Magnetic Susceptibility as an Important Tool in Stratigraphy: Instruments, Methods, Problem Areas, Previous Work, Cycles, Applications

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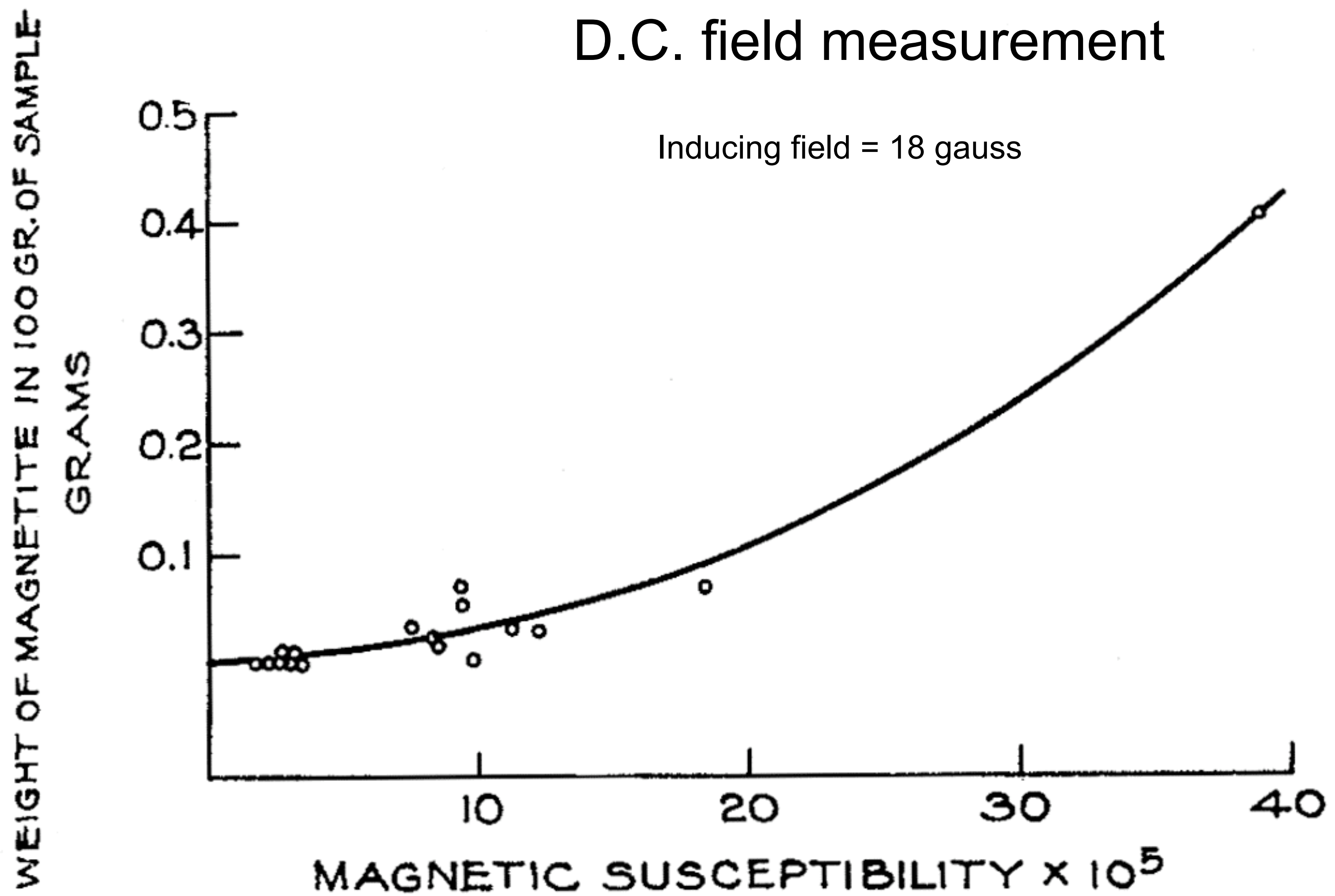
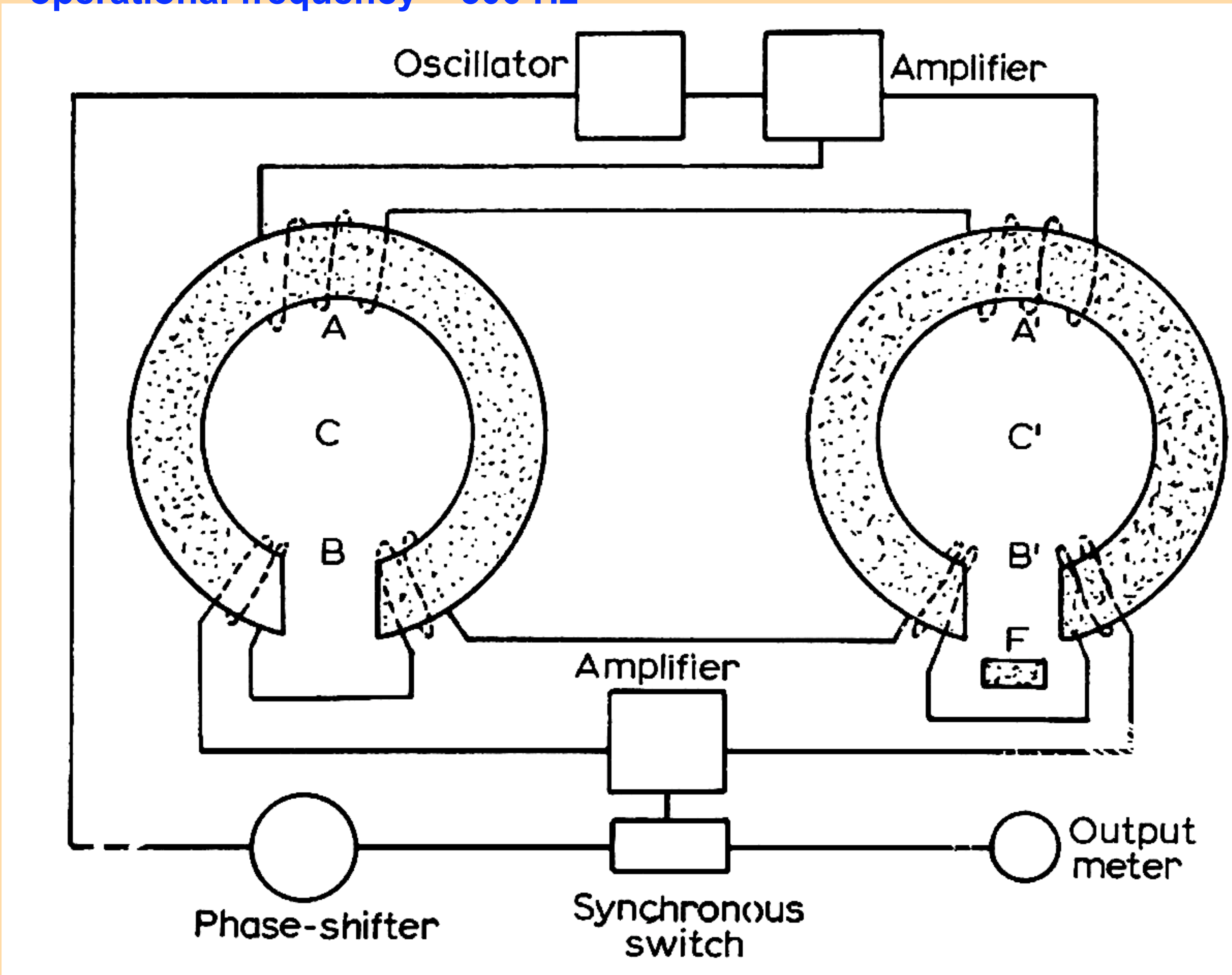
Collingwood, D.M., 1930. Magnetic susceptibility and magnetite content of sands and shales: AAPG Bulletin, v. 14, 1187-1190.



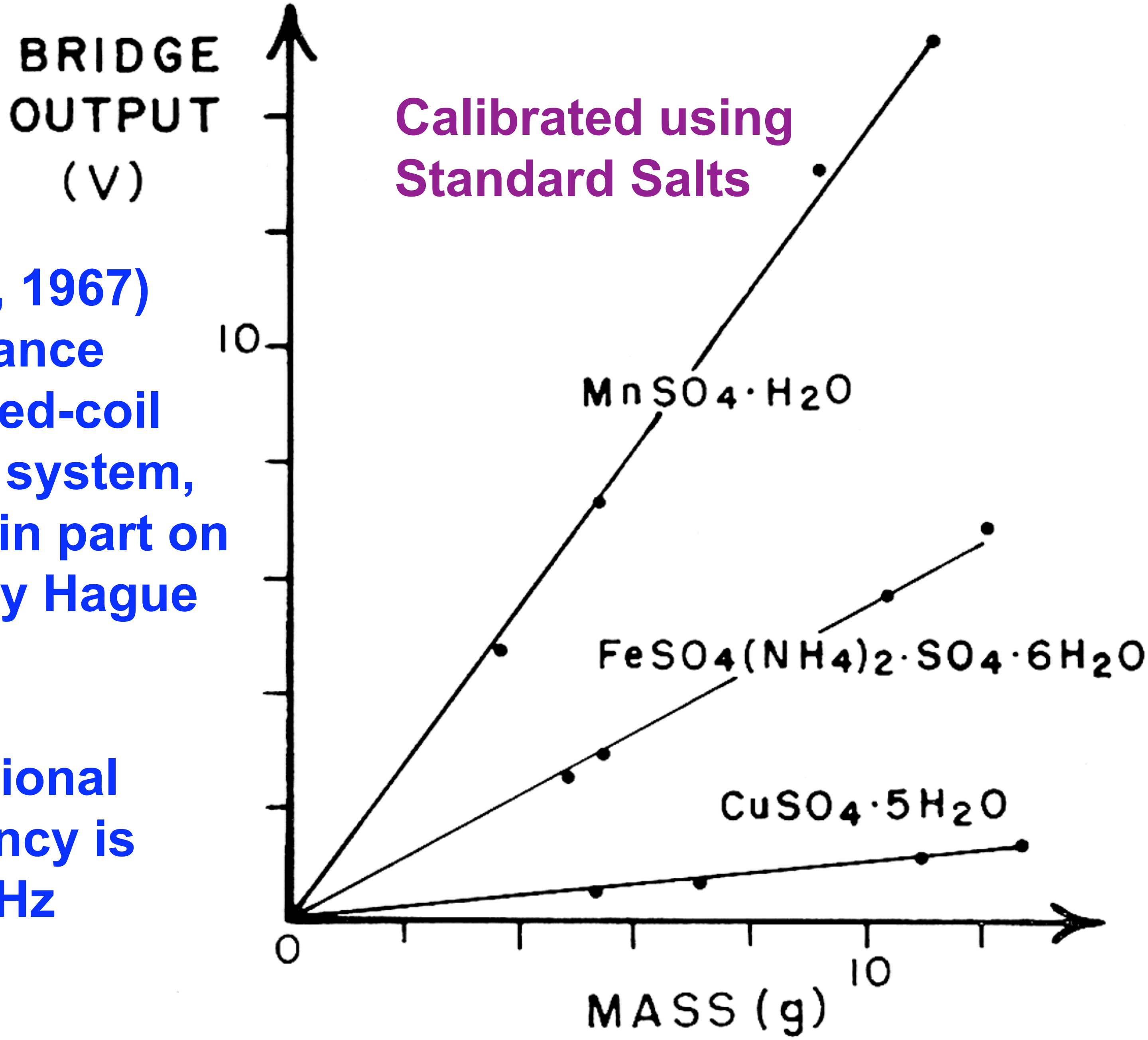
Comment: Early (1950s on) MS bridges and other measurement systems, use alternating frequency (AF) current, thus reducing remanent magnetic effects in single (such as magnetite produced by magnetotactic algal and bacterial organisms) and pseudo-single domain (high coercivity) ferrimagnetic components of lithified samples - crushing the sample further, also helps

(Collinson and Molyneux, 1967) Balanced coil system balanced using a ferrite core - operational frequency ~ 500 Hz

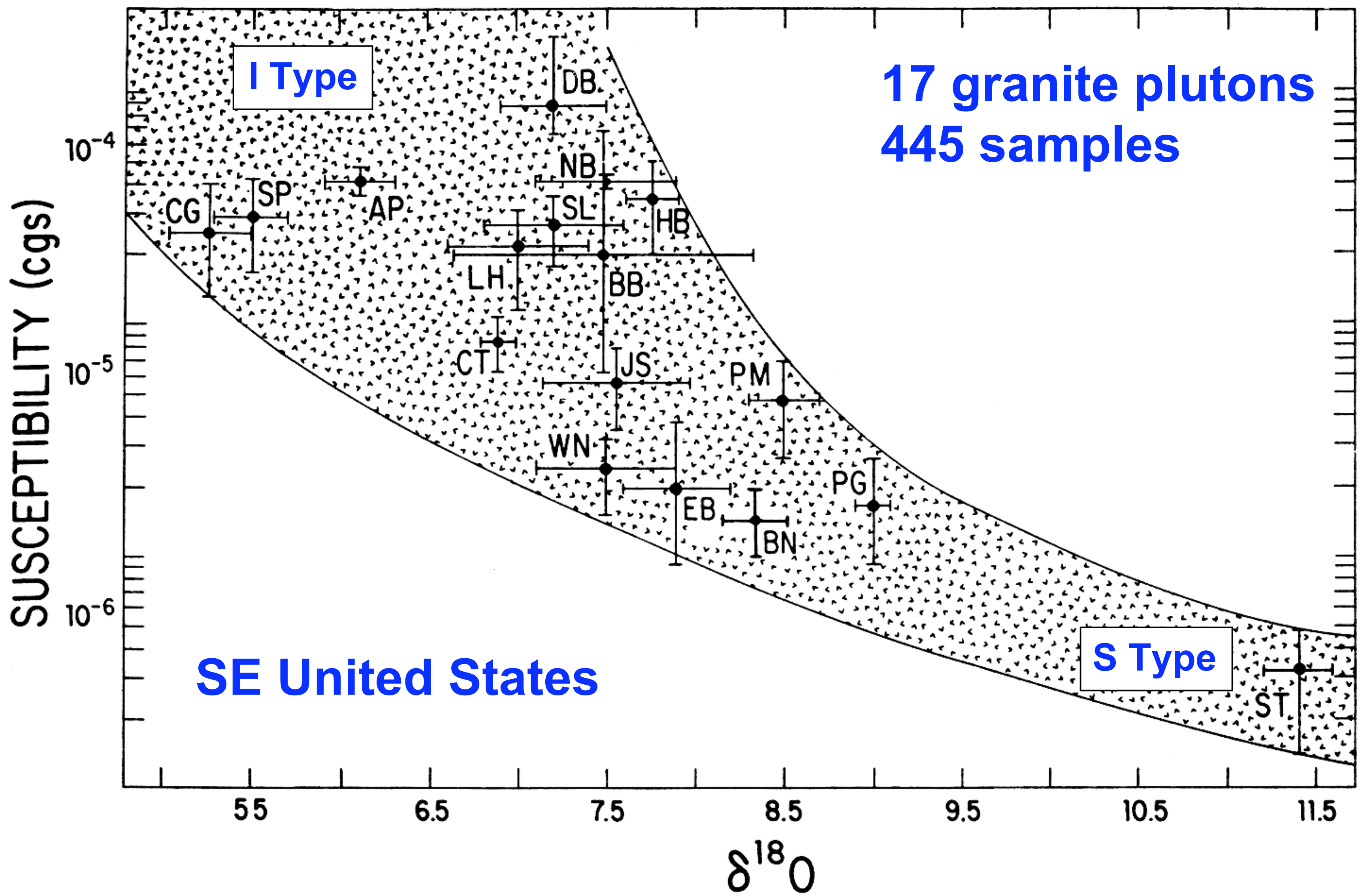


(Fuller, 1967) Inductance balanced-coil bridge system, based in part on work by Hague (1957).

Operational frequency is ~1000 Hz



Bison Instruments - 1960's



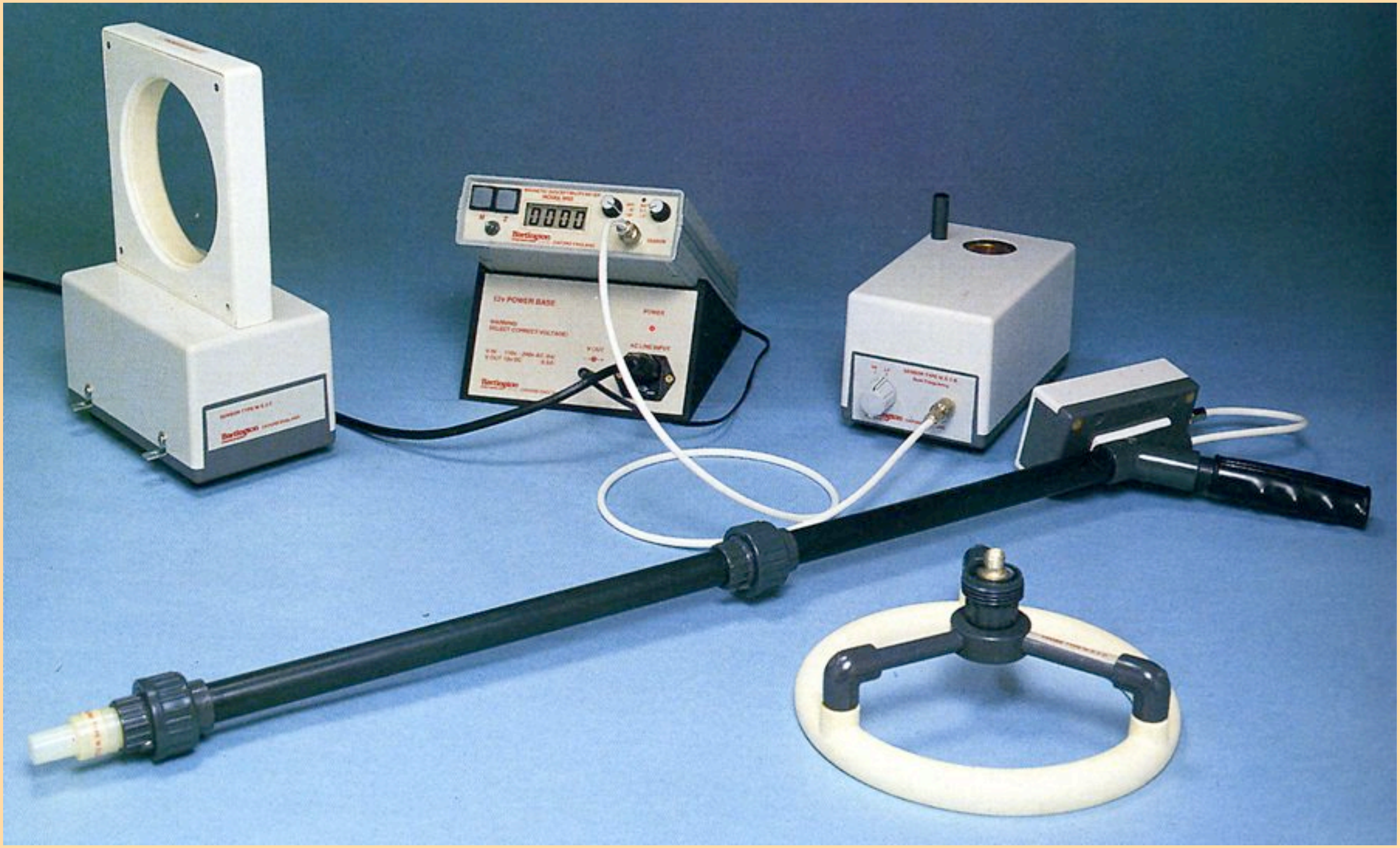
(Ellwood and Wenner, *EPSL* - 1981)


Main MS Bridge at LSU

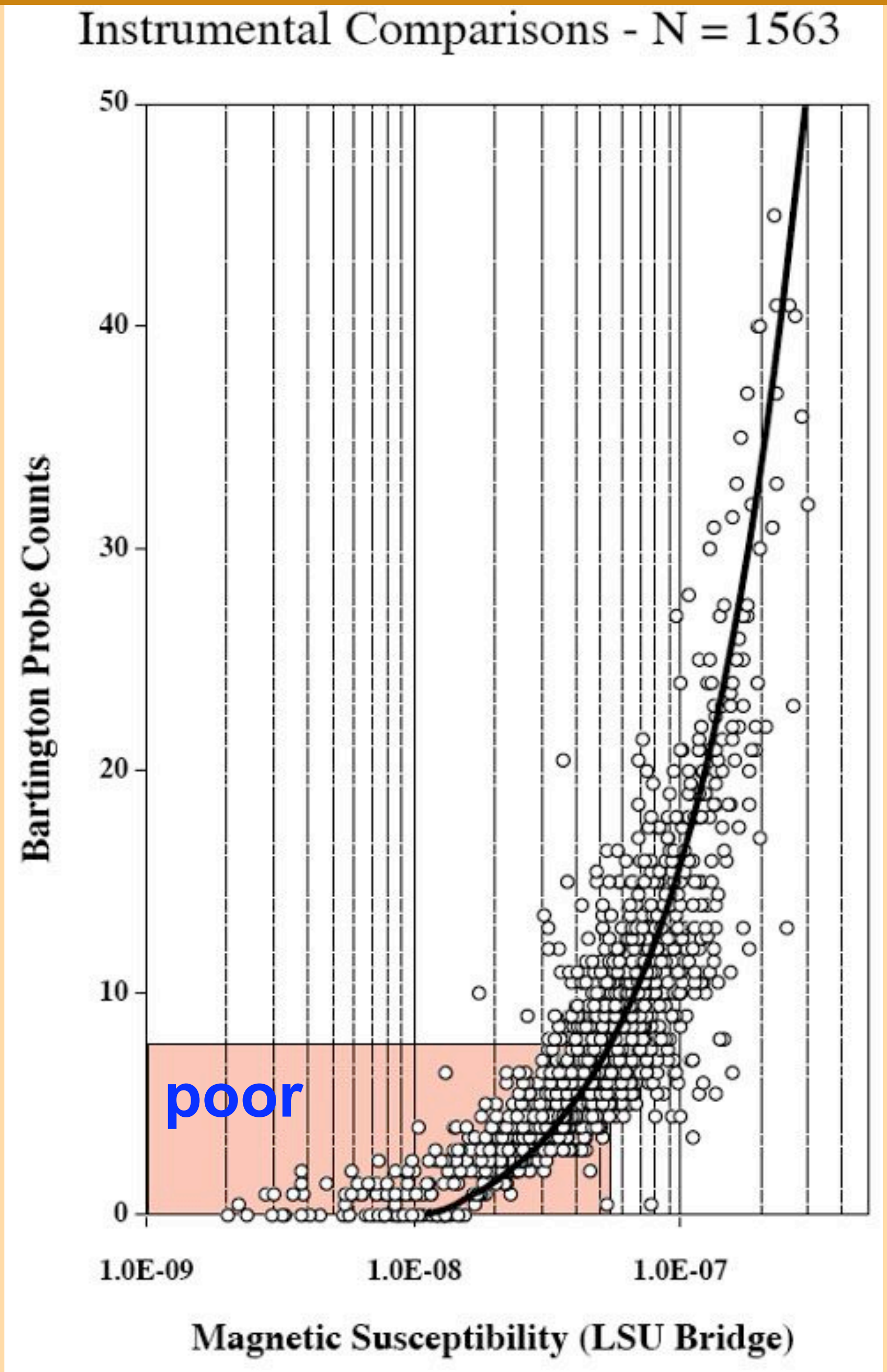
MS Balance Designed for Liquids and Powders

2009 Cost: $6,650; $13,900 (sens: x100)

Bartington Instruments

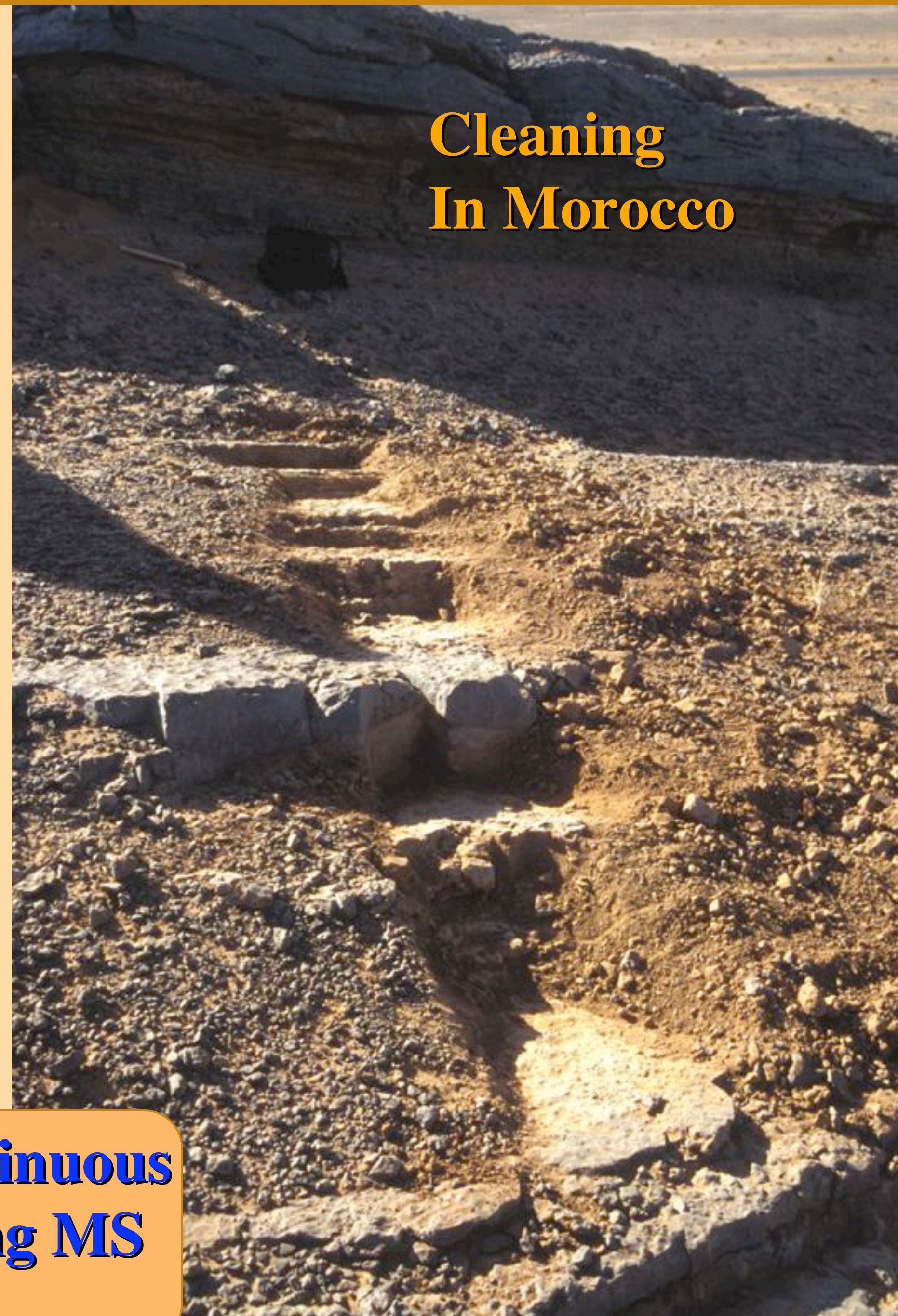


Bartington field probe in operation - Morocco



Field Probe
vs
MS bridge

Sampling methods

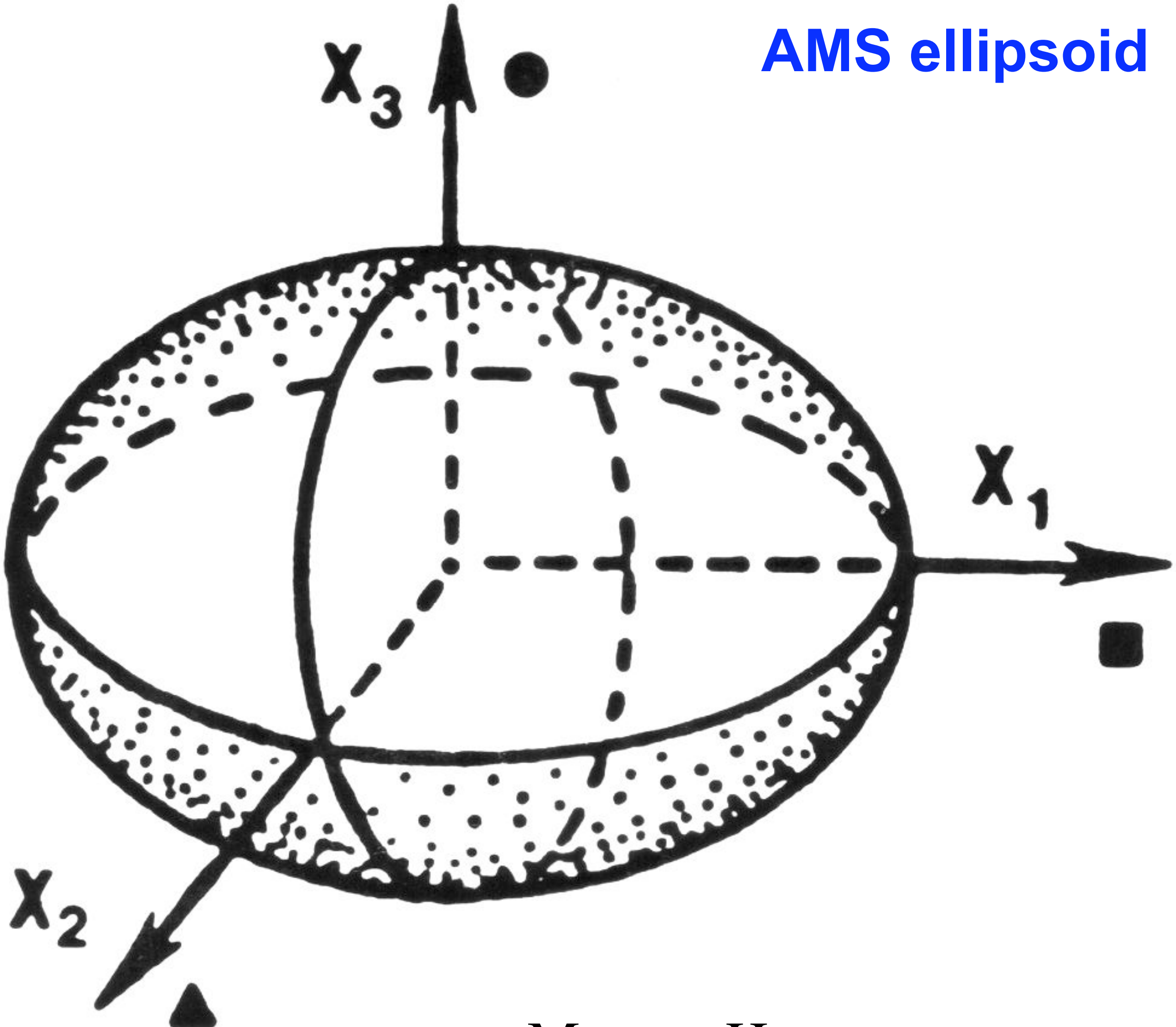


High resolution - essentially continuous sample sets are used in developing MS data and interpretations.

