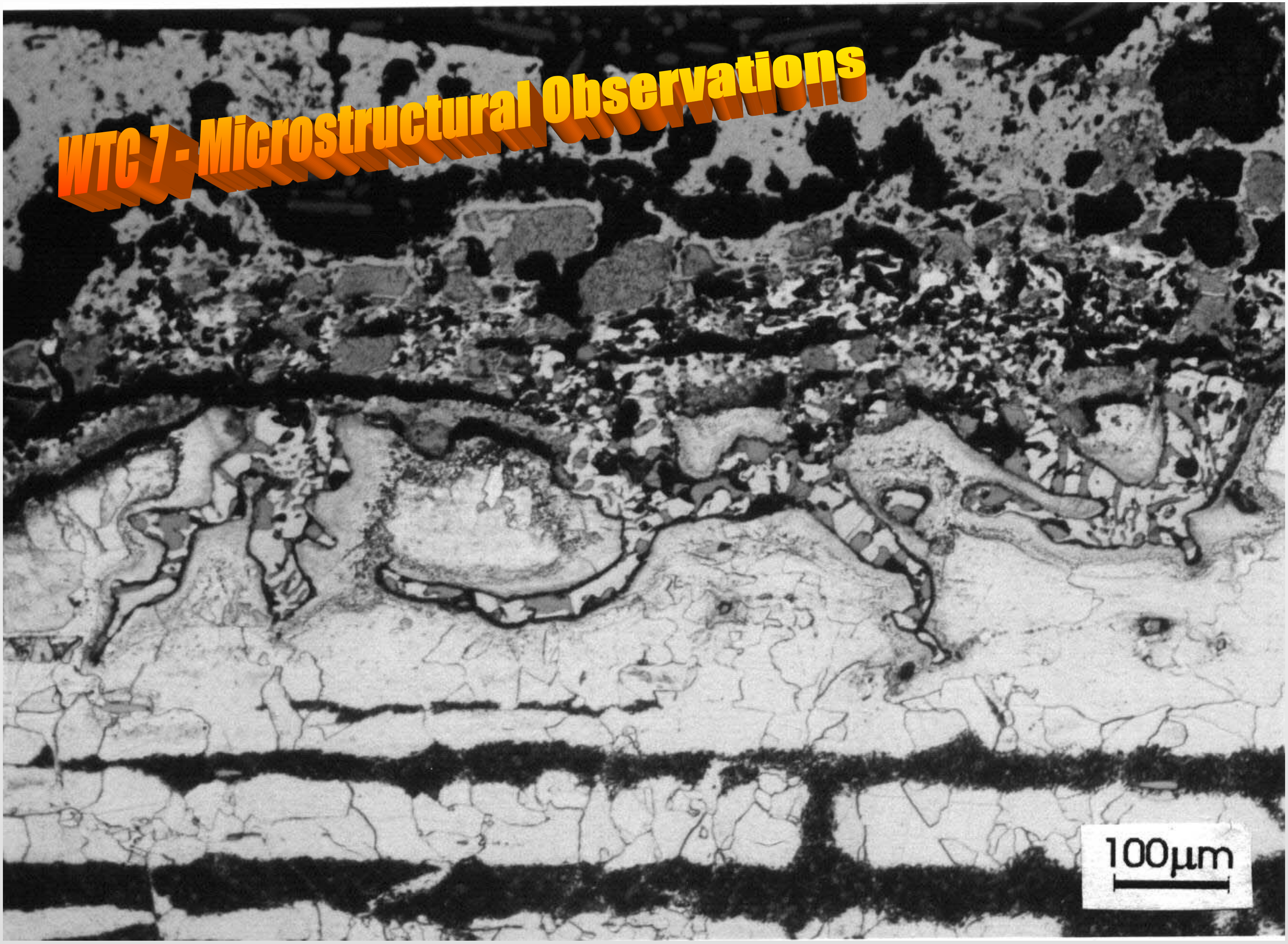
➋ What caused the observed severe erosion of the steel?

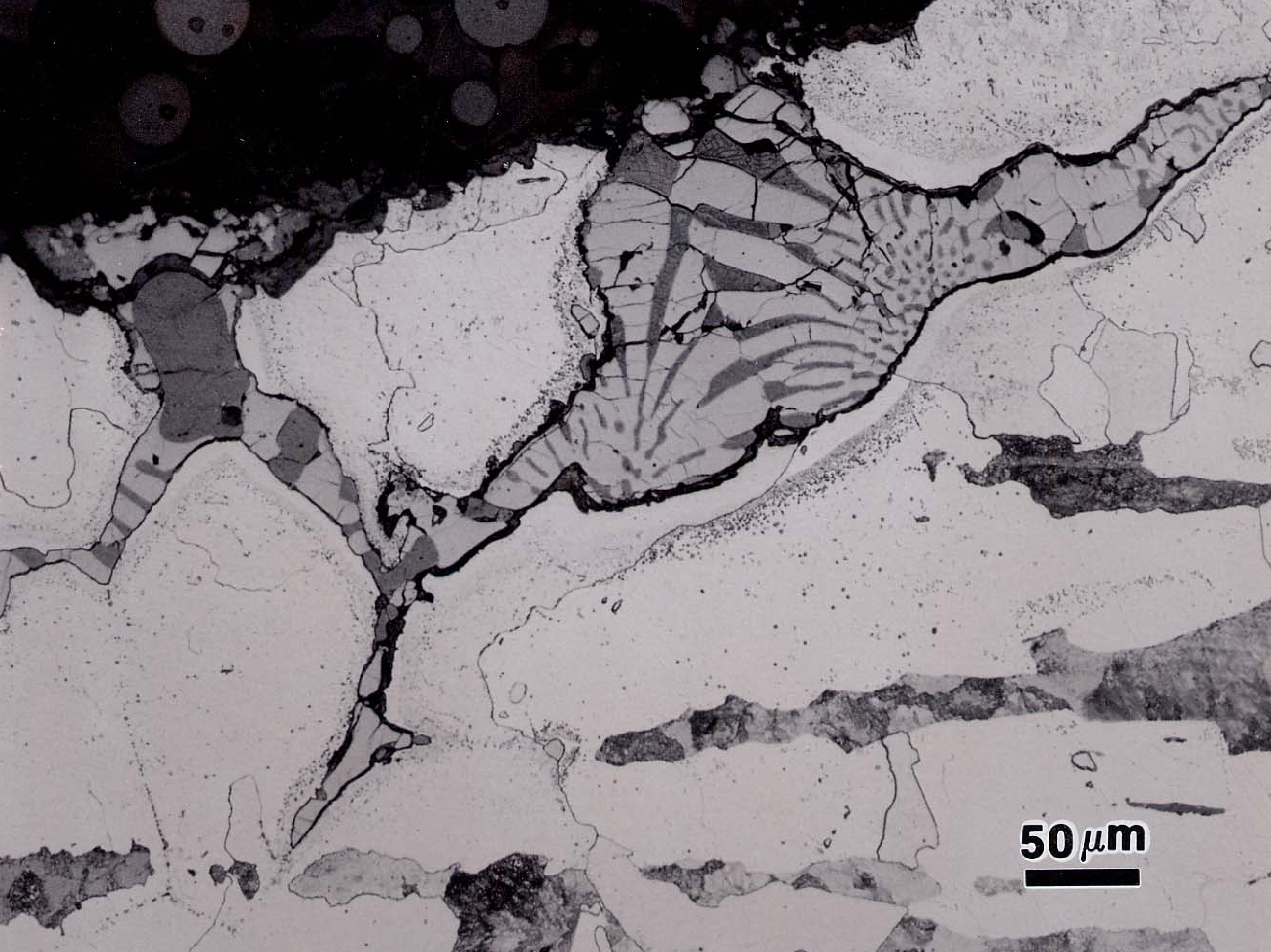
WPI Team

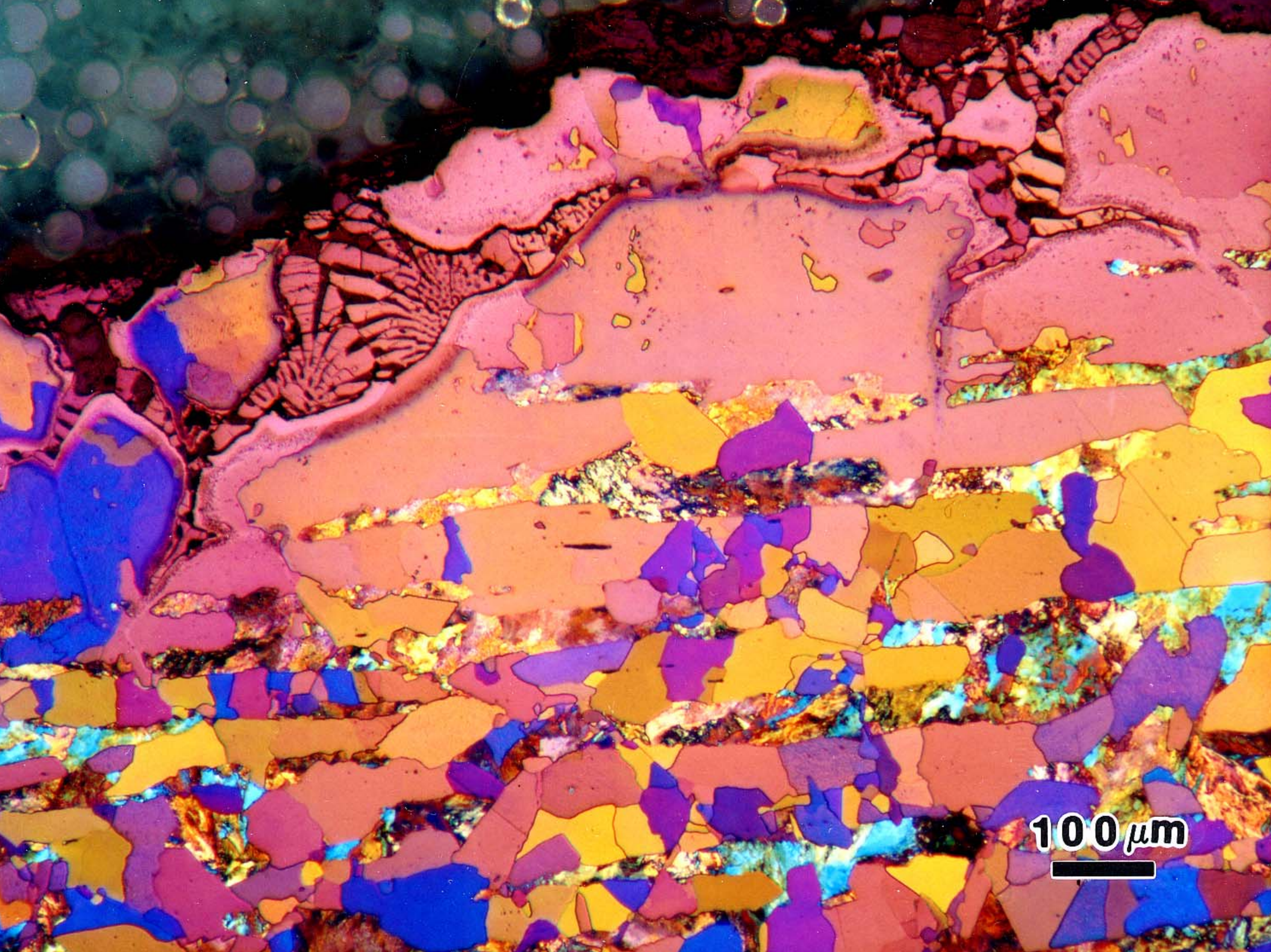
1. **Professor J. R. Barnett,** Fire Protection Engineering, WPI and FEMA
2. **Professor R. D. Sisson, Jr.,** Materials Science and Engineering
3. **Professor R. R. Biederman,** Materials Science and Engineering
4. **Jeremy Bernier,** Undergraduate Student in Mechanical Engineering
5. **Marco Fontecchio,** Undergraduate Student in Mechanical Engineering
6. **Erin Sullivan,** Graduate Student in Materials Science and Engineering
7. **Dr. Sumanth Shanker,** Postdoctoral Researcher MPI/ACRC

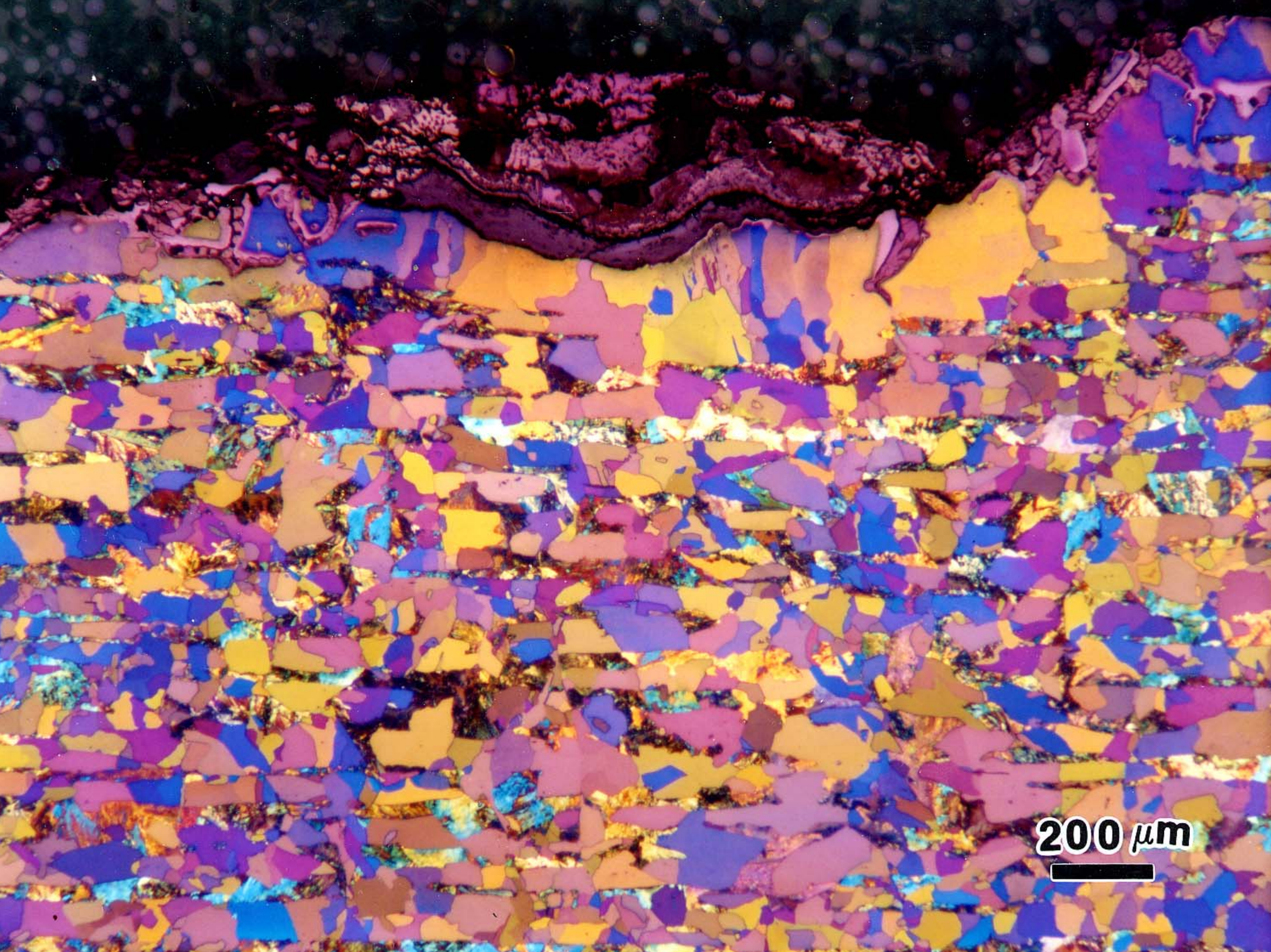
Special Contributions from: George VanderVoort, Buehler, Ltd.