Anisotropy of Magnetic Susceptibility (AMS):

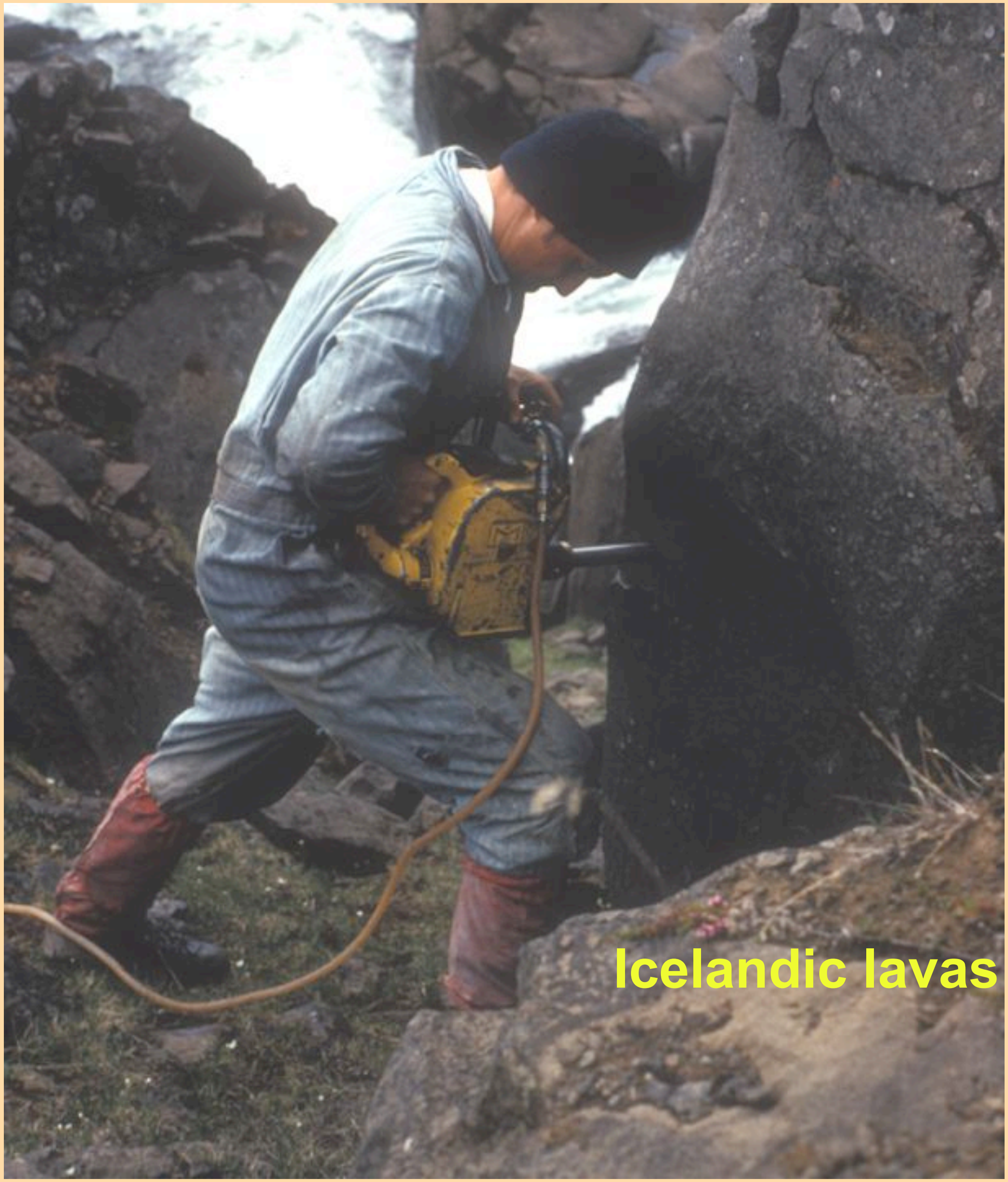
Much early MS work, AMS, required oriented samples, was time consuming and this restricted the number and type of samples that could be measured

AMS ellipsoid



$$M_i = \chi_{ij} H_j$$

First work: Ising, G. 1942. On the magnetic properties of varved clay, Arkiv for Matematic, Astronomi och Fysik, 29A, 1-37.



Collecting oriented samples for AMS

Fish Canyon Tuff, Colorado

Collecting friable material

Two-bladed dry saw

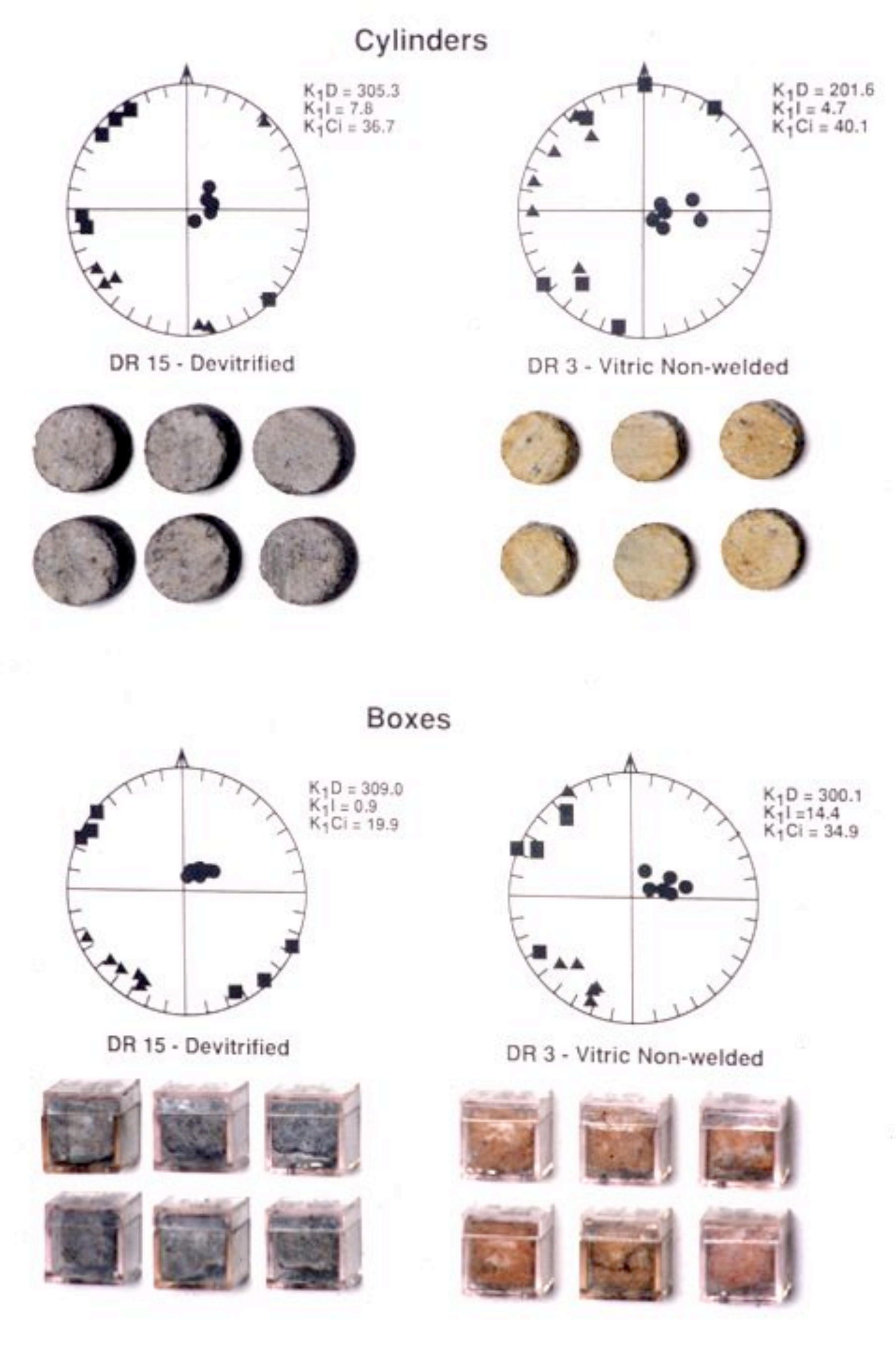
Used to collect square samples

Carved pedestal - plastic box then pushed over sample

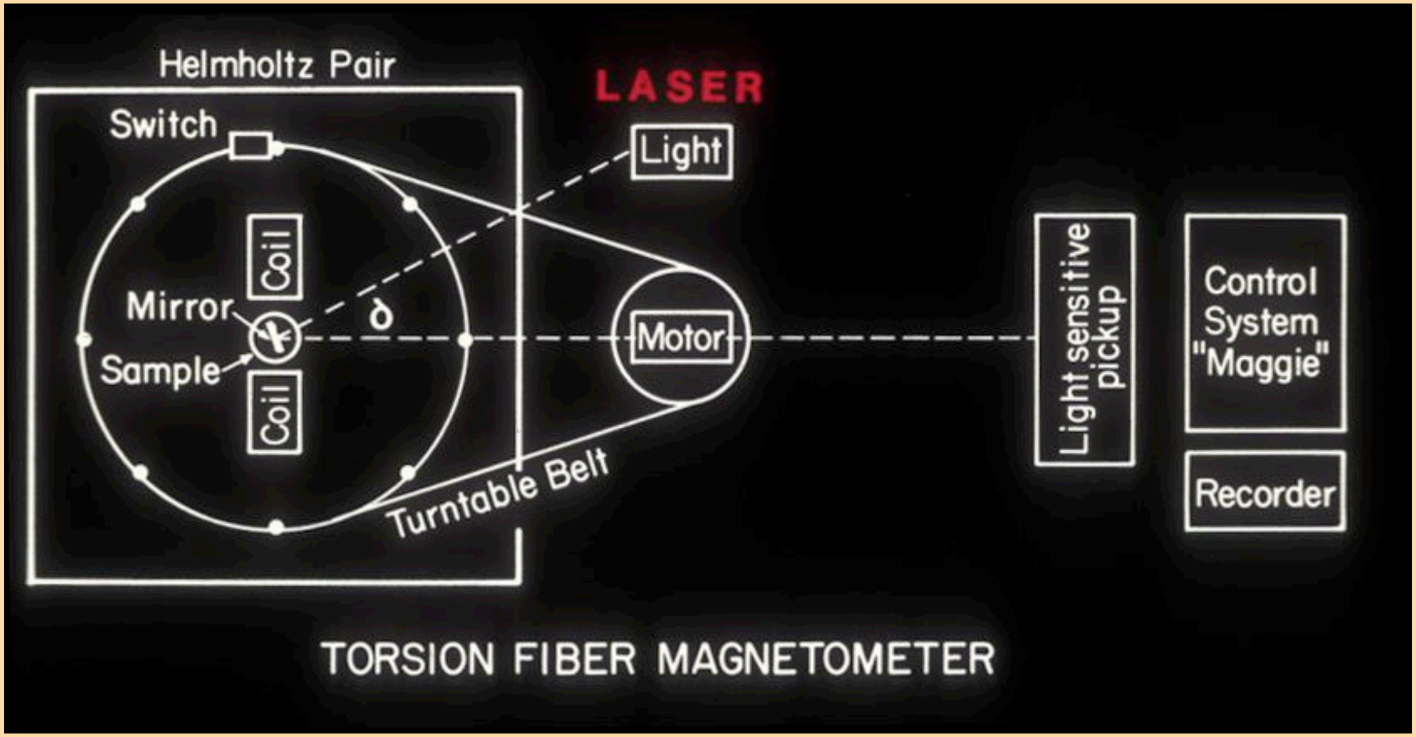
AMS results

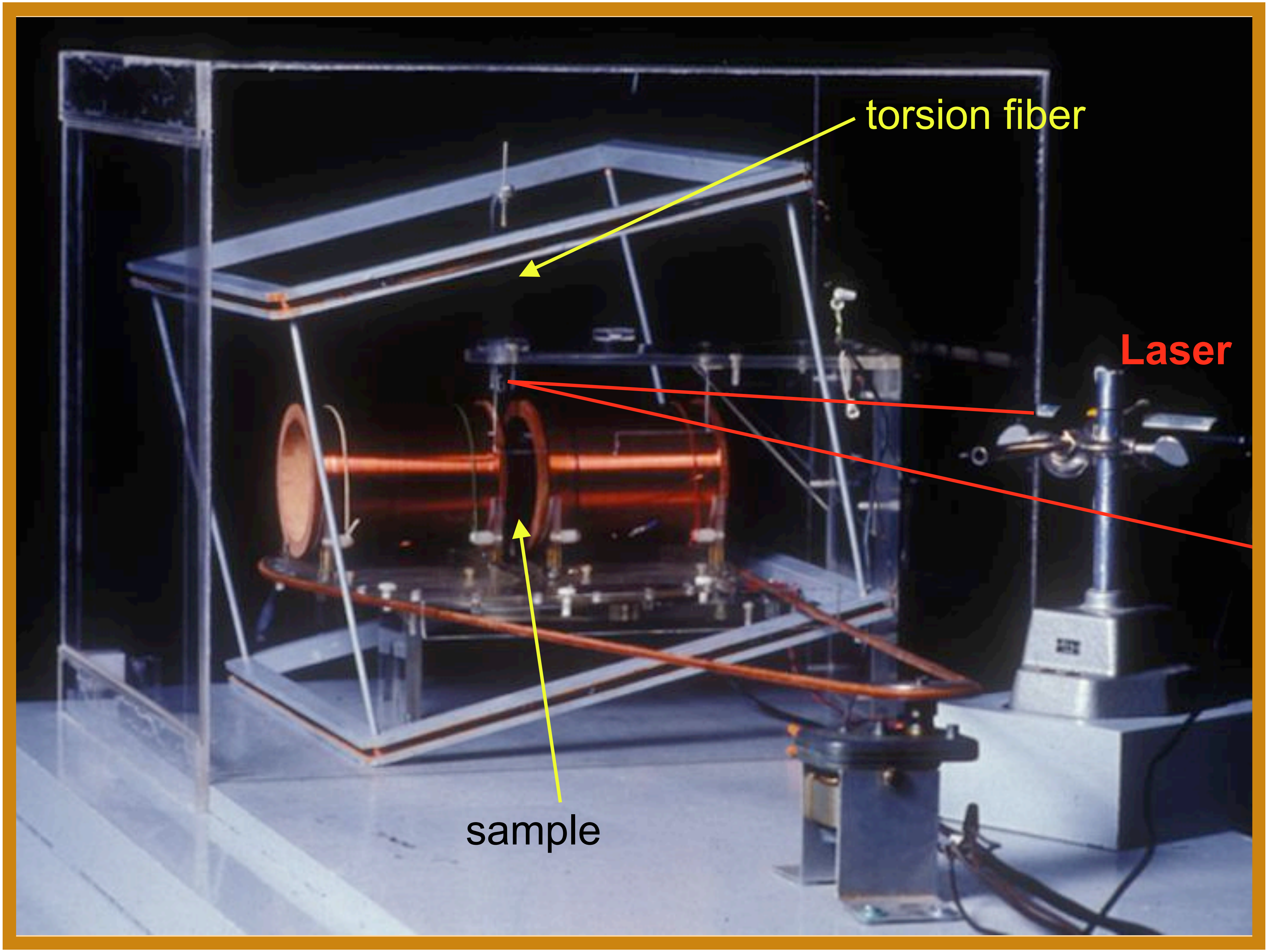
Bandelier Tuff New Mexico

Sampling method comparison



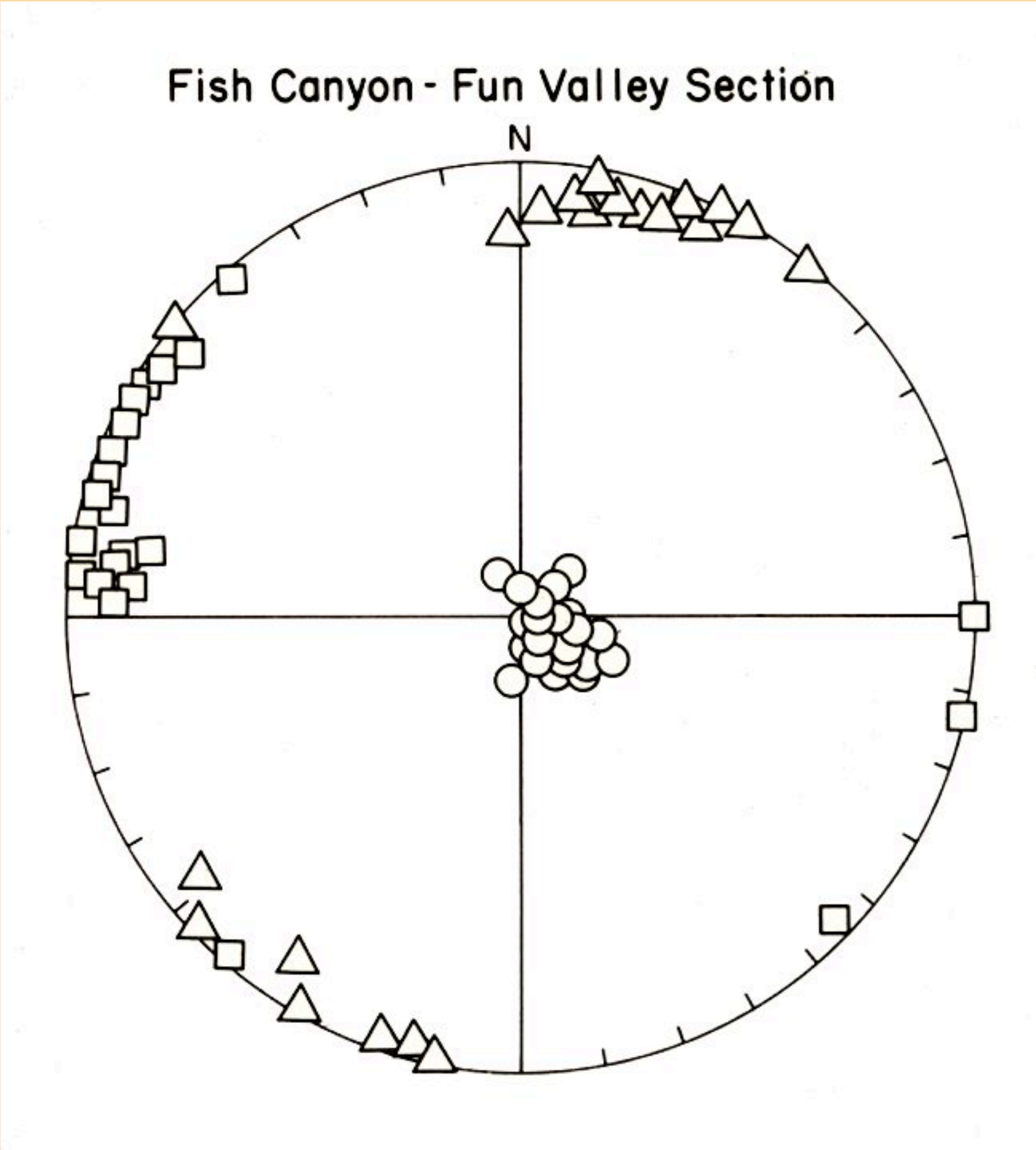
Early difference AMS measurements (similar to astatic magnetometers for RM measurement) required independently measured bulk MS for absolute (total) ellipsoid - difference measurement allows extremely high sensitivity and easy instrument modification





torsion fiber
Laser
sample

AMS of a 250 m thick volcanic tuff



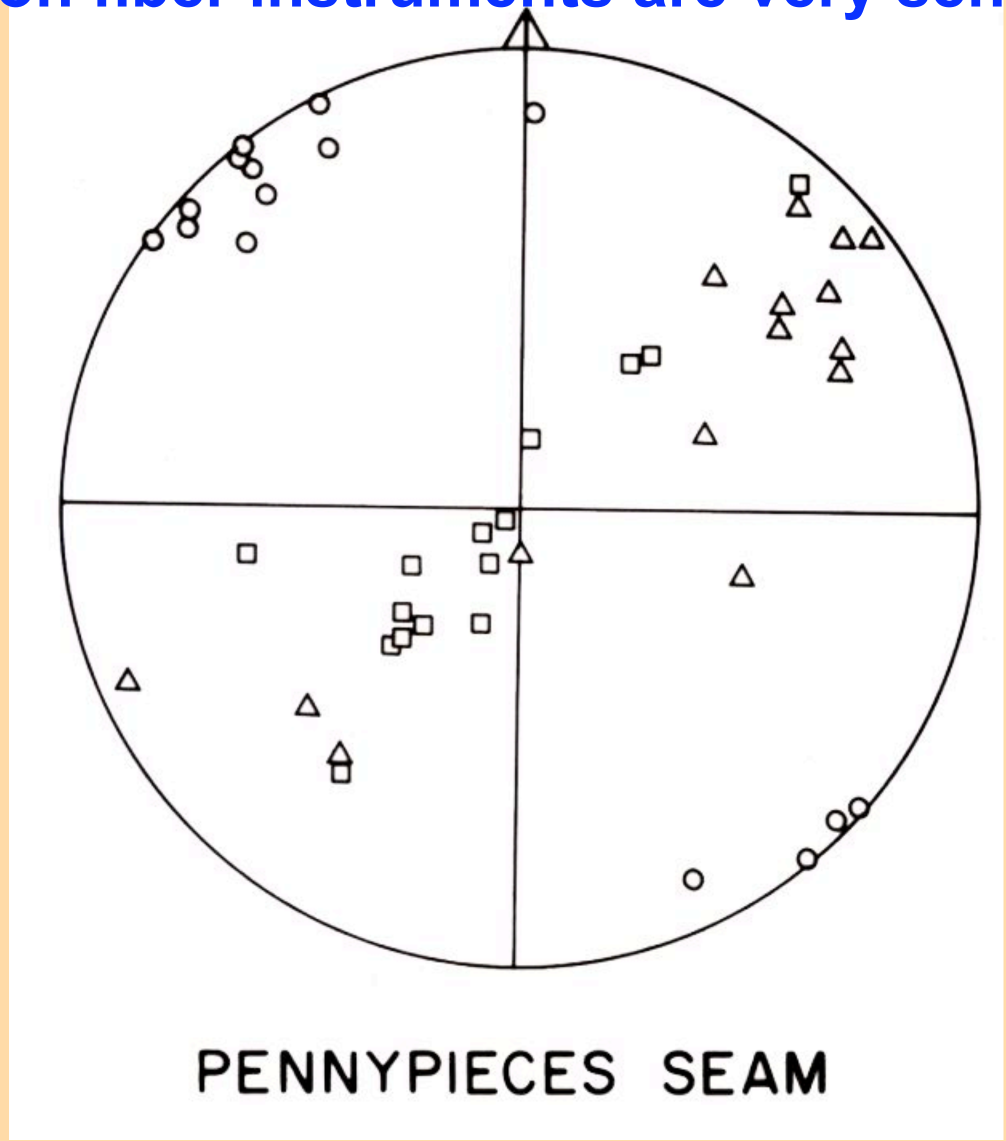
Typical AMS fabric diagram - projection of intersections of fabric ellipsoidal directions on a sphere

χ_1 - squares (maximum axes)
χ_2 - triangles (intermediate axes)
χ_3 - spheres (minimum axes)