WTC 7 - Microstructural Observations

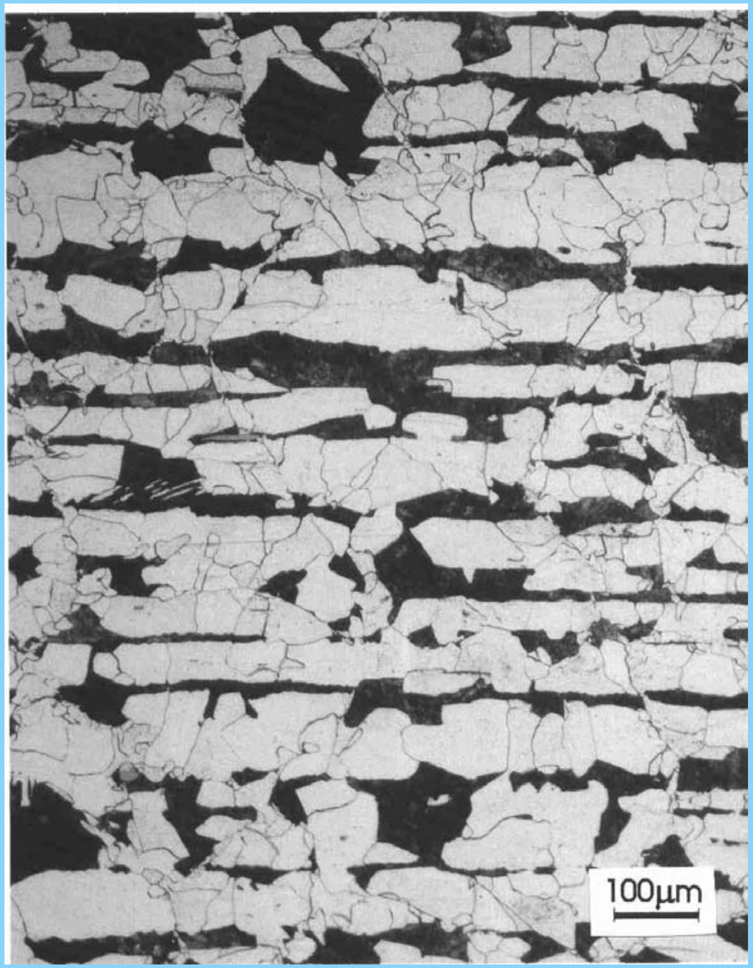



50 μm

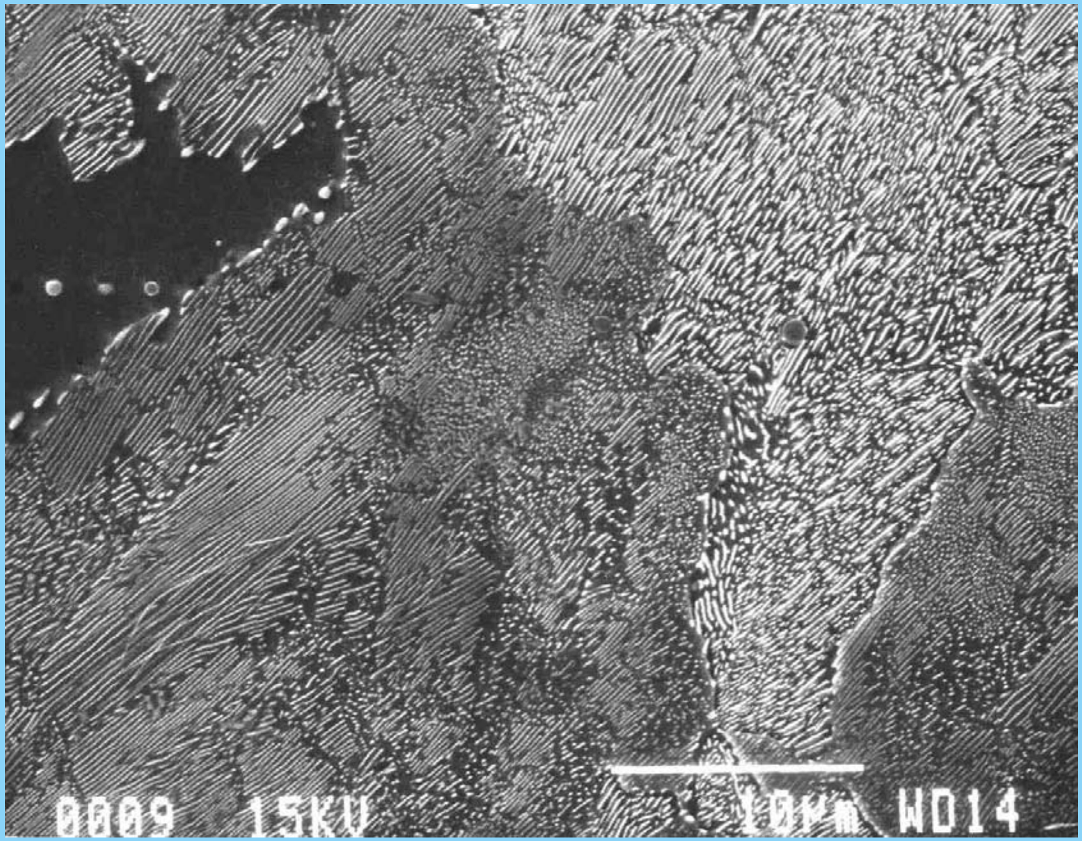

100 μm


200 µm

Microstructure of Unaffected A36 Steel



Pearlite Region

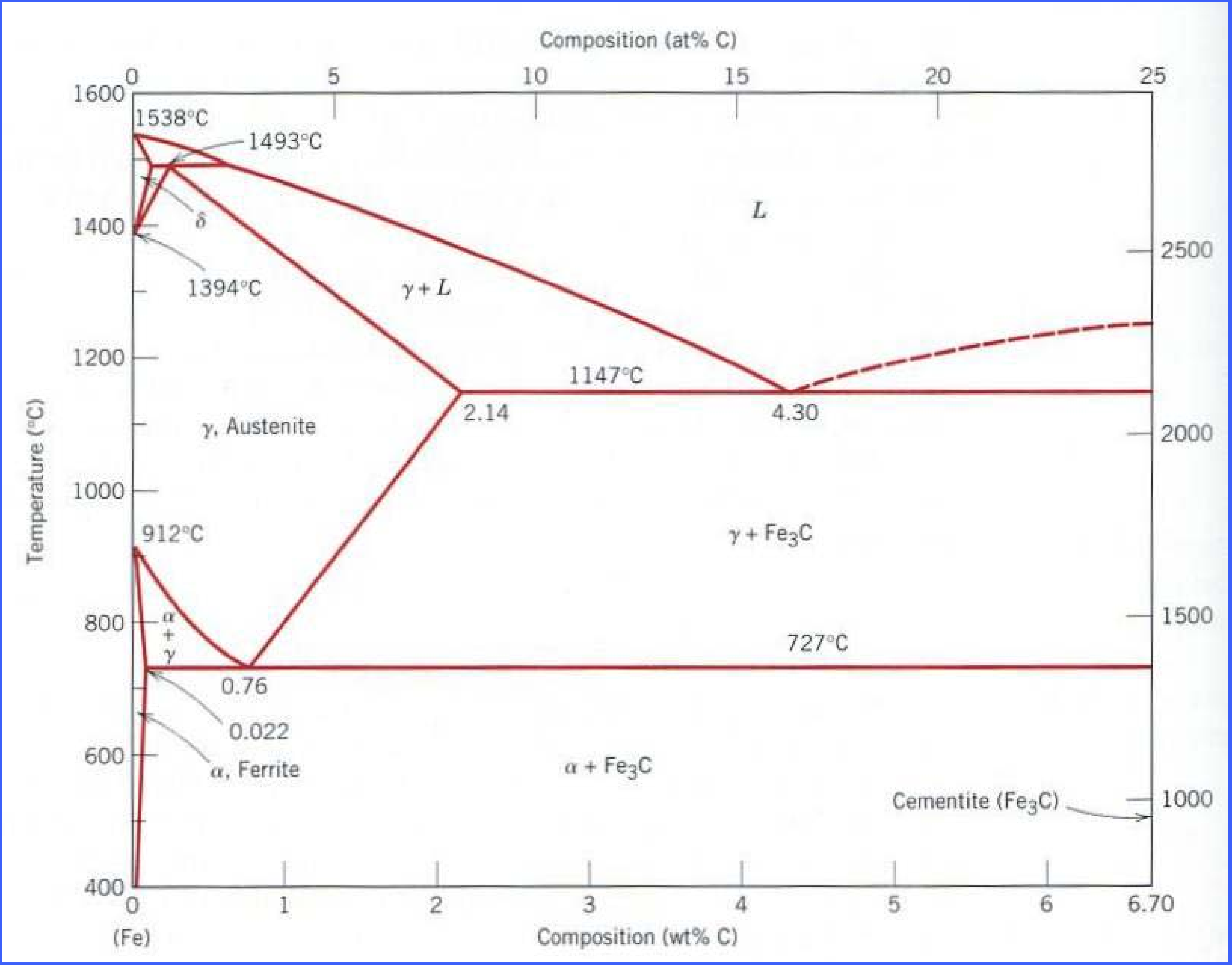


4% Nital Etch

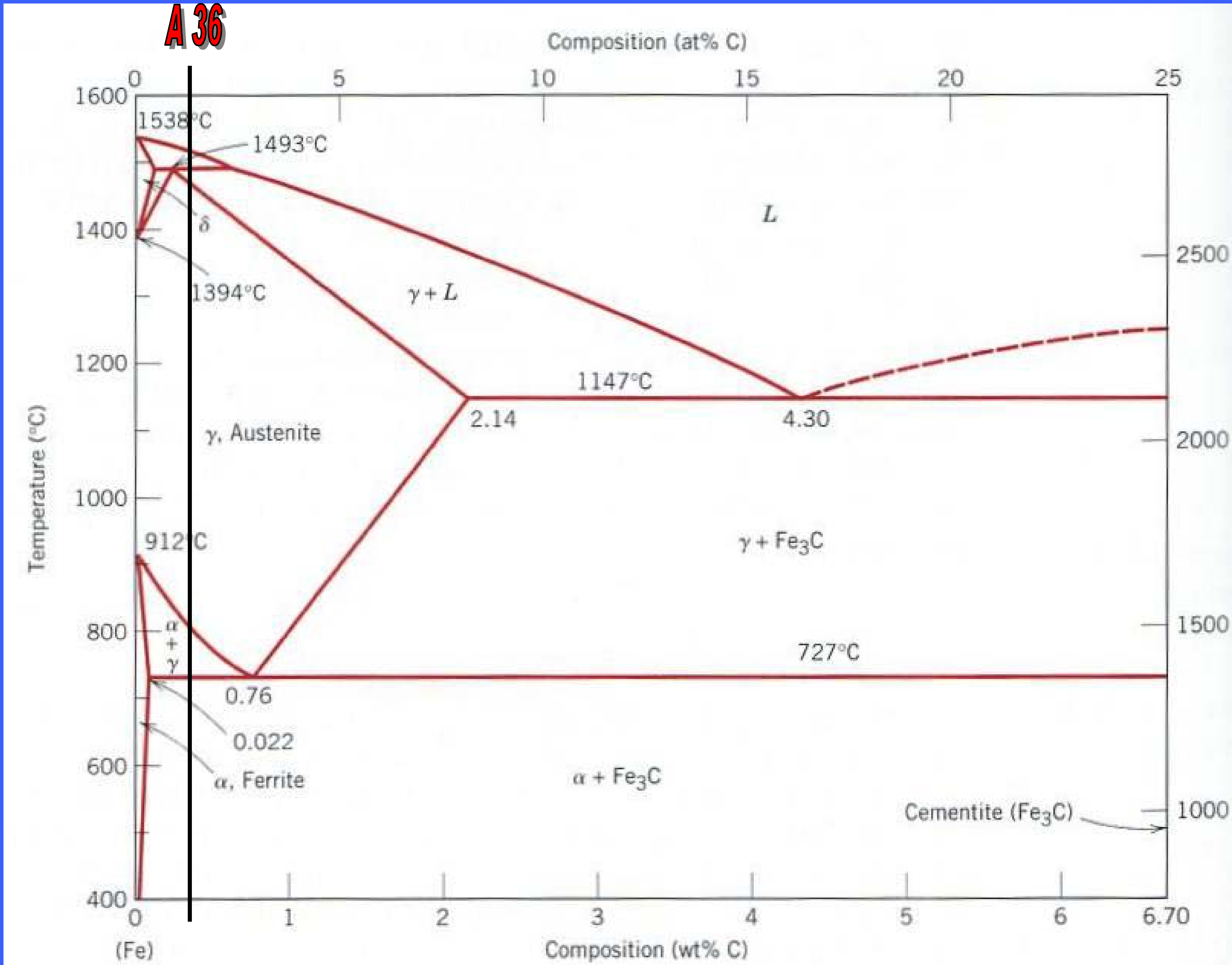
White - Ferrite, Dark - Banded Pearlite

Pearlite forms in bands due to manganese segregation and prior hot working

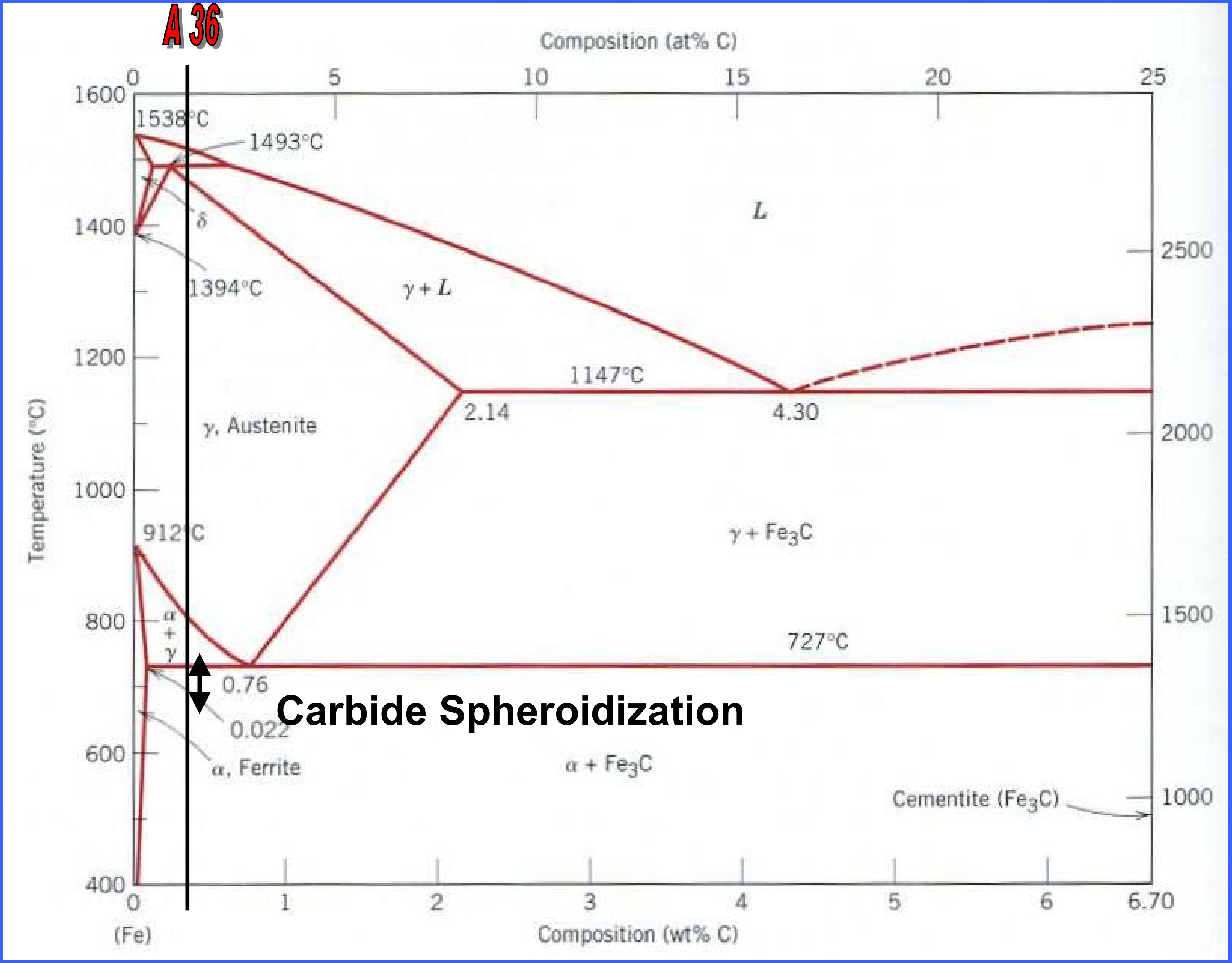
Iron – Iron Carbide Equilibrium Phase Diagram



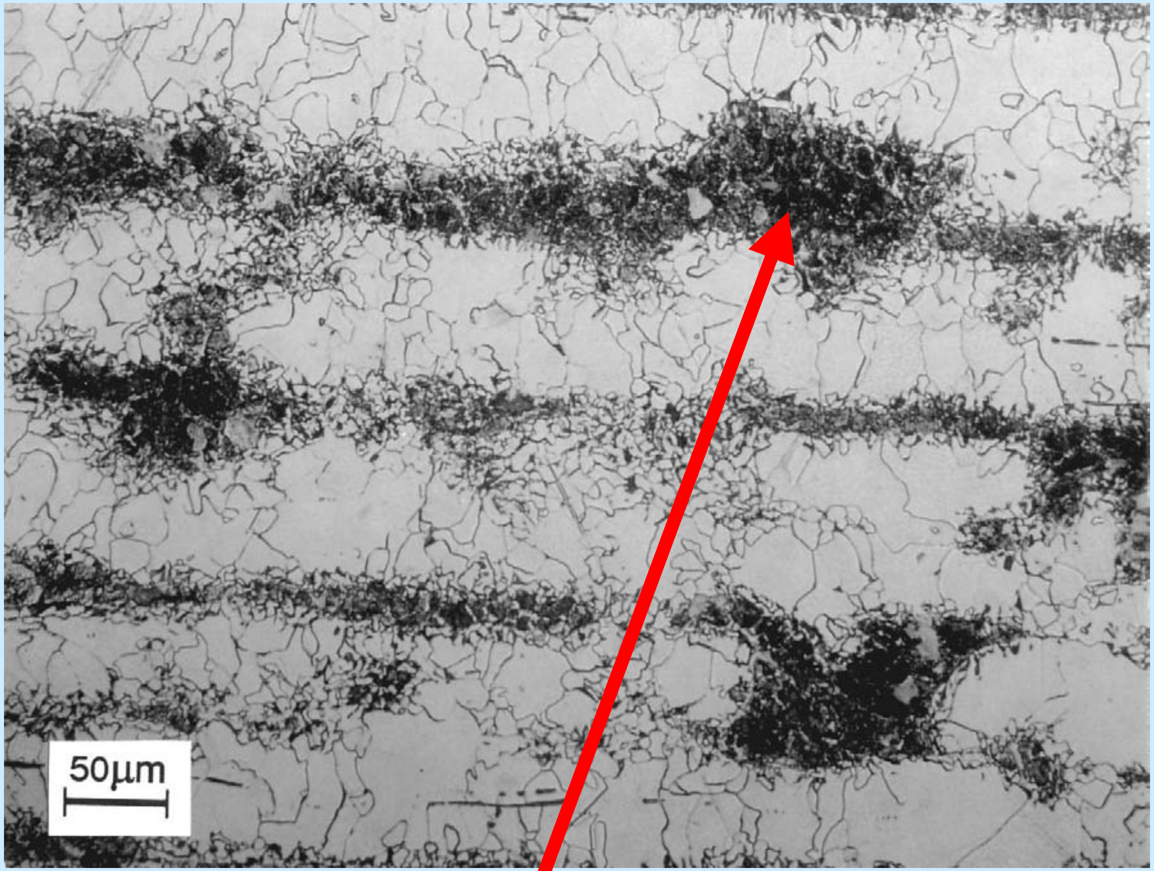
Iron – Iron Carbide Equilibrium Phase Diagram



Iron – Iron Carbide Equilibrium Phase Diagram

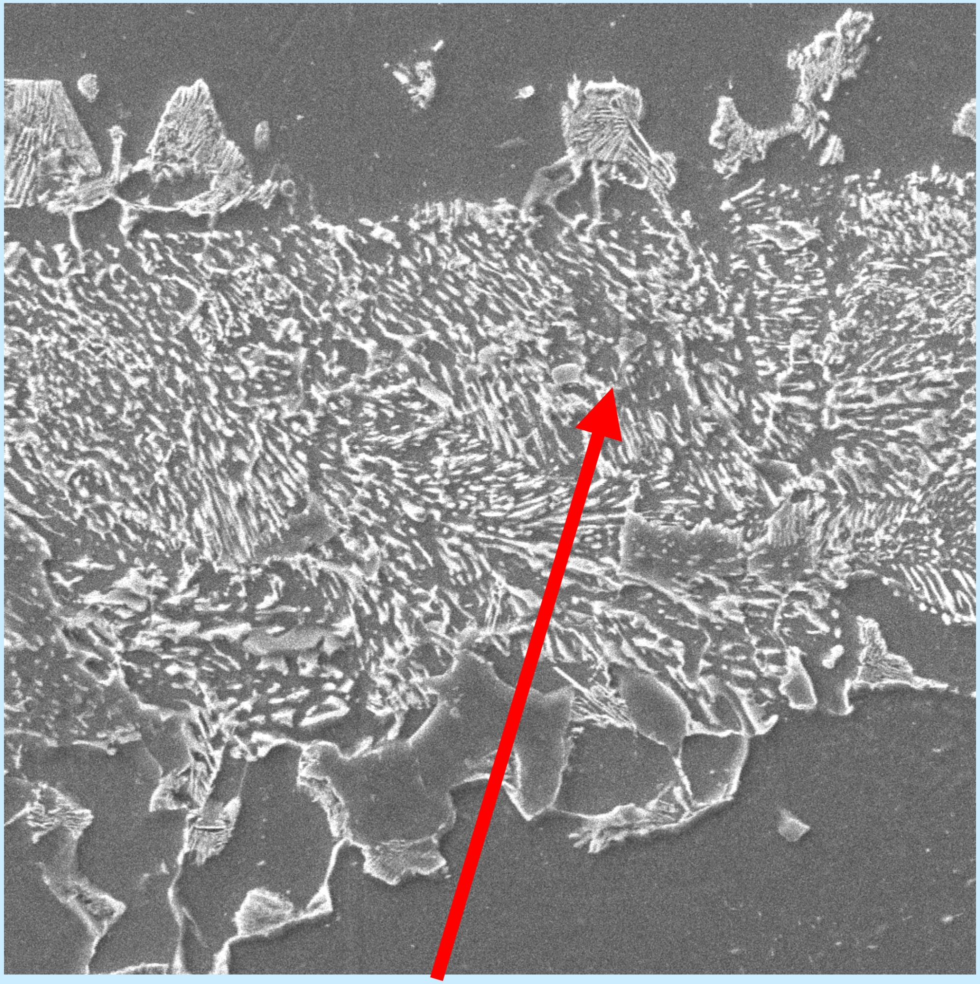


Typical Microstructural Changes That Occur When A36 Steel is Heated to the Vicinity of the Eutectoid Reaction ~727C (1340F), Held for a Short Time, and Cooled to Ambient Temperature



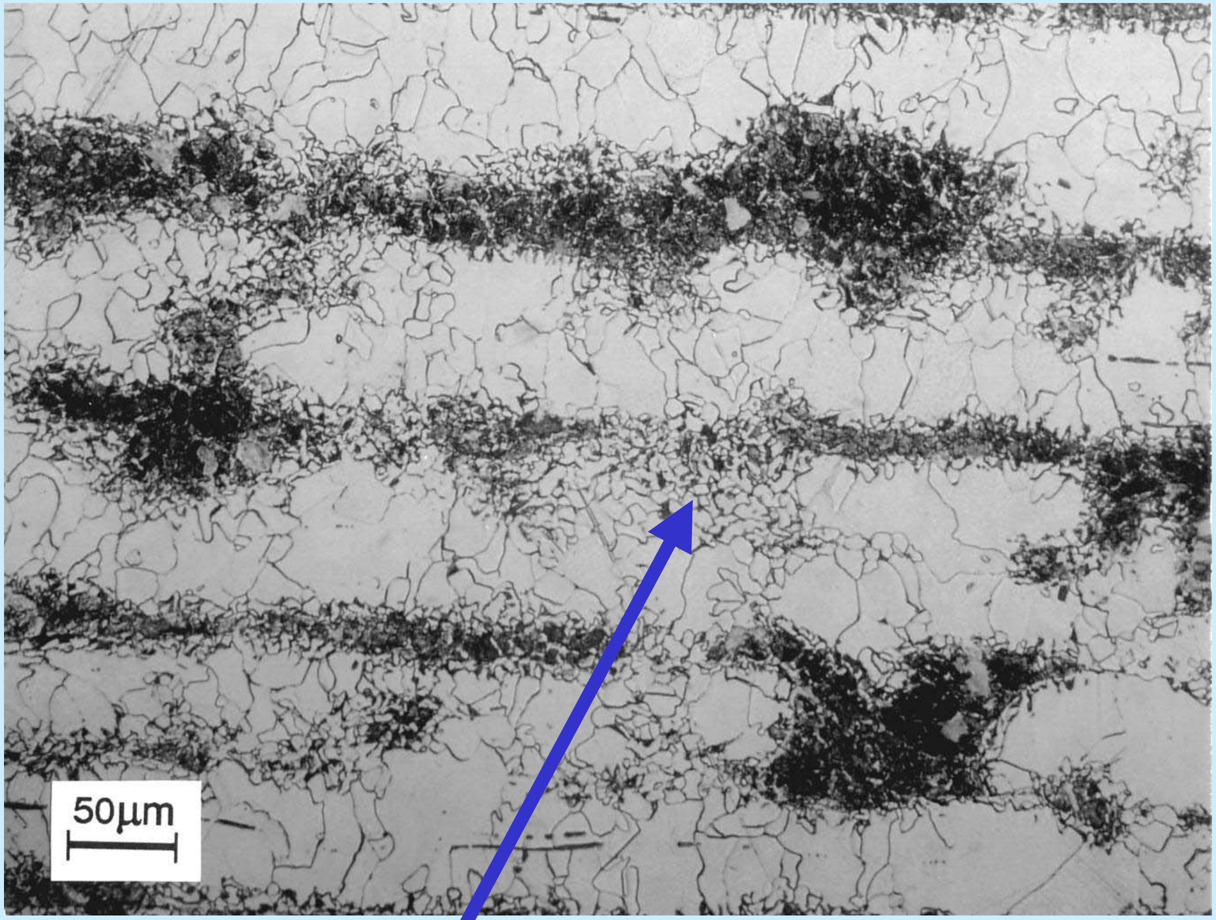
Partial Carbide Spheroidization

Typical Microstructural Changes That occur When A36 Steel is Heated to the Vicinity of the Eutectoid Reaction ~727C (1340F), Held for a Short Time, and Cooled to Ambient Temperature



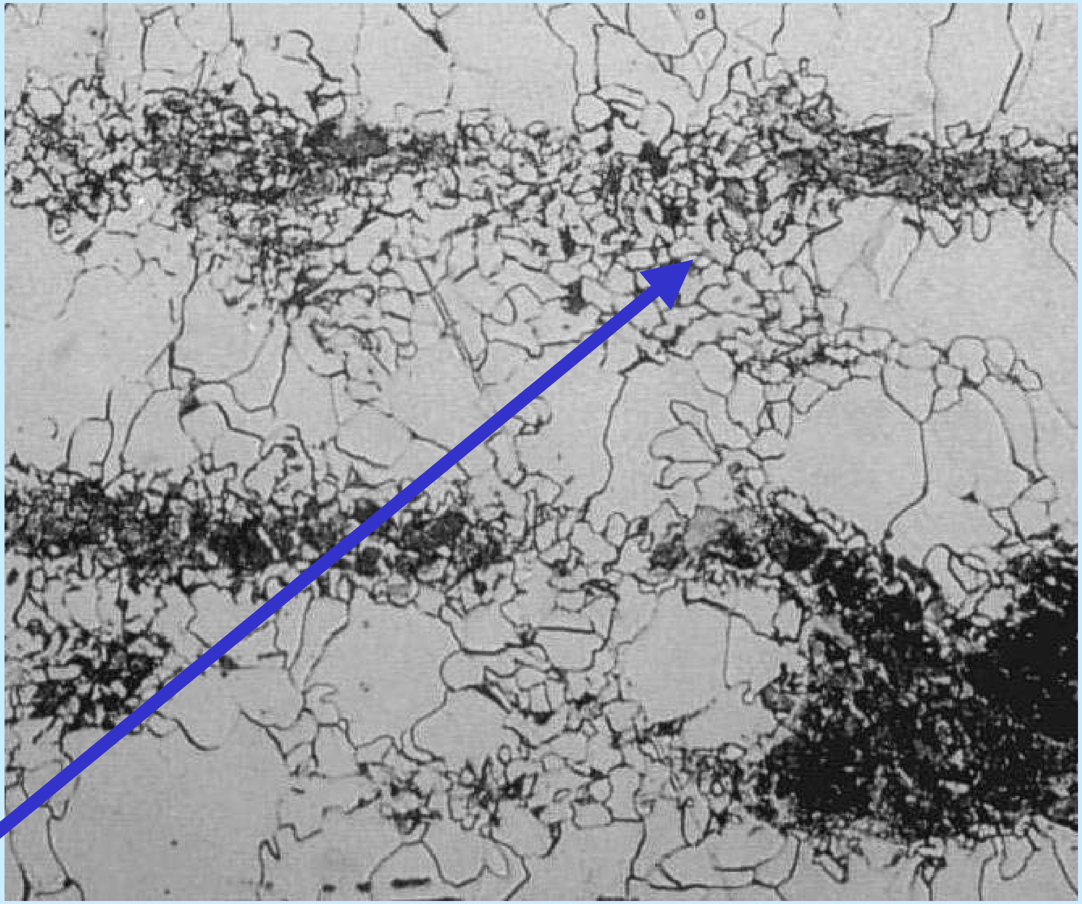
Partial Carbide Spheroidization

Typical Microstructural Changes That Occur When A36 Steel is Heated to the Vicinity of the Eutectoid Reaction ~727C (1340F)and cooled to Ambient Temperature



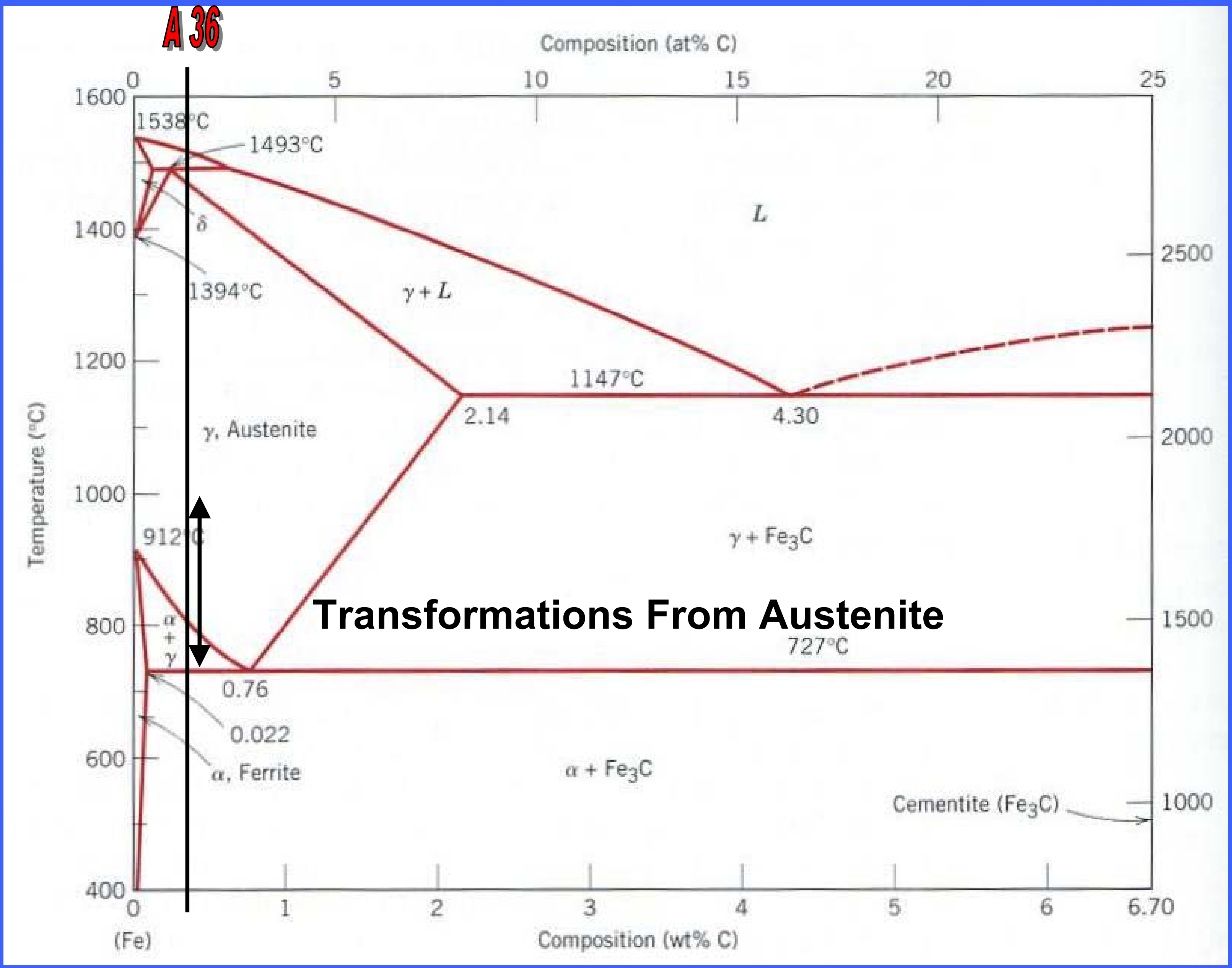
A Typical Region Where Conversion to an Austenite Matrix (on Heating) Occurred Followed by a Retransformation to a Ferrite Matrix on Cooling

Typical Microstructural Changes That Occur When A36 Steel is Heated to the Vicinity of the Eutectoid Reaction ~727C (1340F)and cooled to Ambient Temperature

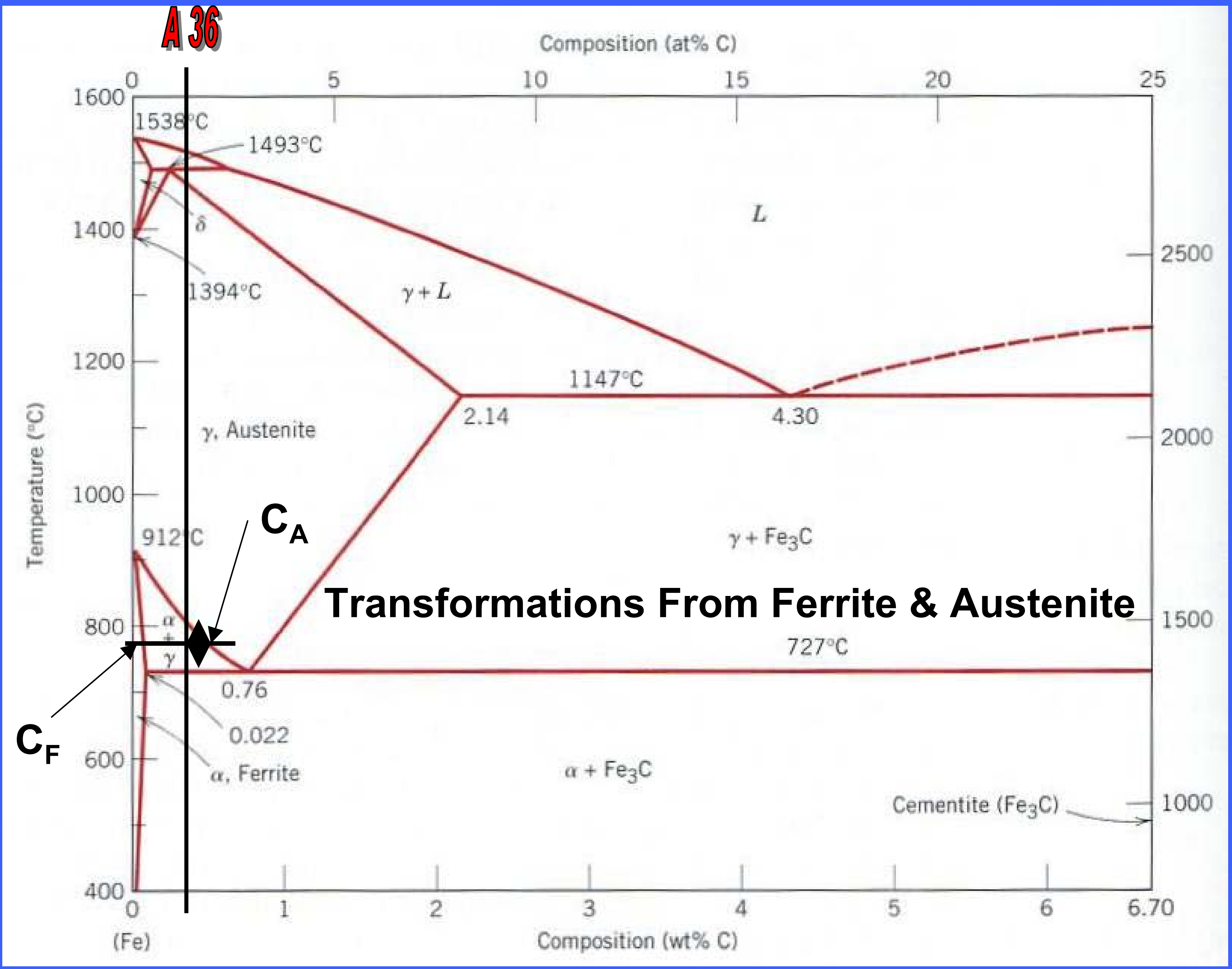


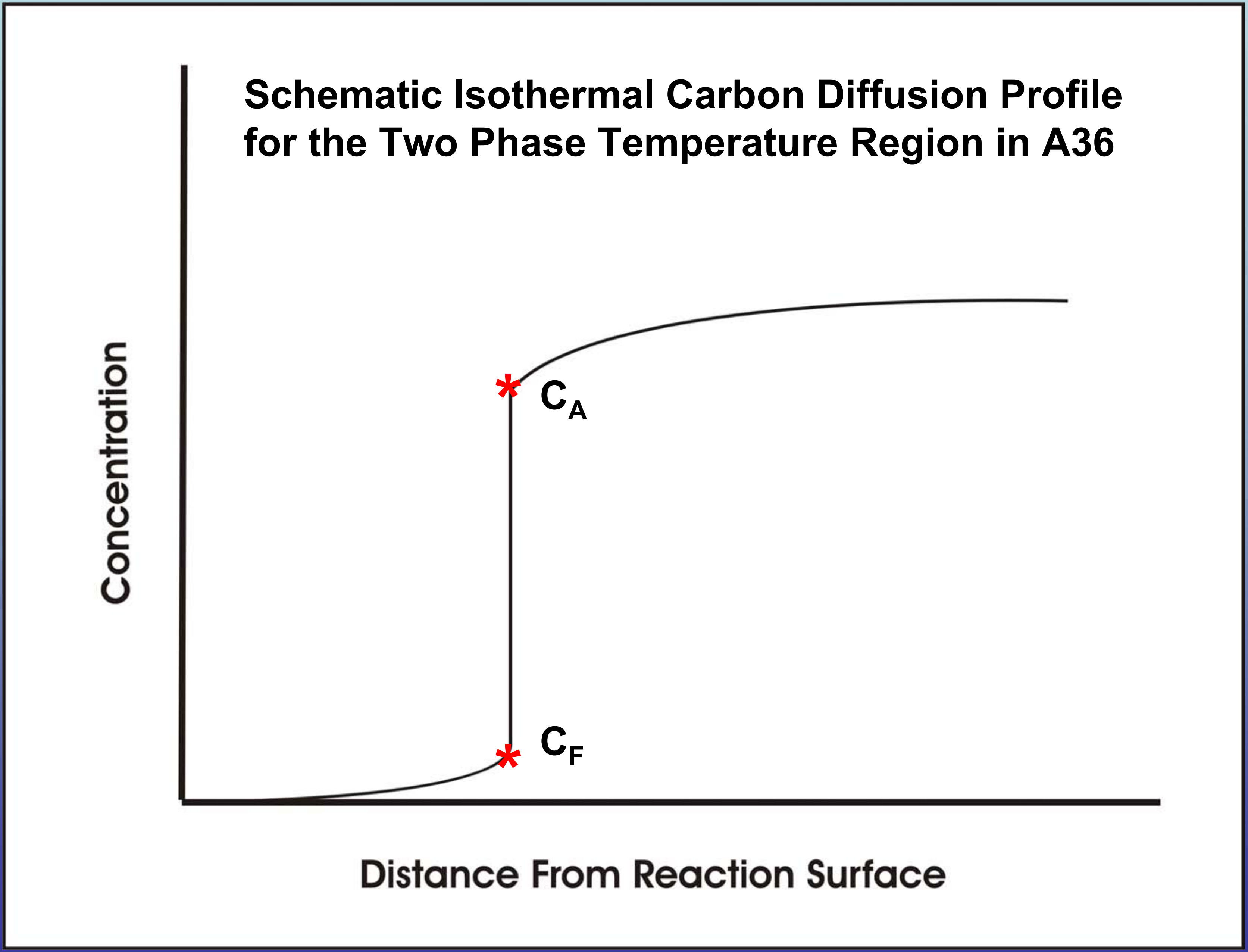
Conversion to Austenite Matrix (on heating) and Return to Ferrite Matrix (on Cooling)