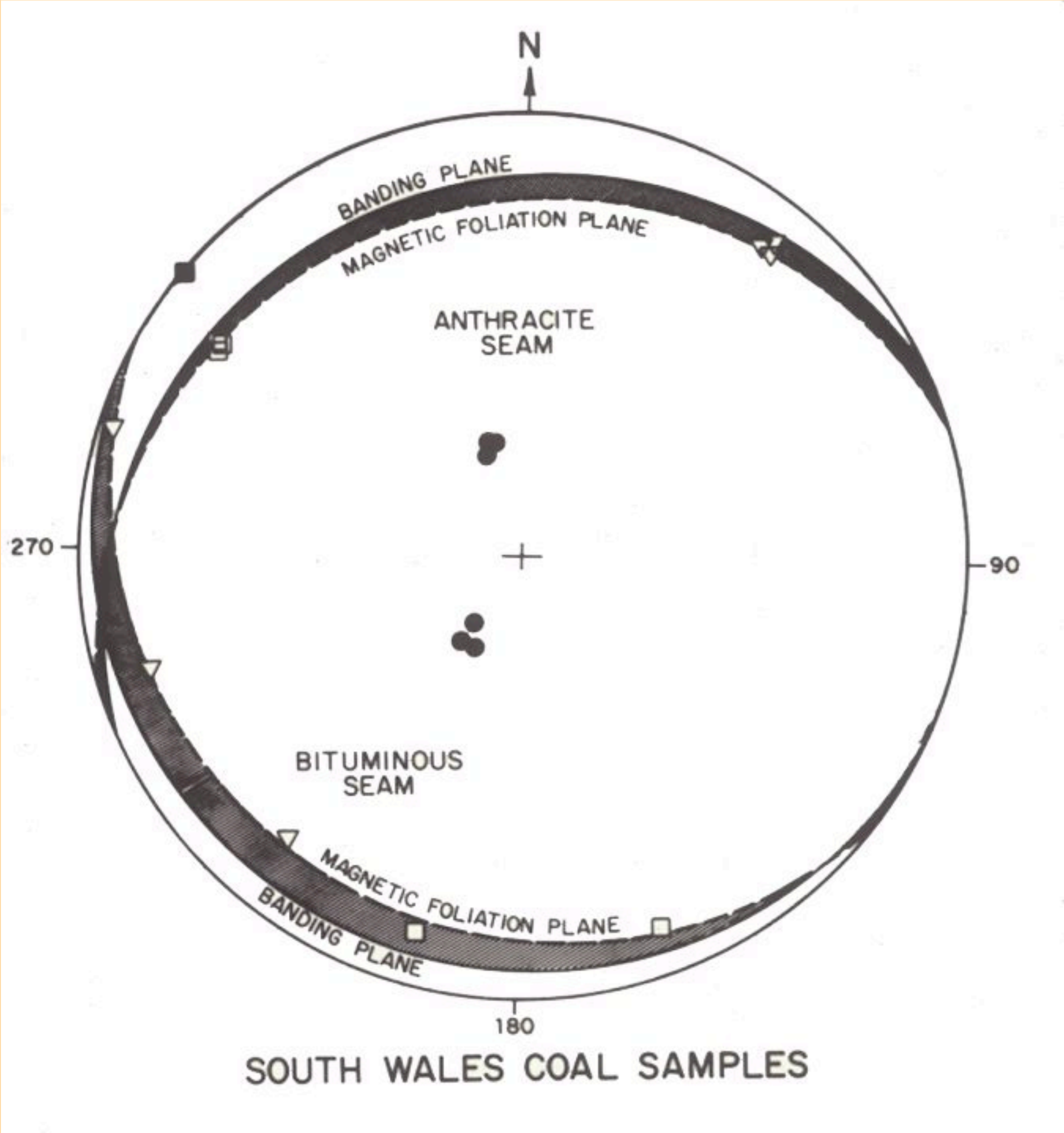
Here typical sedimentary fabric is illustrated with the χ_3 axis well-clustered and near vertical

Sampling in the South Wales Coal Field

AMS Measurement of Diamagnetic Coals
AMS of an anthracite coal seam
Tortion fiber instruments are very sensitive

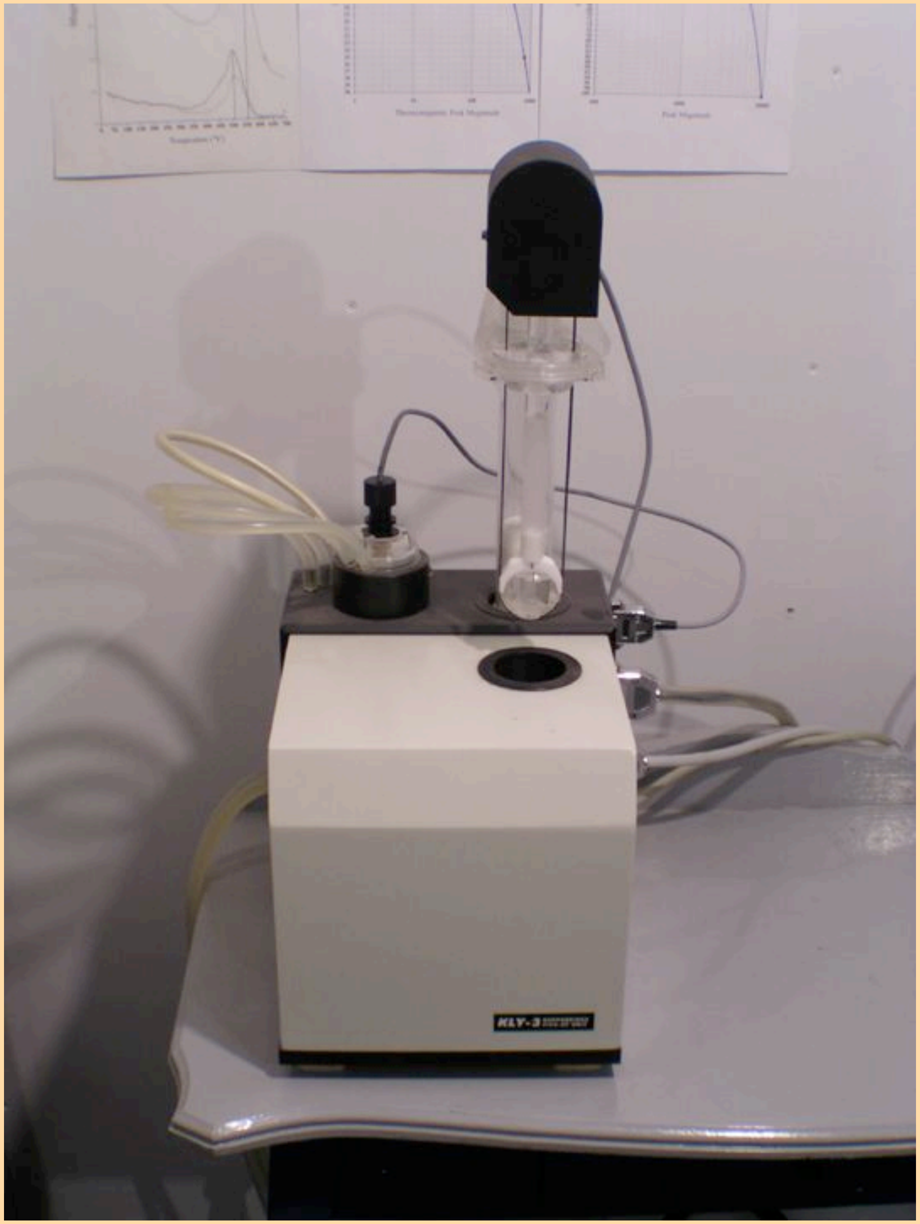


AMS Measurement of Diamagnetic Coals



KLY 3S Kappabridge at LSU

Used for MS + AMS measurement



Sapphire Instruments

MS + AMS

Chemistry:

(1) what can be expected

(2) what is producing the MS

(3) what are the controlling components

Table 1—Iron-Bearing Minerals

Group	Mineral	Chemical Formula	Magnetic Susceptibility[a]
Oxides	Magnetite	Fe_3O_4	***
	Maghemite	γFe_2O_3	**
	Hematite	αFe_2O_3	*
Sulfides	Smythite (?)	Fe_9S_{11}	?
	Greigite	Fe_3S_4	***
	Mackinwite (?)	FeS_{1-x}, Fe_9S_8	?
	Pyrrhotite	$Fe_{1-x}S$	*/**
	Sulfided iron (?)	Fe_2S_3	?
	Marcasite	FeS_2	*
	Pyrite	FeS_2	*
	Chalcopyrite	$CuFeS_2$	*
Hydrated sulfates	Jarosite	$KFe_3(SO_4)_2(OH)_6$	?
	Coquimbite	$Fe_2(SO_4)_3 \cdot 9H_2O$	*** ?
	Melanterite	$FeSO_4 \cdot n$H2O	*** ?
	Rozenite	$FeSO_4 \cdot n$H2O	*** ?
	Siderotil	$FeSO_4 \cdot n$H2O	*** ?
	Szomolnokite	$FeSO_4 \cdot n$H2O	*** ?
	Halotrichite	$FeAl_2(SO_4)_4 \cdot 22H_2O$	*** ?
Oxyhydroxides	Geothite	$\alpha FeO(OH)$	*
	Lepidocrocite	$\gamma FeO(OH)$	*
	Ferrihydrate	$Fe_5O_7(OH) \cdot 4H_2O$	?
Carbonates	Ankerite	$Ca(Mg,Fe,Mn)(CO_3)_2$	*
	Siderite	$FeCO_3$	*
Clays	Chlorite (chamosite)	$(Mg,Fe,Al)_6(Al,Si)_4O_{10}(OH)_8$	*
	Berthierine	$(Fe_{1.7}Mg_{0.2}Al_{0.8})(Si_{1.2}Al_{0.8})_4O_5(OH)_4$	*
	Glauconite	$K(Fe,Mg,Al)_2(Si_4O_{10})(OH)_2$	*
Phosphates	Vivianite	$Fe_3(PO_4)_2 \cdot 8H_2O$	*

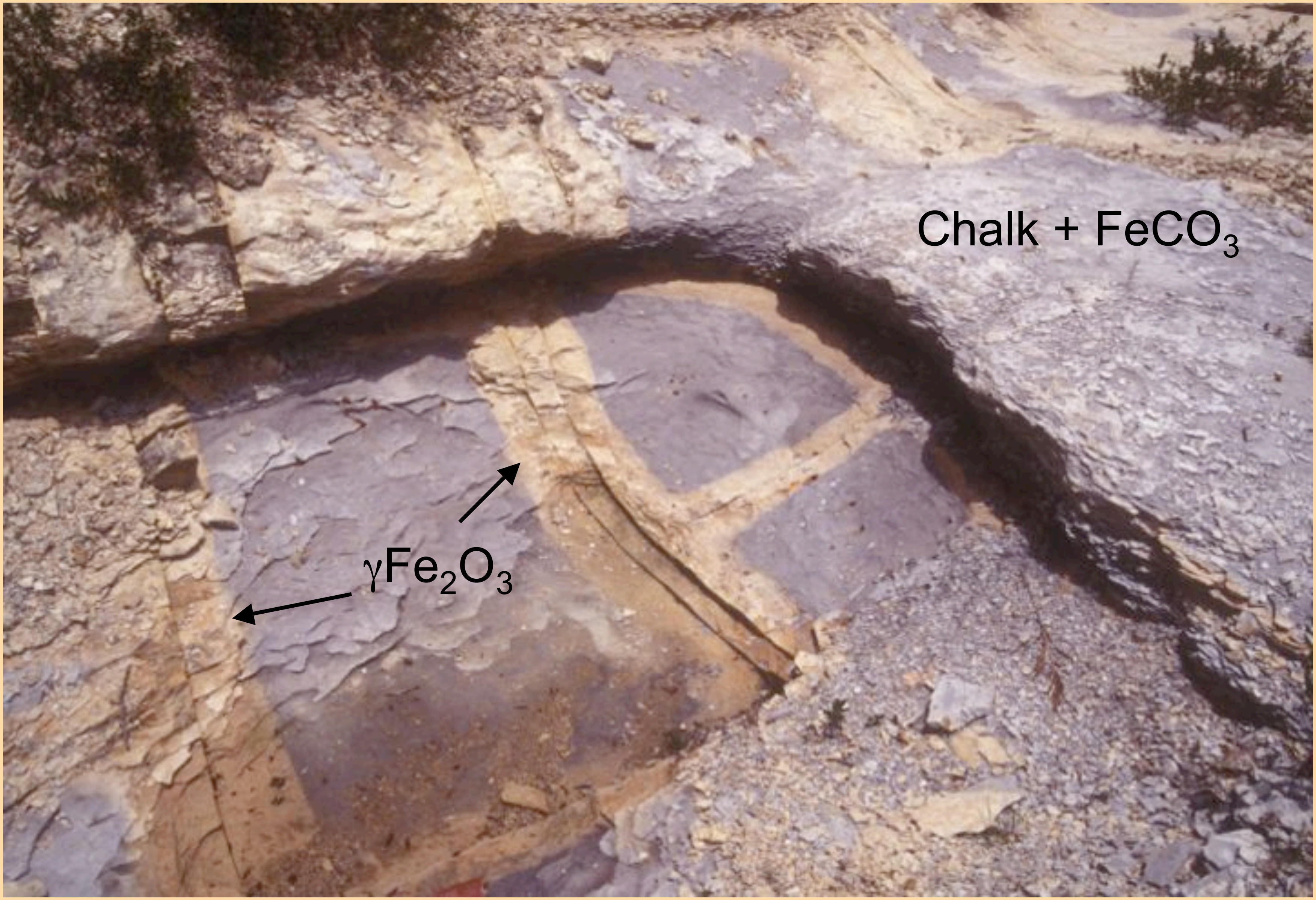
[a] Magnetic susceptibility: *** = high, ** = intermediate, * = low.

Comment: As with all instrumental analyses on rock samples there are also some problems when measuring magnetic properties - for MS work, careful field and laboratory procedures as well as high-resolution sample sets often helps to mitigate many problems

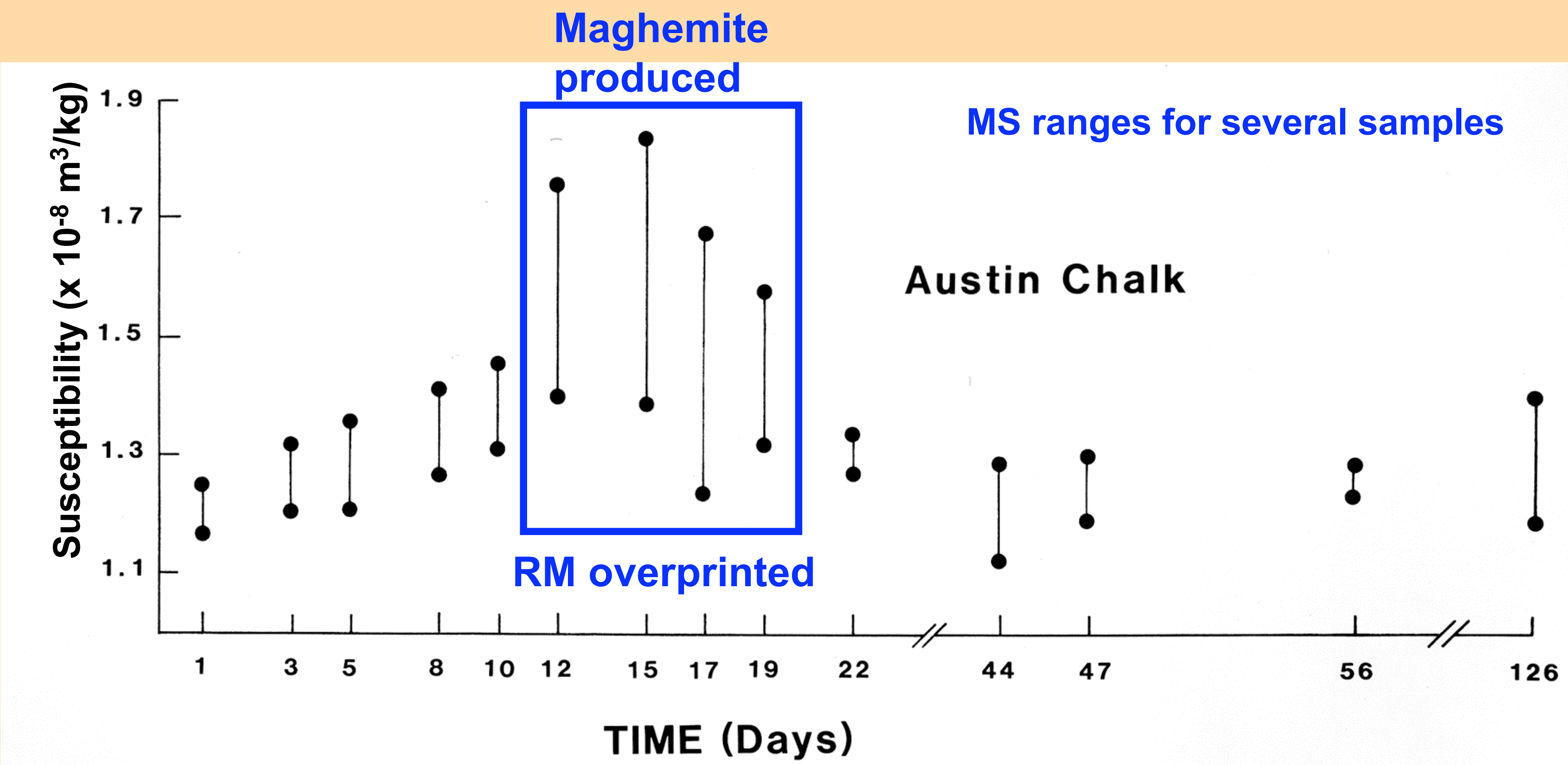
While these problems can be mitigated in MS data sets, some of these problems may cause complete remagnetization of the RM in rocks, destroying RM utility

Remagnetization in most rocks only affects the RM in these rocks; e.g. heating at low temperature for long periods of time often remagnetizes the RM signature of those rocks

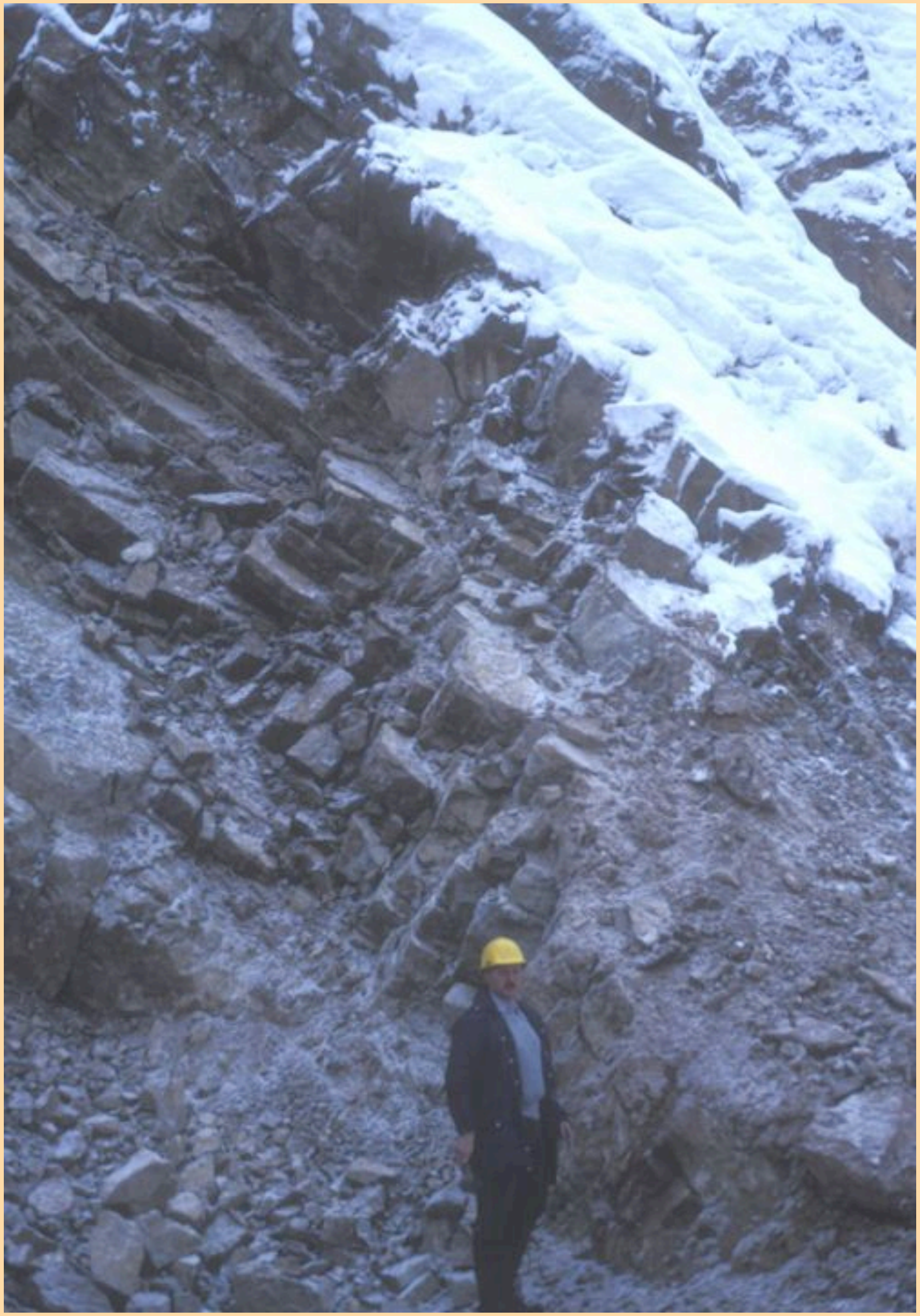
Natural Oxidation - Liesgand Structures in Austin Chalk



Progressive natural breakdown in air of siderite within a chalk

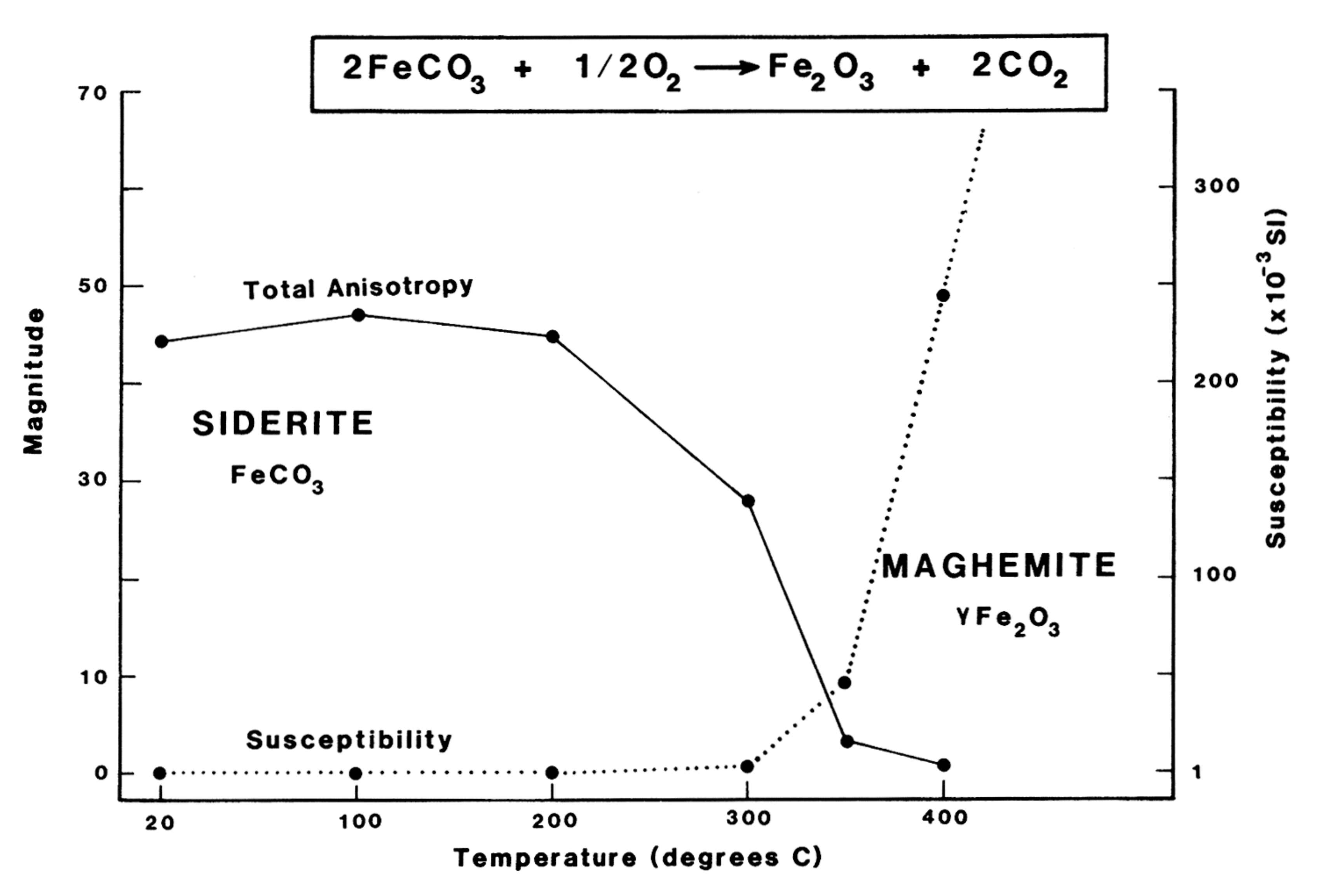


MS can be recovered and is not radically altered

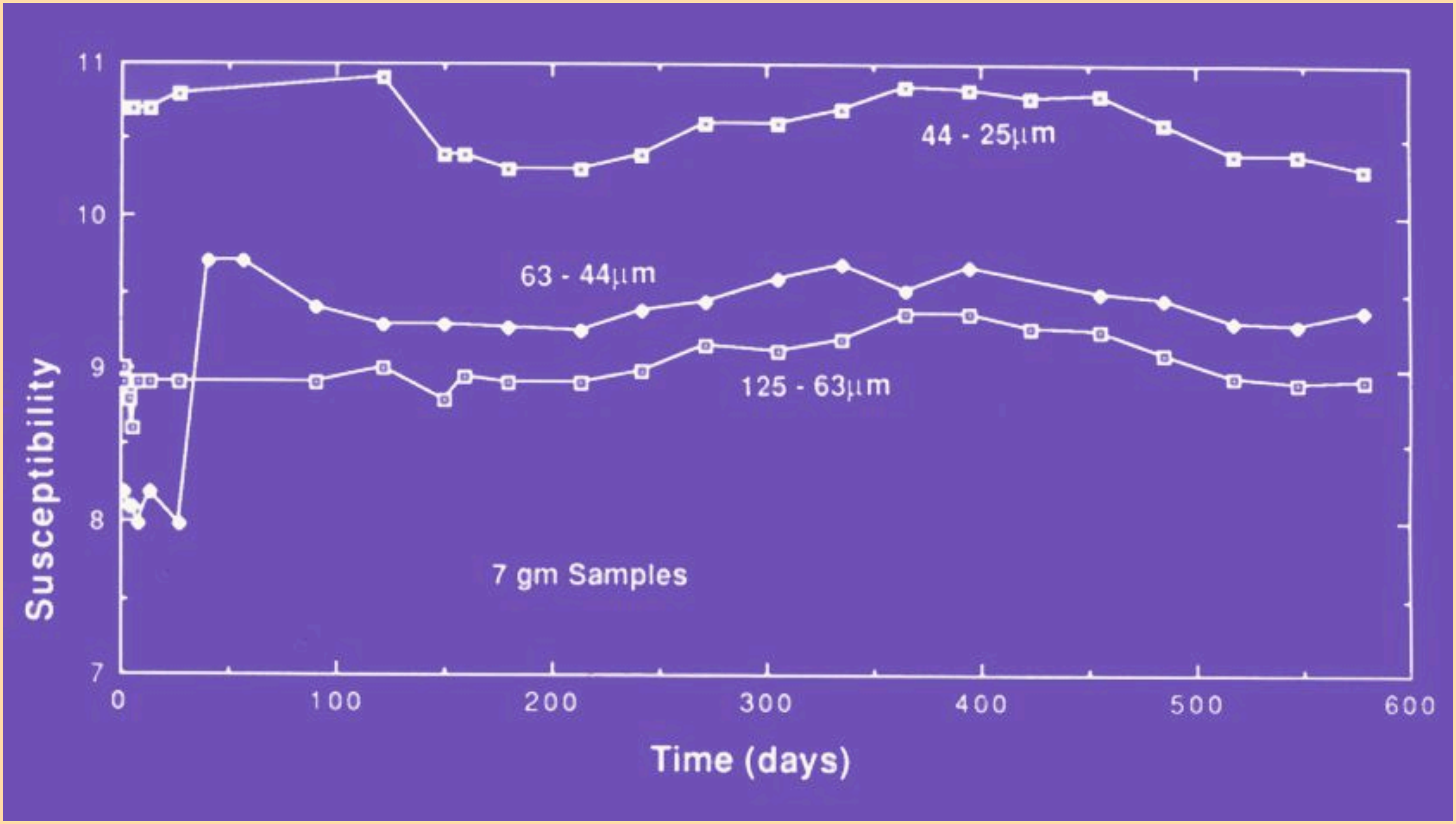


Austrian siderite mine - source of experimental samples

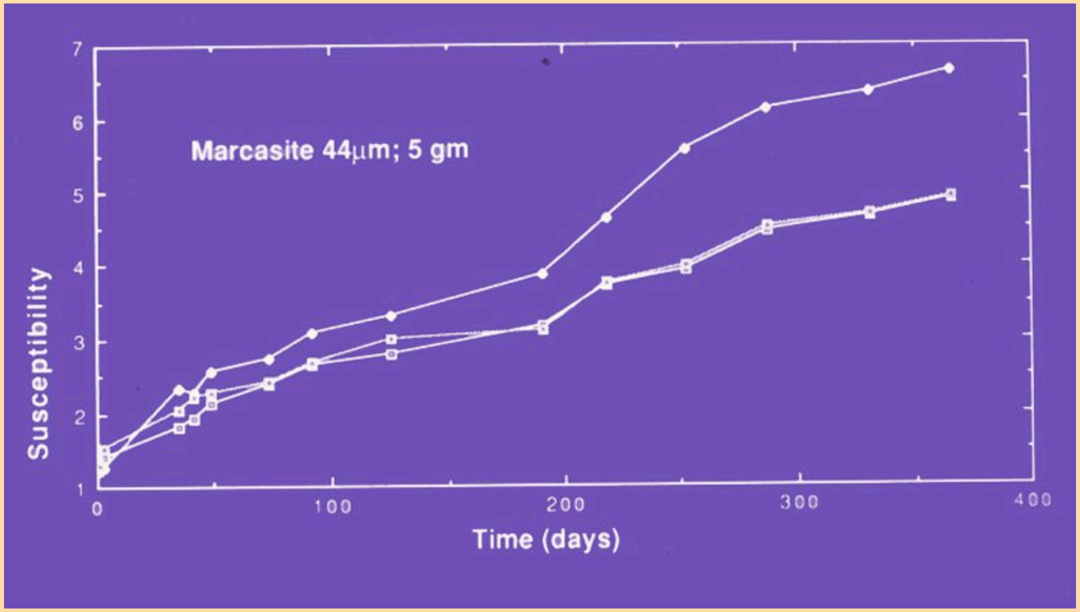
Siderite breakdown with increasing temperature

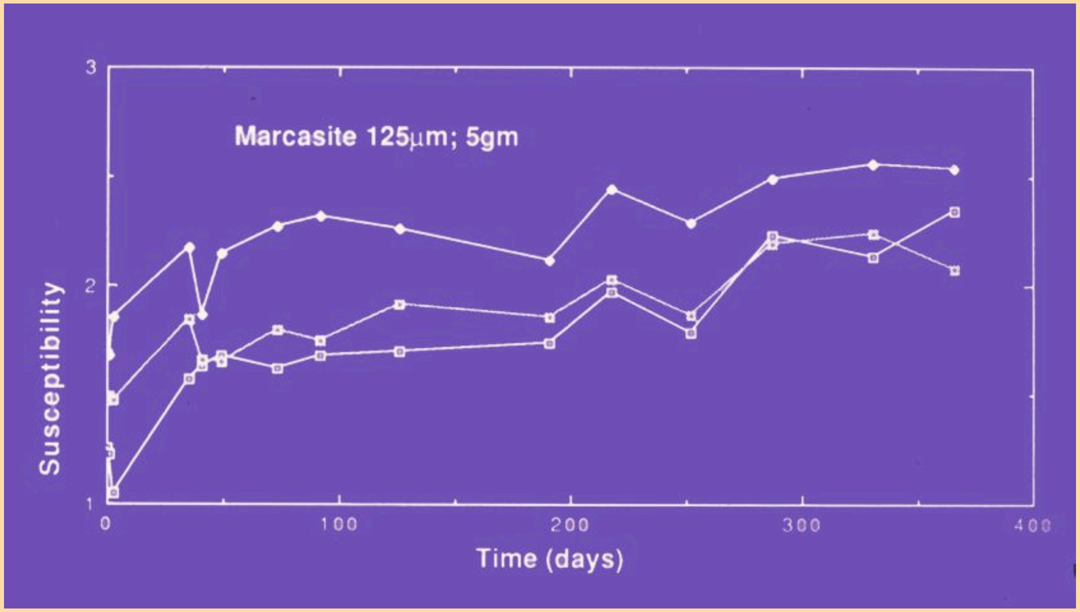


Natural alteration of siderite samples - 3 size ranges



Natural alteration of marcasite samples - 2 sizes

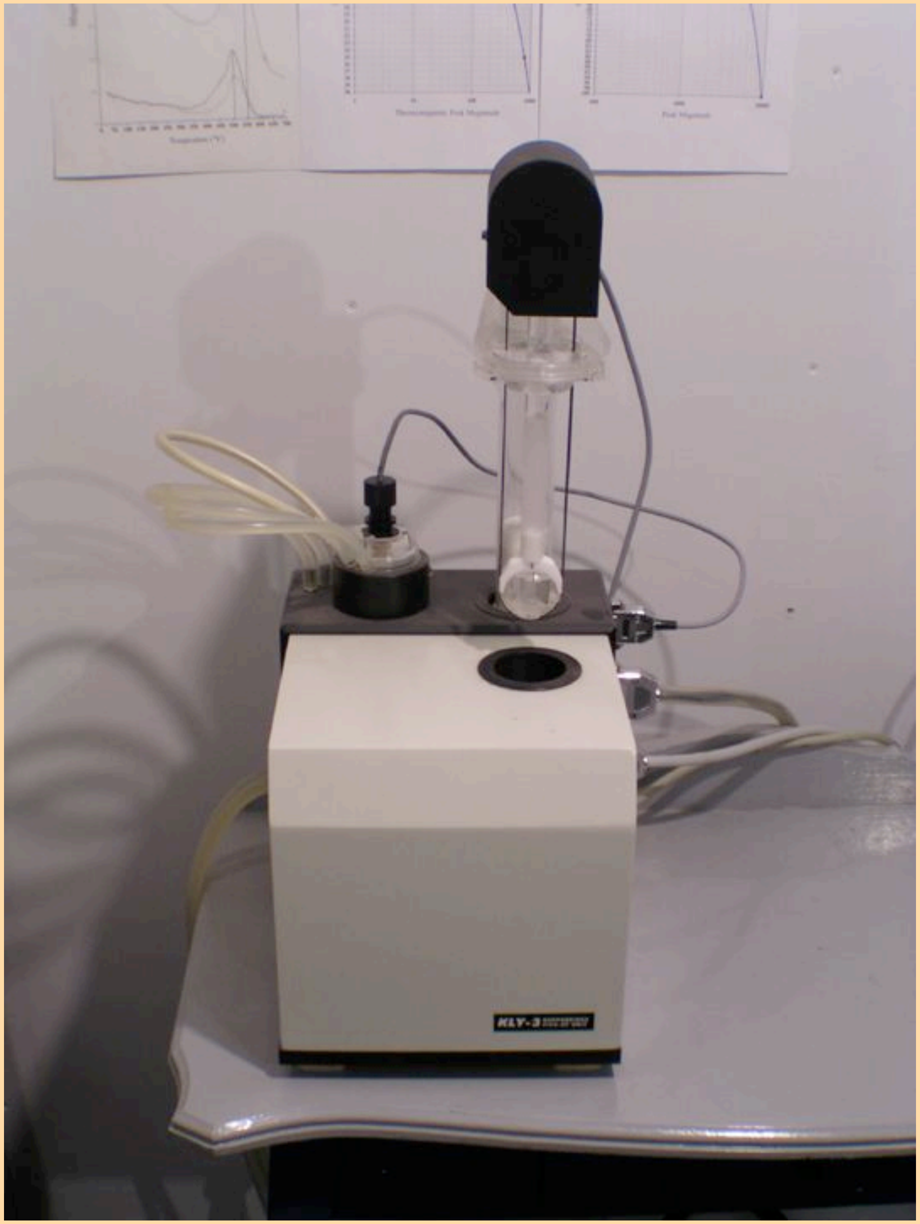




Evaluating MS samples using Thermomagnetic measurements

KLY 3S Kappabridge at LSU

Used for AMS measurement



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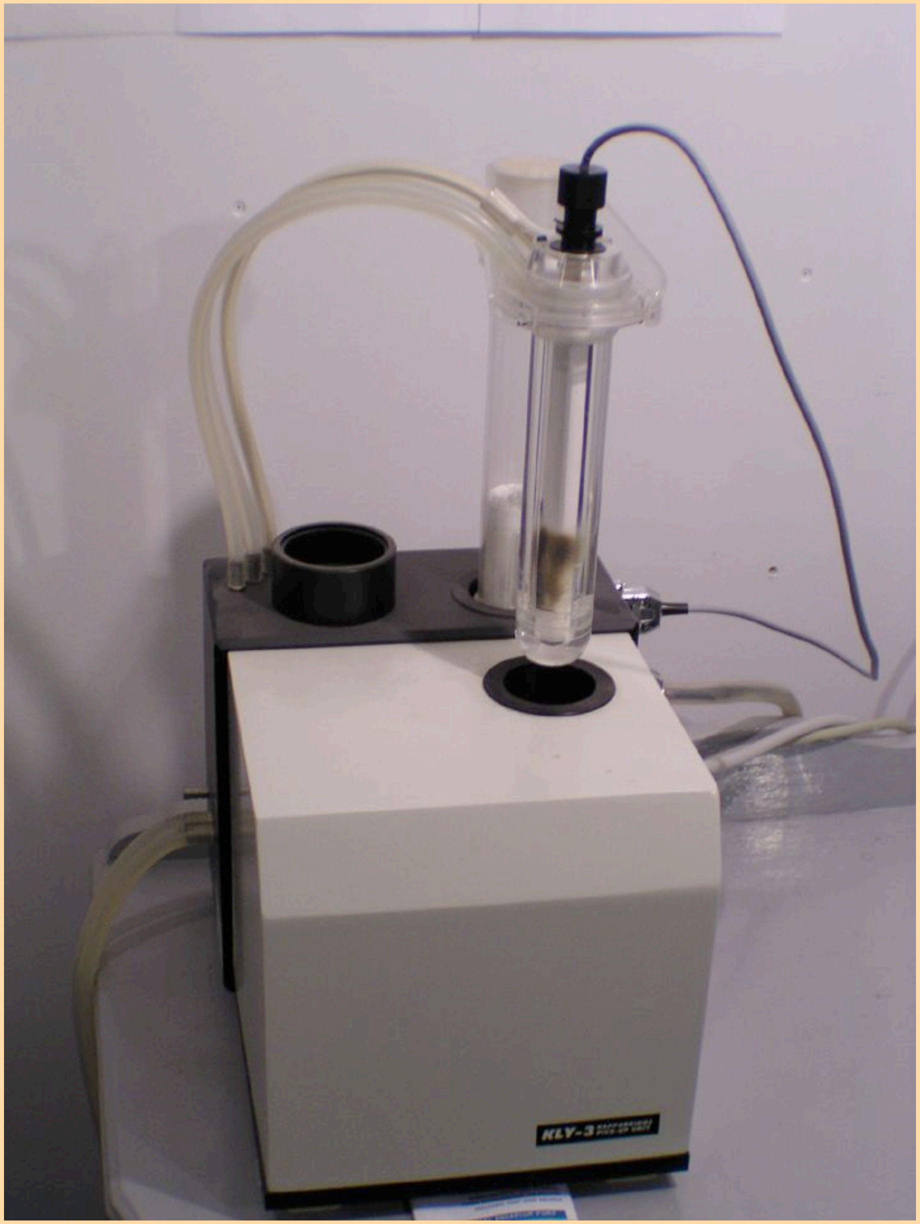
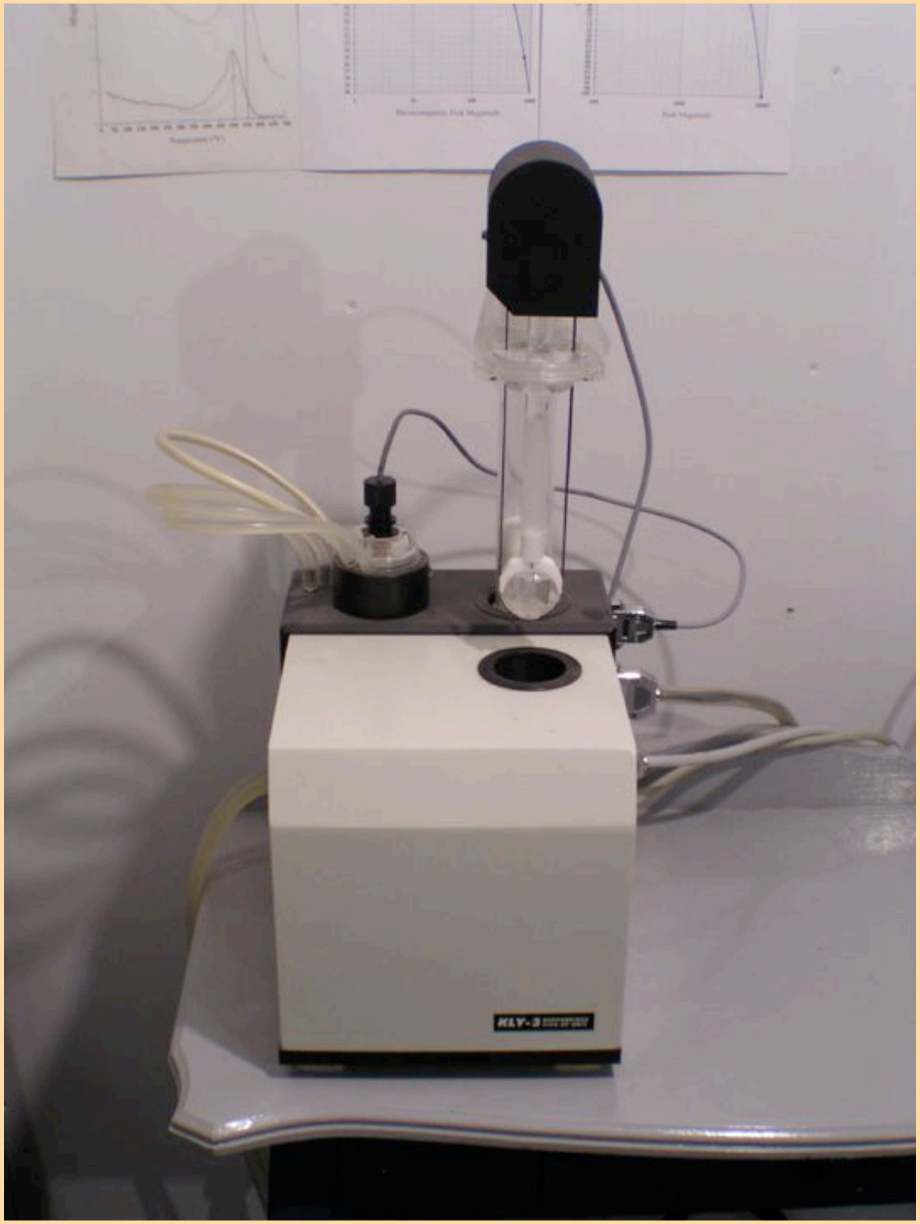
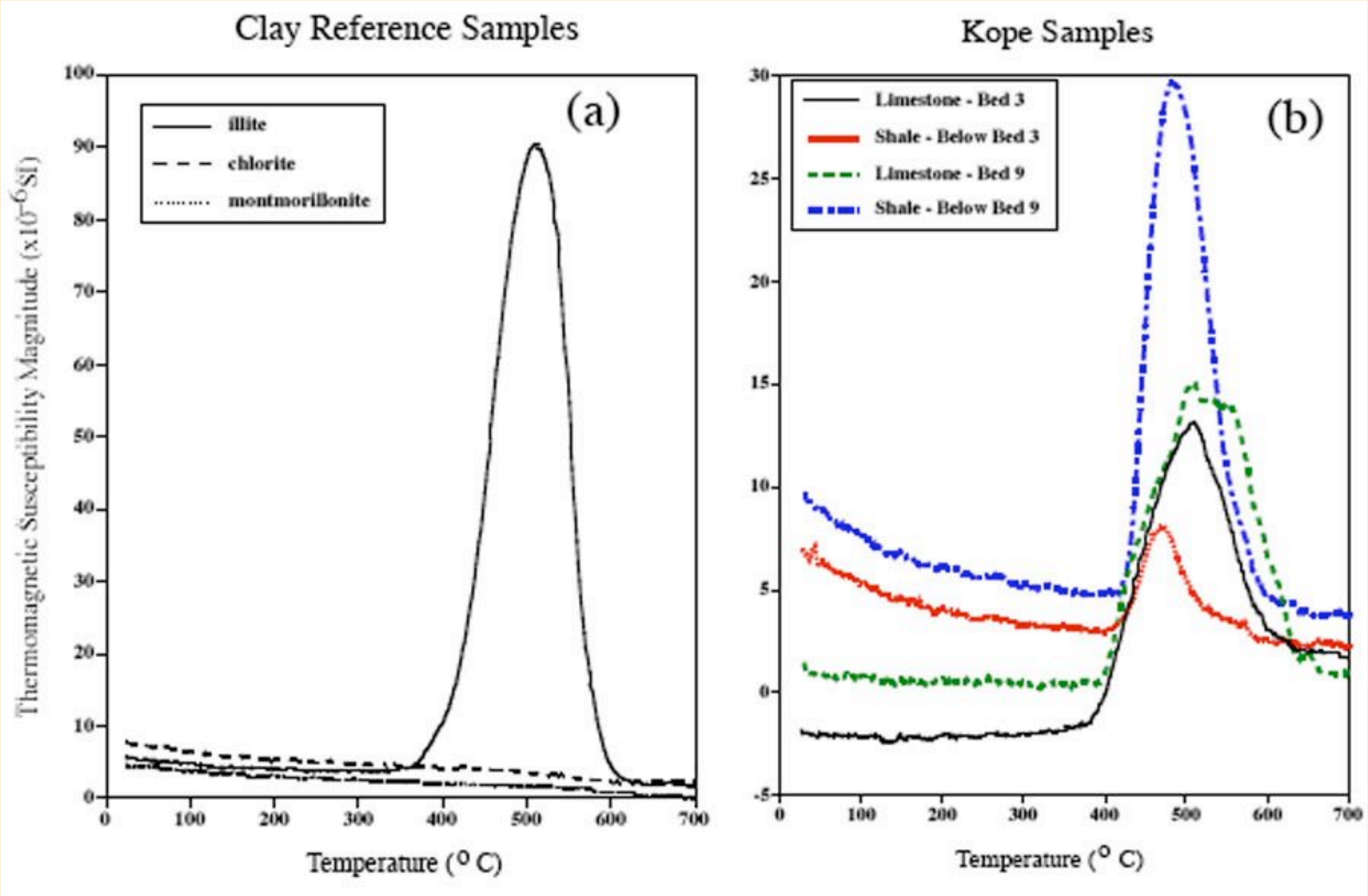
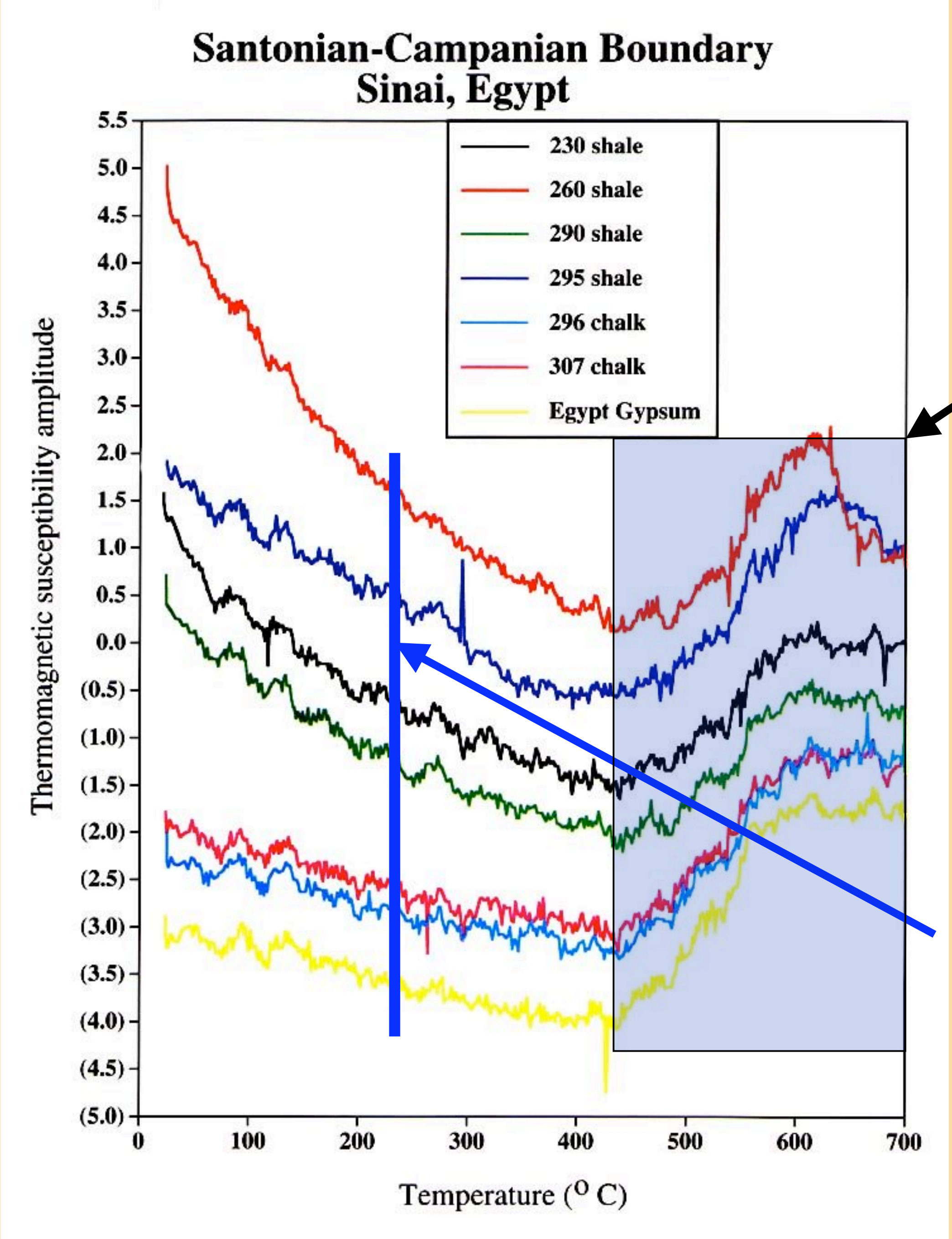




Identifying Illite as the Primary Source of the MS in some samples

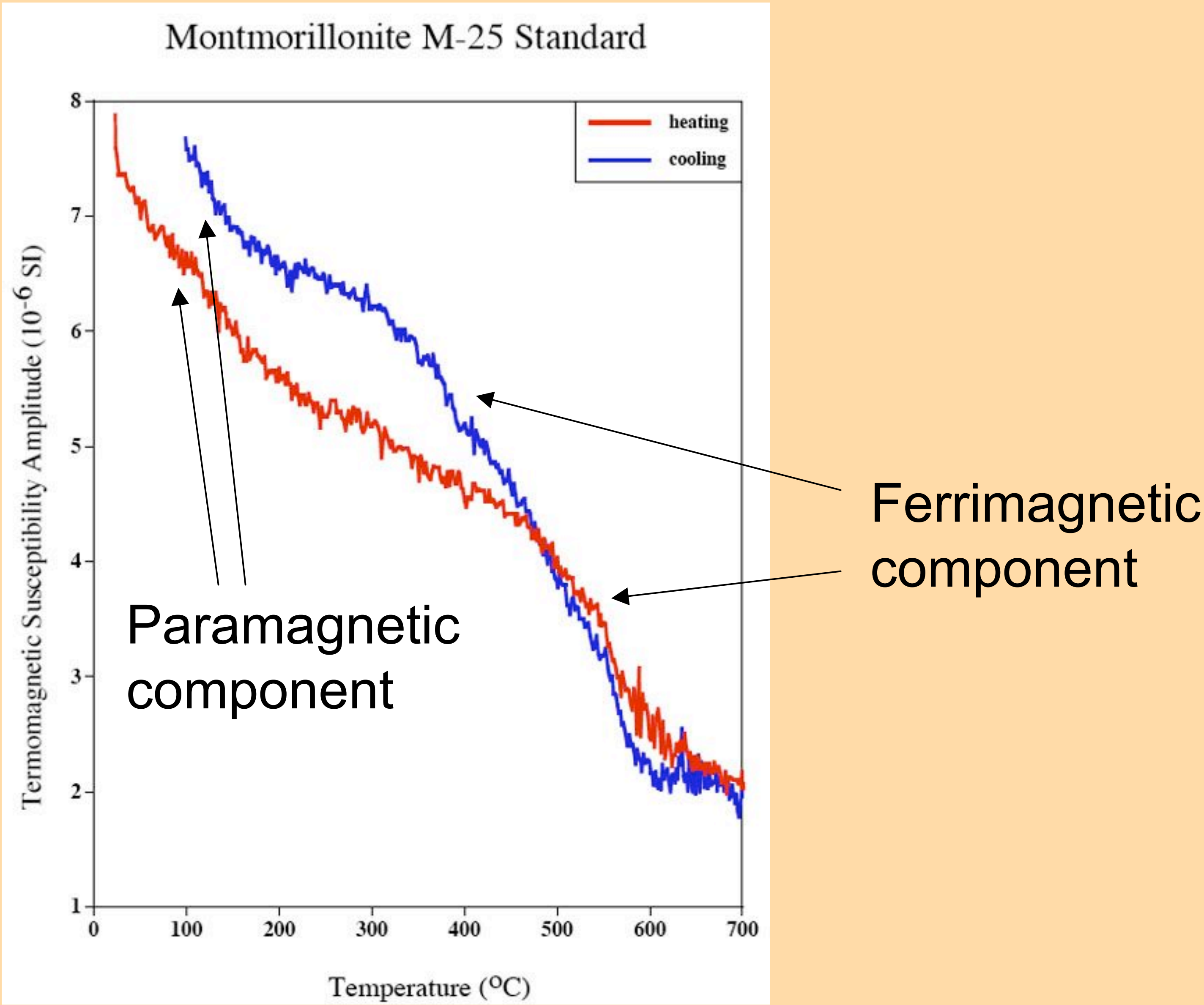




Instrumental problem: A contaminated sample holder

Paramagnetic minerals dominate

Thermal Evaluation of Montmorillonite Standards



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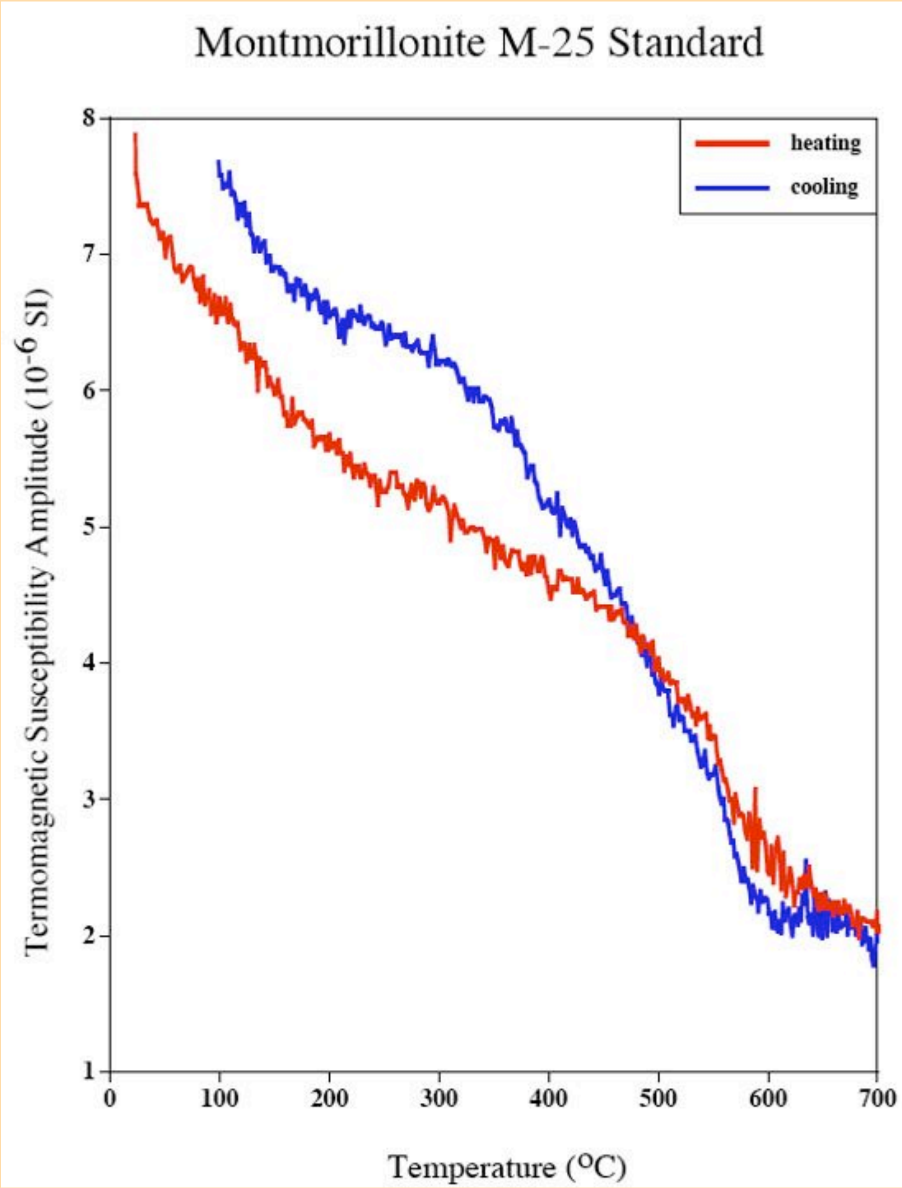