Iron – Iron Carbide Equilibrium Phase Diagram

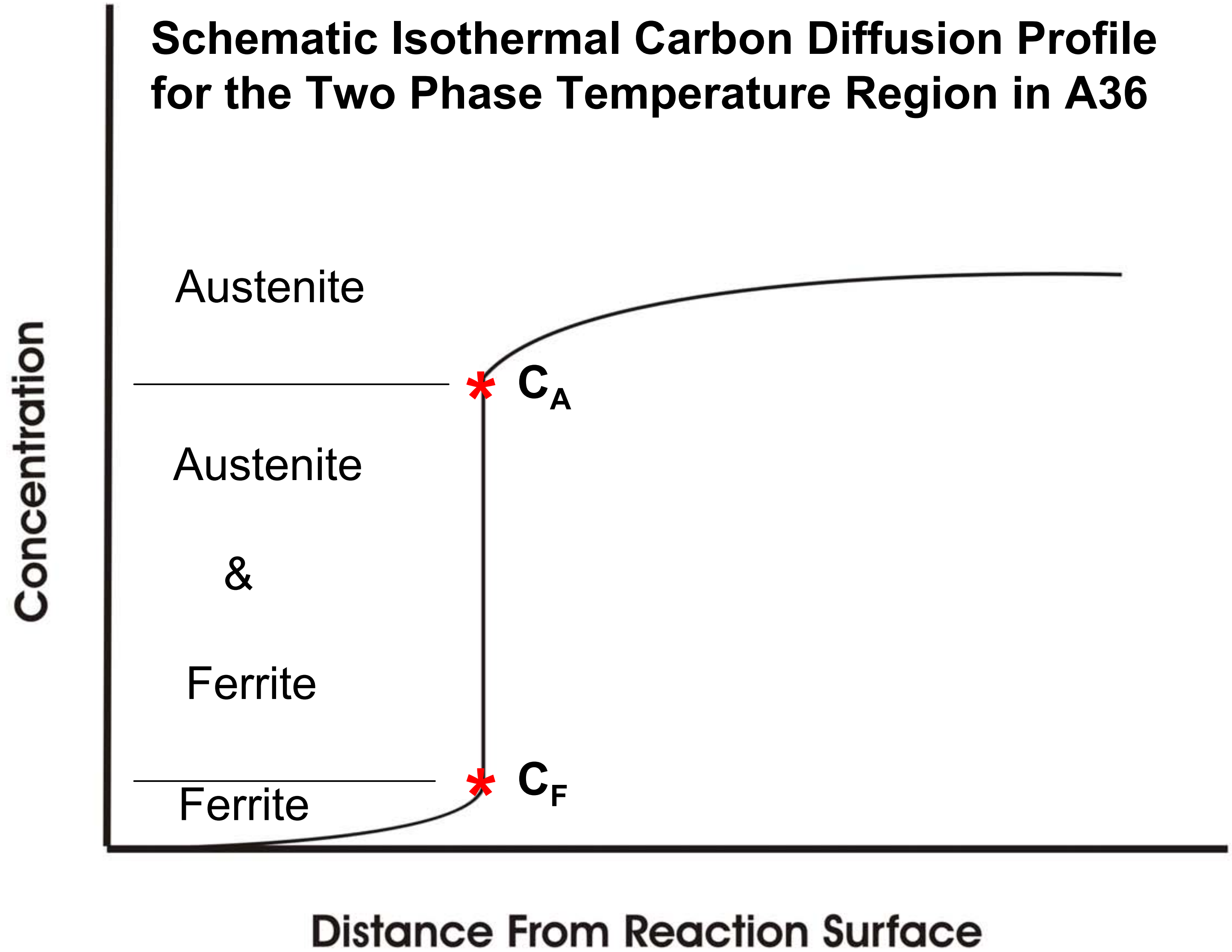


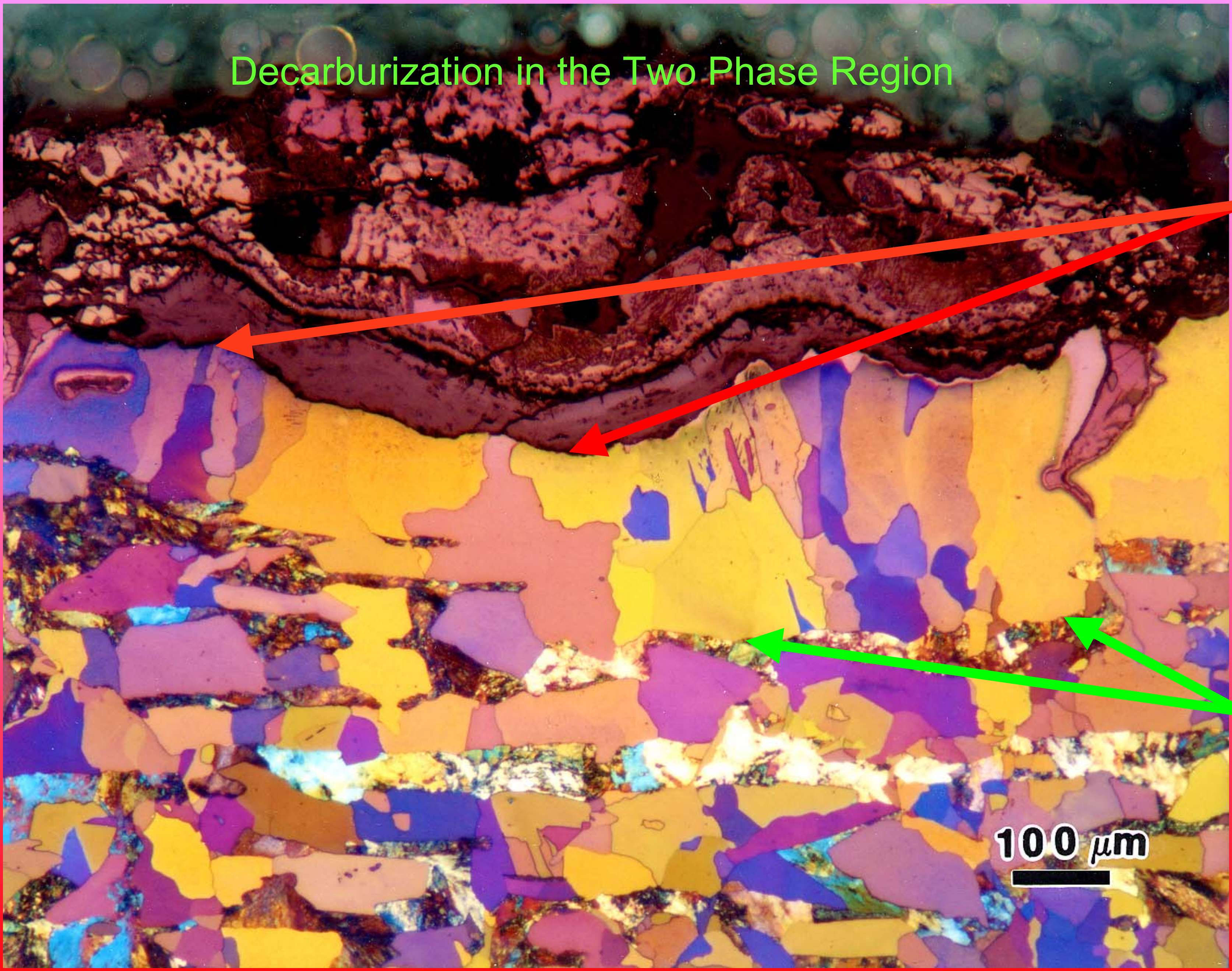
Iron – Iron Carbide Equilibrium Phase Diagram



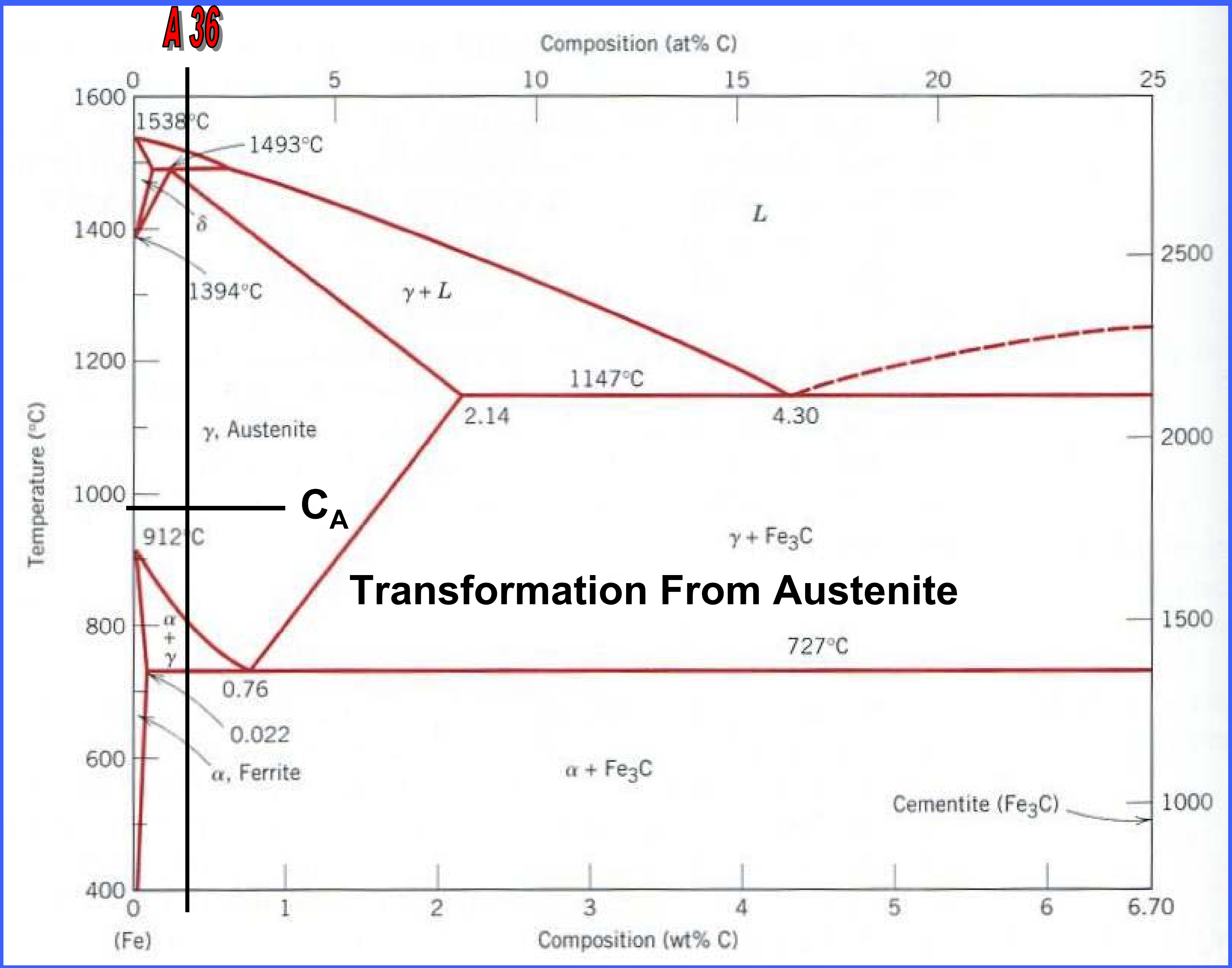

Schematic Isothermal Carbon Diffusion Profile
for the Two Phase Temperature Region in A36
Concentration
C_A
C_F
Distance From Reaction Surface

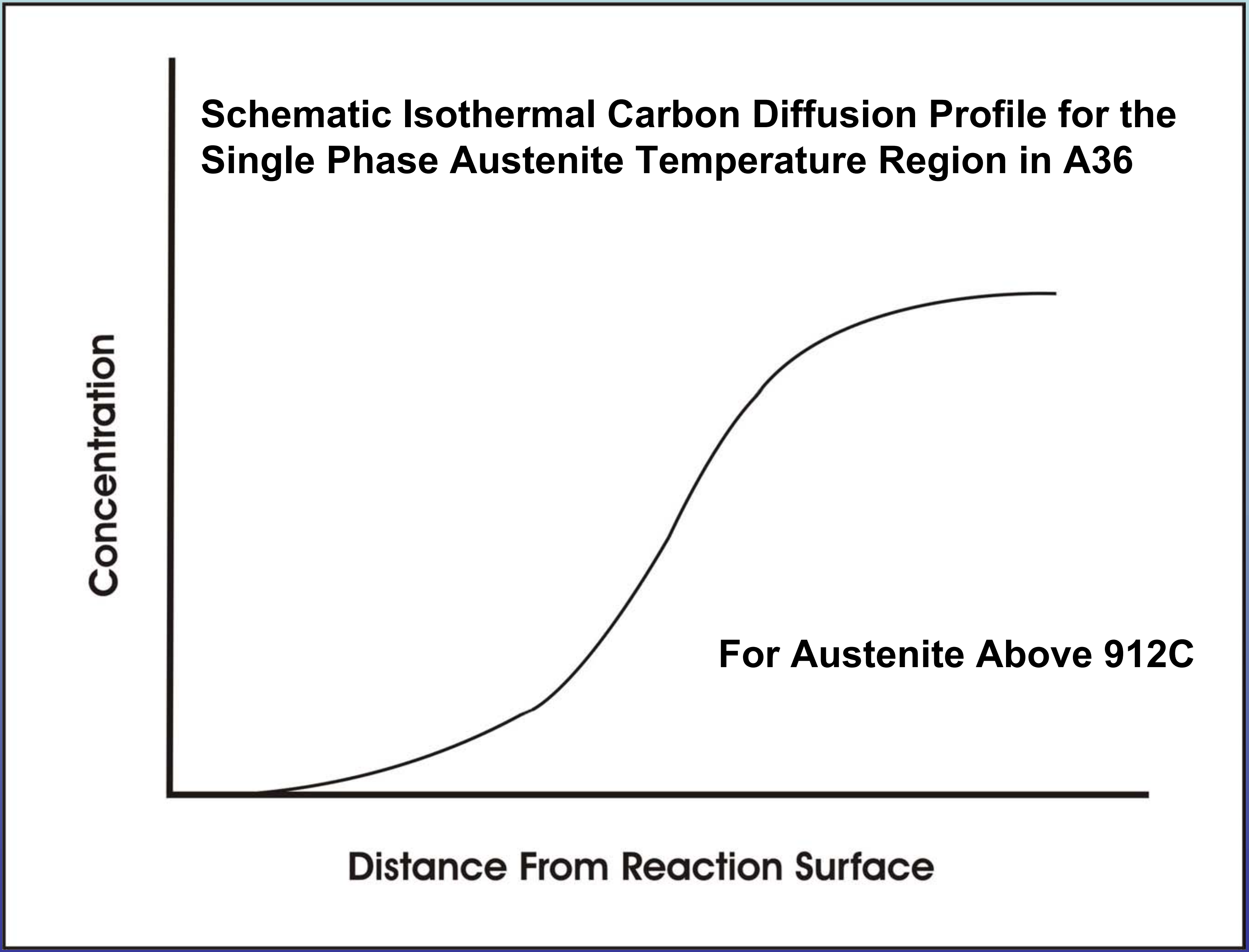
Schematic Isothermal Carbon Diffusion Profile for the Two Phase Temperature Region in A36

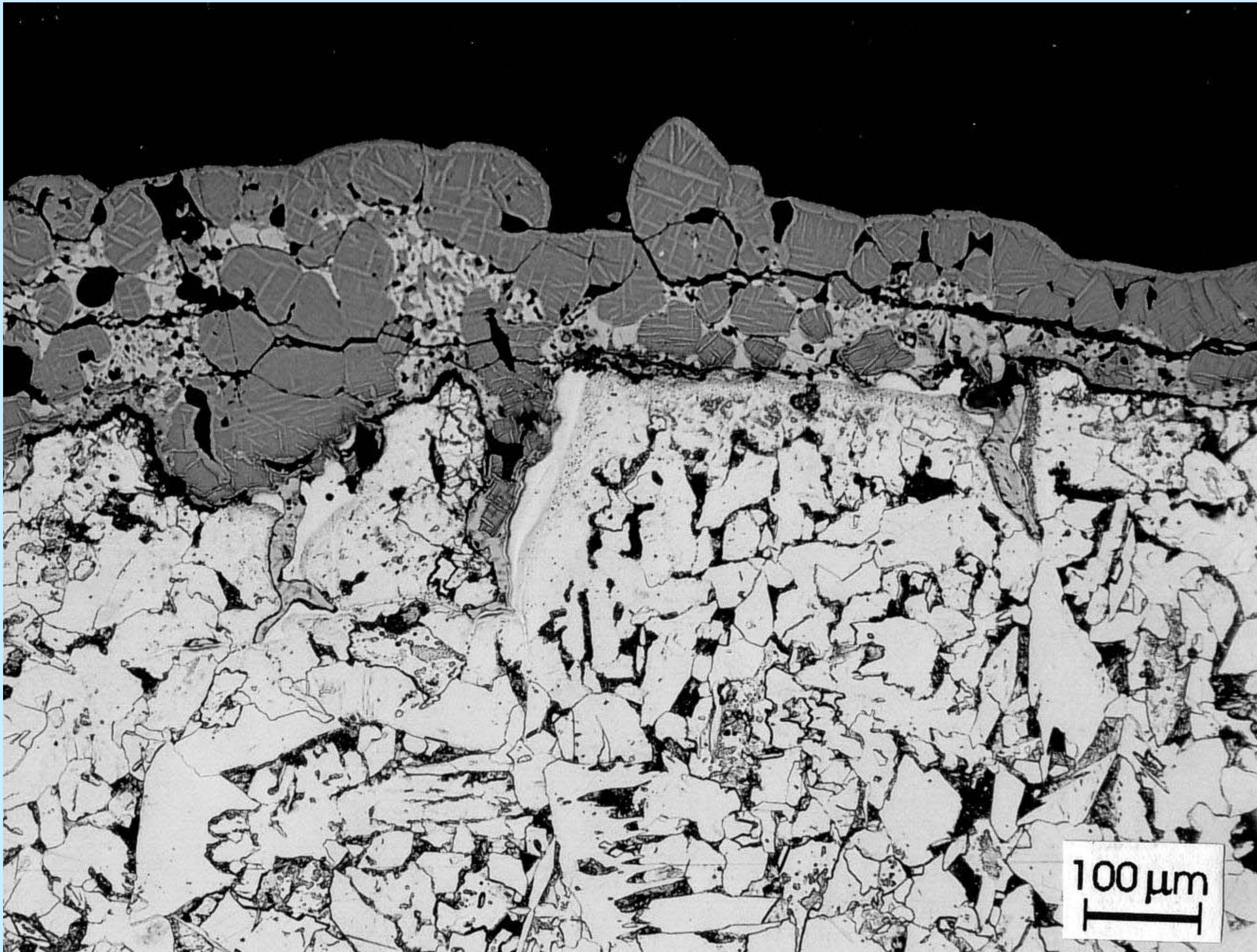



Decarburization in the Two Phase Region
C_F
C_A
100 µm

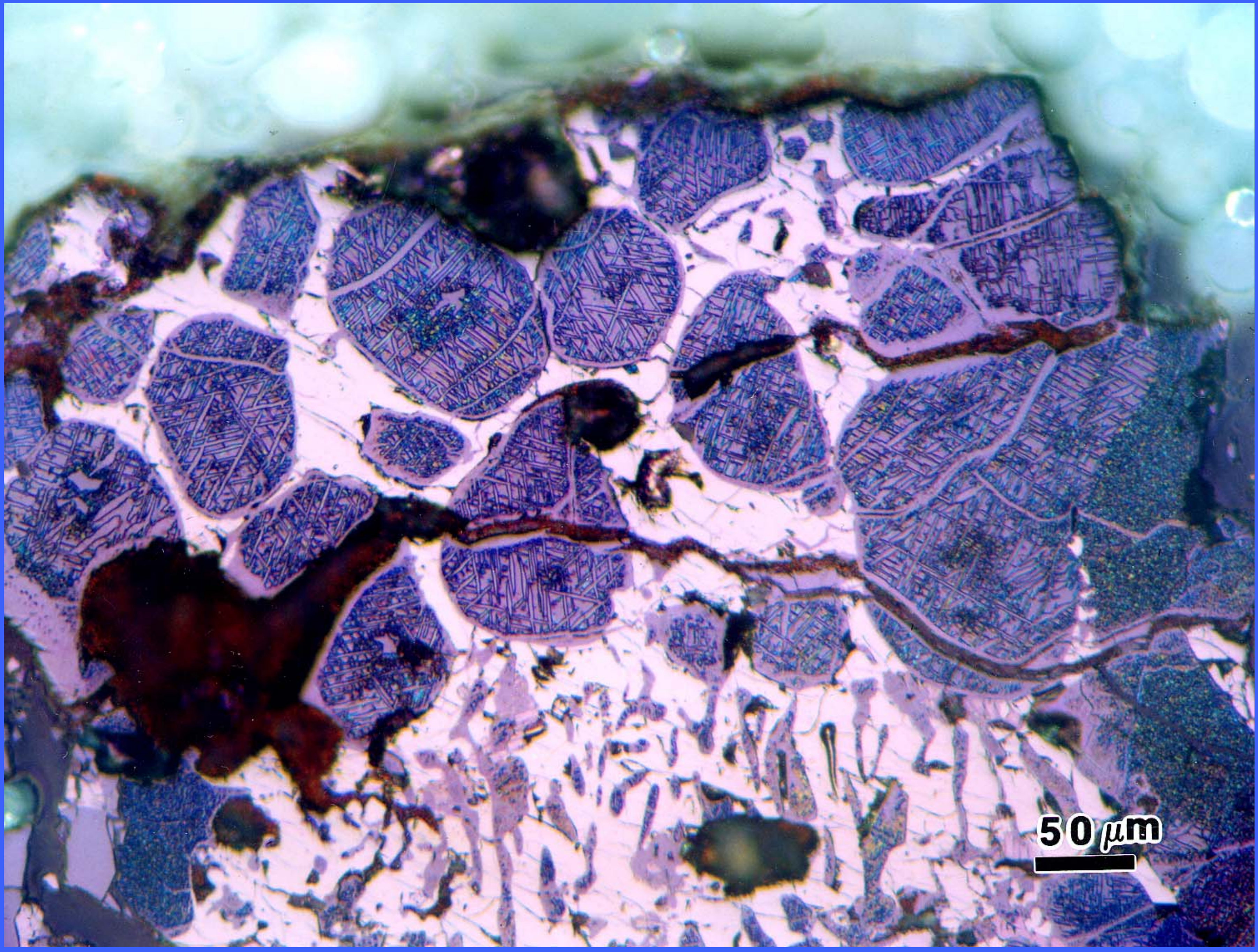
Iron – Iron Carbide Equilibrium Phase Diagram

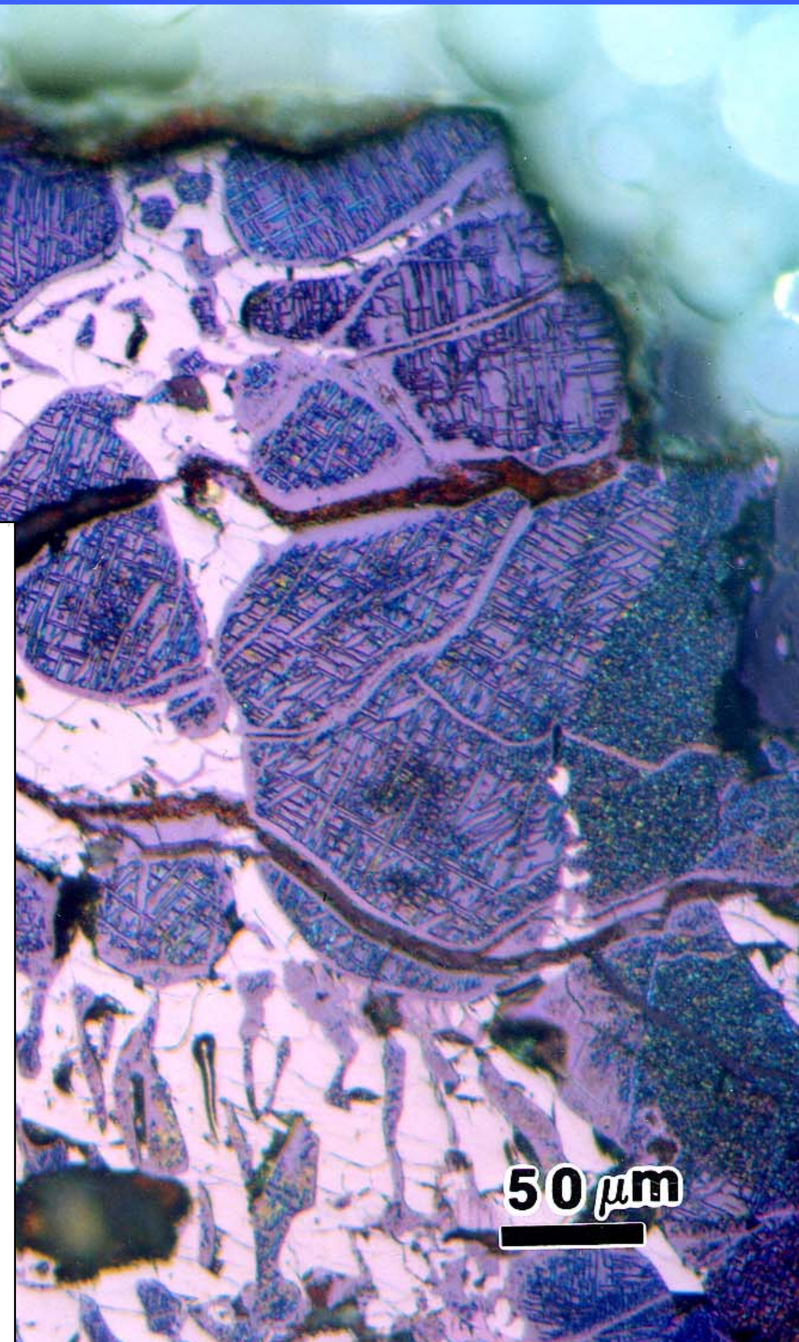



Schematic Isothermal Carbon Diffusion Profile for the Single Phase Austenite Temperature Region in A36
Concentration
For Austenite Above 912C
Distance From Reaction Surface

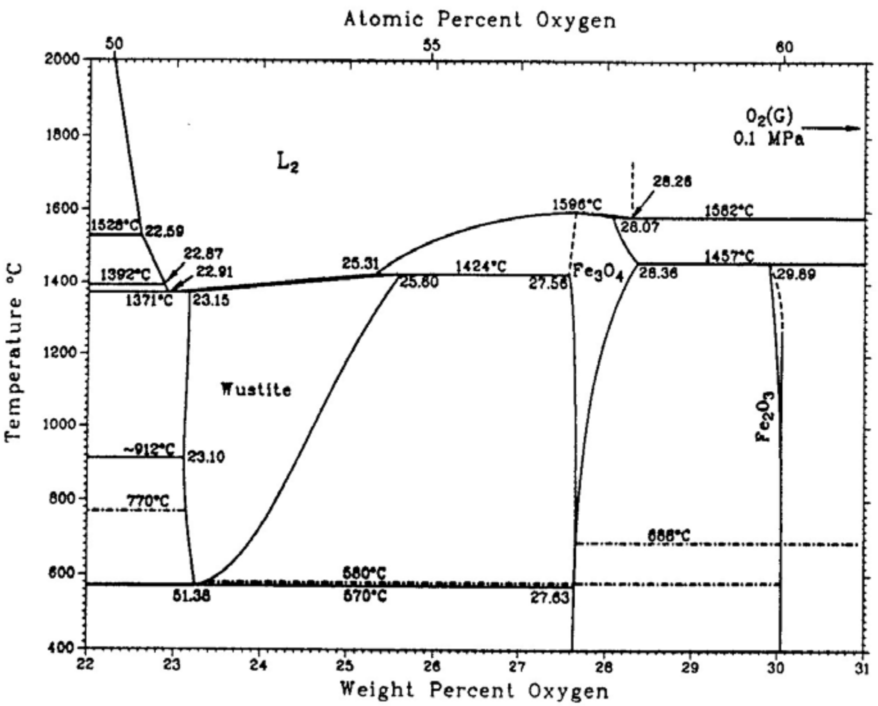


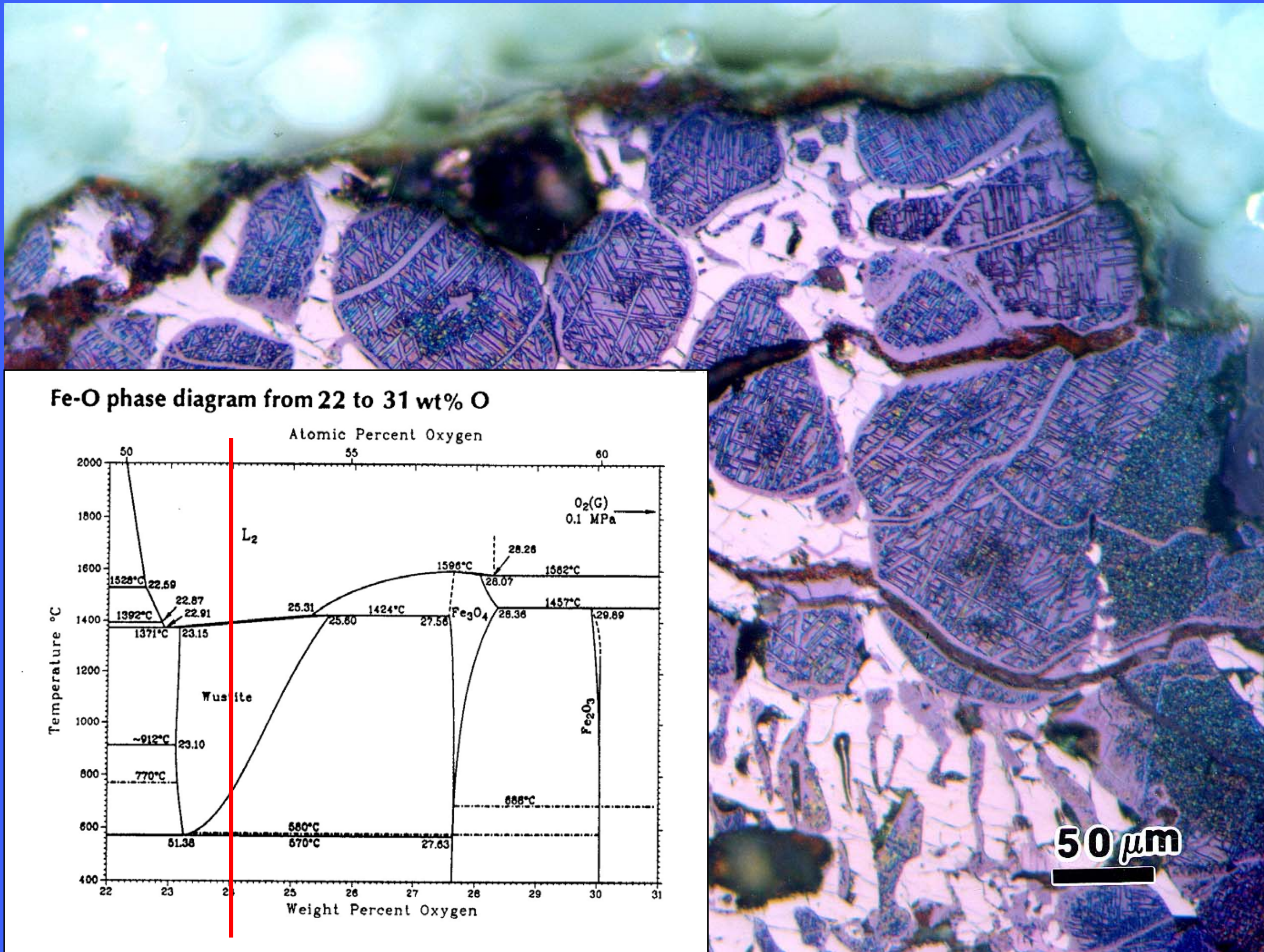
4% Nital Etch


50 μm



Fe-O phase diagram from 22 to 31 wt% O




50 μm
Fe-O phase diagram from 22 to 31 wt% O
Atomic Percent Oxygen
50
55
60
Temperature °C
2000
1800
1600
1400
1200
1000
800
600
400
$O_2(G)$
0.1 MPa
L_2
28.26
1596°C
1582°C
1528°C
22.59
28.07
22.87
22.91
25.31
1424°C
1457°C
1392°C
25.60
27.56
Fe_3O_4
28.36
29.89
1371°C
23.15
Wustite
Fe_2O_3
~912°C
23.10
770°C
686°C
560°C
570°C
51.38
27.63
22
23
24
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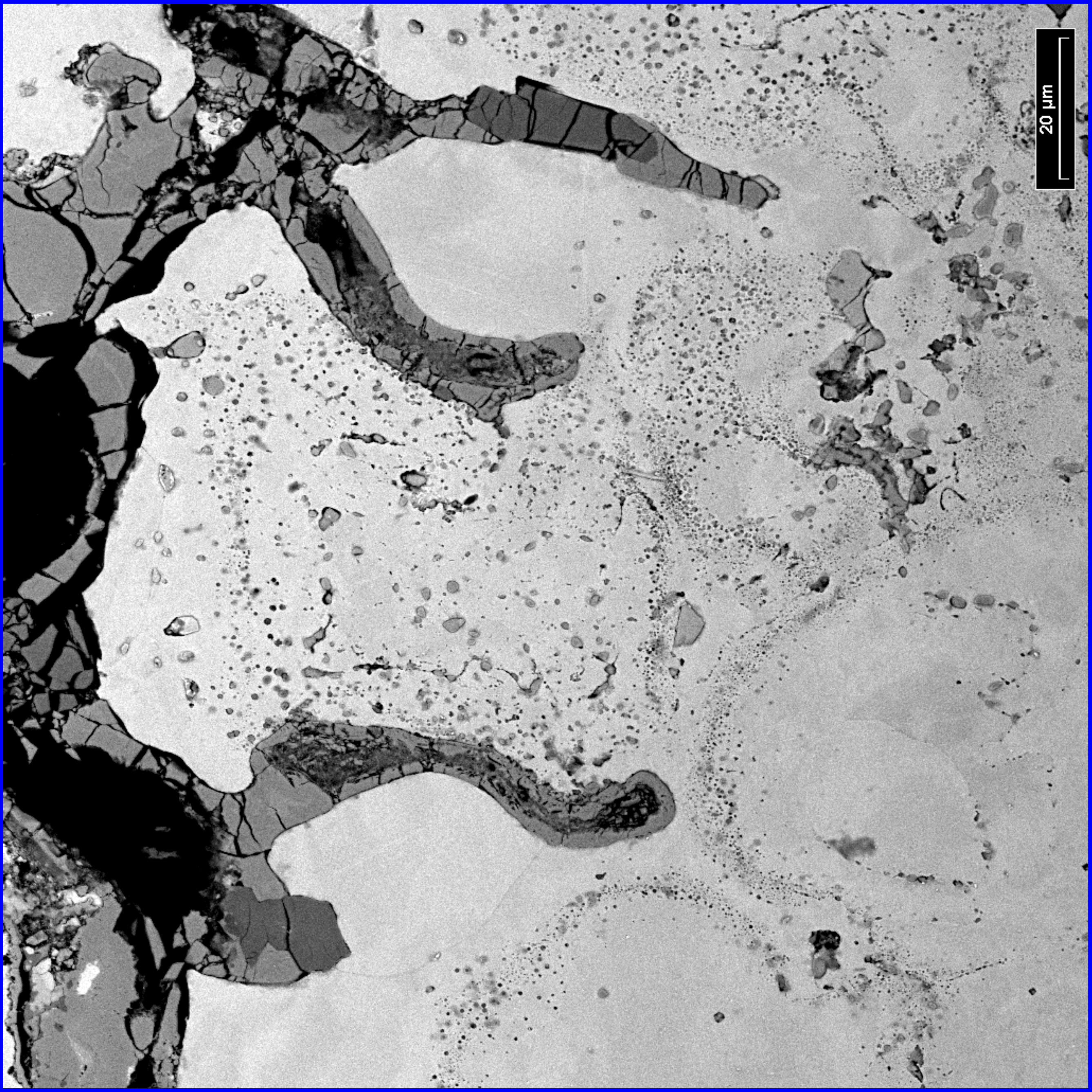
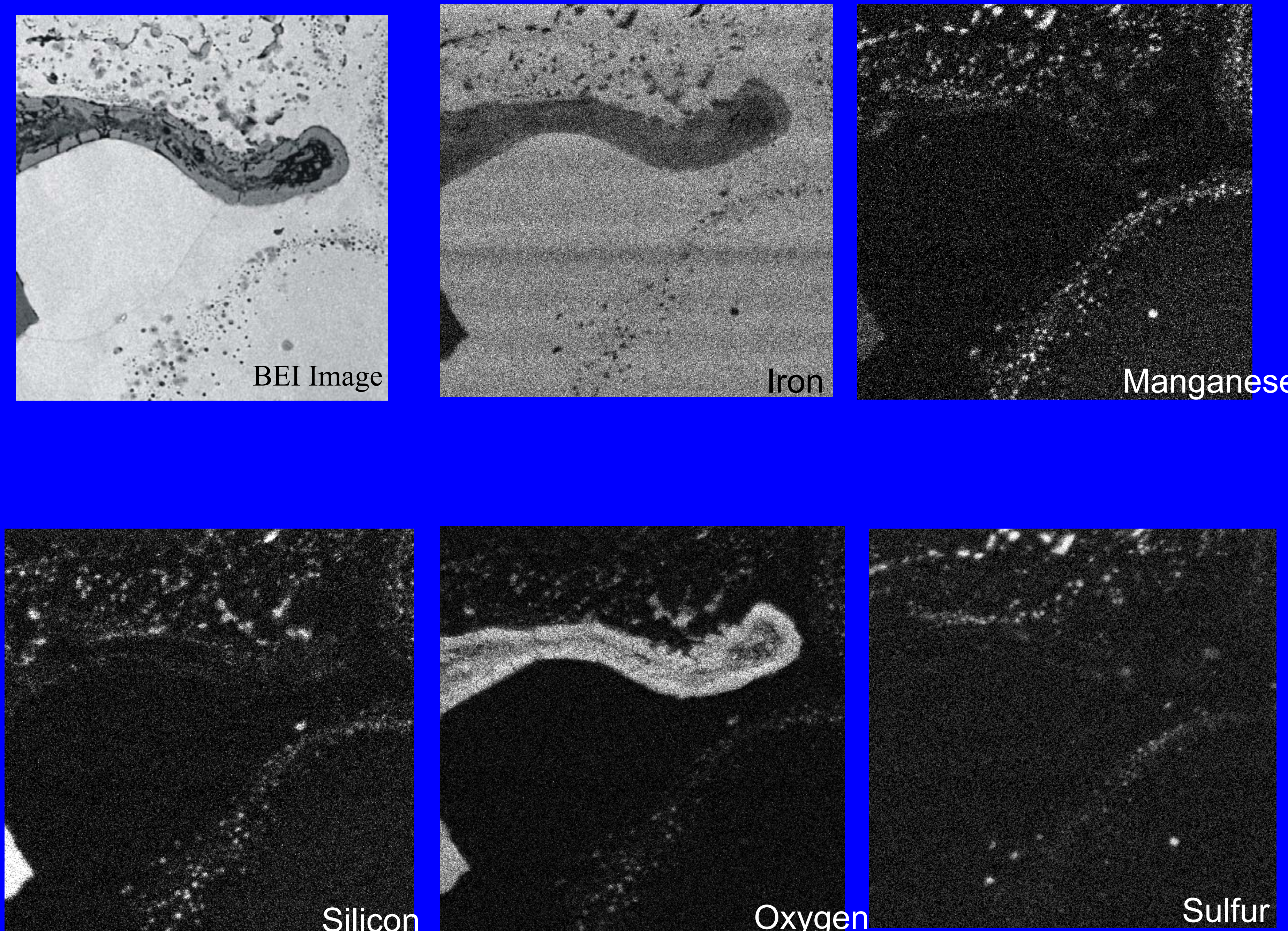
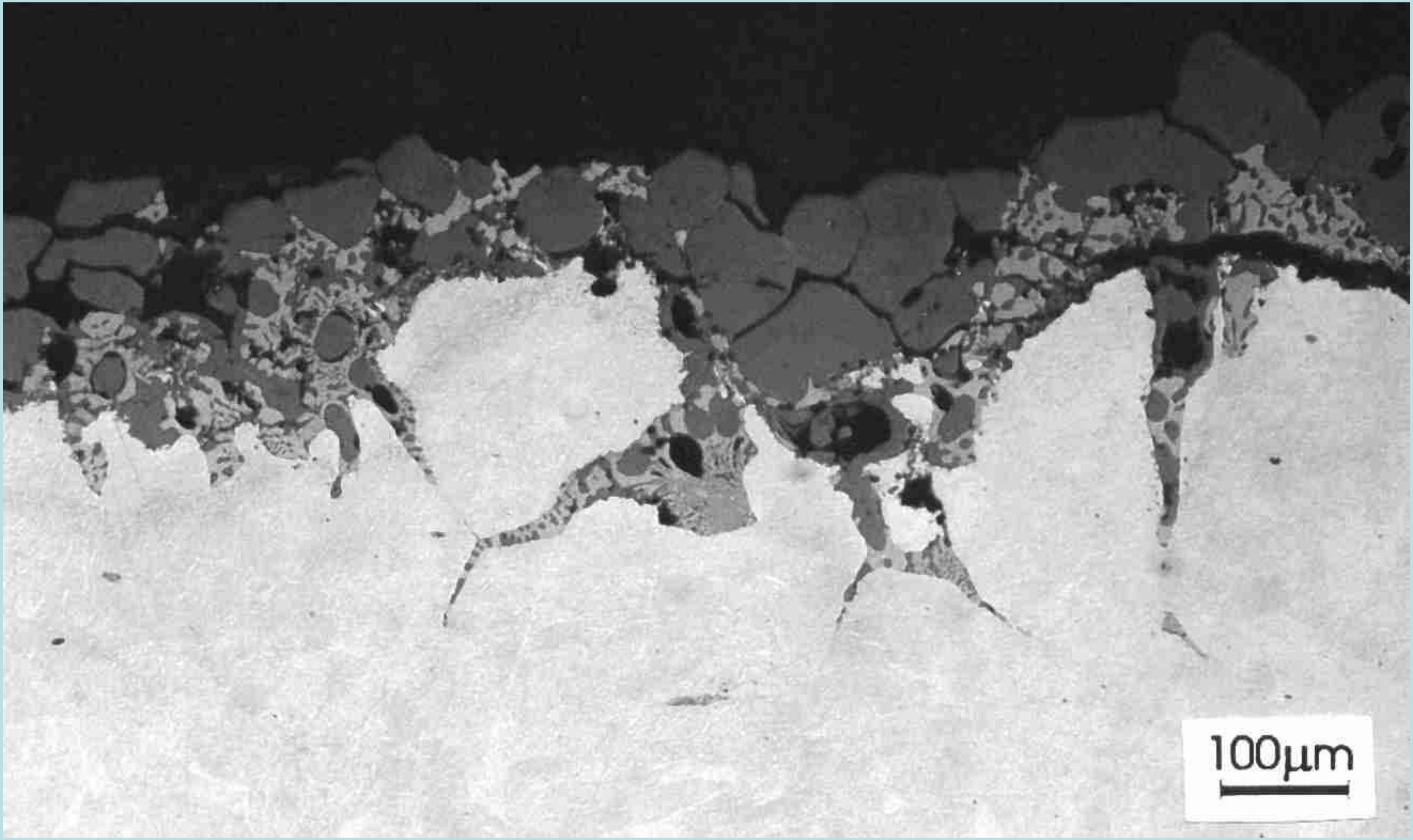
28
29
30
31
Weight Percent Oxygen