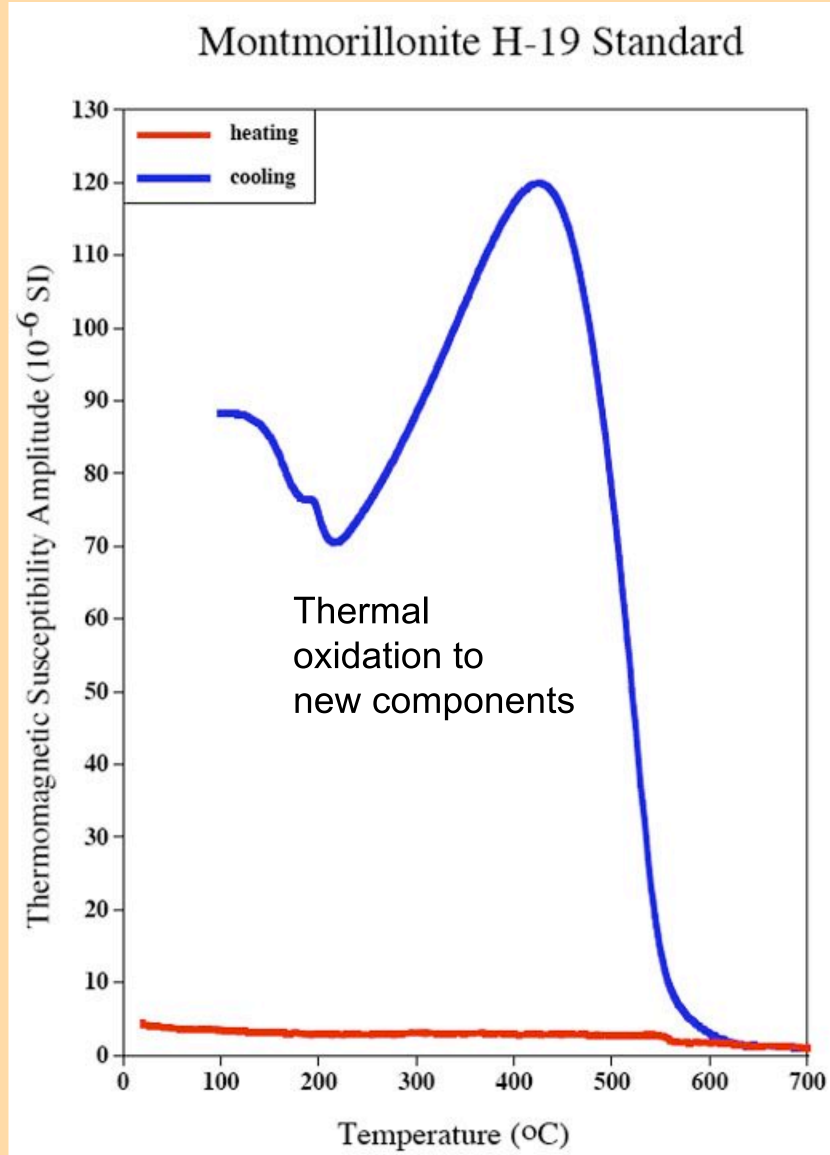

What are the truly global processes that we can use in stratigraphic analyses? Changes driving global erosion

Climate - climate proxies
Eustacy - proxies for eustacy

What are the truly global processes that we can use in stratigraphic analyses? Changes driving global erosion? How can they be used for global correlation?

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Eustacy - proxies for eustacy

What can be used as proxies for climate and eustacy?

certain geochemical parameters - $\delta^{18}O$
due to changes in ice volume

MS trends (variations not absolute magnitudes)
monitors the total contribution of the detrital/aeolian components due to base-level or rainfall erosion rate changes

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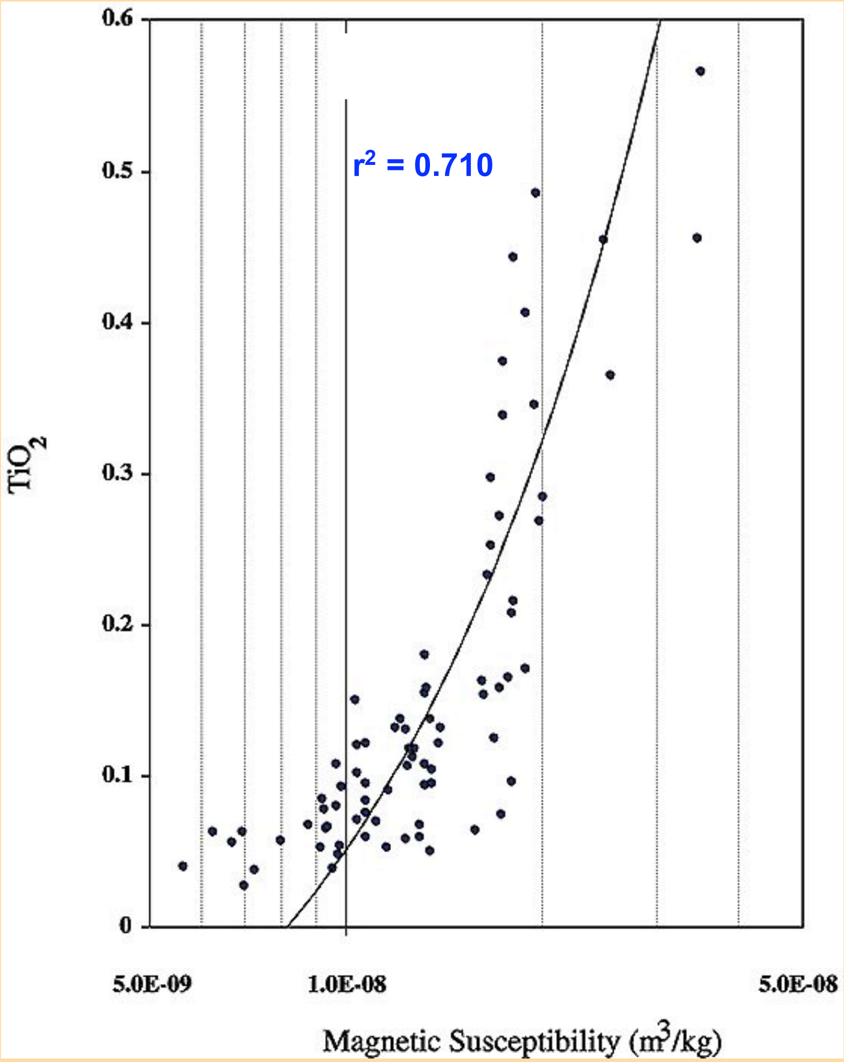
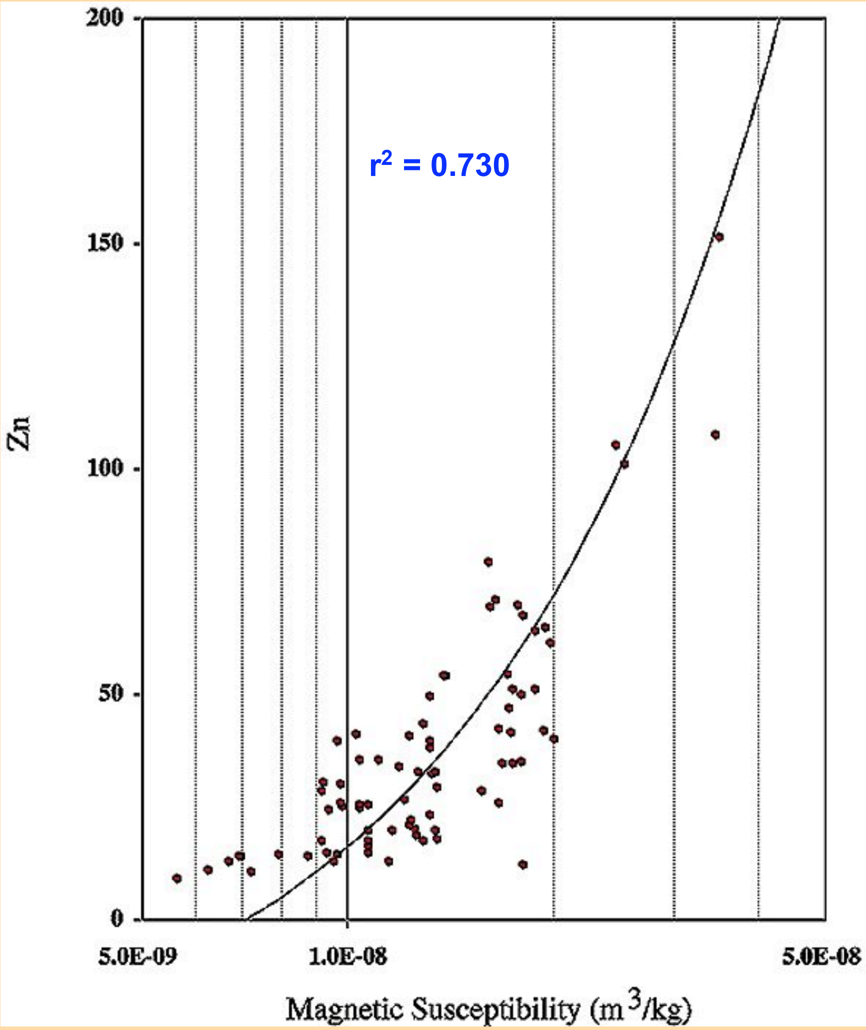
  - **due to changes in ice volume**

- **MS trends (variations not absolute magnitudes)**
  - **monitors the total contribution of the detrital/aeolian components due to base-level or rainfall erosion rate changes**

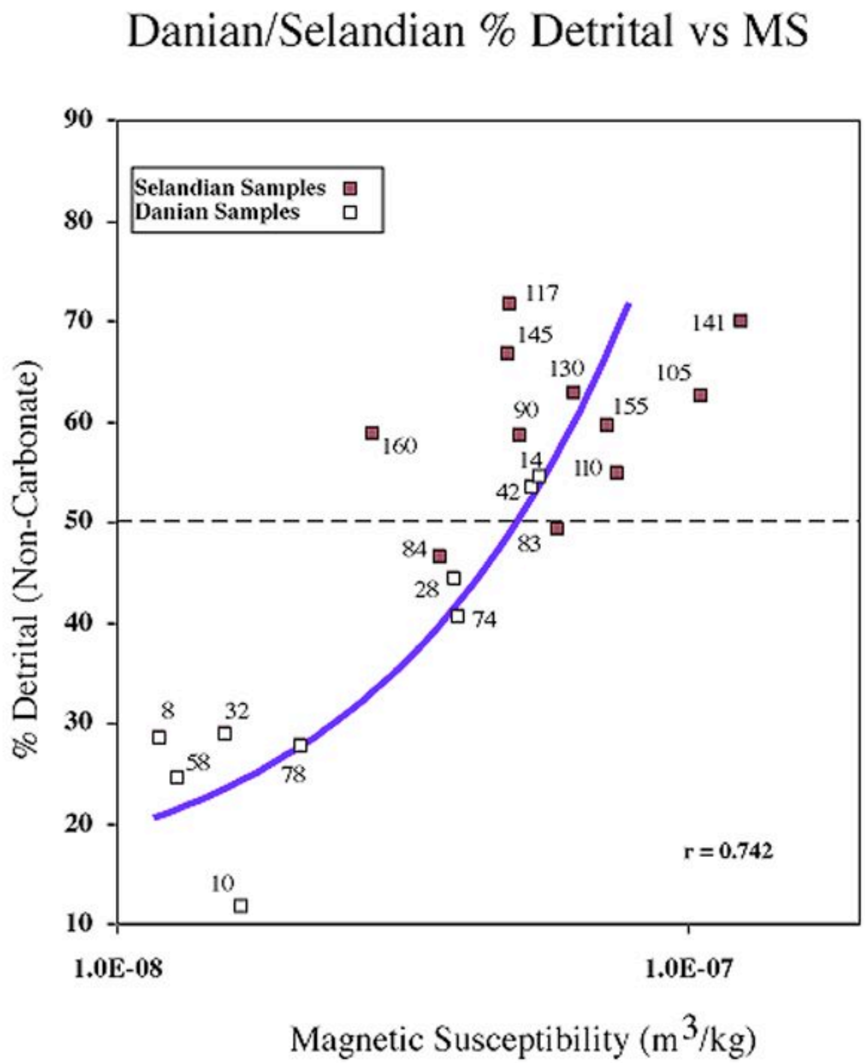
Where do we agree? We agree that MS is controlled by the detrital/aeolian components in marine rocks

Cenomanian-Turonian GSSP



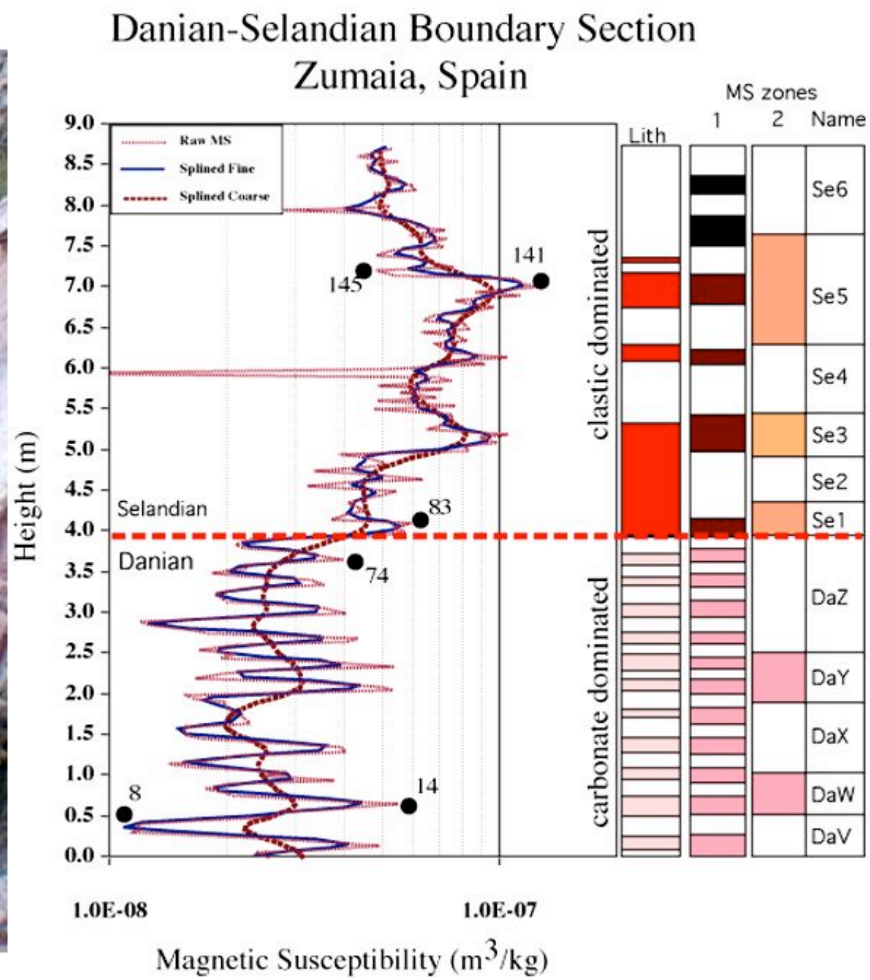


MS is highly correlated to detrital chemistry

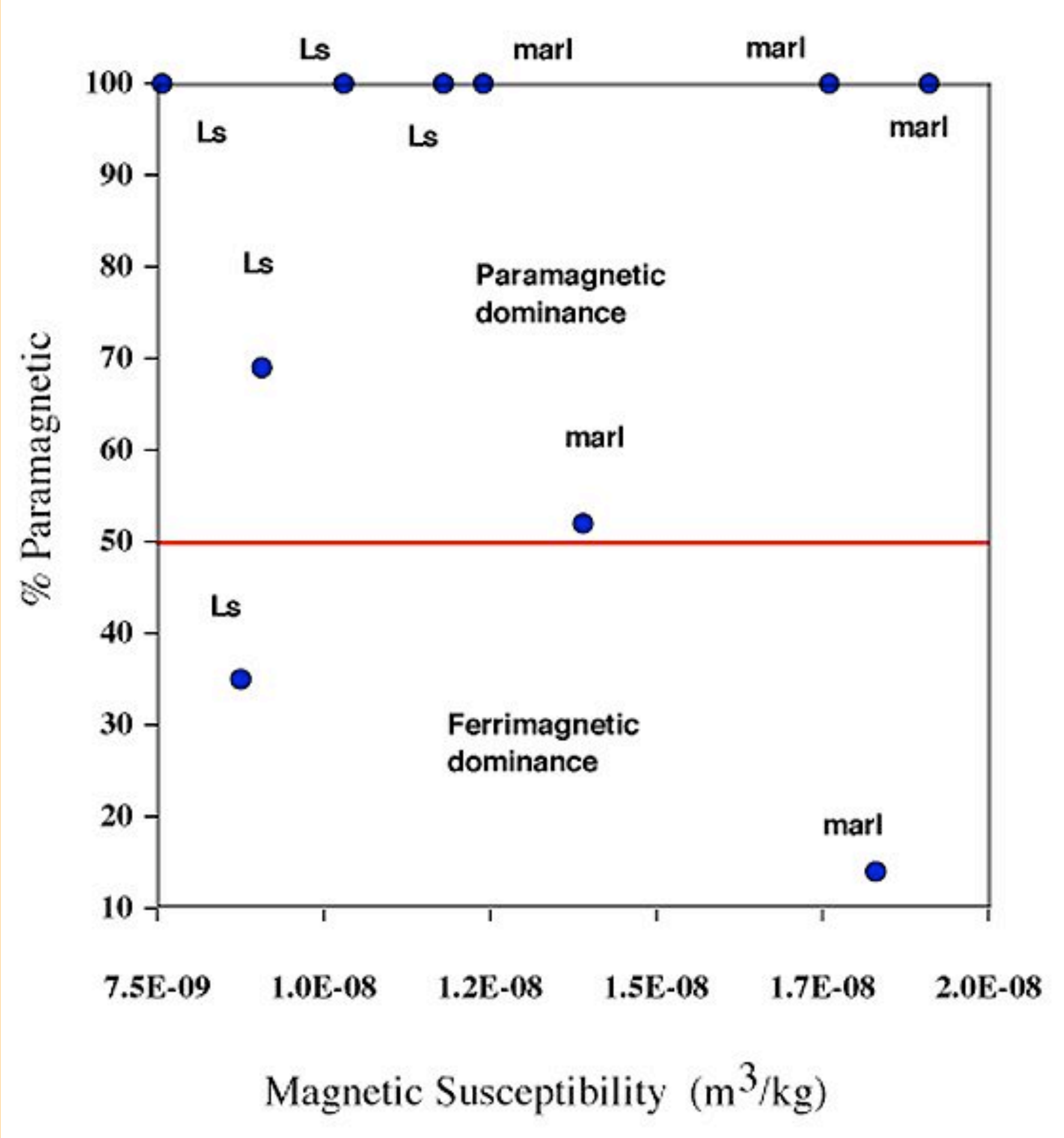


(Ellwood et al., 2008)

Lower Paleogene Danian-Selandian Proposed GSSP - Zumaia, Spain

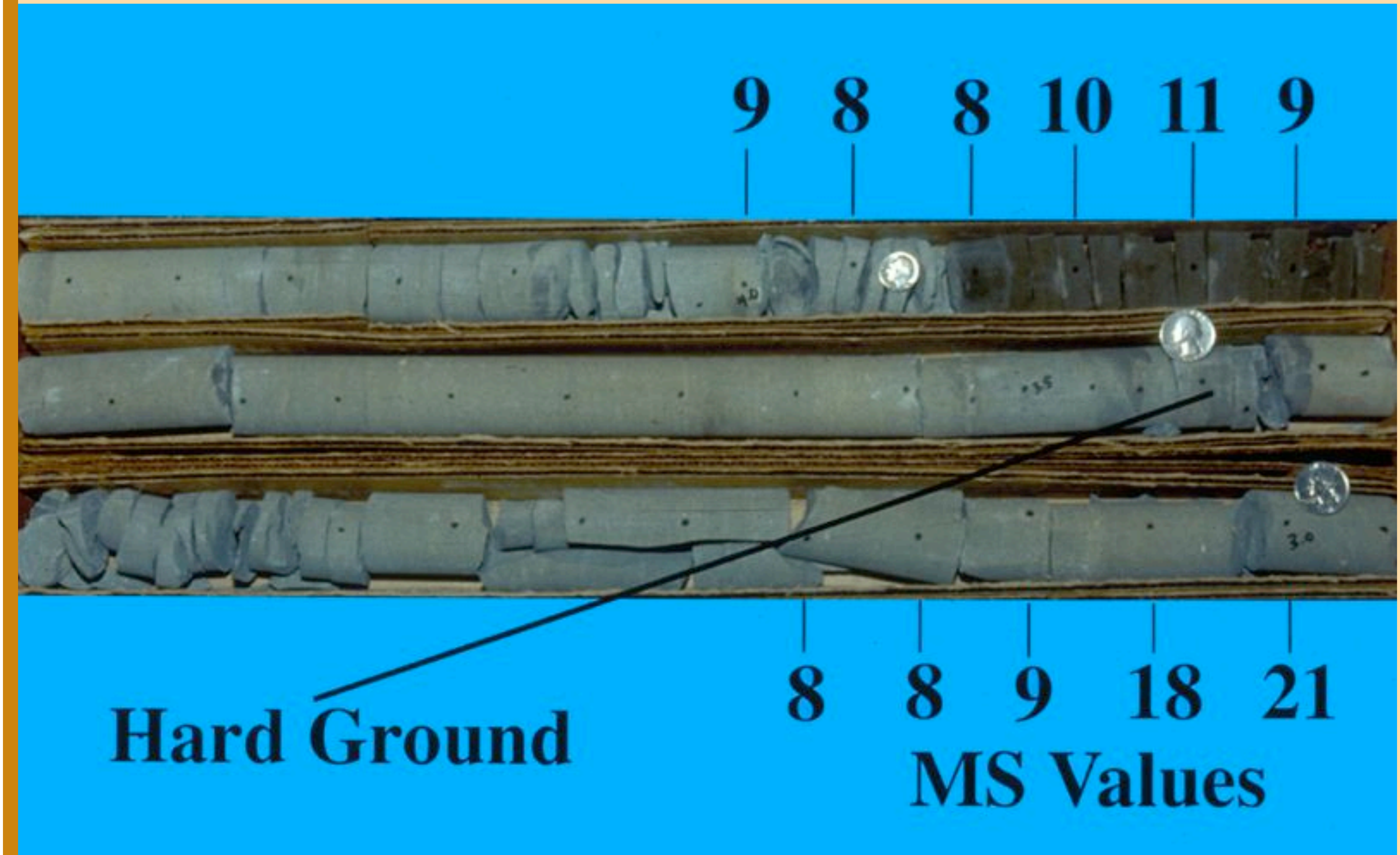


(Ellwood et al., 2008.)



Kappa-bridge data

(Ellwood et al., 2008)



In many cases MS varies independently of macrolithology

(Ellwood et al., 2007)

References Supporting MS control by detrital components:

Barthès et al. (1999): "**Magnetic susceptibility of deep-sea sediments is often a sensitive indicator of the supply of terrigenous material to the sedimentary environment [1–6].**"

Mayer and Appel (1999): "**The excellent negative correlation between susceptibility and carbonate content verifies that the susceptibility signal reflects the concentration of the non-carbonate fraction, hence a primary depositional feature**"

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Barthès et al. (1999): "**Magnetic susceptibility of deep-sea sediments is often a sensitive indicator of the supply of terrigenous material to the sedimentary environment [1–6].**"

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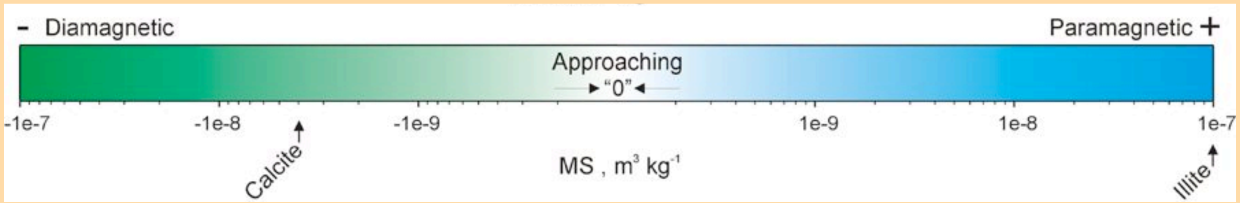
This leads to the question concerning carbonate variations and its effect on MS. But first, three important points:

1. If the %non carbonate content (siliceous, organic and detrital components) varies, %carbonate must vary inversely

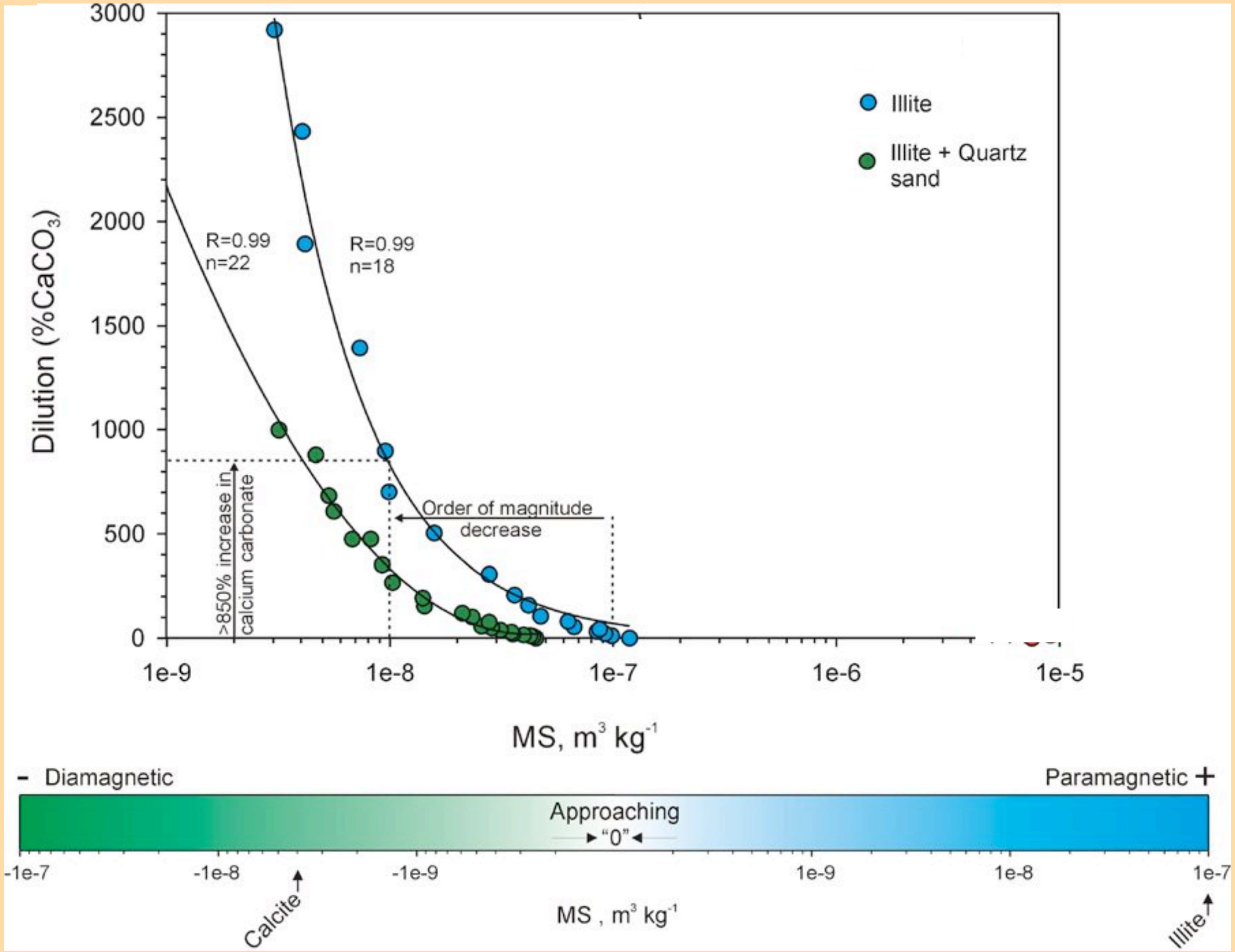
2. The carbonate, siliceous and organic components are diamagnetic

3. The carbonate content is easy to measure and therefore reported

The main question then is: What is the primary control on the magnetic susceptibility of samples - carbonate or detrital dilution?