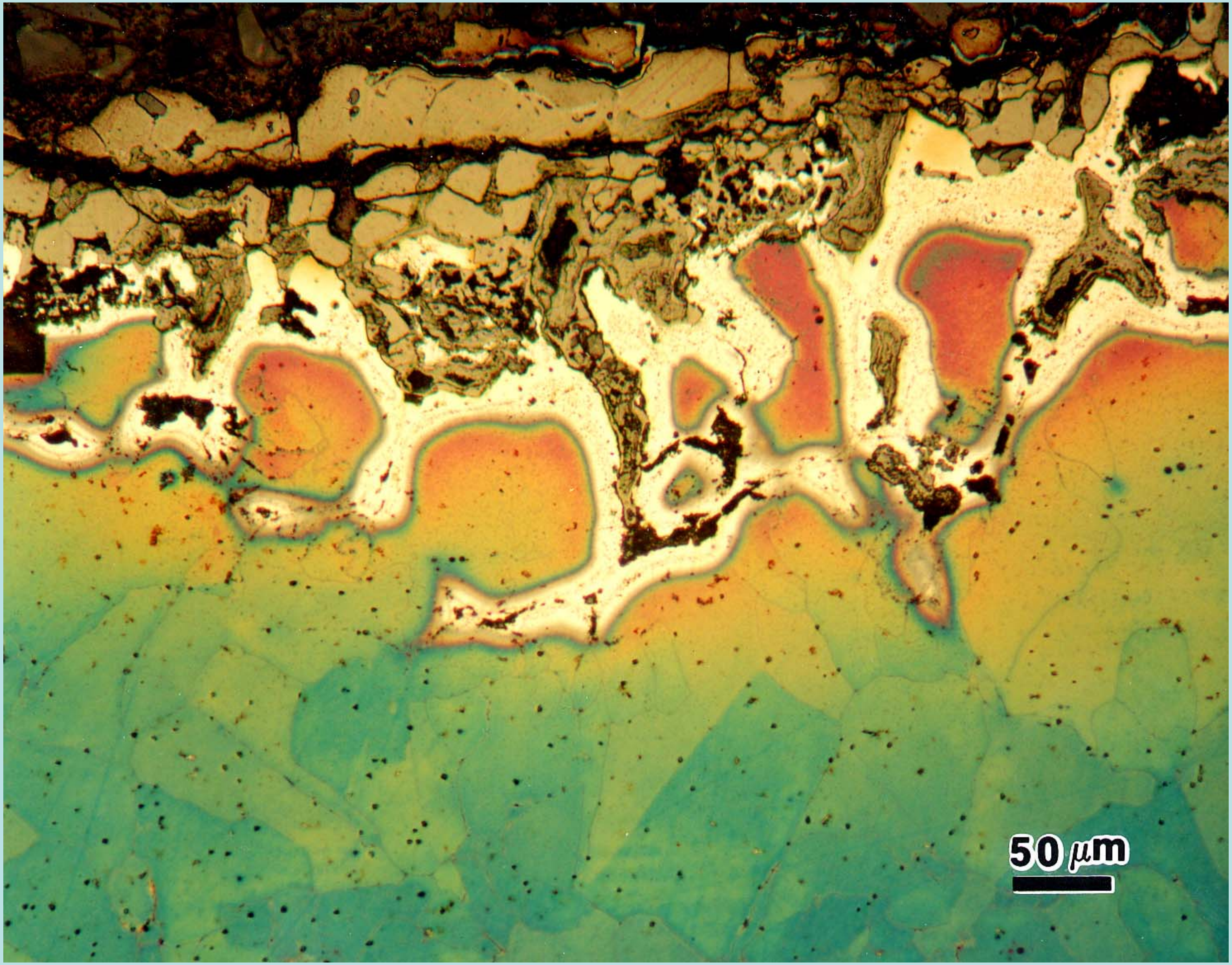

20 µm


BEI Image
Iron
Manganese
Silicon
Oxygen
Sulfur

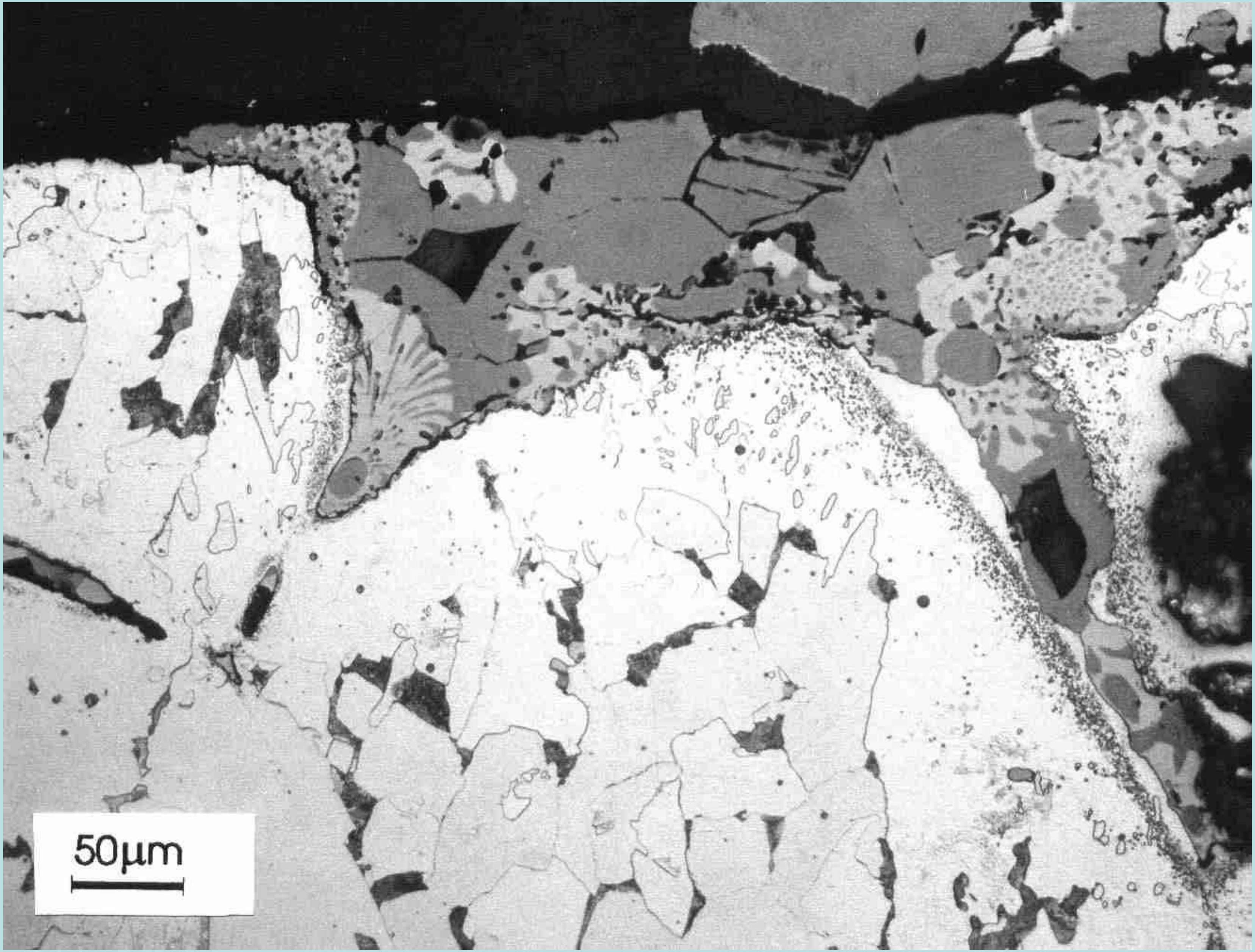
Oxidation and Intergranular Attack



Unetched

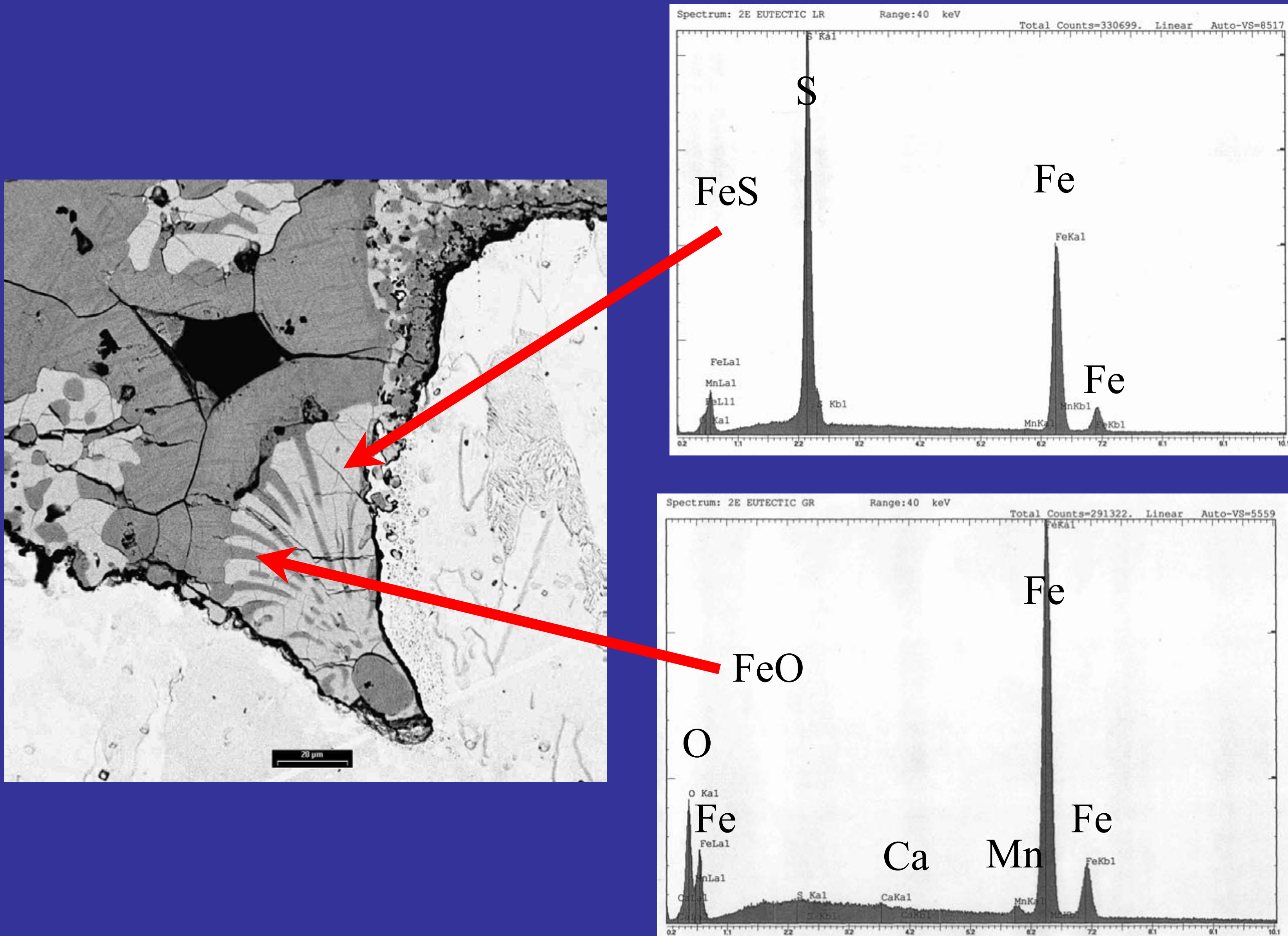


Oxygen-enrichment detection using Fine's alkaline chromate hot etch

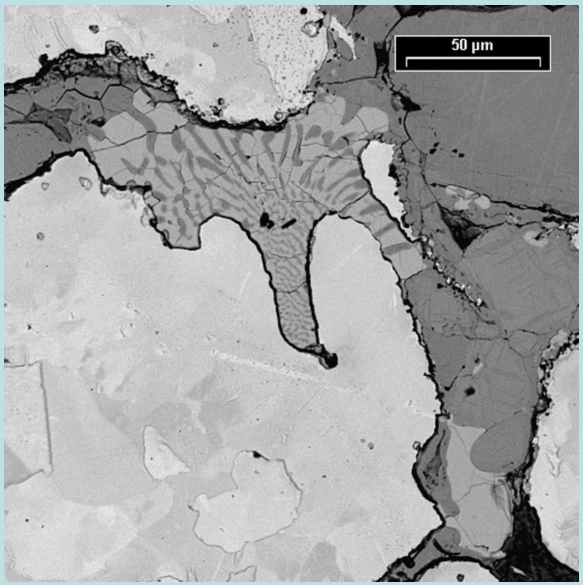


4%Nital Etch

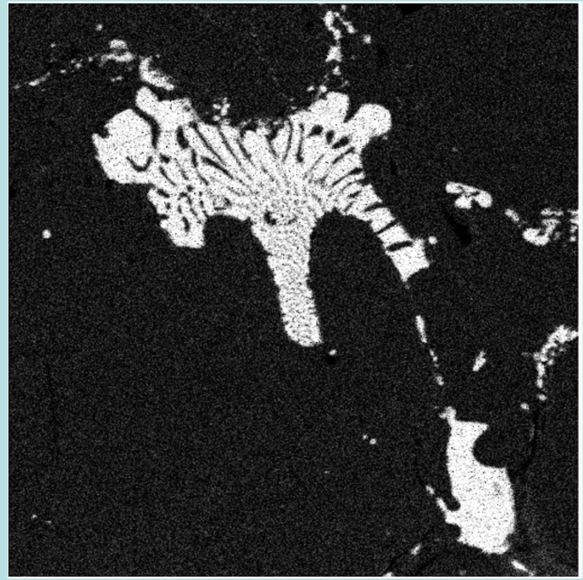
EDX Analysis of Eutectic Region



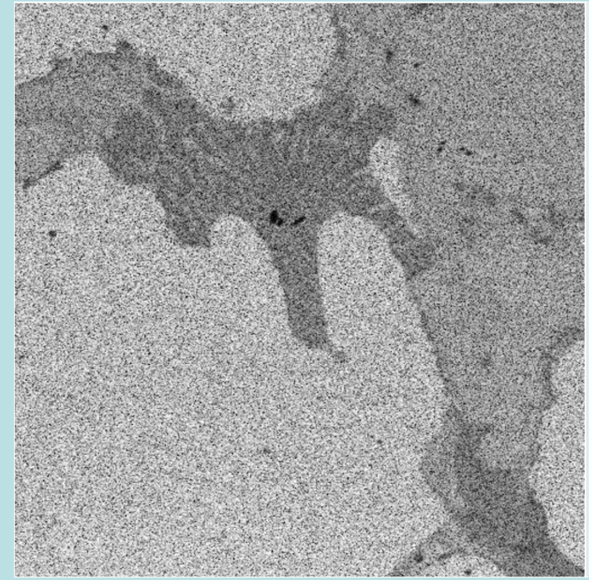
Digital X-Ray Map of the Eutectic Reaction Product



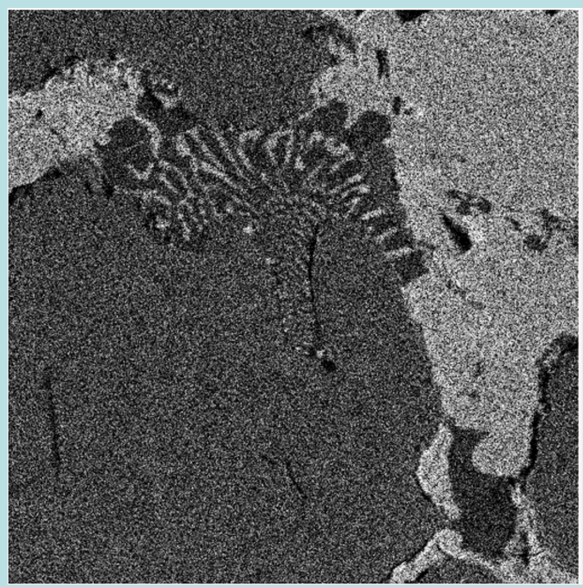
Image



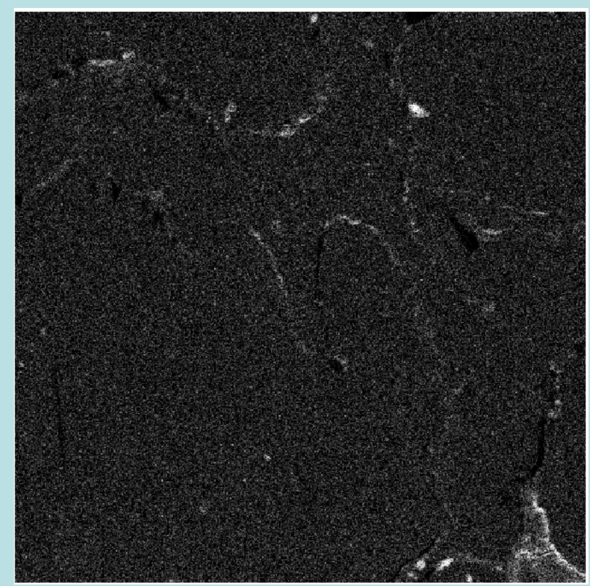
S



Fe

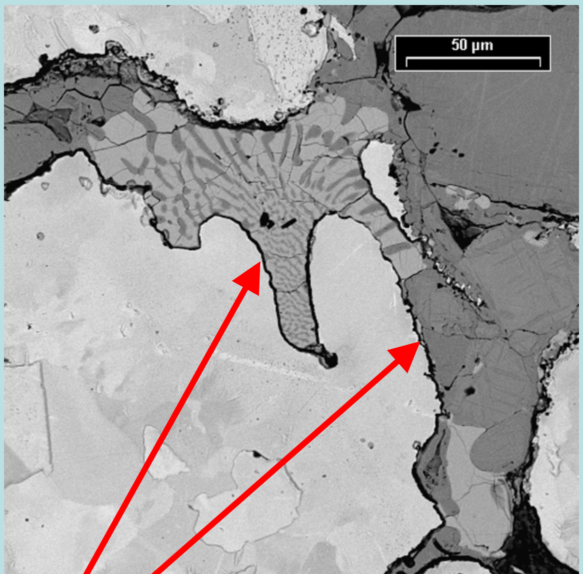


O



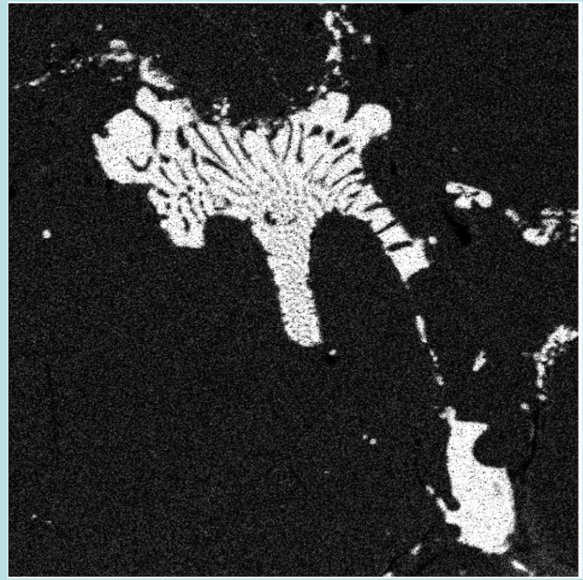
Si

Digital X-Ray Map of the Eutectic Reaction Product



Image

Carbon, Silicon and Sulfur are Segregated at Interfaces



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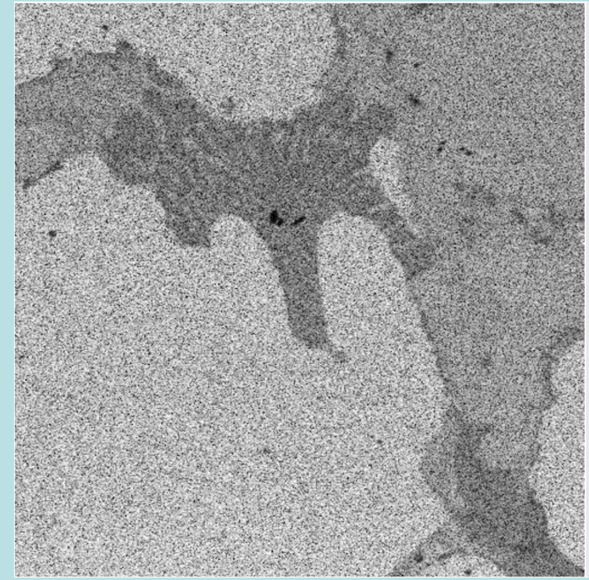
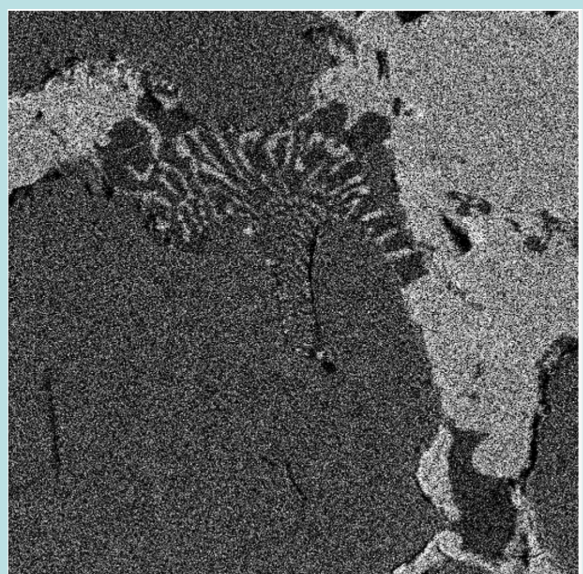
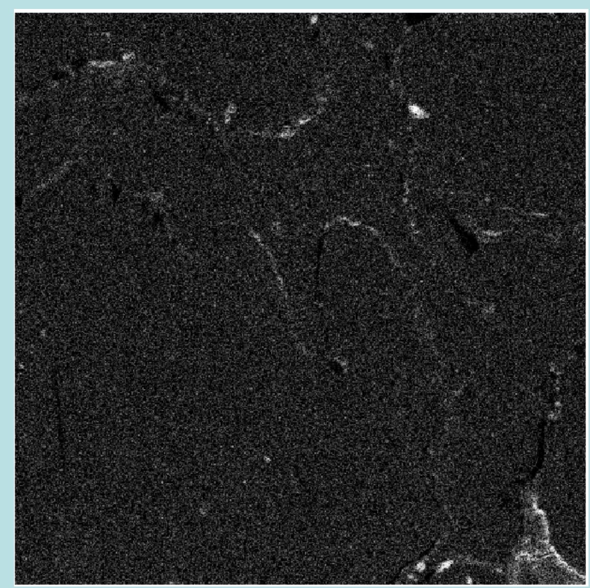


Fe

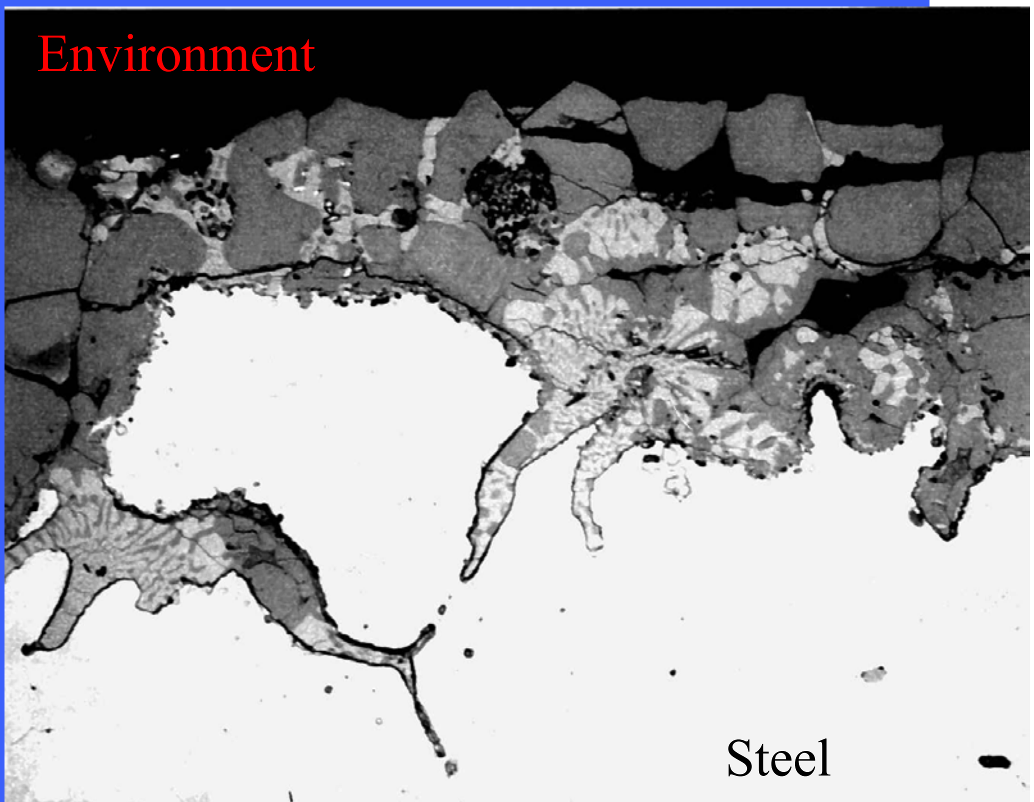


O



Si

Analysis



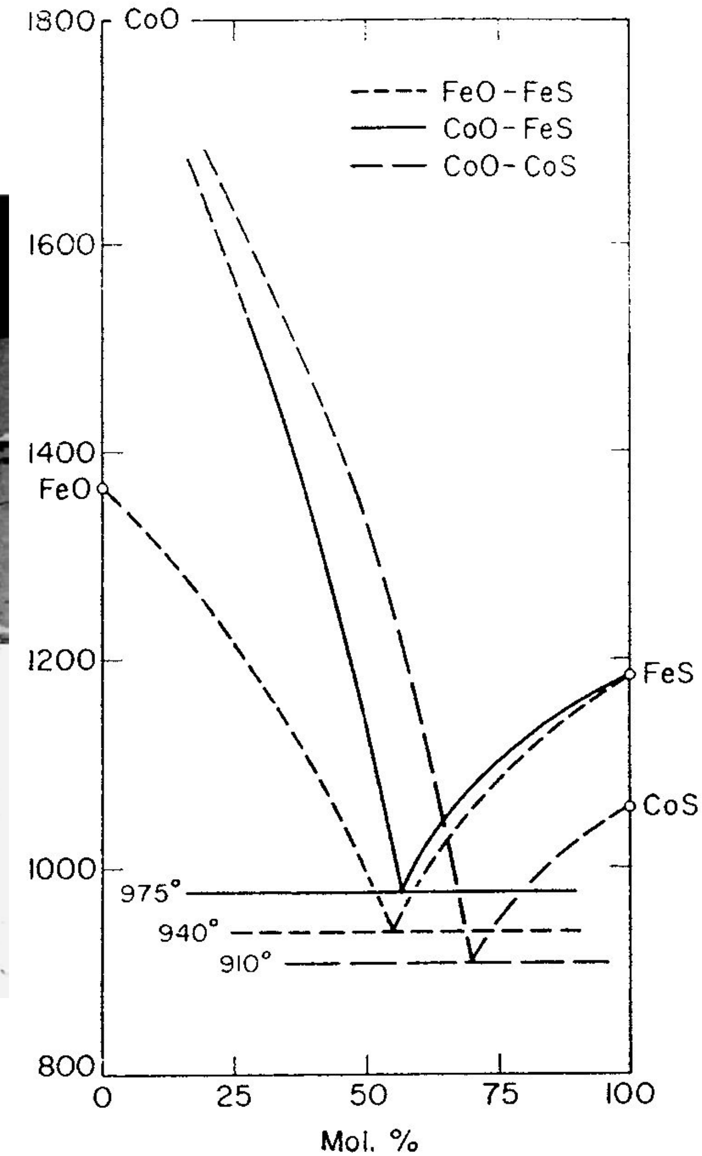
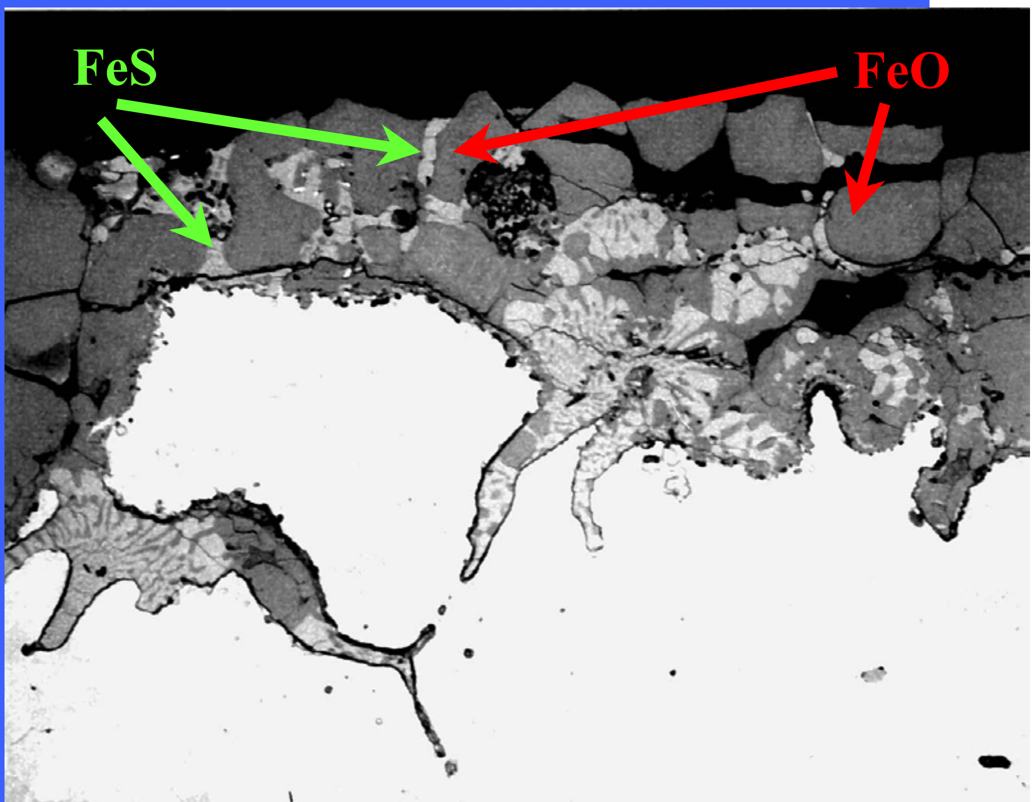


FIG. **720.**—Liquidus curves of systems FeO–FeS, CoO–FeS, CoO–CoS.

P. Asanti and E. J. Kohlmeyer, *Z. anorg. chem.*, **265,** 94 (1951).

Analysis



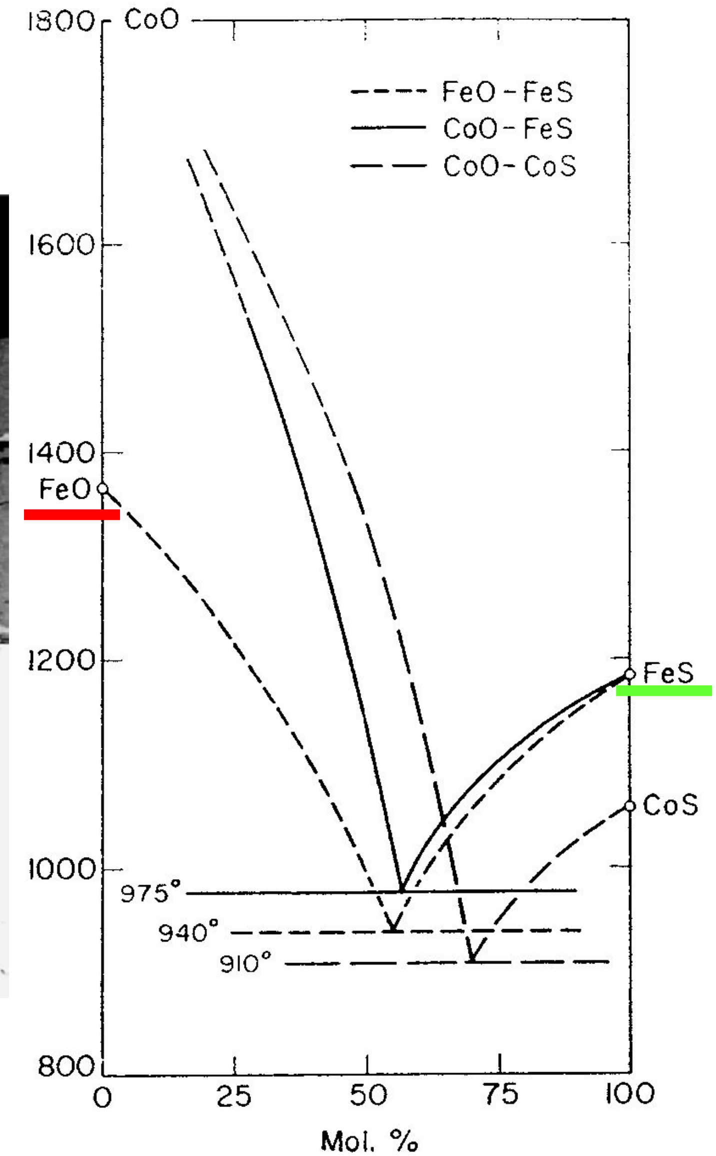
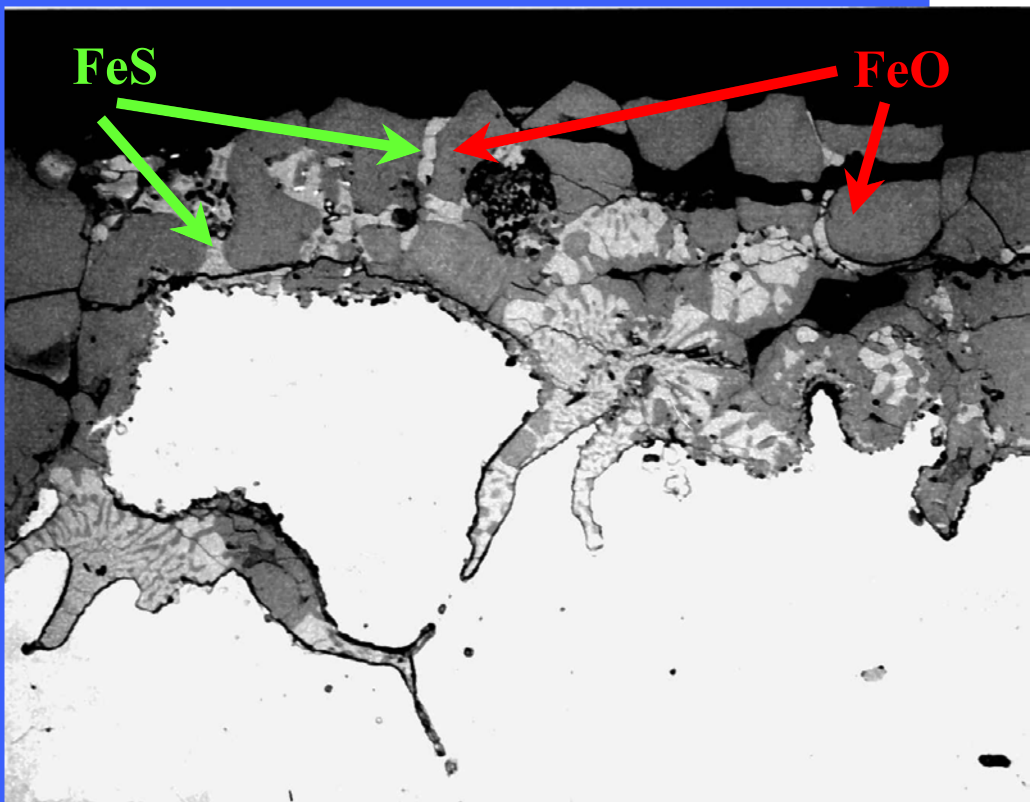


FIG. 720.—Liquidus curves of systems FeO–FeS, CoO–FeS, CoO–CoS.