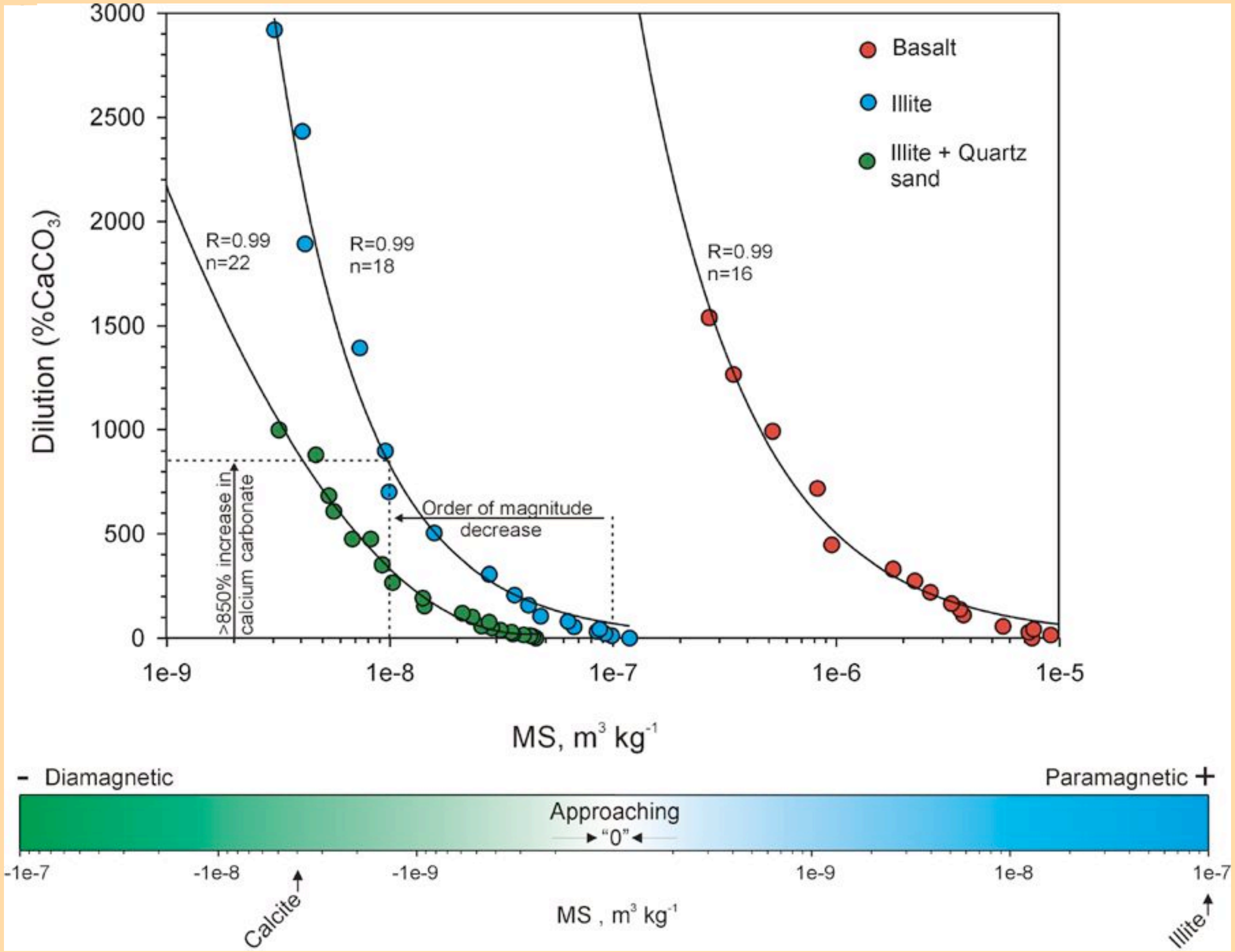
(Febo, 2008)



Dilution (%CaCO3)
3000
2500
2000
1500
1000
500
0
Illite
Illite + Quartz sand
R=0.99
n=22
R=0.99
n=18
>850% increase in calcium carbonate
Order of magnitude decrease
1e-9
1e-8
1e-7
1e-6
1e-5
MS, m3 kg-1
- Diamagnetic
Paramagnetic +
Approaching "0"
-1e-7
-1e-8
-1e-9
1e-9
1e-8
1e-7
Calcite
MS , m3 kg-1
Illite

(Febo, 2008)

Note: the MS data are plotted on a log scale - they show highly significant inverse correlation with %$CaCO_3$



(Febo, 2008)

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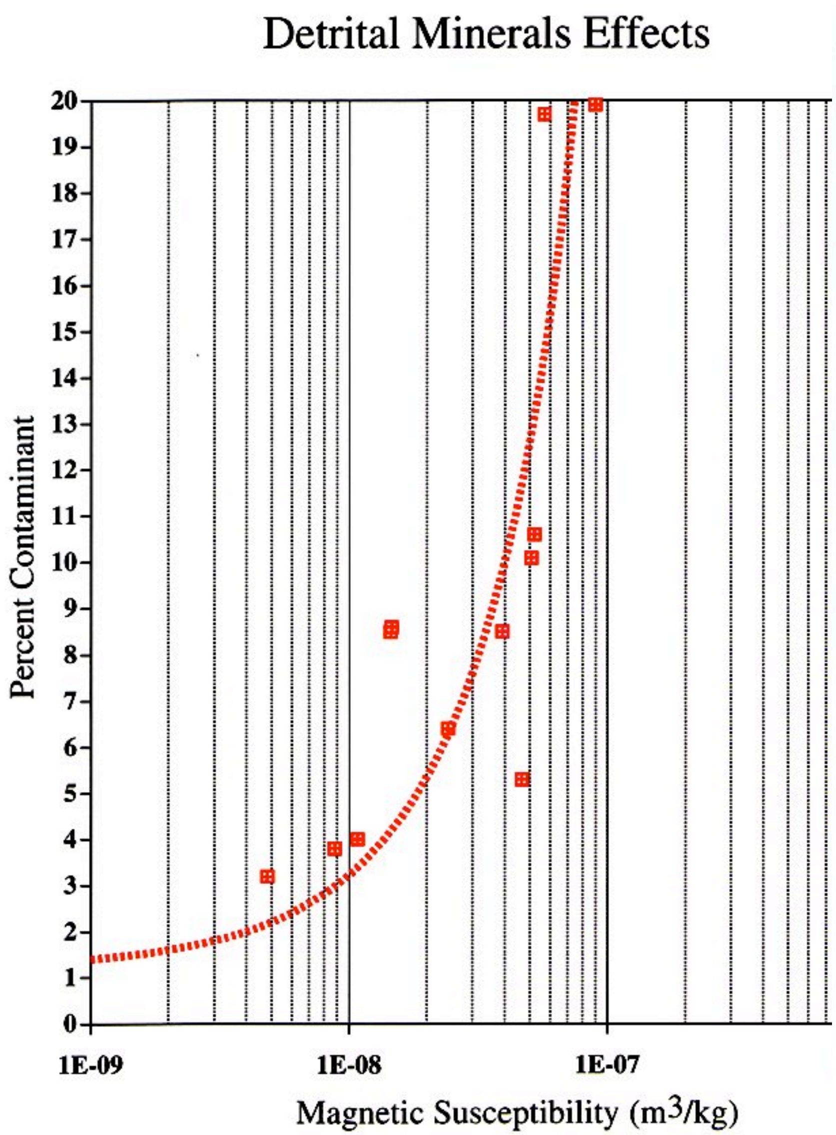
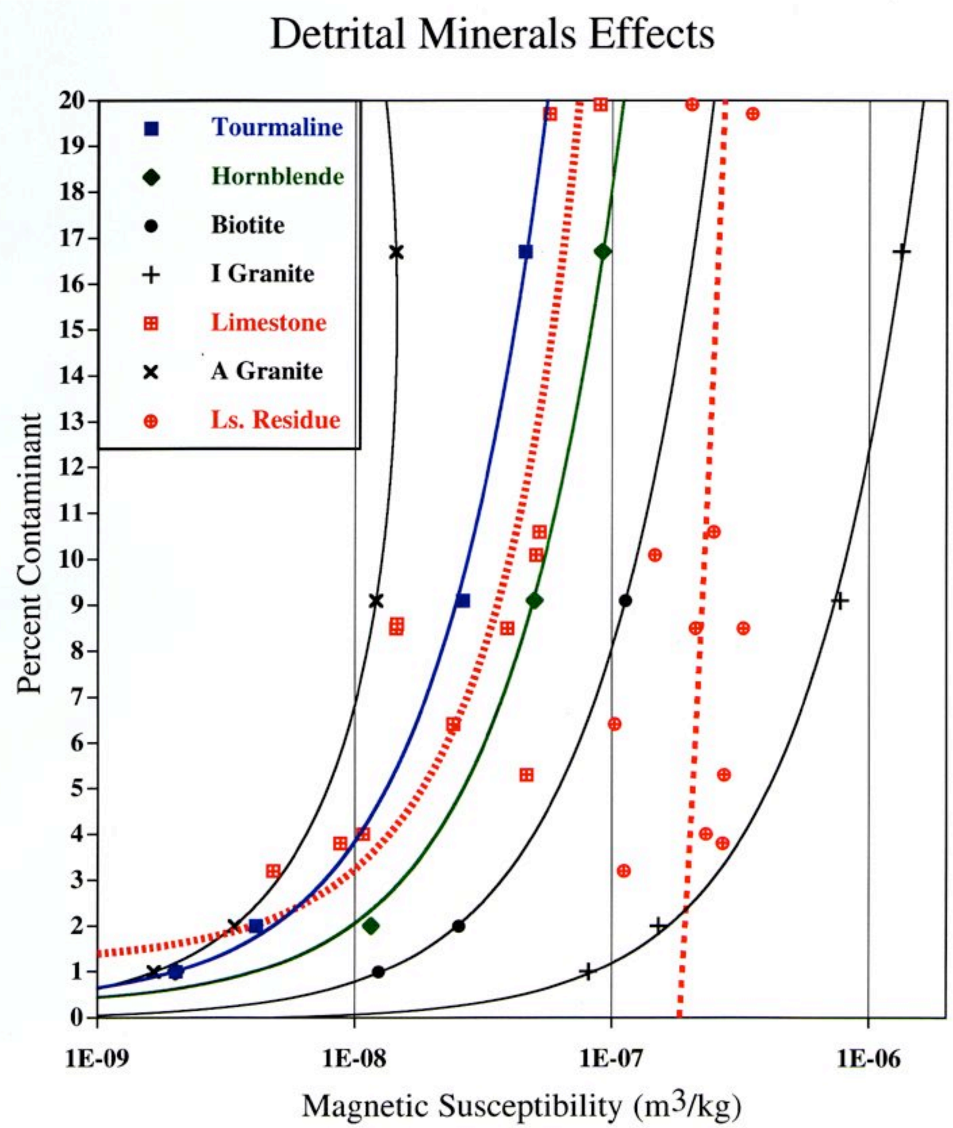
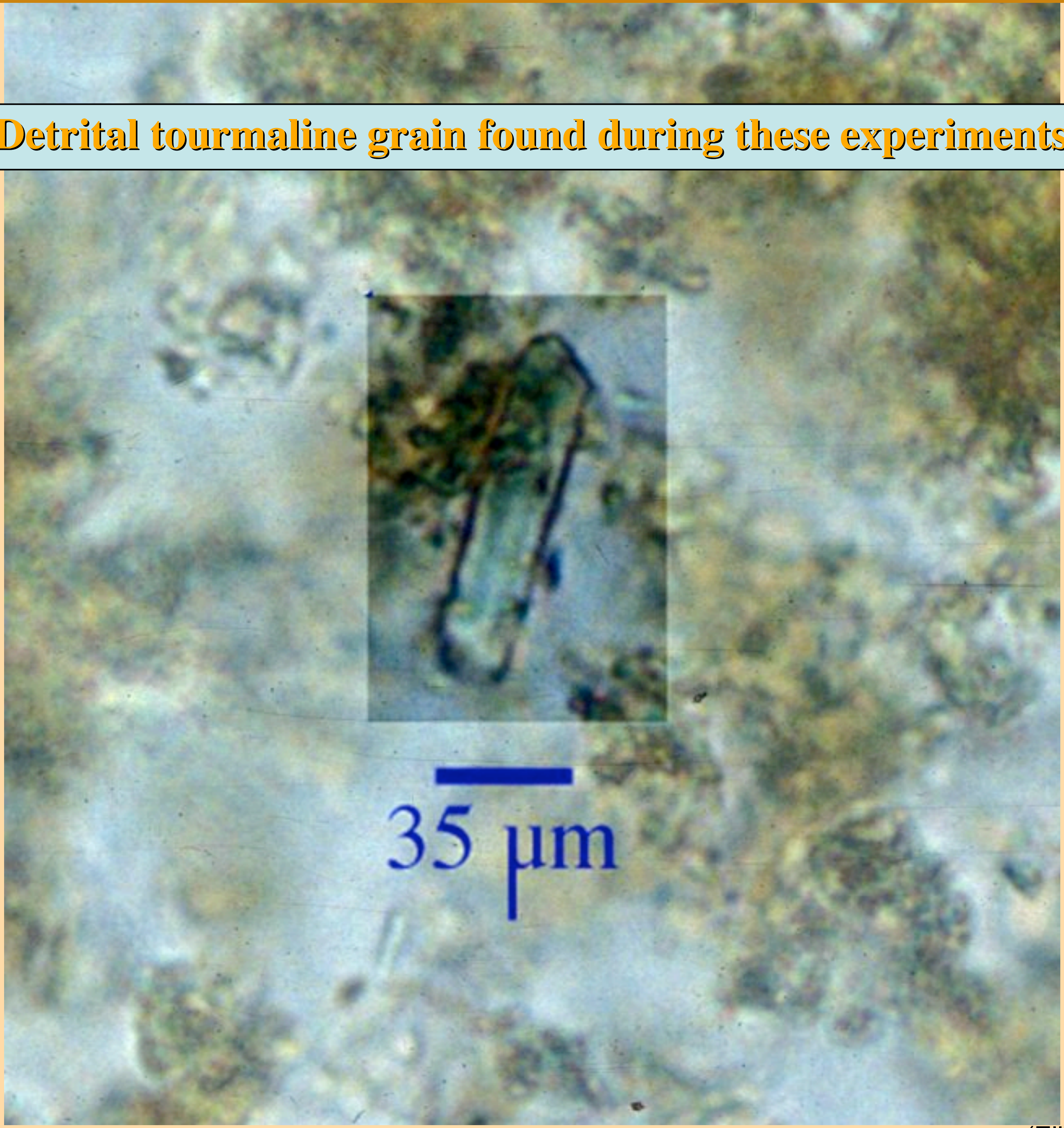




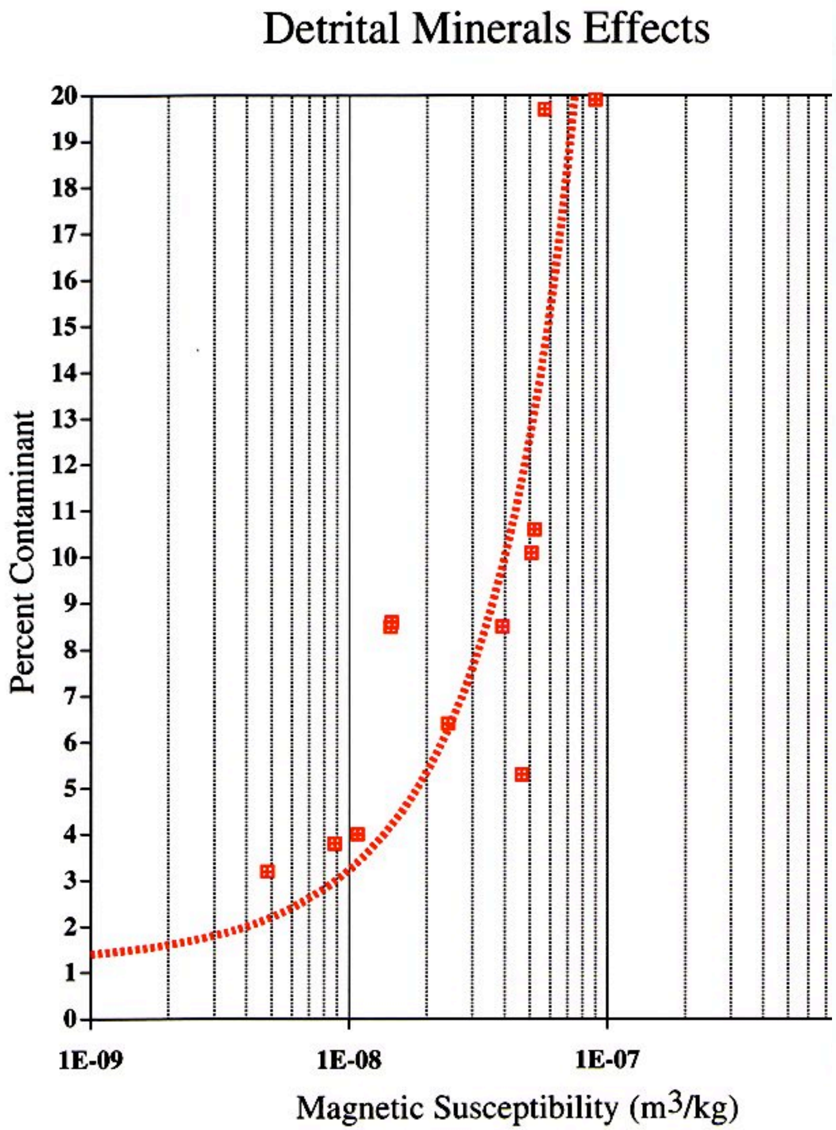
(Ellwood et al., 2000)

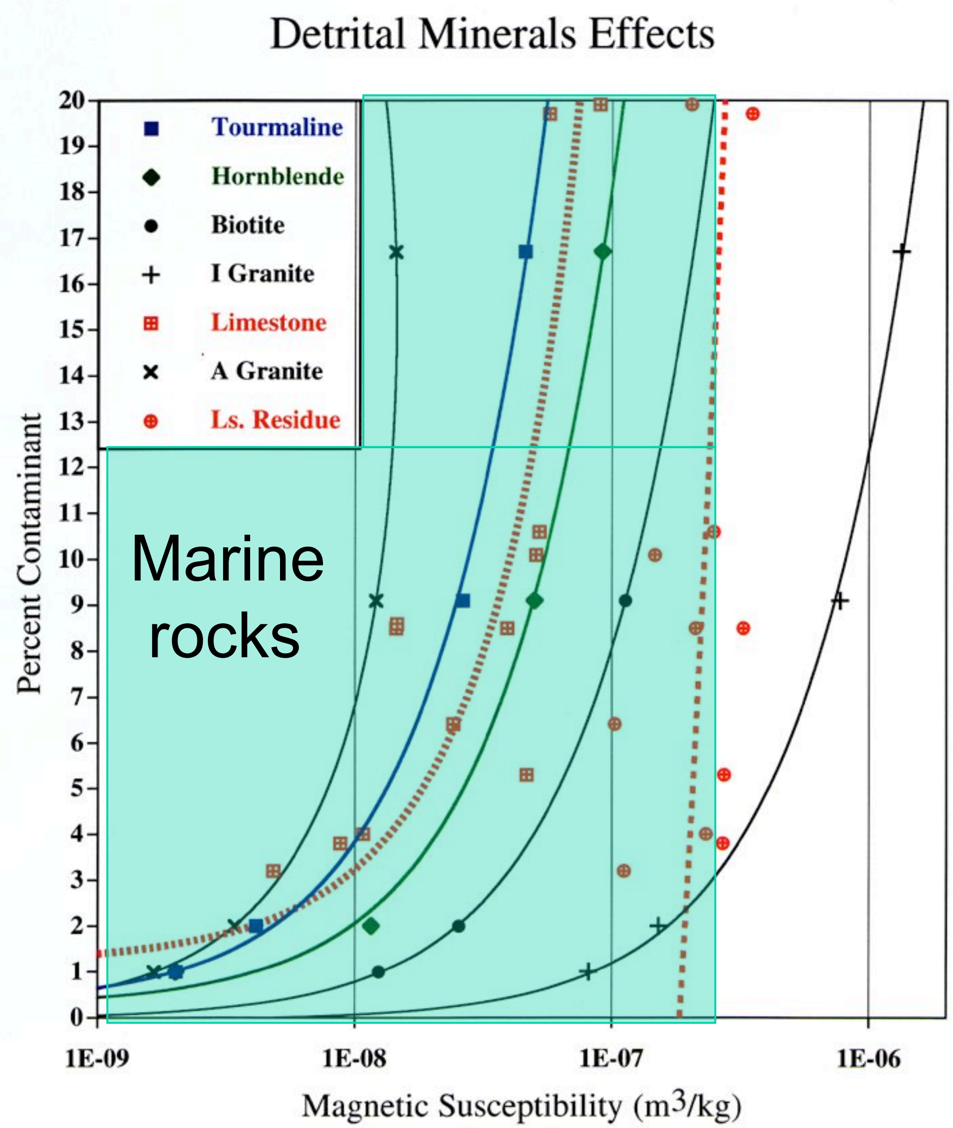
Detrital tourmaline grain found during these experiments



(Ellwood et al., 2000)

Why magnetite can't be the main MS carrier in most marine rocks, Even when the detrital/aeolian component is extremely - low <3%

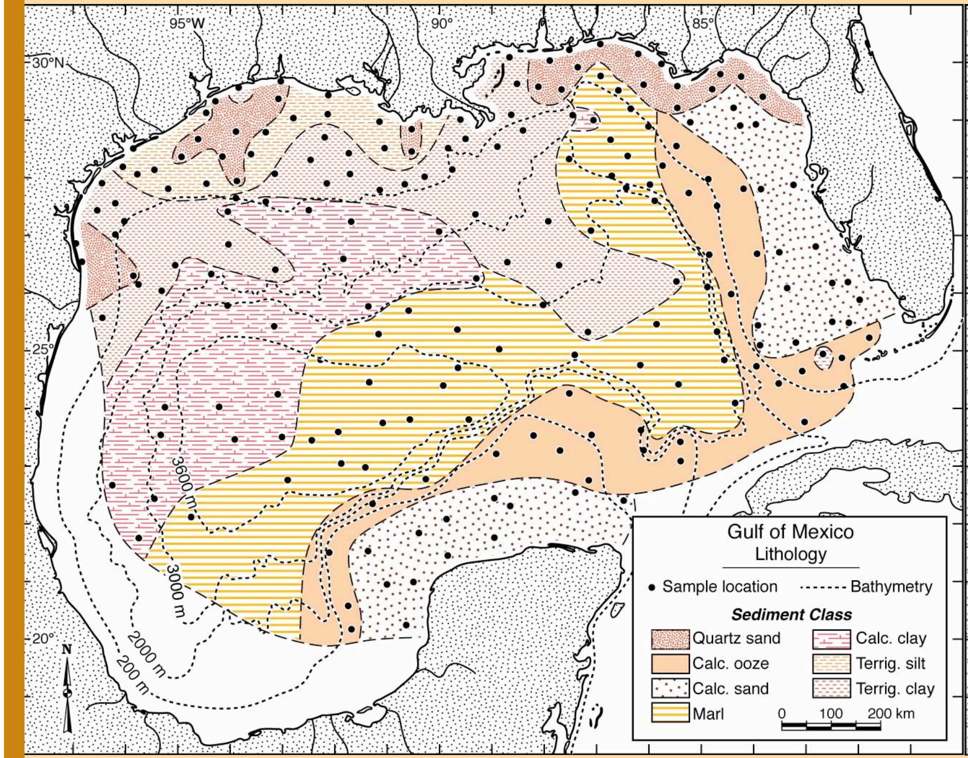


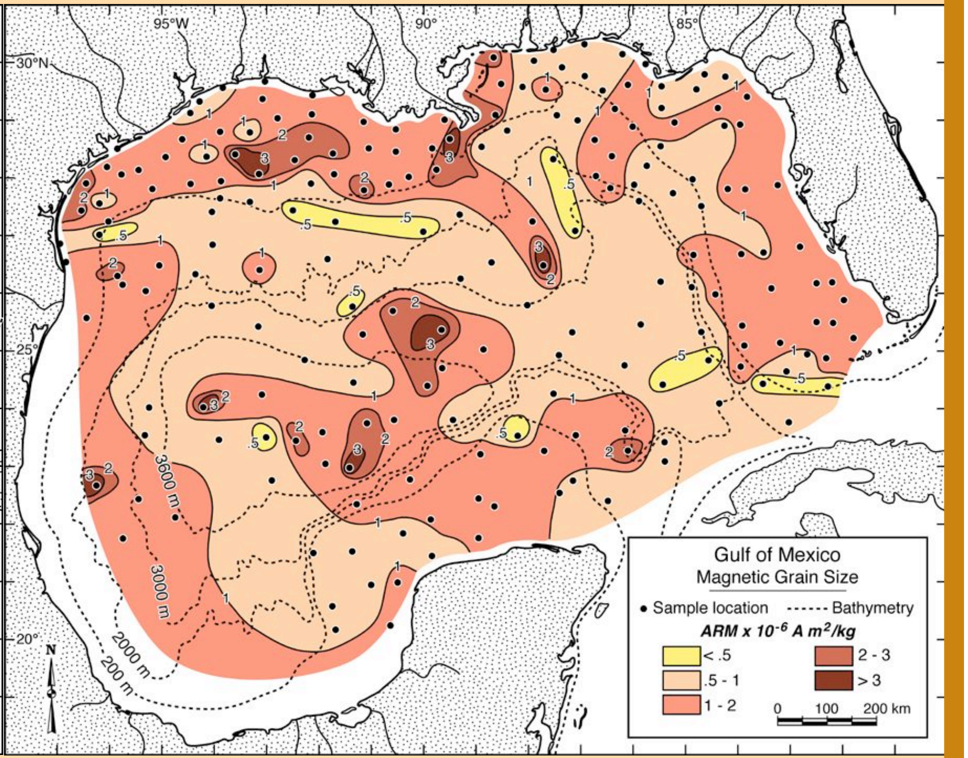


(Ellwood et al., 2000)