P. Asanti and E. J. Kohlmeyer, *Z. anorg. chem.*, 265, 94 (1951).

Analysis



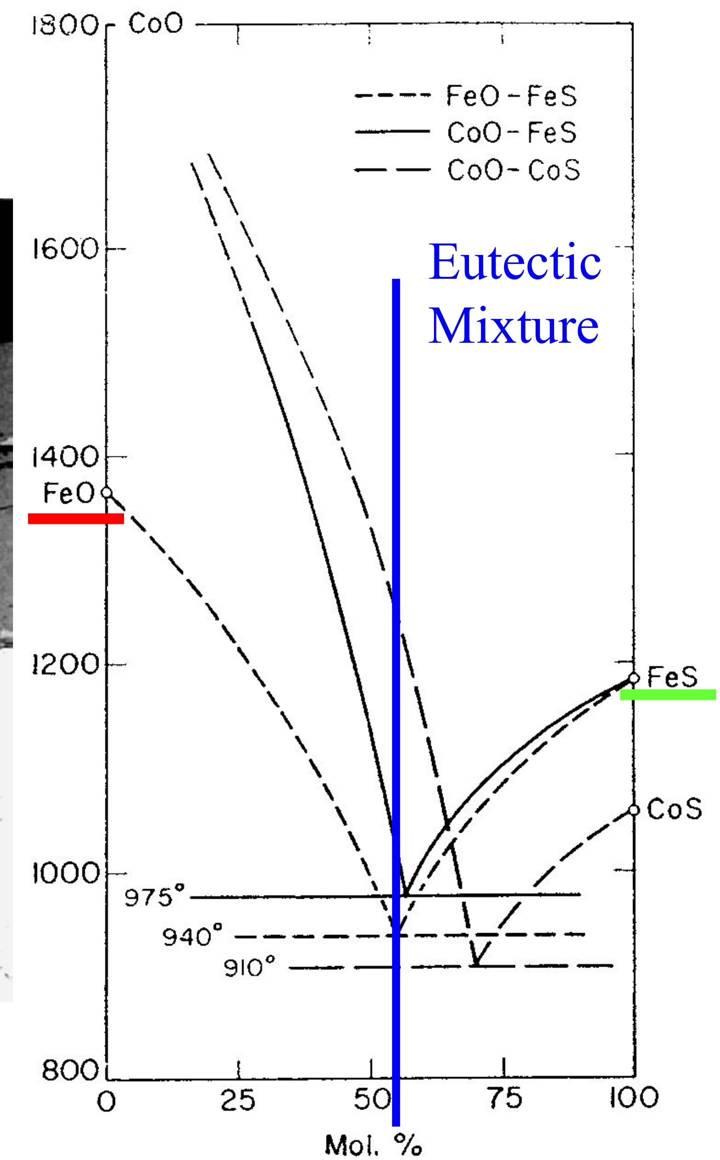


FIG. 720.—Liquidus curves of systems FeO–FeS, CoO–FeS, CoO–CoS.

P. Asanti and E. J. Kohlmeyer, *Z. anorg. chem.*, 265, 94 (1951).

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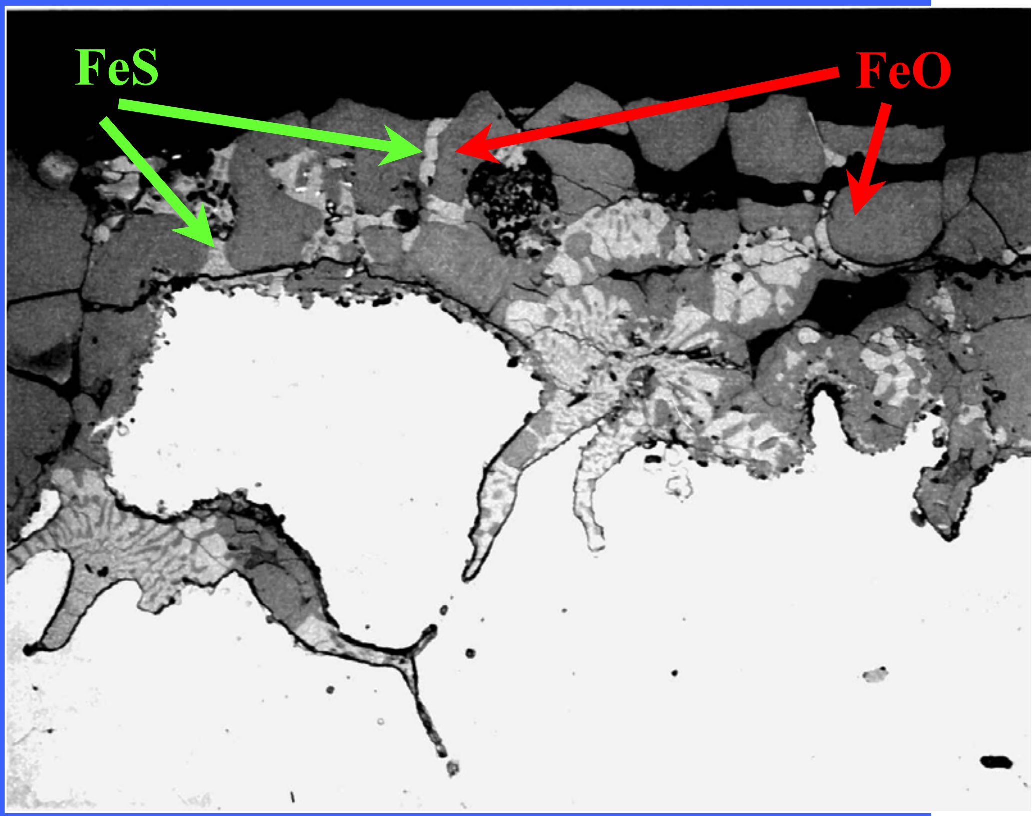

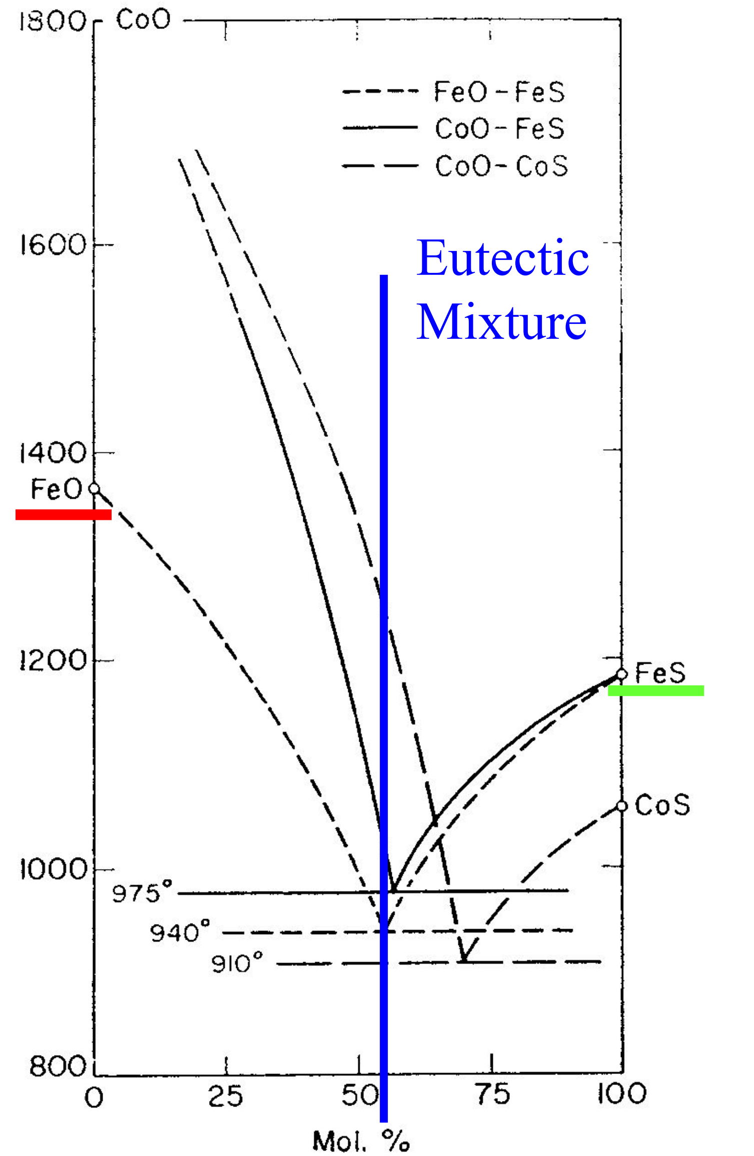

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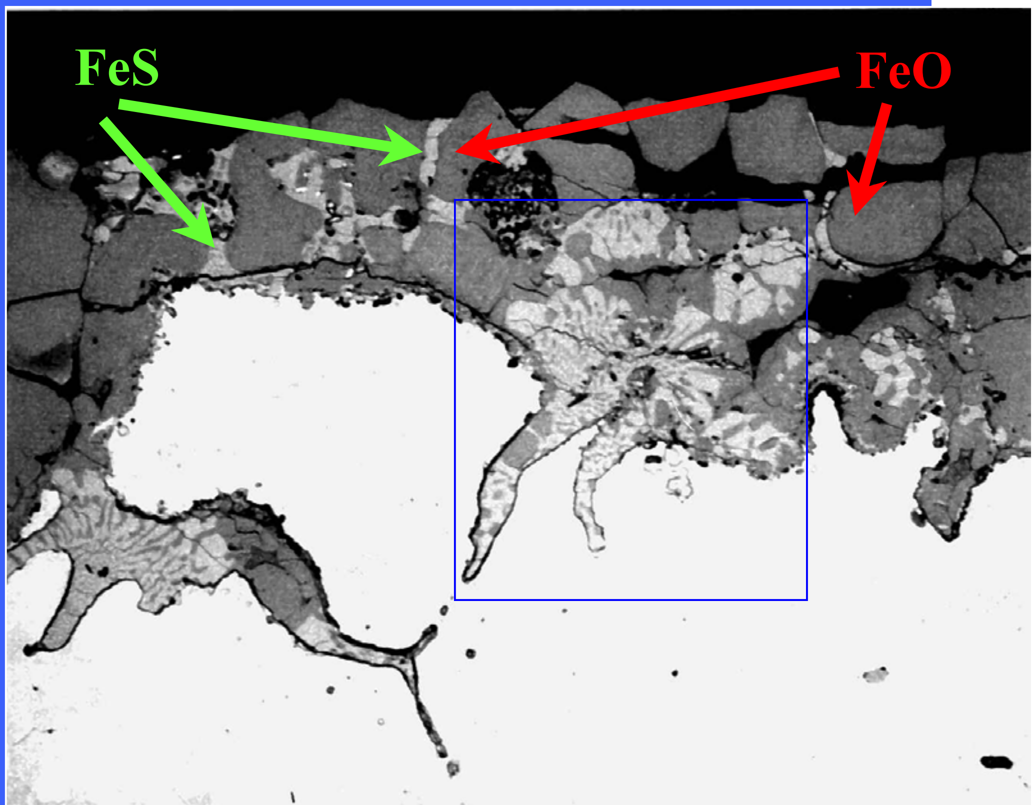
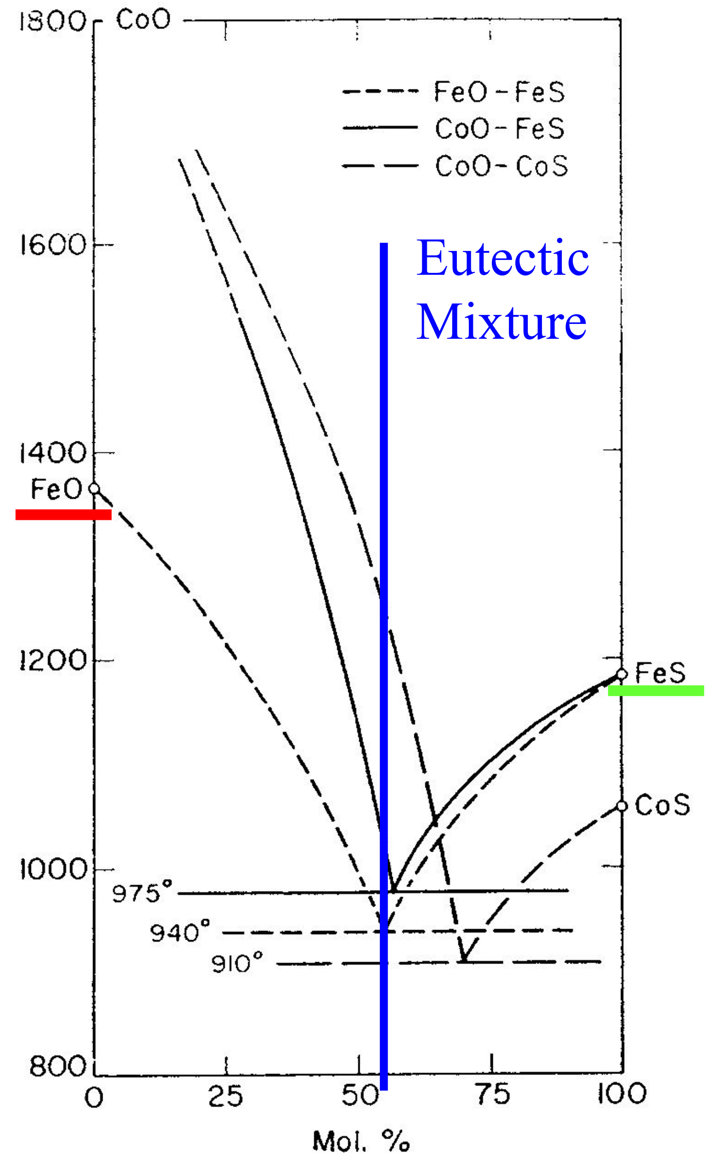
Liquid $\rightleftarrows$ FeO + FeS

940C

Analysis





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2. Heating in an environment containing oxygen and sulfur resulted in intergranular melting which transformed to an Iron Oxide and Iron Sulfide eutectic mixture on cooling .

3. The reaction that results in the formation of this eutectic lowers the temperature at which liquid can form in this steel to about 940C or lower depending on Silicon and Carbon effects at the reaction interfaces.

Where did the Sulfur come from?

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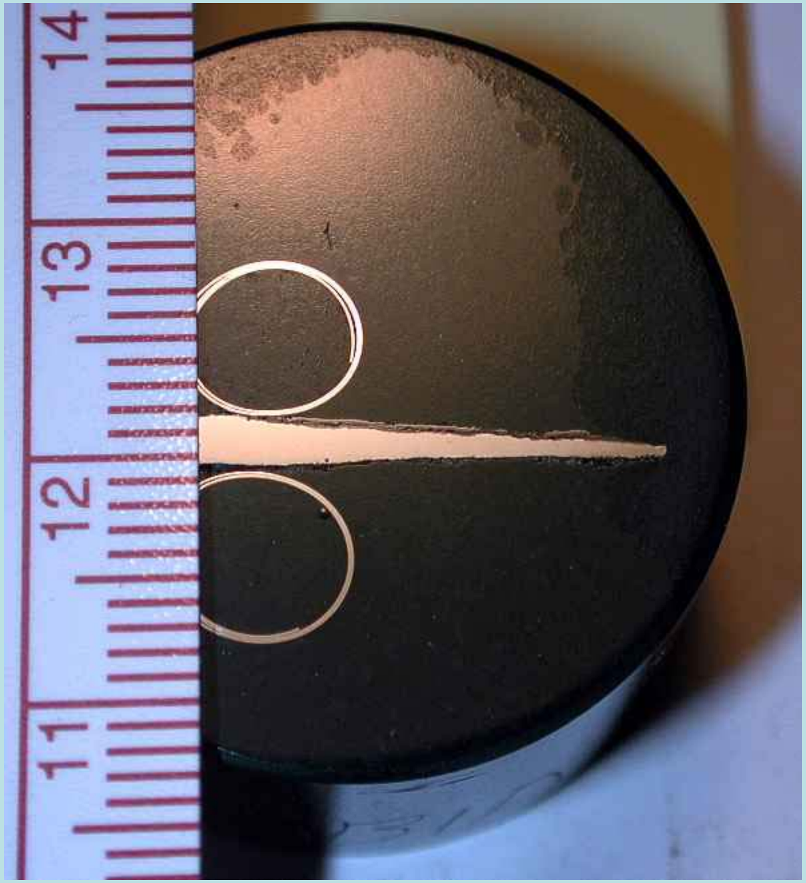
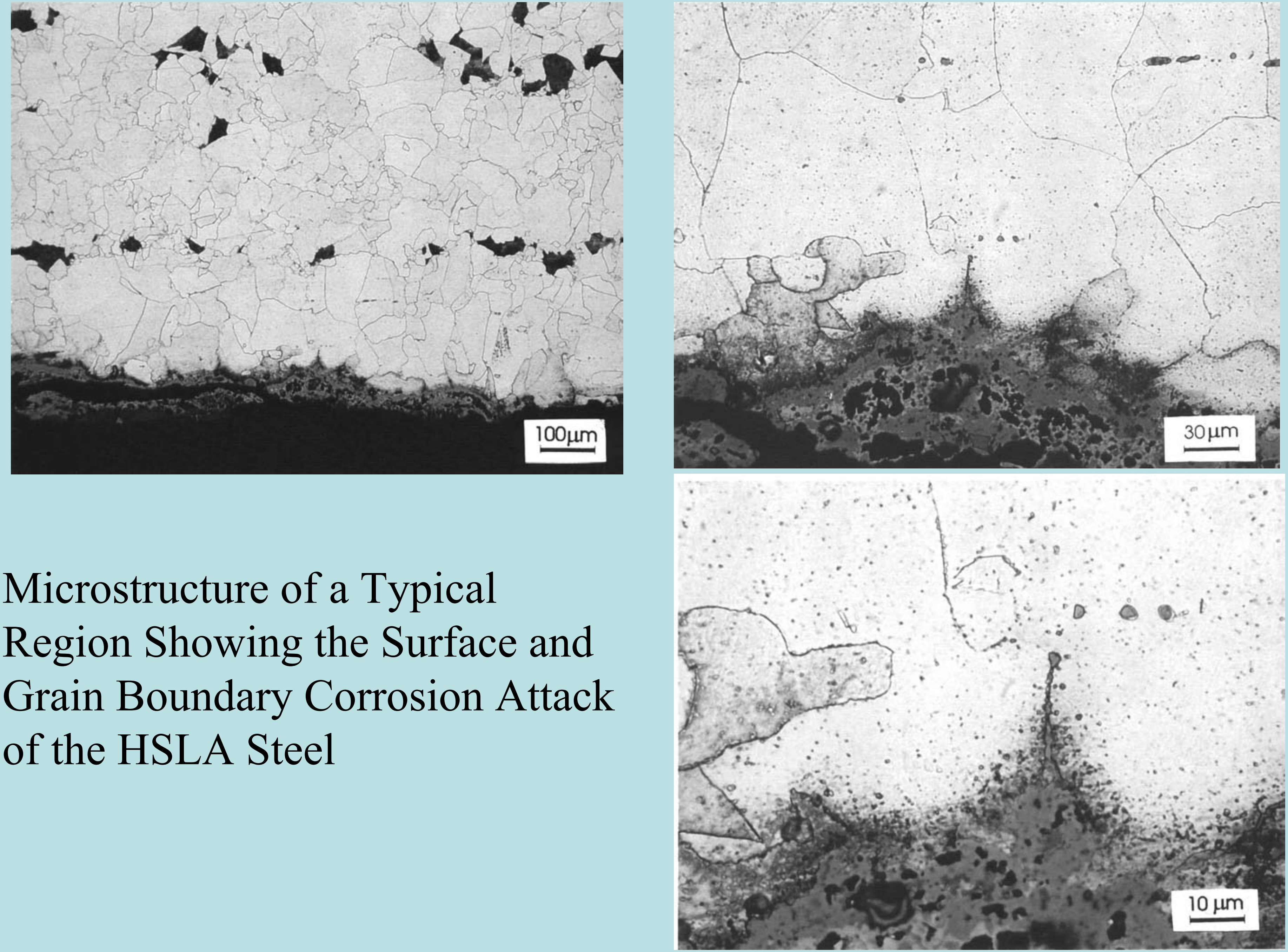
Did a similar deterioriation occur in steel from WTS 1 or WTS 2 ?

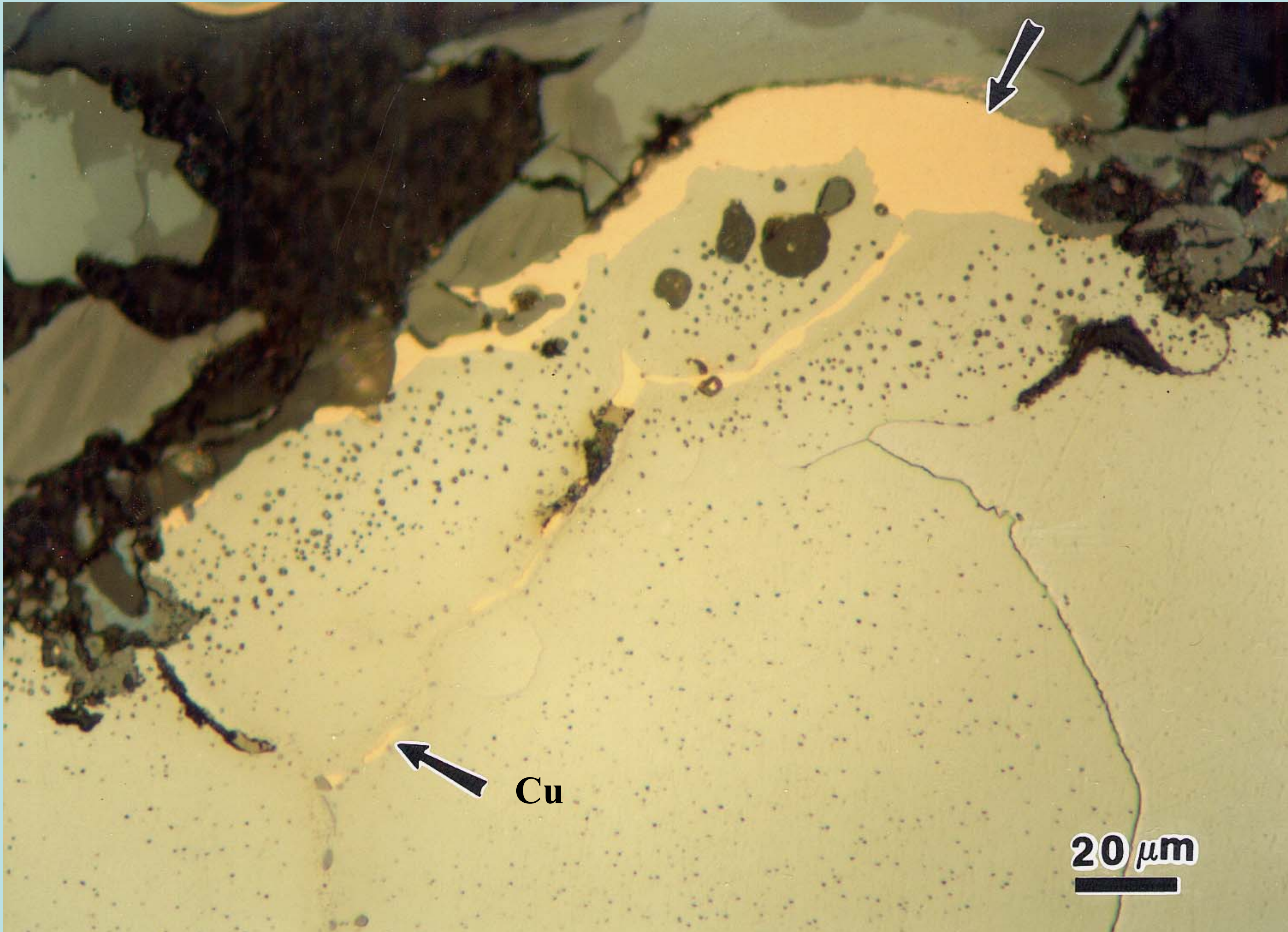
A Section from a HSLA steel Column thought to be from either WTC building 1 or 2.