Lithologic variations in the Gulf

ARM variations in the Gulf



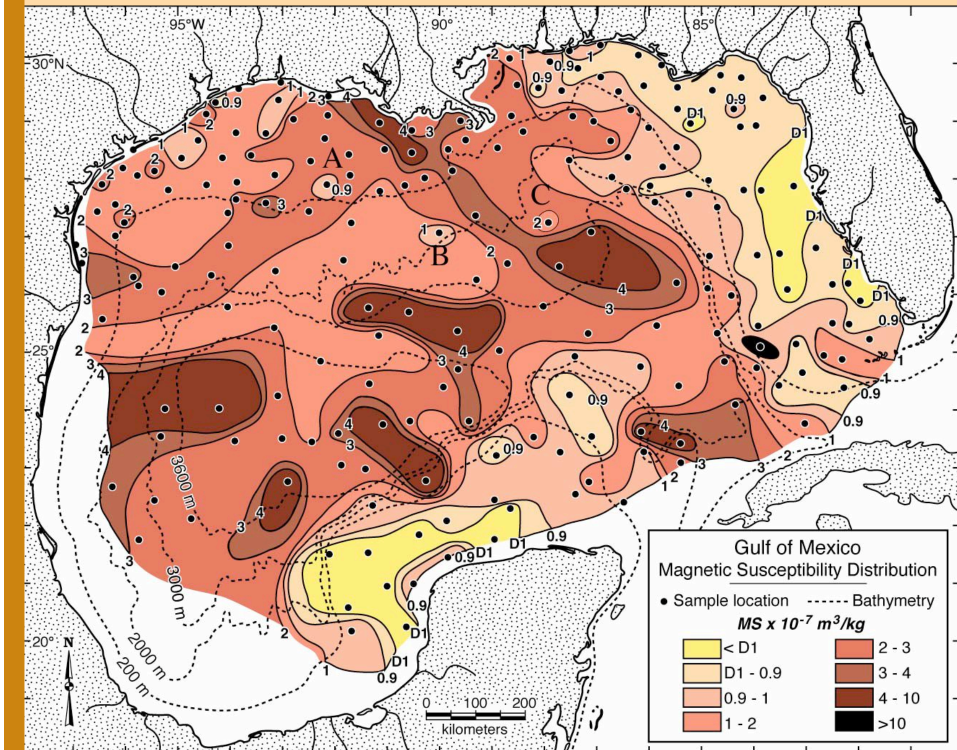


RM values are a measure of only those compounds in a sediment sample that are ferrimagnetic

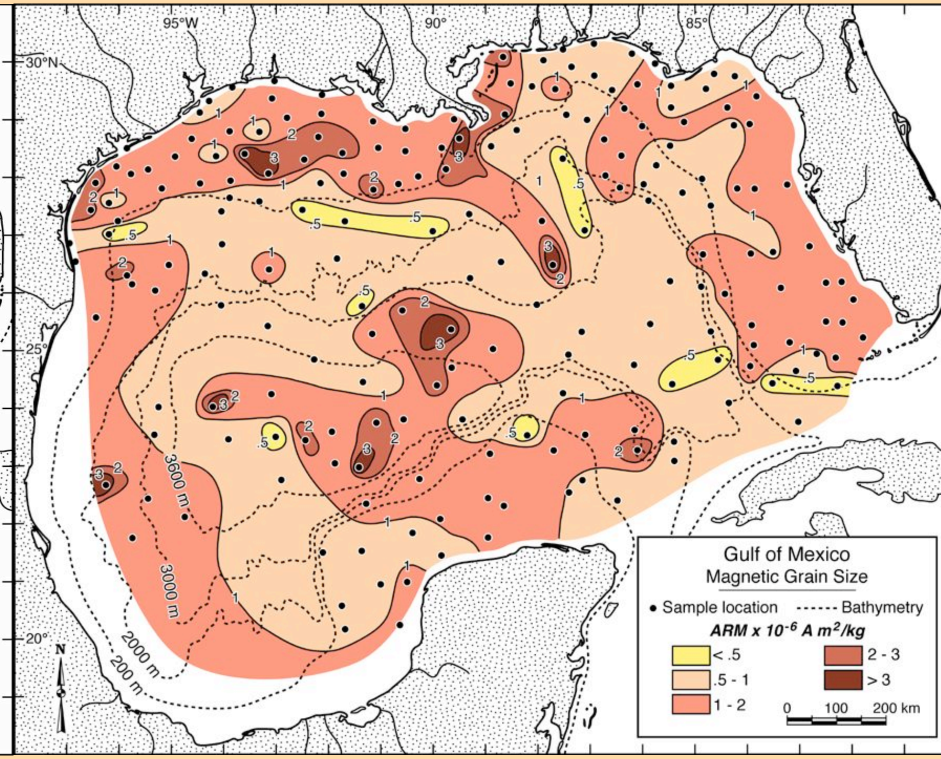
(Ellwood et al., 2006)

Surface sediment variability

MS produces an **asymmetrical** Gulf



ARM produces a **symmetrical** Gulf



MS is a measure of the all the compounds making up the sediment sample

RM values are mainly a measure of only those compounds in a sediment sample that are ferrimagnetic

(Ellwood et al., 2006)

Changes in MS during diagenesis in marine rocks

Start

1. Surface values - can be > 1 x 10^{-6} m^3/kg

2. Unlithified samples magnetite grains 7-14 μm in size

Changes in MS during diagenesis in marine rocks

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Burial diagenesis →

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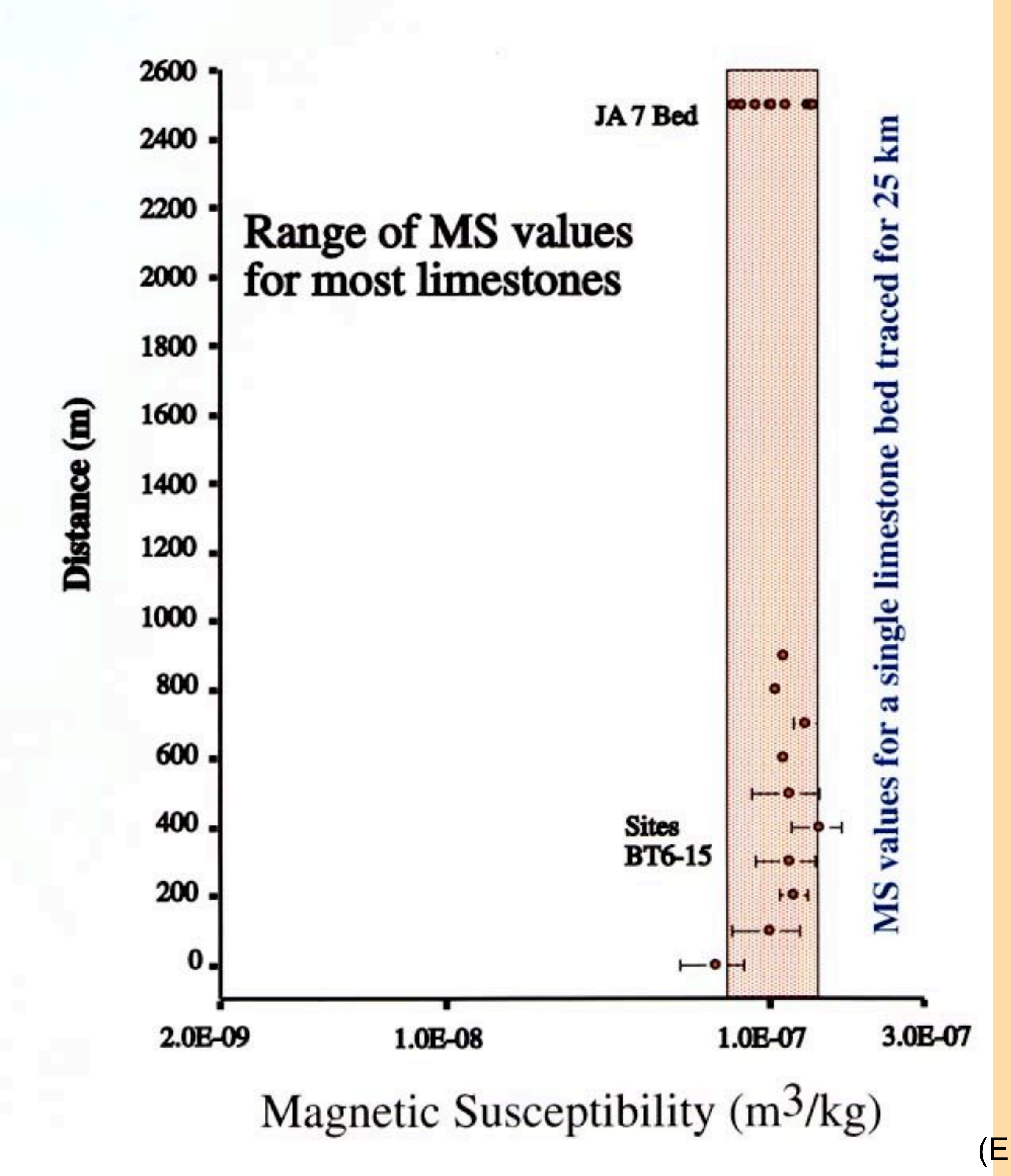
8. **Because iron is conserved AND detrital minerals are not easily destroyed by low-moderate alteration - MS is robust**



(Ellwood et al., 1999)

There are many other examples where the MS pattern is conserved including:

the <u>Eifelian-Givetian Boundary</u> interval (shown on Thusday here at the meeting) and seen in three sections in Morocco, sections in France, the U.S., the Czech Republic;

the <u>Emsian sequence</u> correlated between Morocco and Bolivia I showed at the beginning of the meeting;

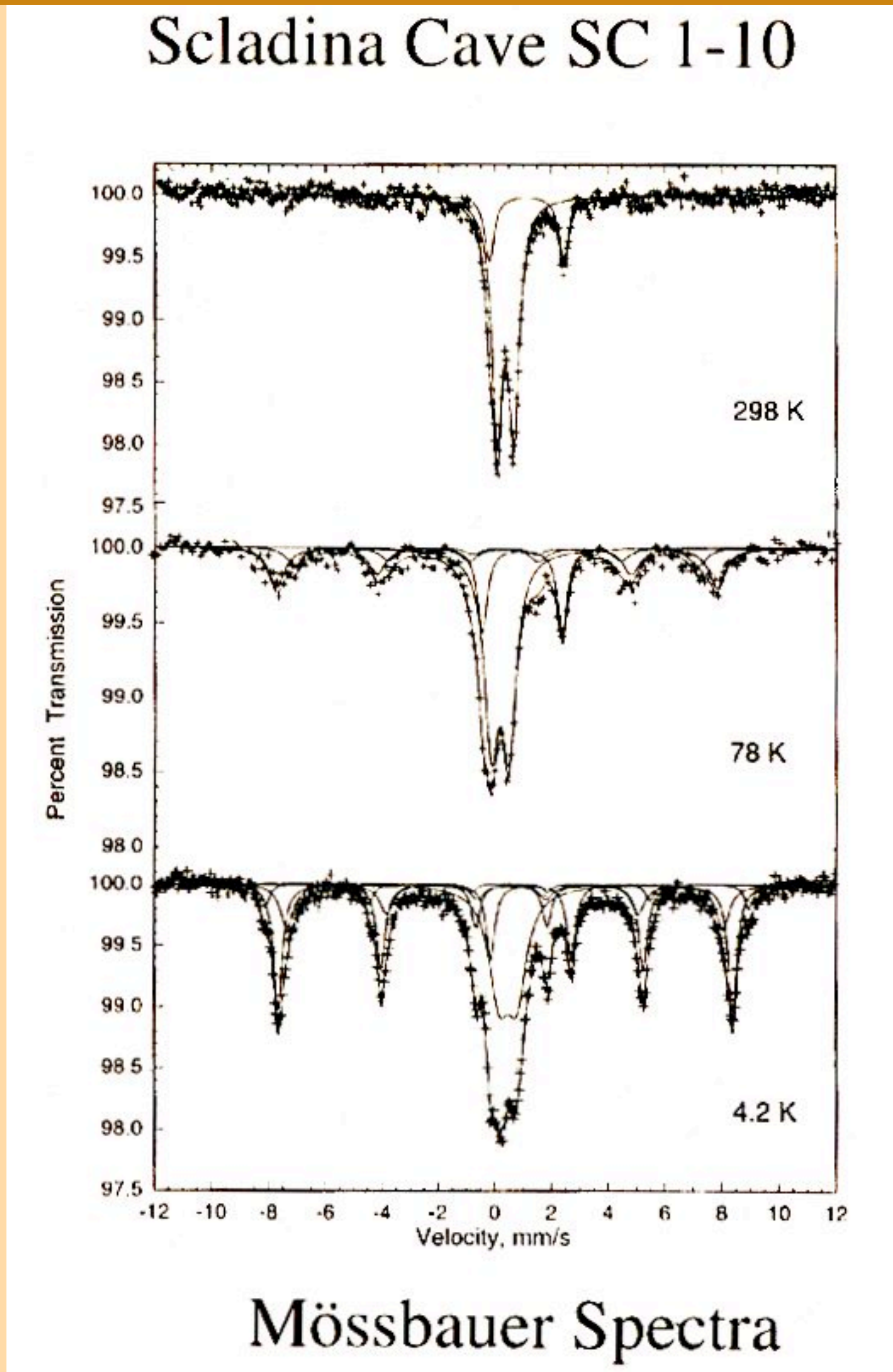
and others not in the Devonian.

The use of other data in support of MS is important - but these other data may not answer the same questions that MS can be used to ask and thus may not be useful in testing the reliability of the MS data. For example:

Global Correlations: We need parameters truly reflecting global variations. MS trends (not absolute magnitudes) can work when applied after careful instrumental, sampling, and additional tests; it works because it resides in the broad range of detrital material in samples that are global fluxes into the marine environment.

MS does not stand alone. In addition to careful sampling, sample preparation, measurements, additional tests that reflect each unique setting, FOREMOST MS requires good BIOSTRATIGRAPHY.

A few types of measurement tests follow

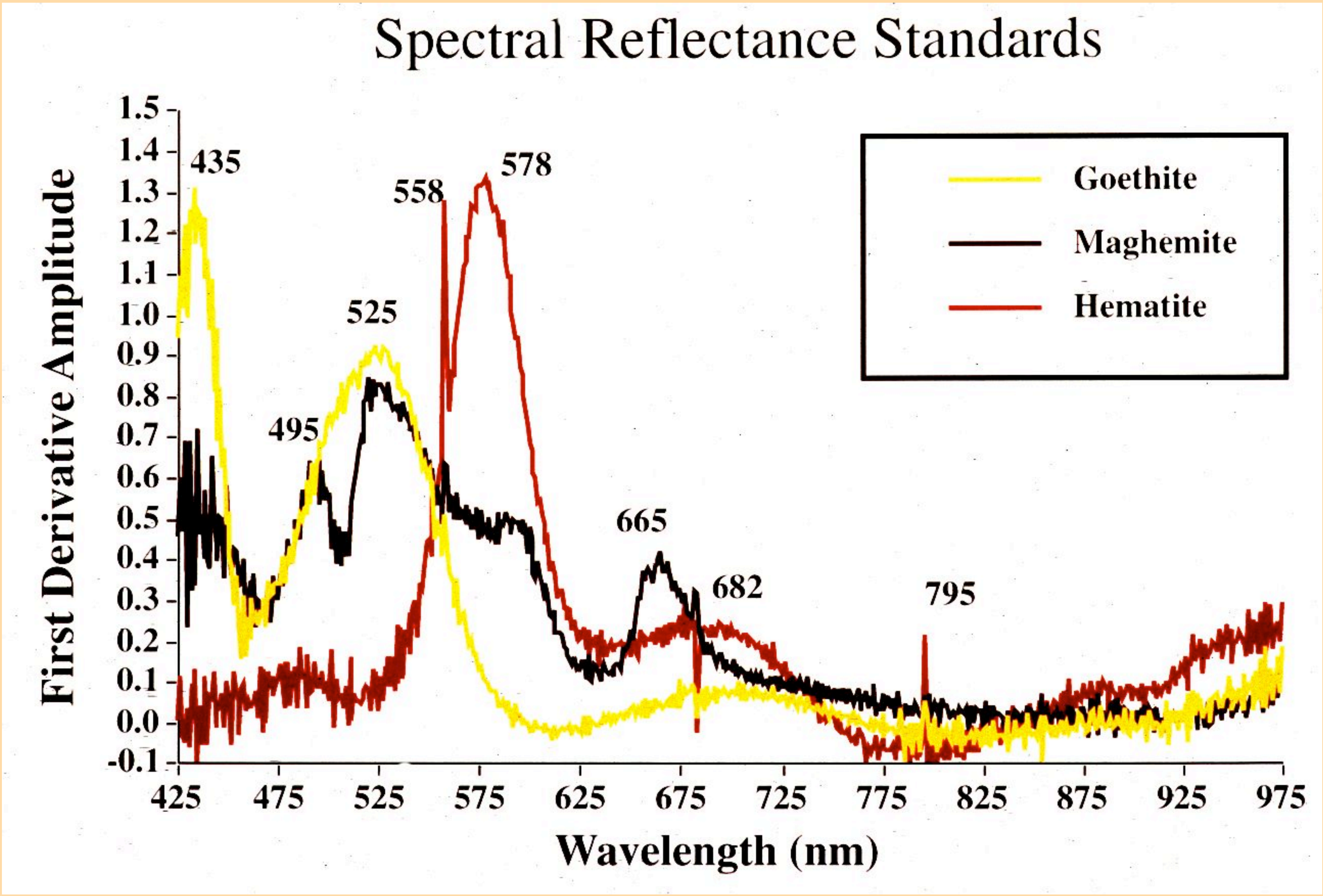


Typical spectra for very fine-grained maghemite

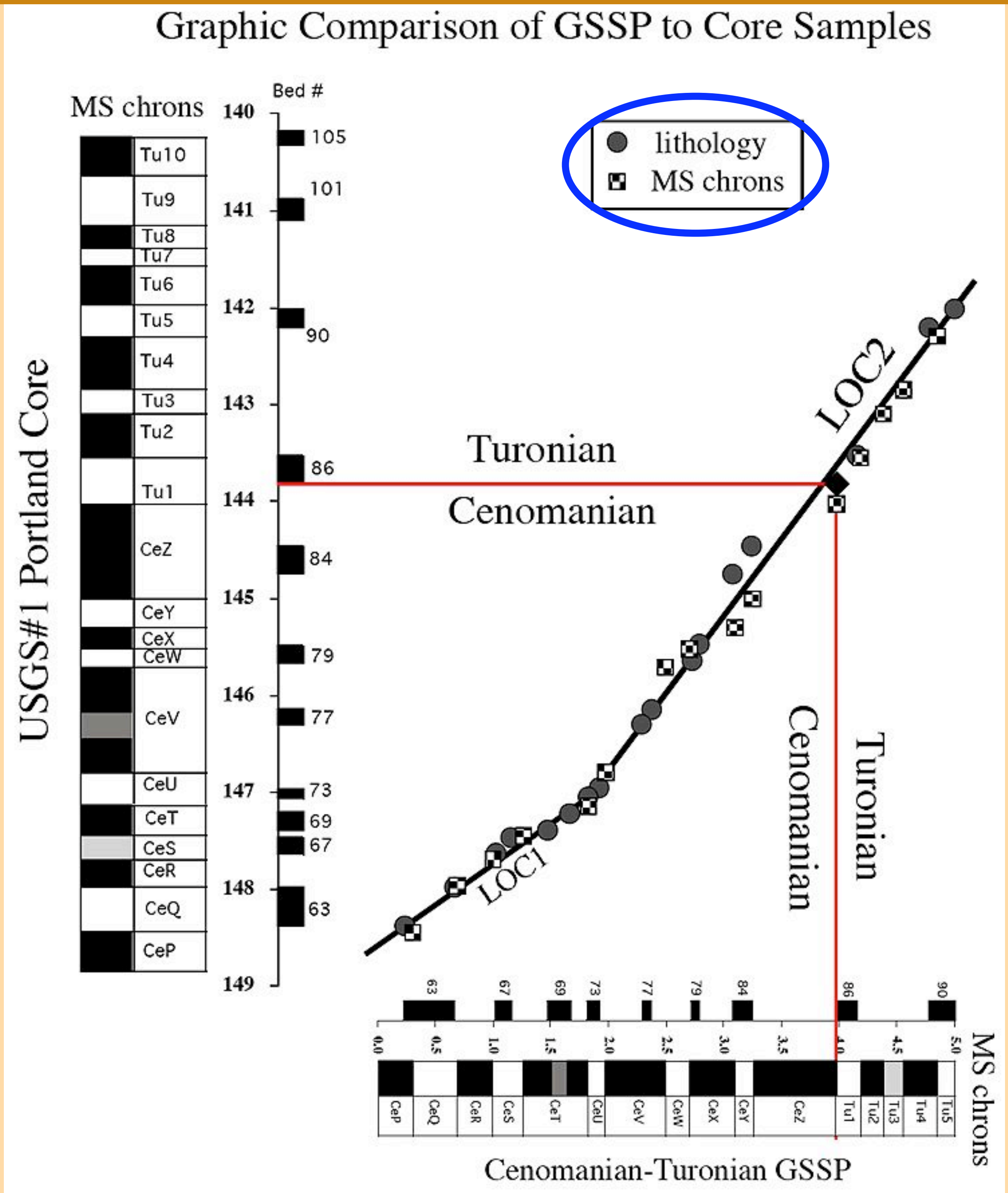
<u>Disorded</u> at room temperature

<u>Ordering begins</u> to appear at liquid nitrogen temperatures

<u>Well ordered</u> maghemite at liquid helium temperatures because Brownian motion is significantly reduced

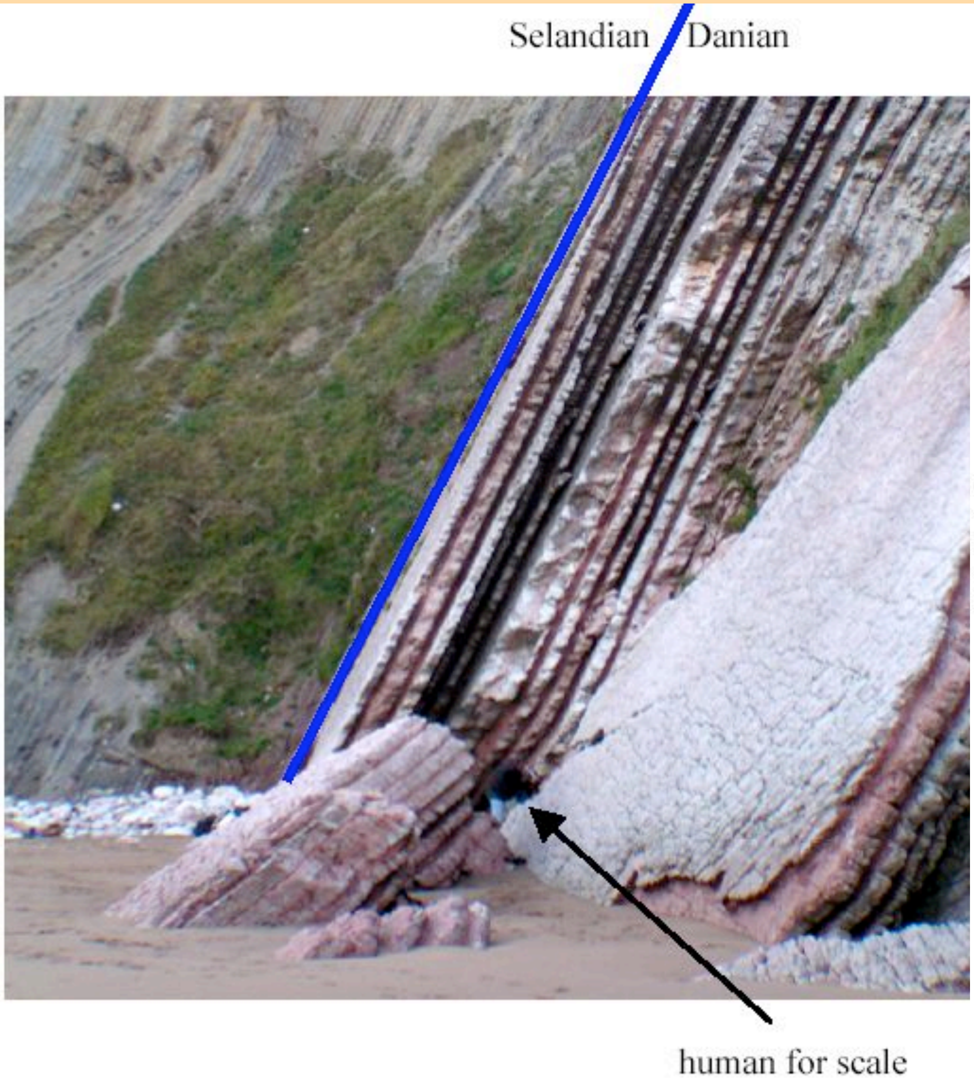


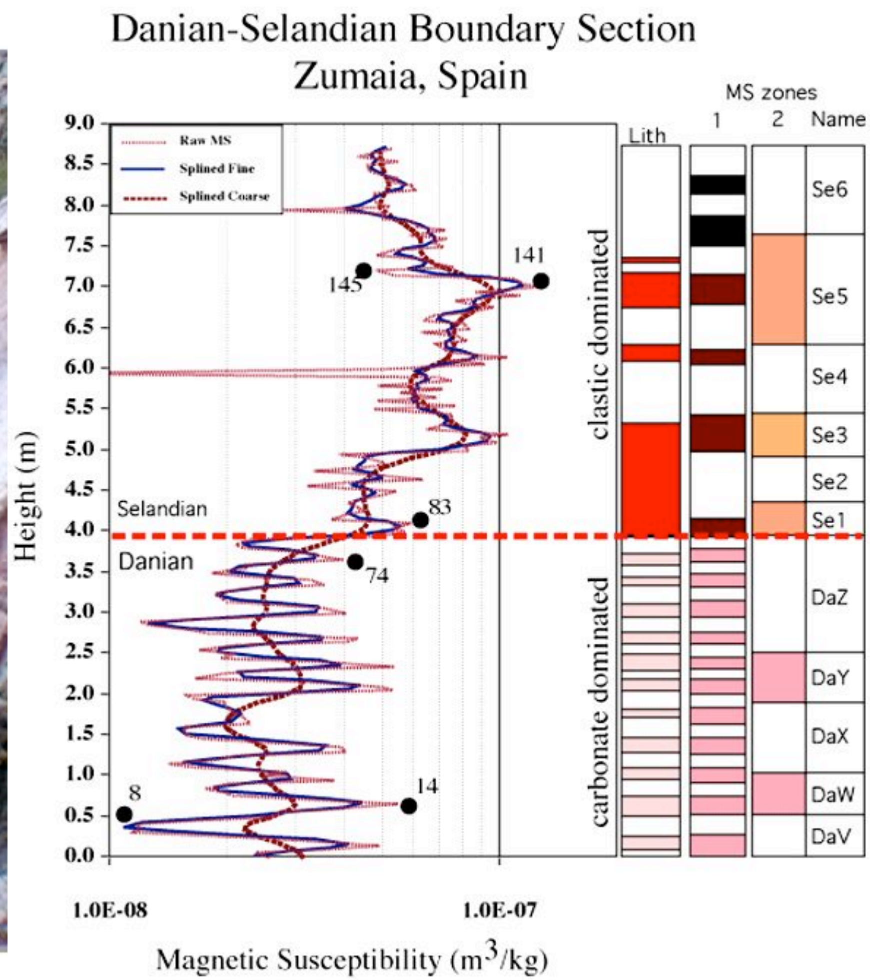
Spectral Reflectance Standards
First Derivative Amplitude
Wavelength (nm)
Goethite
Maghemite
Hematite
435
495
525
558
578
665
682
795
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
425
475
525
575
625
675
725
775
825
875
925
975