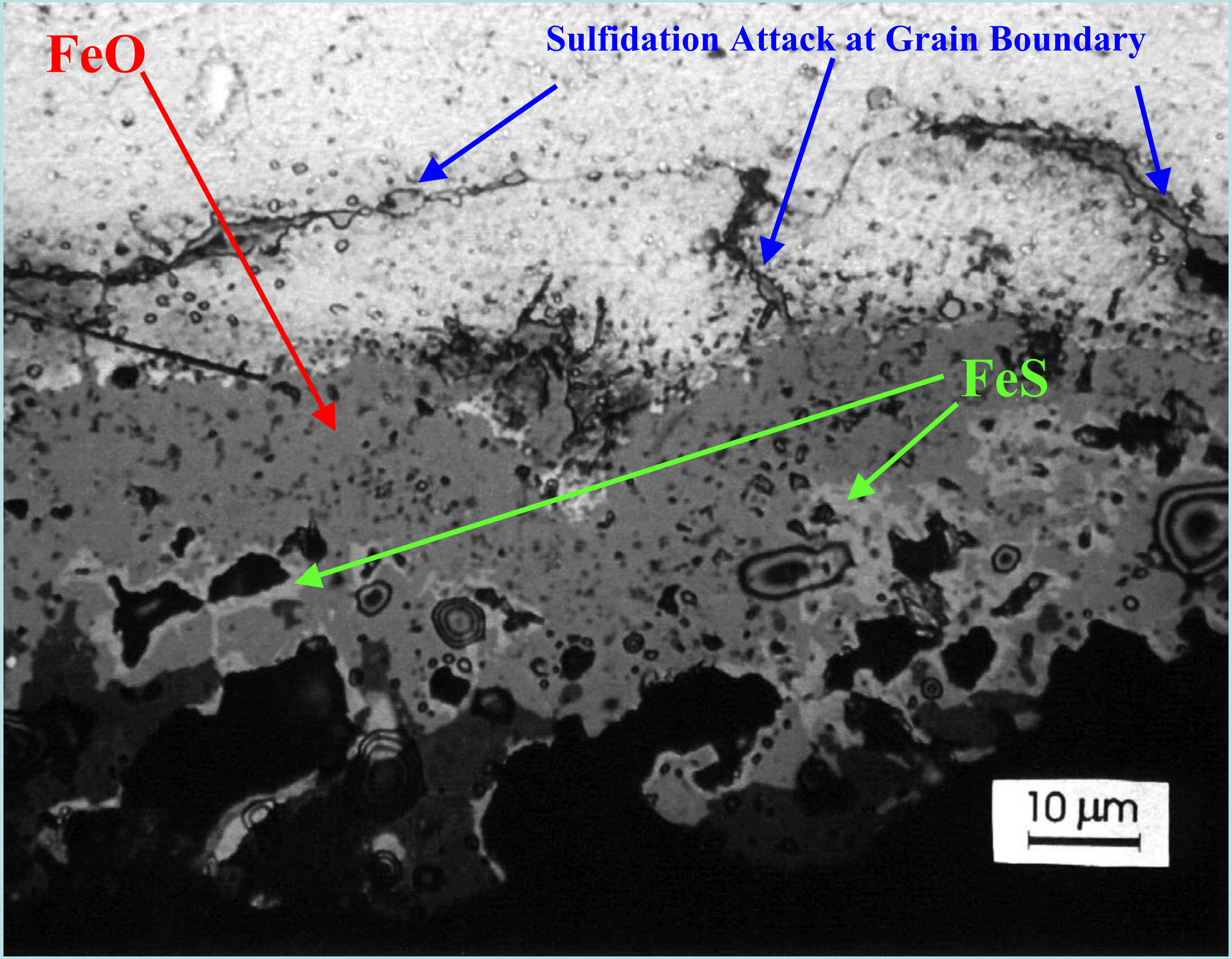


Column Section Showing Region with Severe Thinning



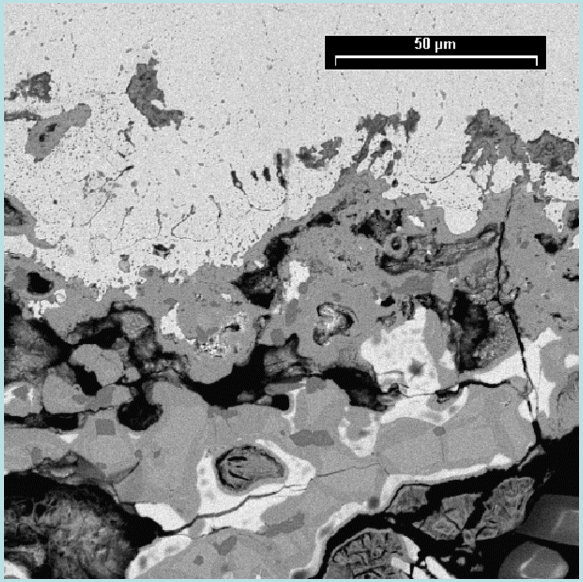
Microstructure of a Typical Region Showing the Surface and Grain Boundary Corrosion Attack of the HSLA Steel


Cu
20 μm

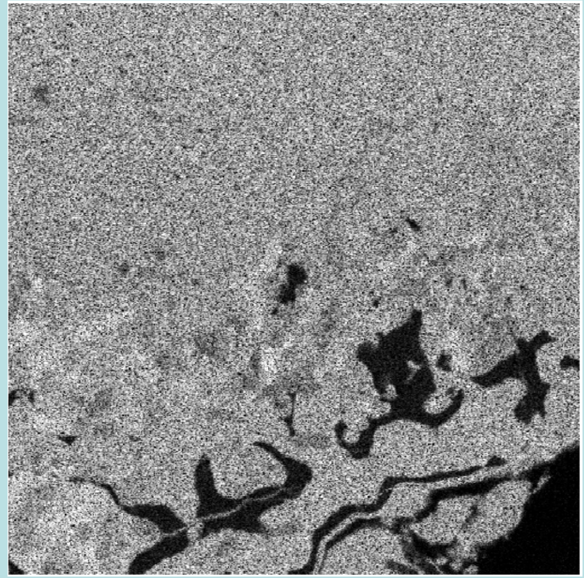


Etch with 4% Nital

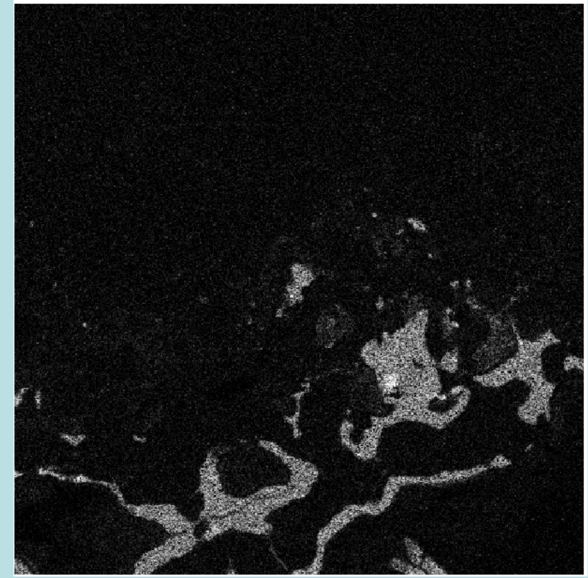
Higher Magnification of the Surface Reaction Region



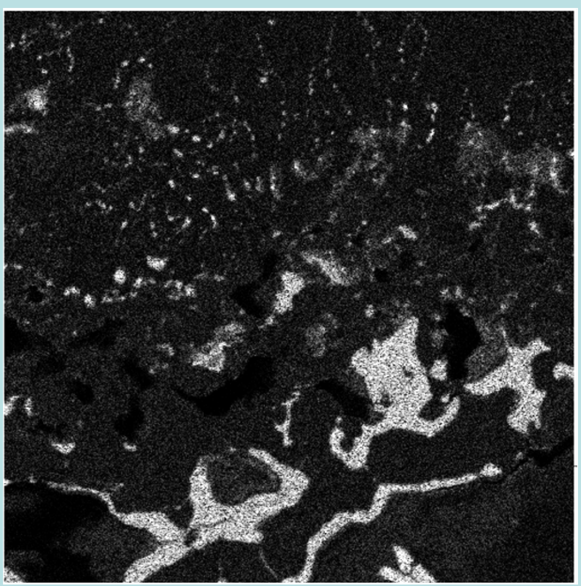
Image



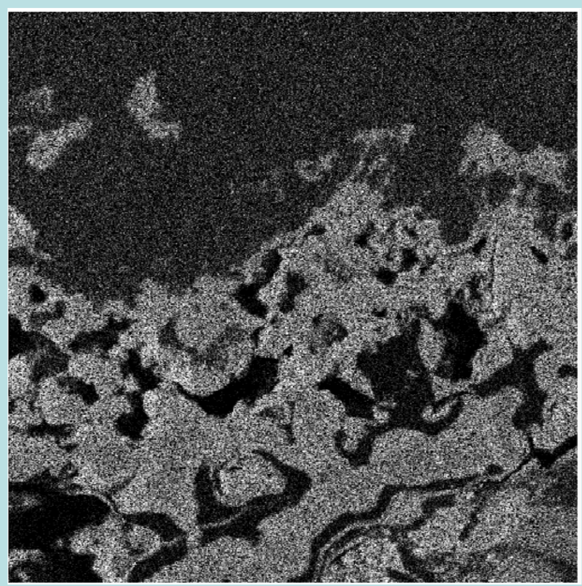
Fe



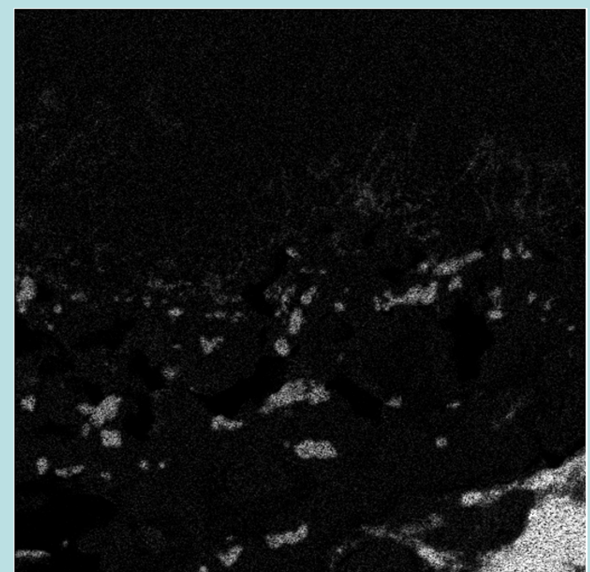
Cu



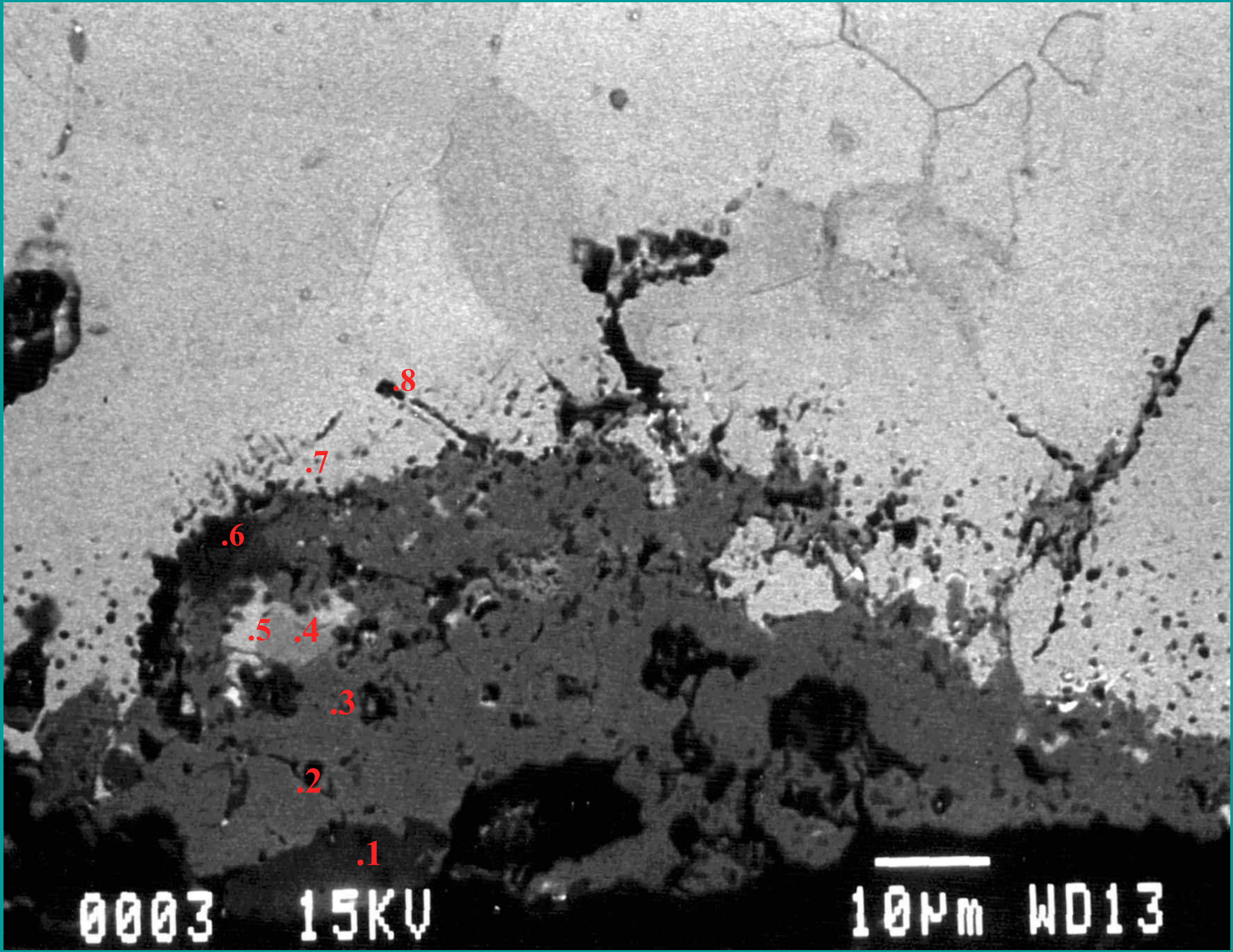
S



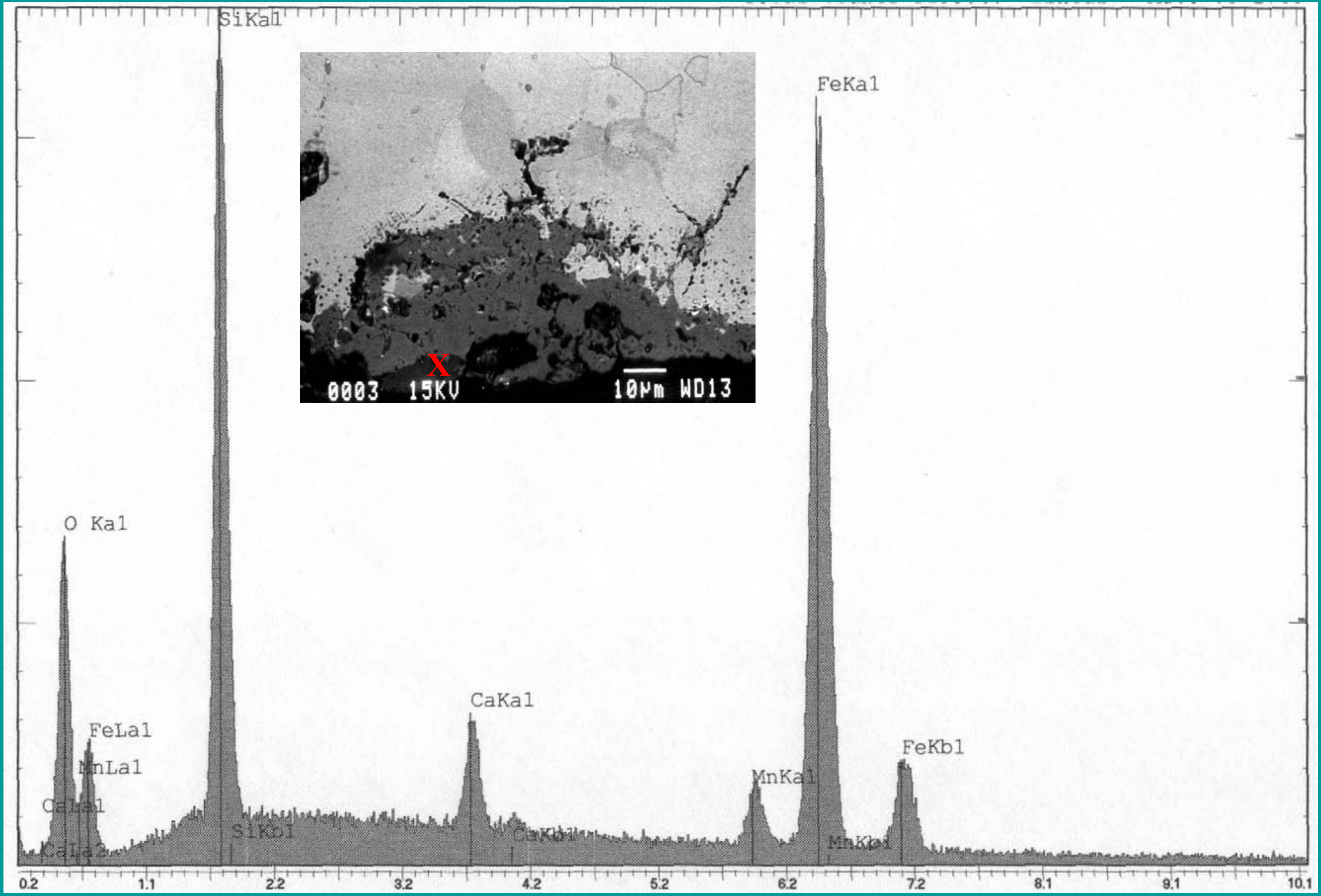
O



Si



Locations where Qualitative Chemical Analysis was performed



Spot Location 1 in Figure 5

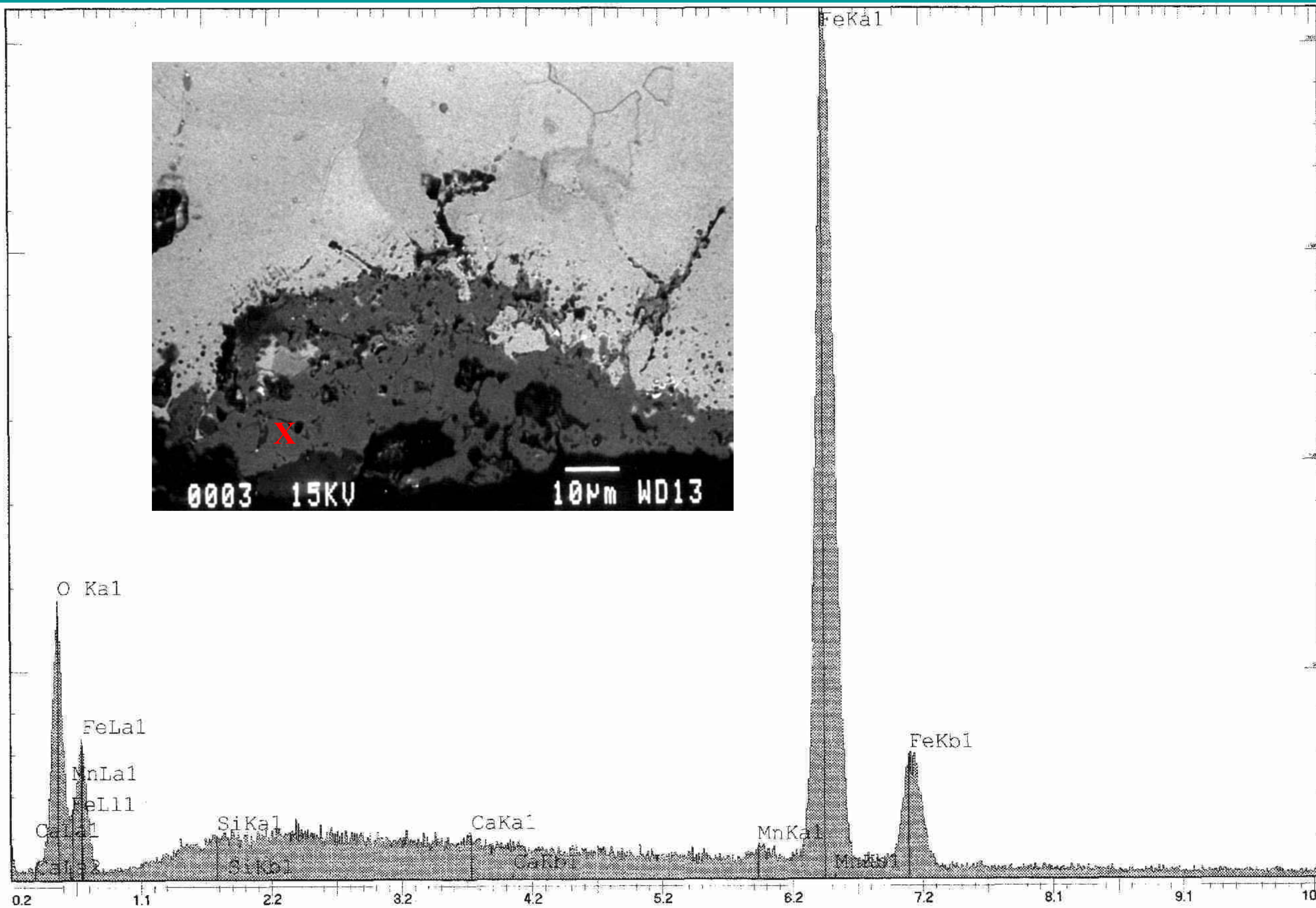


Figure 5A. Spot Location 2

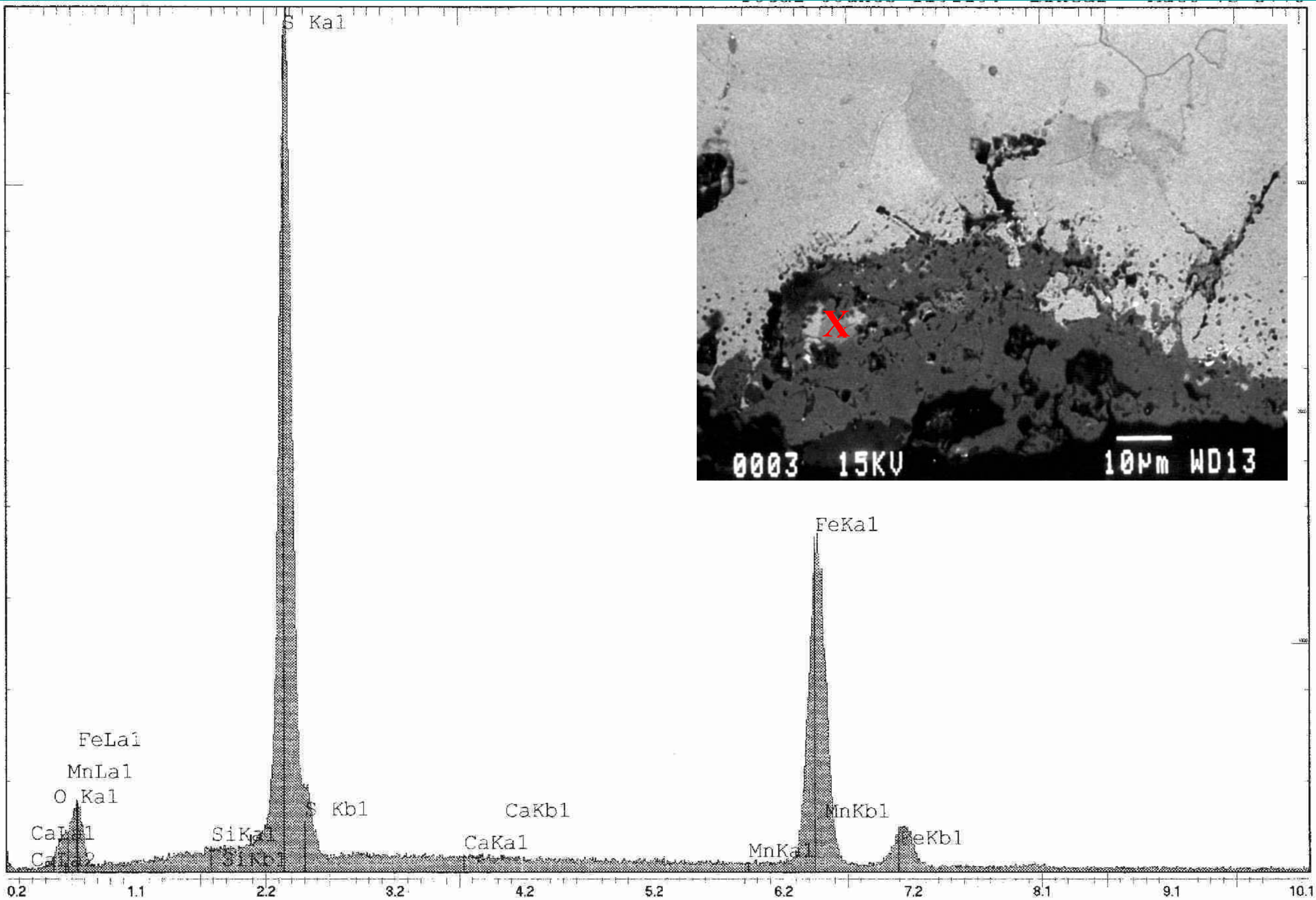


Figure 5A. Spot Location 4

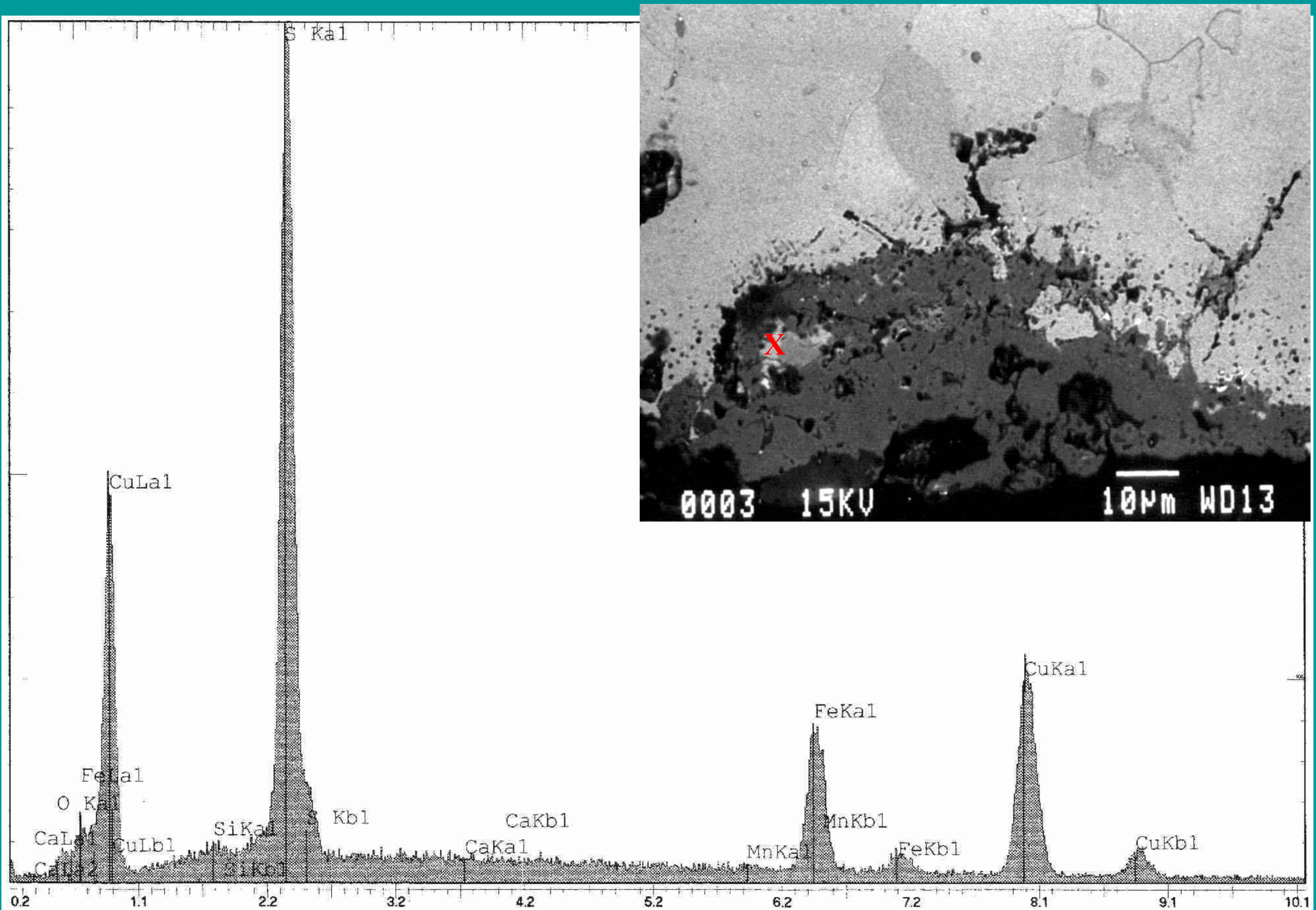


Figure 5A. Spot Location 5

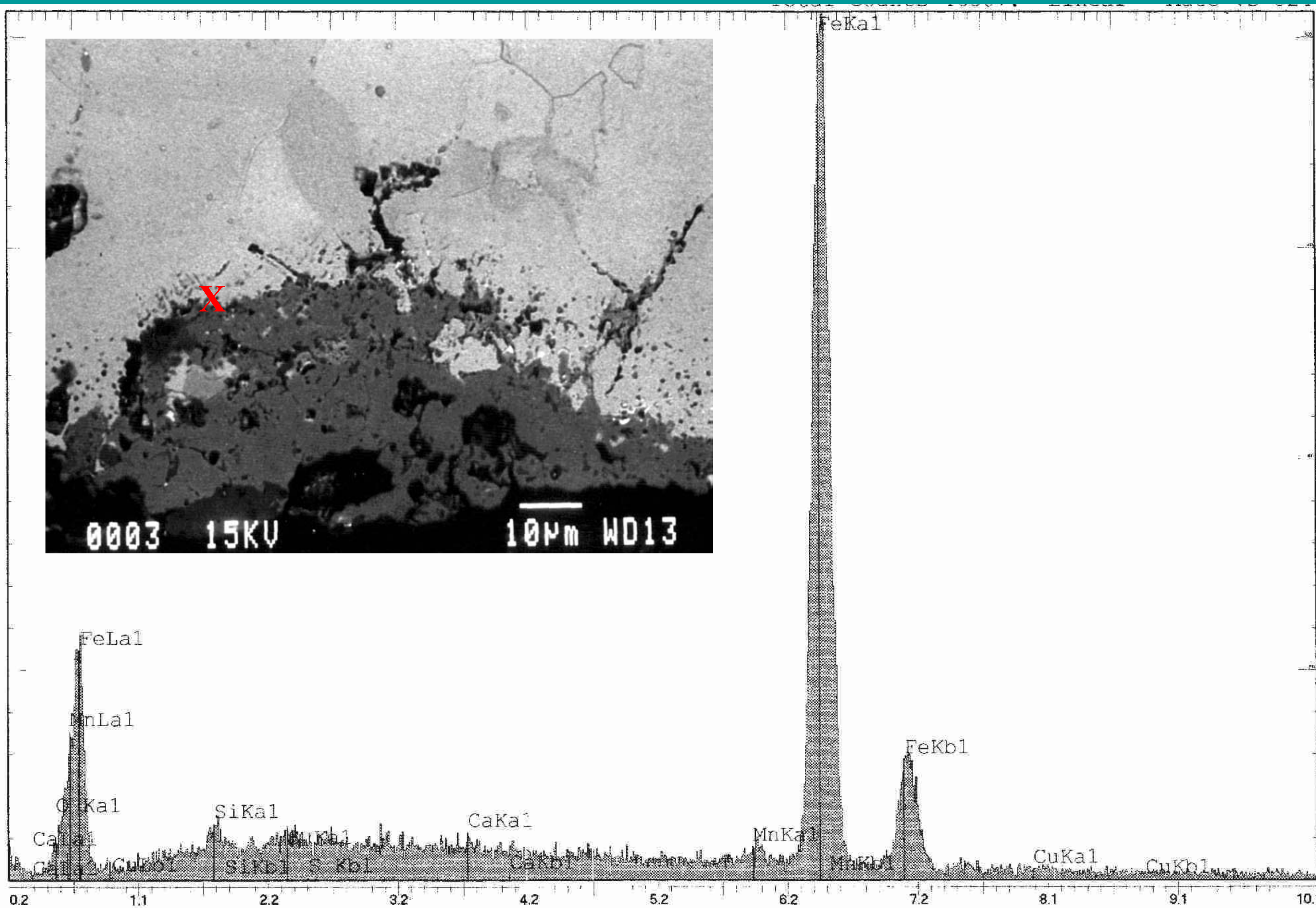


Figure 5A. Spot Location 7

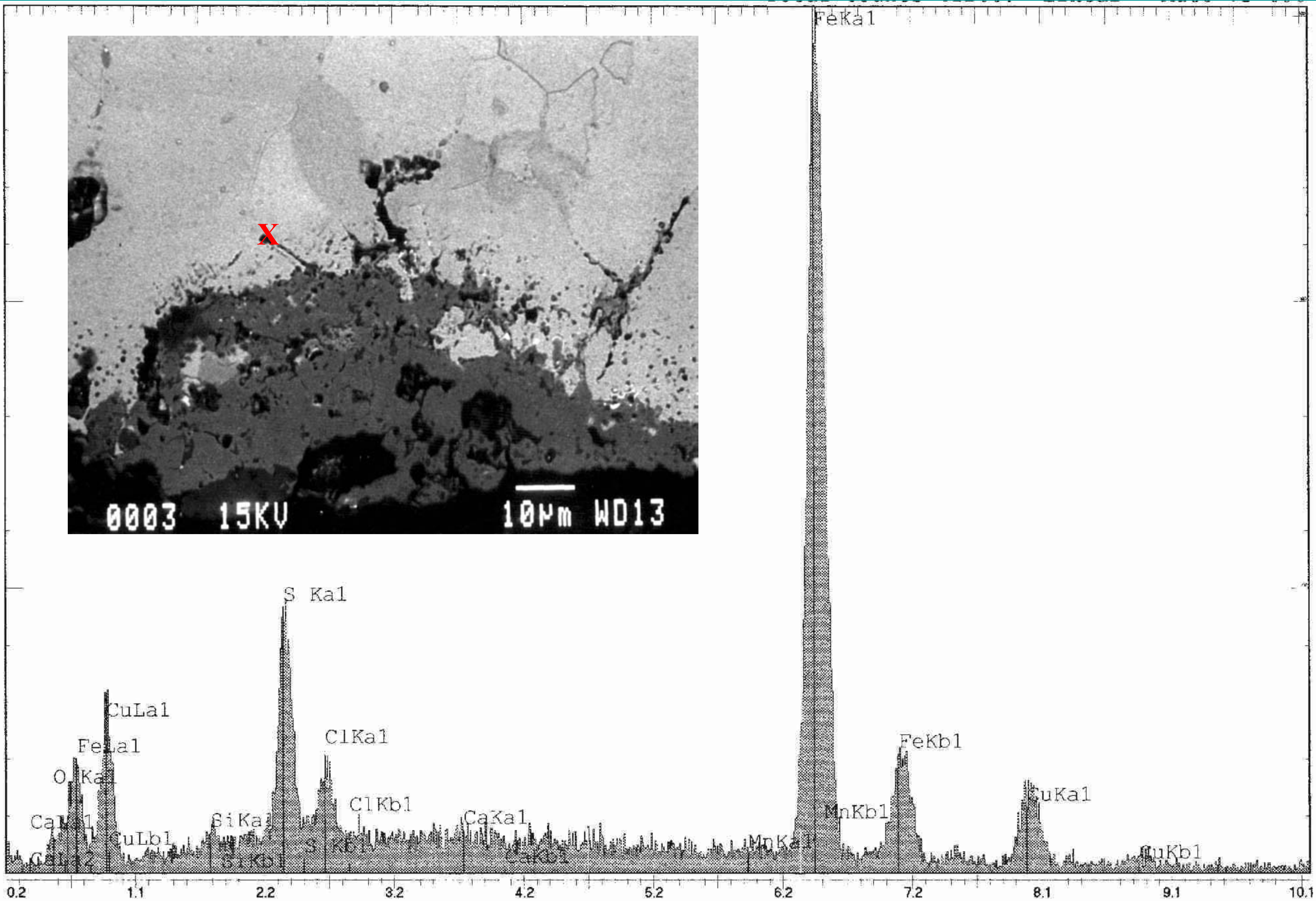
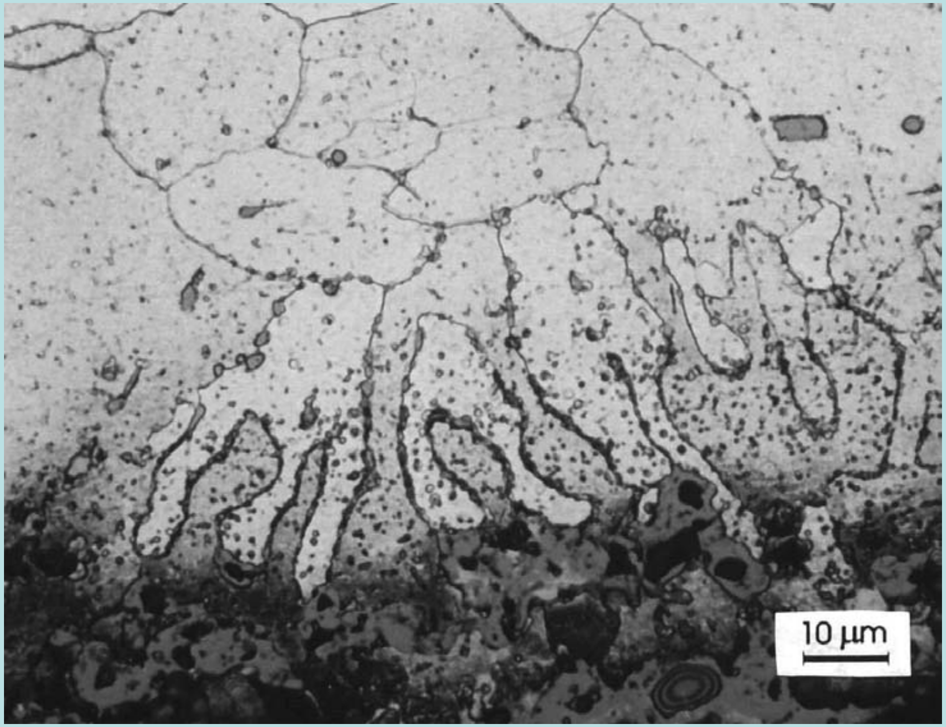
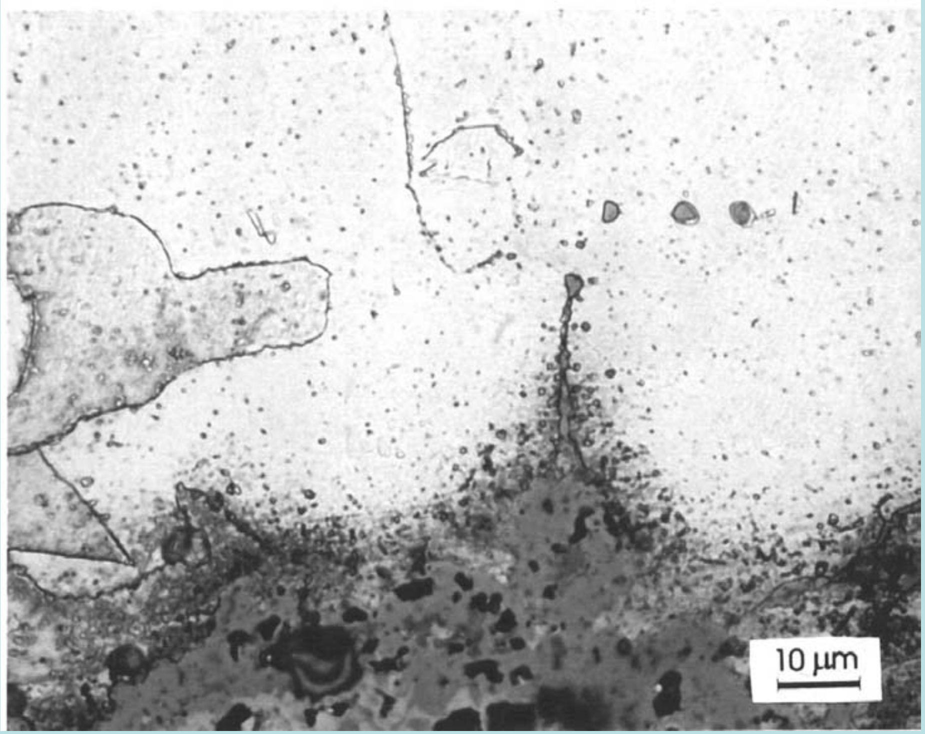


Figure 5A. Spot Location 8

Hot Corrosion of the HSLA Steel

Manganese, Carbon, Silicon, Copper, and Sulfur Segregate at Interfaces where Reaction is Severe





Gradient of Sulfides into the Steel from the Oxide-Metal Interface

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2. Sulfidation of the grain boundaries in the HSLA steel accelerated the corrosion and erosion of the steel.

3. The high concentration of sulfides in the grain boundaries in the corroded regions of the steel occurs due to copper diffusing from the HSLA steel combining with iron, manganese and sulfur making both discrete and continuous sulfides in the steel grain boundaries.

How much sulfur is necessary ?

Where did the sulfur come from?

We can speculate and never know the answers to these questions.

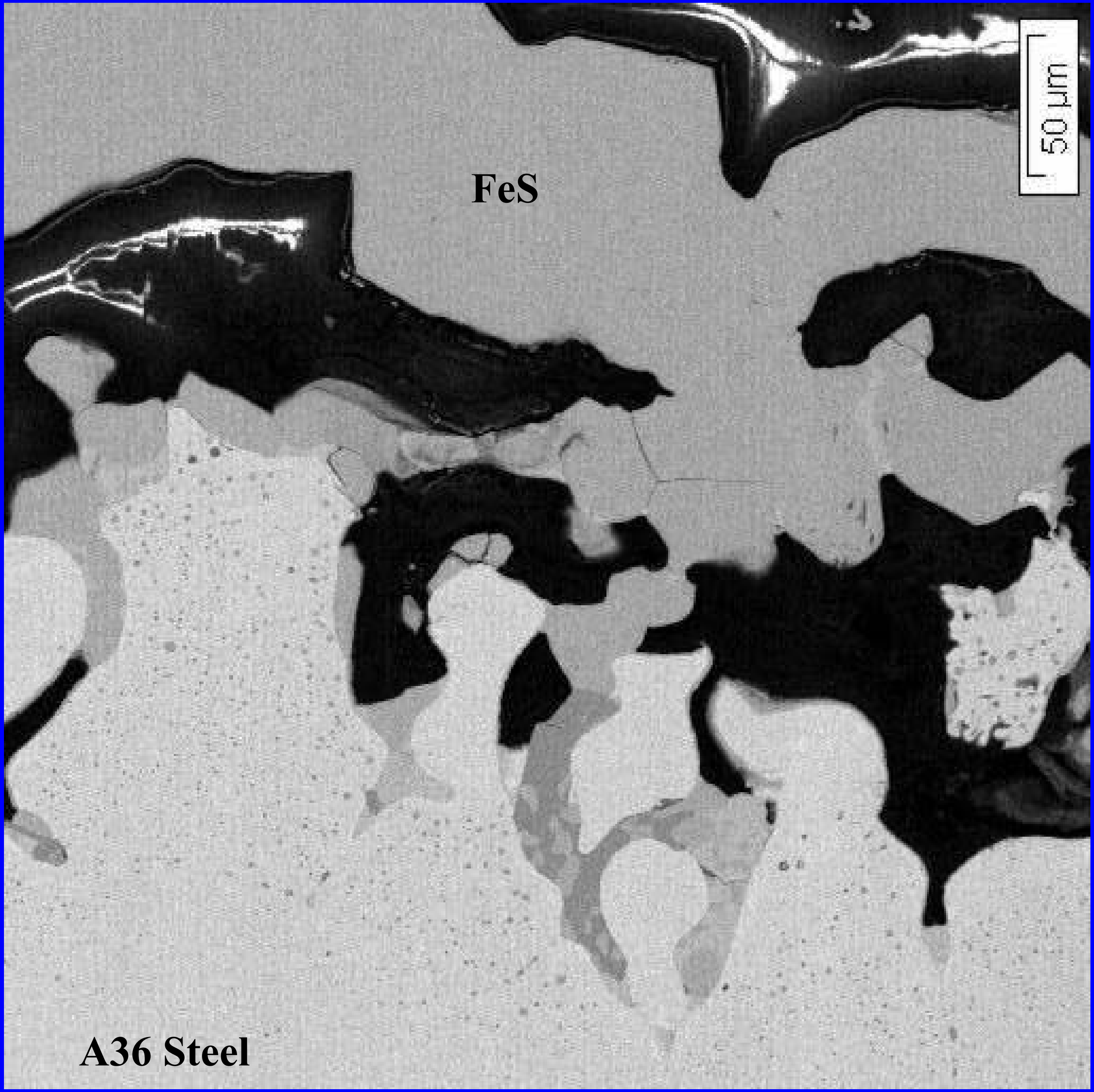
or

Probably, we can answers many of these questions, by developing models and running controlled laboratory experiments in realistic atmospheres for these steel.

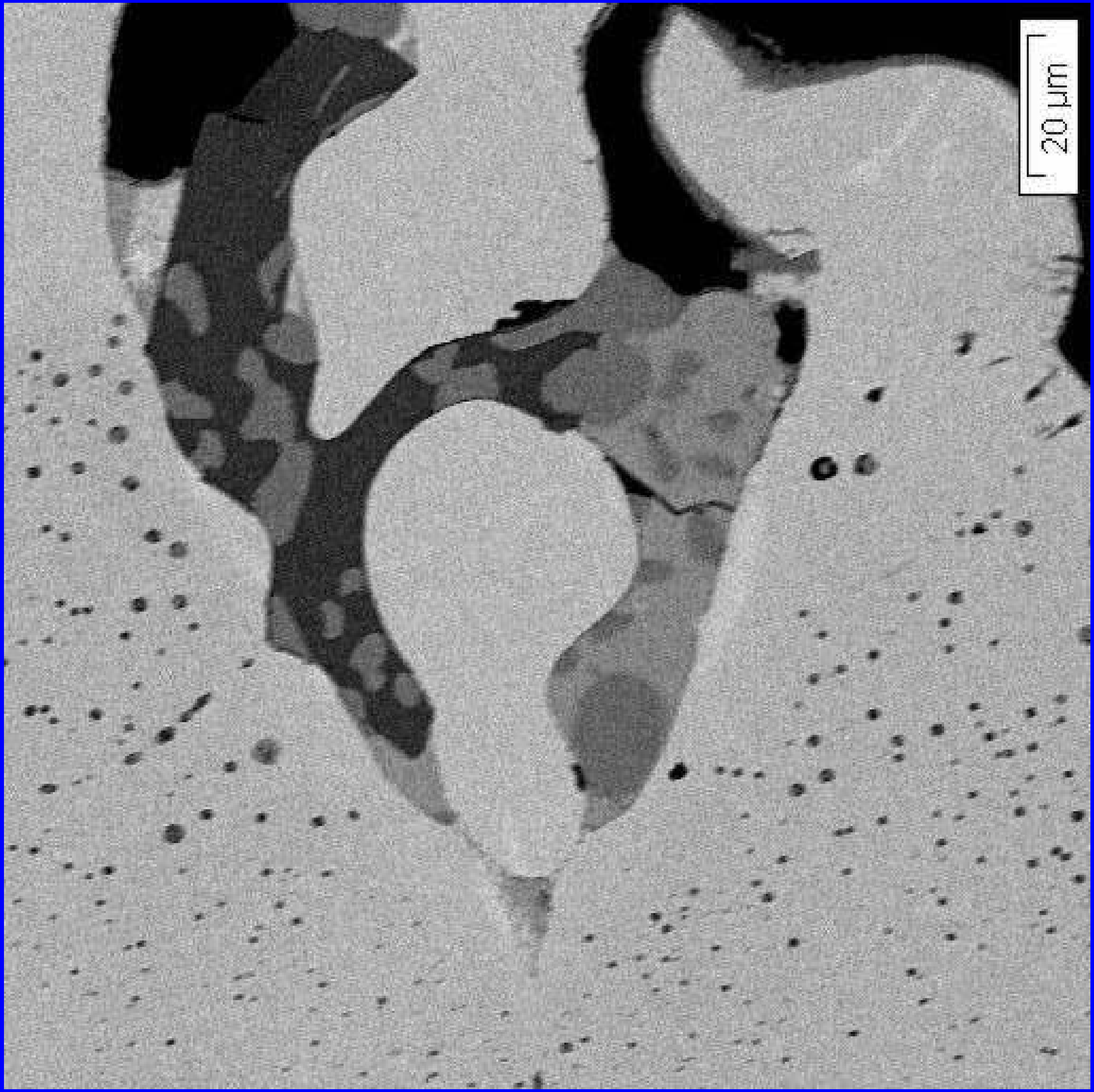
1st Experiment

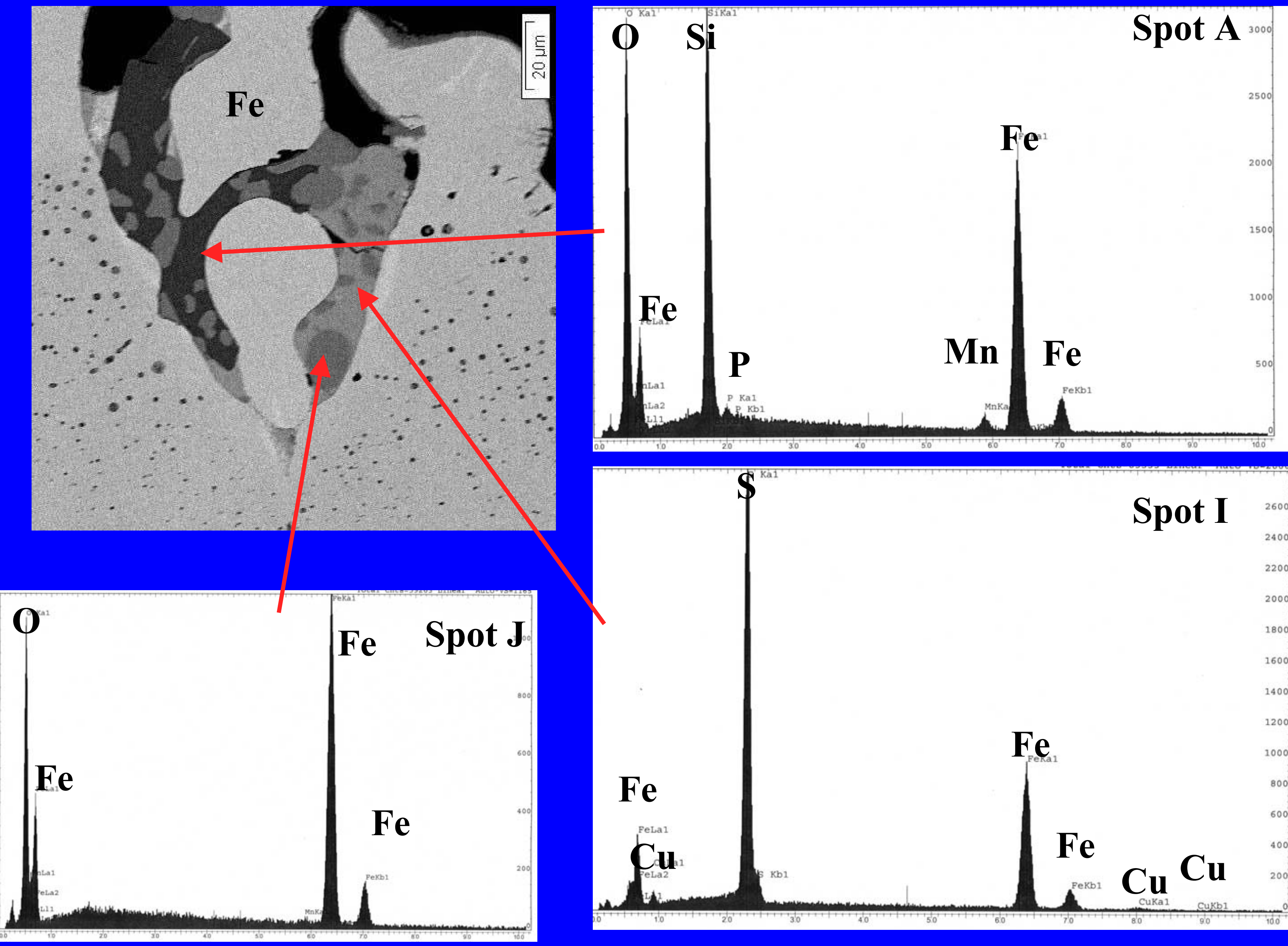
Isothermal Reaction of Compacted FeS Powder on the Ground Surface of A36 In Air for 12 Hours at 1100C.

From Erin M. Sullivan

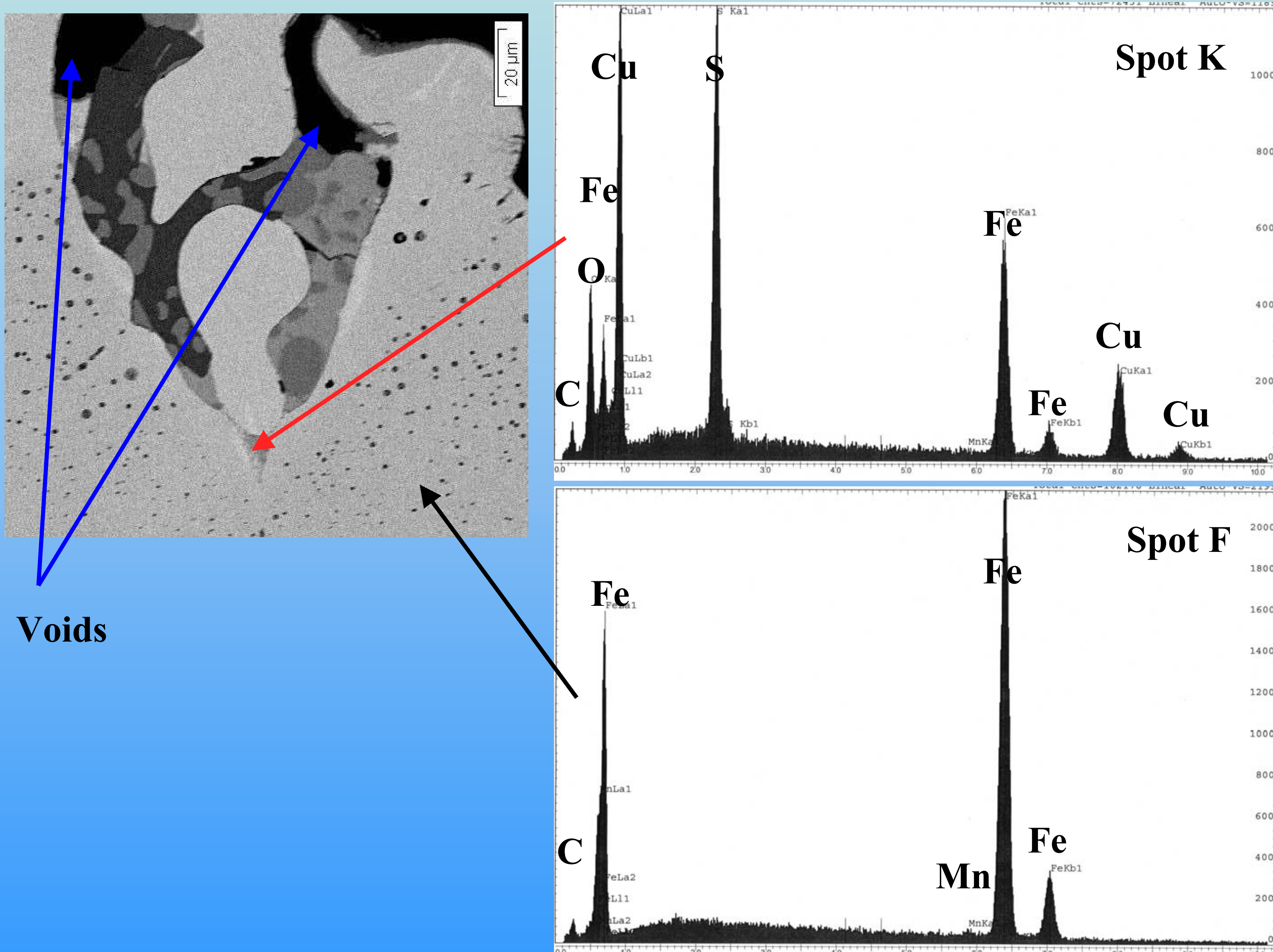


FeS
50 µm
A36 Steel


20 µm



Fe
20 µm
O
Si
Spot A
Fe
Fe
P
Mn
Fe
S
Spot I
Fe
Fe
Cu
Fe
Cu
Cu
O
Fe
Spot J
Fe
Fe


20 µm
Voids
Spot K
Cu
S
Fe
O
C
Fe
Fe
Cu
Cu
Spot F
Fe
Fe
C
Mn
Fe

Could the source of the sulfur be as simple as

- -“acid rain” ?

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Did the ingredients come from building contents, high sulfur fuel oils etc. ?

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Could nearby ocean salts such as sodium sulfate play a role ?

Building Safety

Building safety requires a reliable sprinkler system that will suppress fire temperatures so that no phase transformations in the steel can occur.