A correlation test - these are US Western Interior Seaway sections where the same beds can be traced over hundreds of km

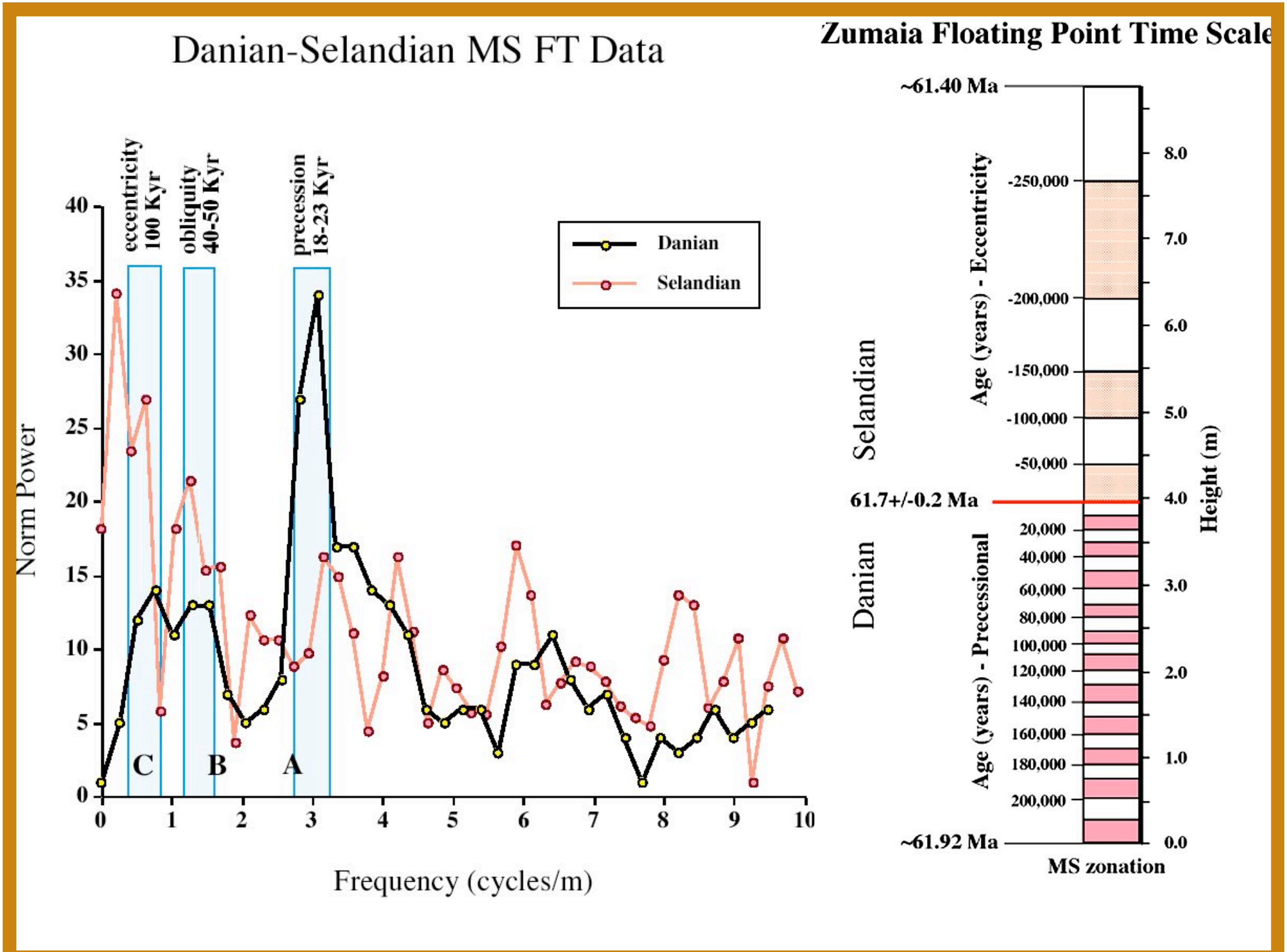
Lower Paleogene Danian-Selandian Proposed GSSP - Zumaia, Spain





Another test example

(Ellwood et al., 2008.)



Danian-Selandian MS FT Data
Norm Power
Frequency (cycles/m)
eccentricity 100 Kyr
obliquity 40-50 Kyr
precession 18-23 Kyr
C
B
A
Danian
Selandian
Zumaia Floating Point Time Scale
~61.40 Ma
61.7+/-0.2 Ma
~61.92 Ma
Age (years) - Eccentricity
Age (years) - Precessional
Height (m)
MS zonation

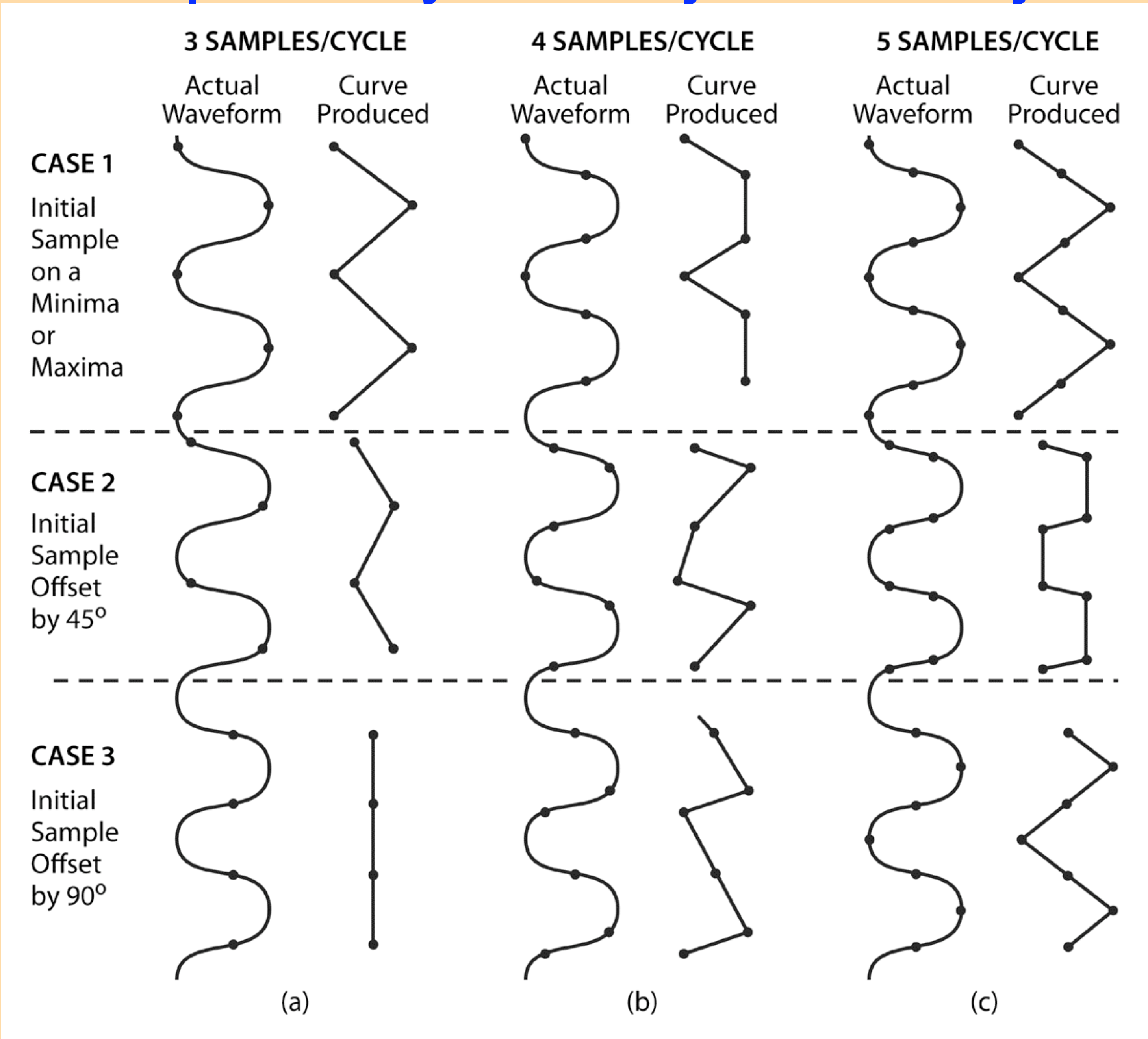
A Twelve Step Process for Ultra-high Resolution Zonation and Development of Floating-point Time Scales Using MS Cyclostratigraphy

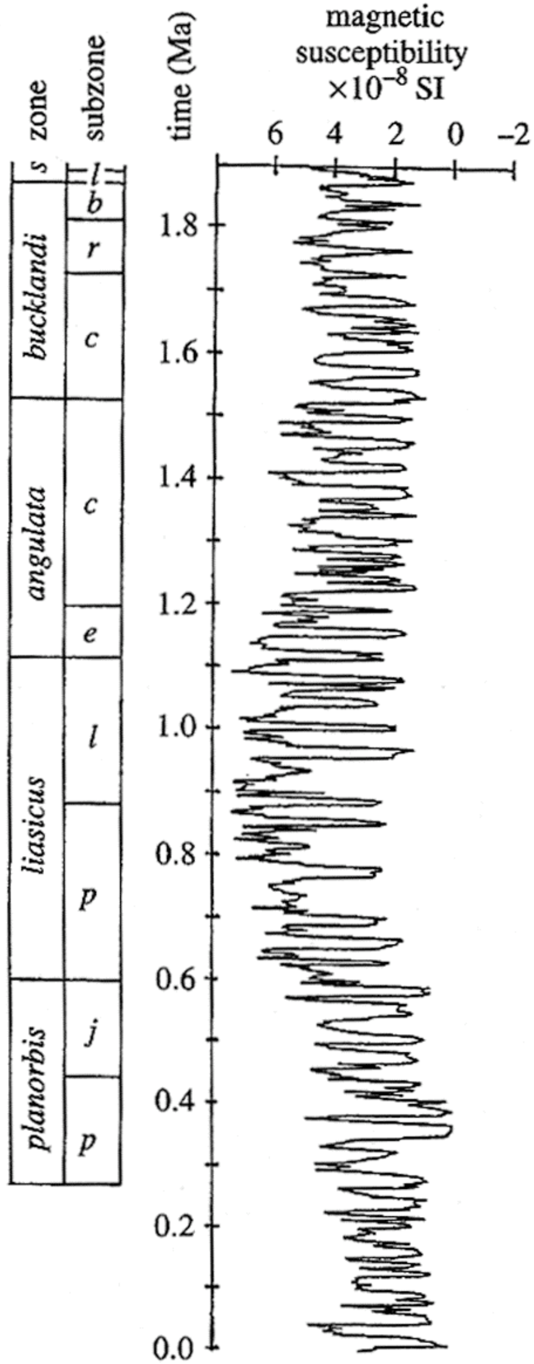
MS Zonation for Complete Geologic Stages: Constrained by GSSPs and Tied to Biostratigraphic Zonations

An Example from the Middle Devonian Givetian Stage - Work currently in Press

First a bit about cycles and one of the first examples of careful MS work and the resulting cyclostratigraphy

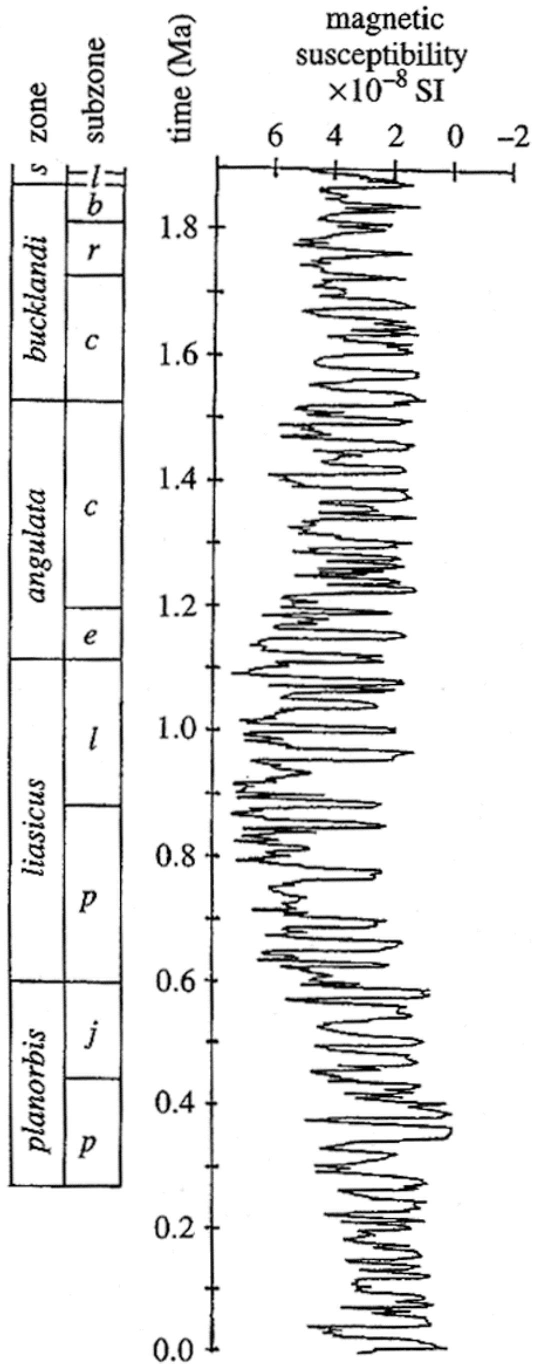
Sample density necessary to recover cycles





Lower Jurassic ~196 Ma; Blue Lias, England

(Weedon et al., 1999)



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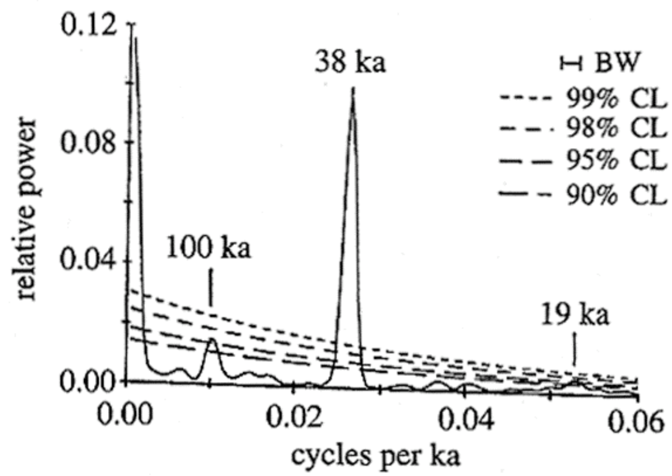


Such well-defined Milankovitch cycles demonstrate a global climate record in MS data sets

(Weedon et al., 1999)

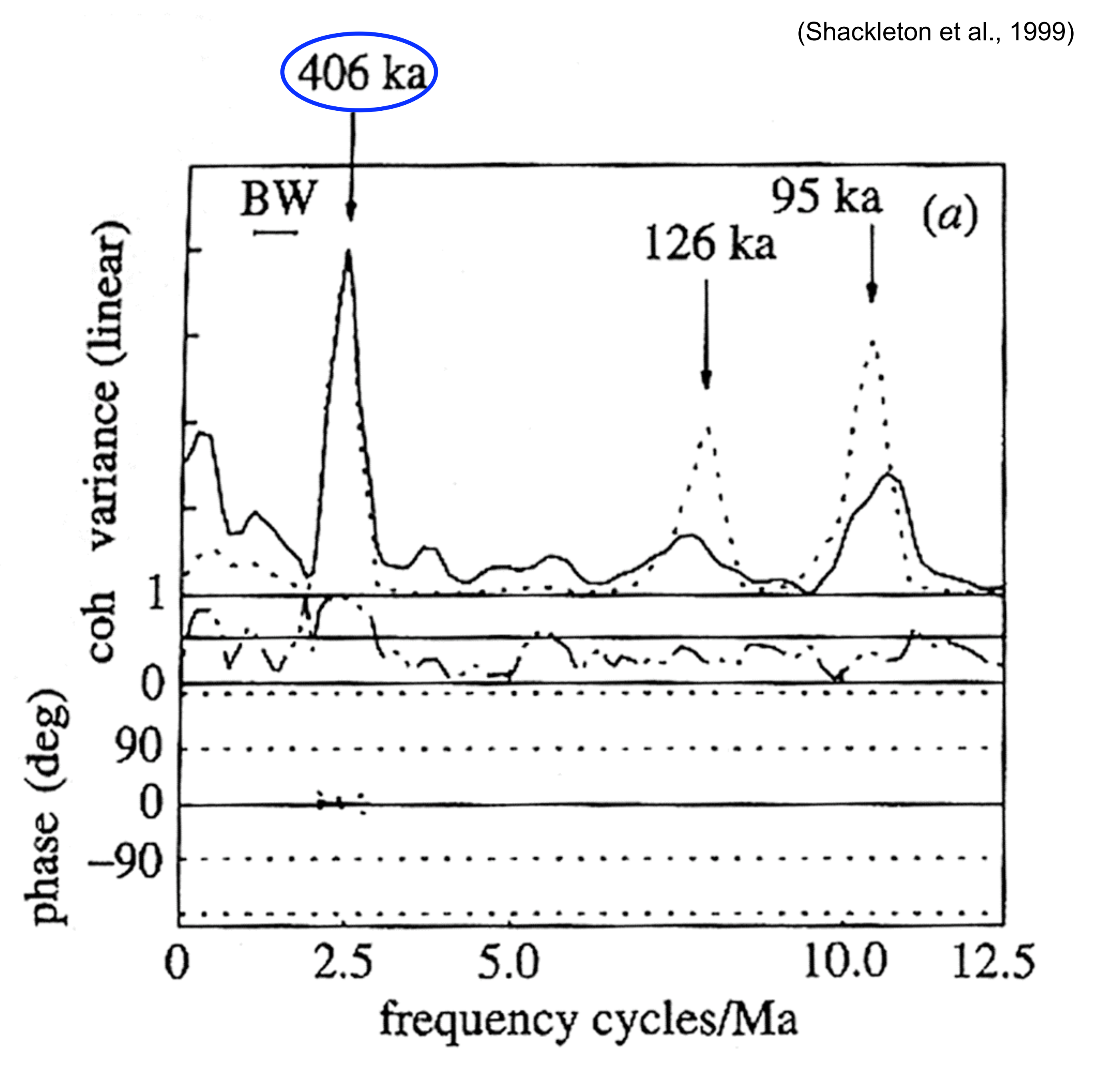
~400 ka Milankovitch Cyclicity as the Basis for a Floating Point Time Scale in Marine Stratigraphic Sequences

Hypothesis: Magnetic Susceptibility (MS) cycles in marine cores and sections can be used as proxies for long-term, Milankovitch climate cyclicities; MS variations being the result of cyclic erosion, detrital influx and deposition within the marine environment. Therefore, given adequate biostratigraphic control, MS cycles can be used to develop Floating Point Time Scales and for high-resolution correlation.

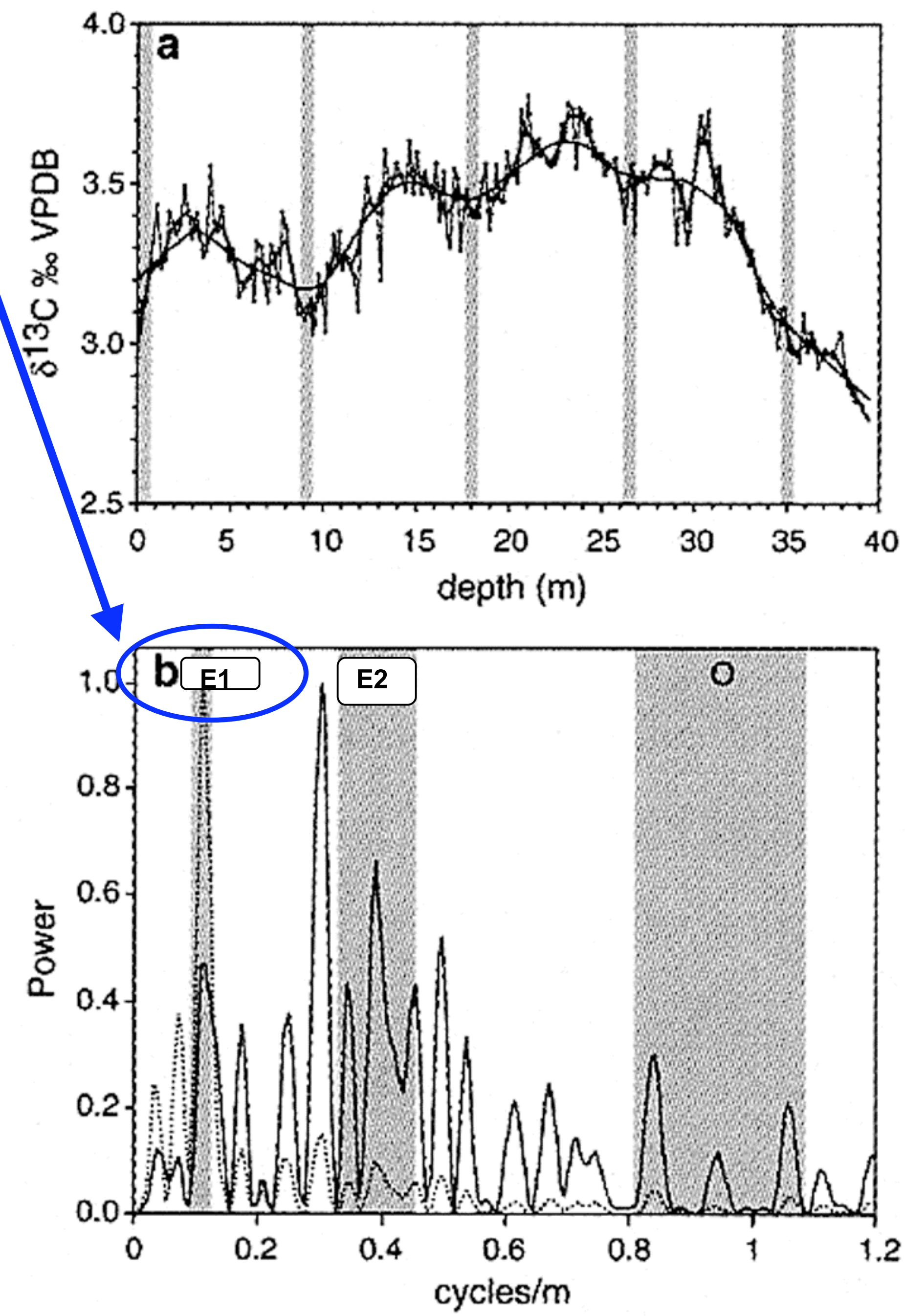
"As Laskar (this issue) points out, despite the fact that a **purely mathematical solution to the orbital calculations is intrinsically limited to a maximum extension into the past of ca. 30 Ma**, some of the long-period frequencies that may be found in geological records are stable or calculable over much longer intervals. **The 406 ka eccentricity cycle is particularly interesting in this respect, and indeed it seems realistic to propose the establishment of a stratigraphic scheme based on this cycle."**

(Shackleton, McCave, Weedon, 1999)

Oligocene-Miocene spectral analysis of MS data from an ODP Leg 154 core.

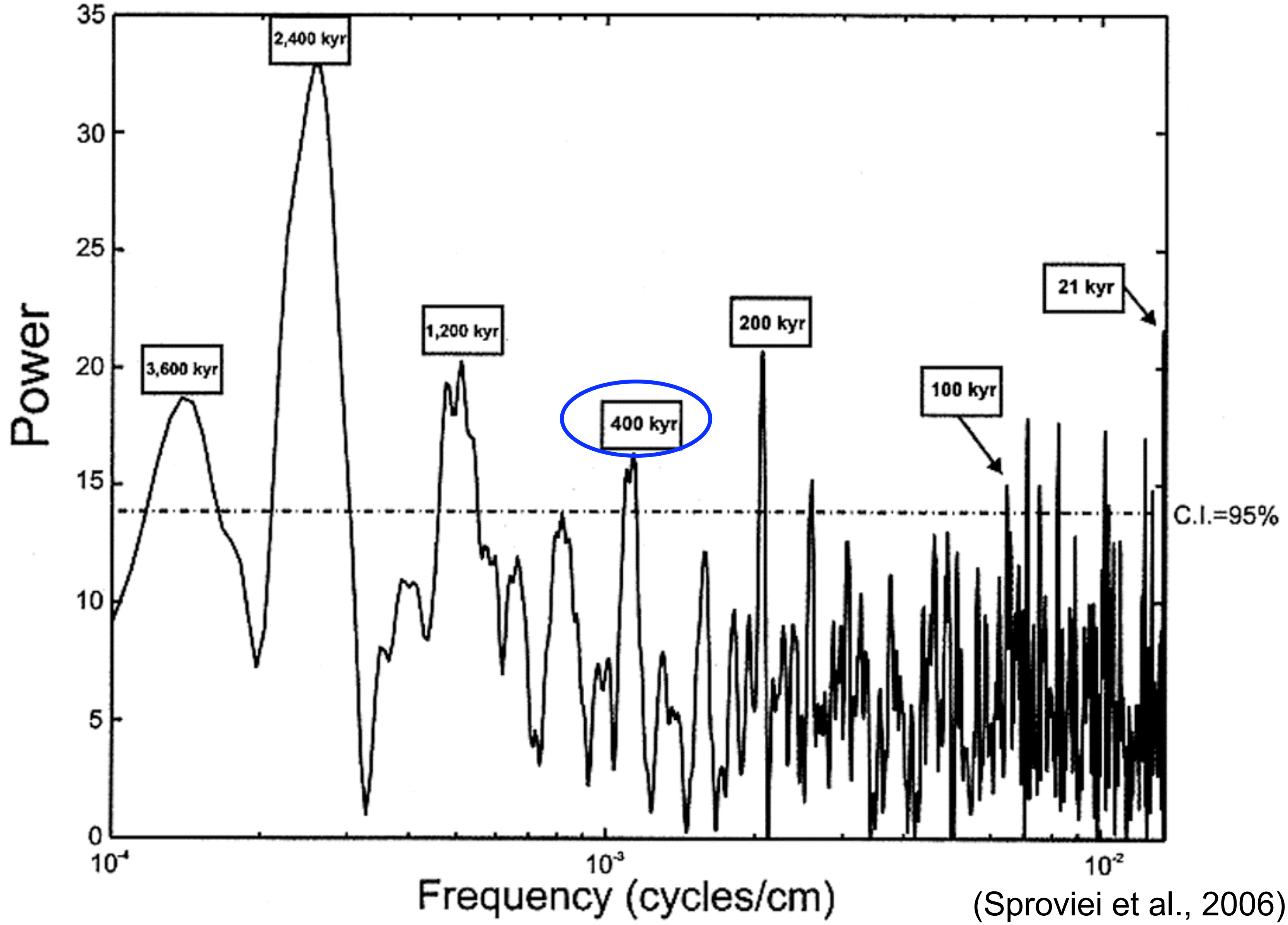


Upper Cretaceous ~400 Ma; Cenomanian-Turonian interval collected in Germany. Spectral character from carbon isotopic ($\delta^{13}C$) data.

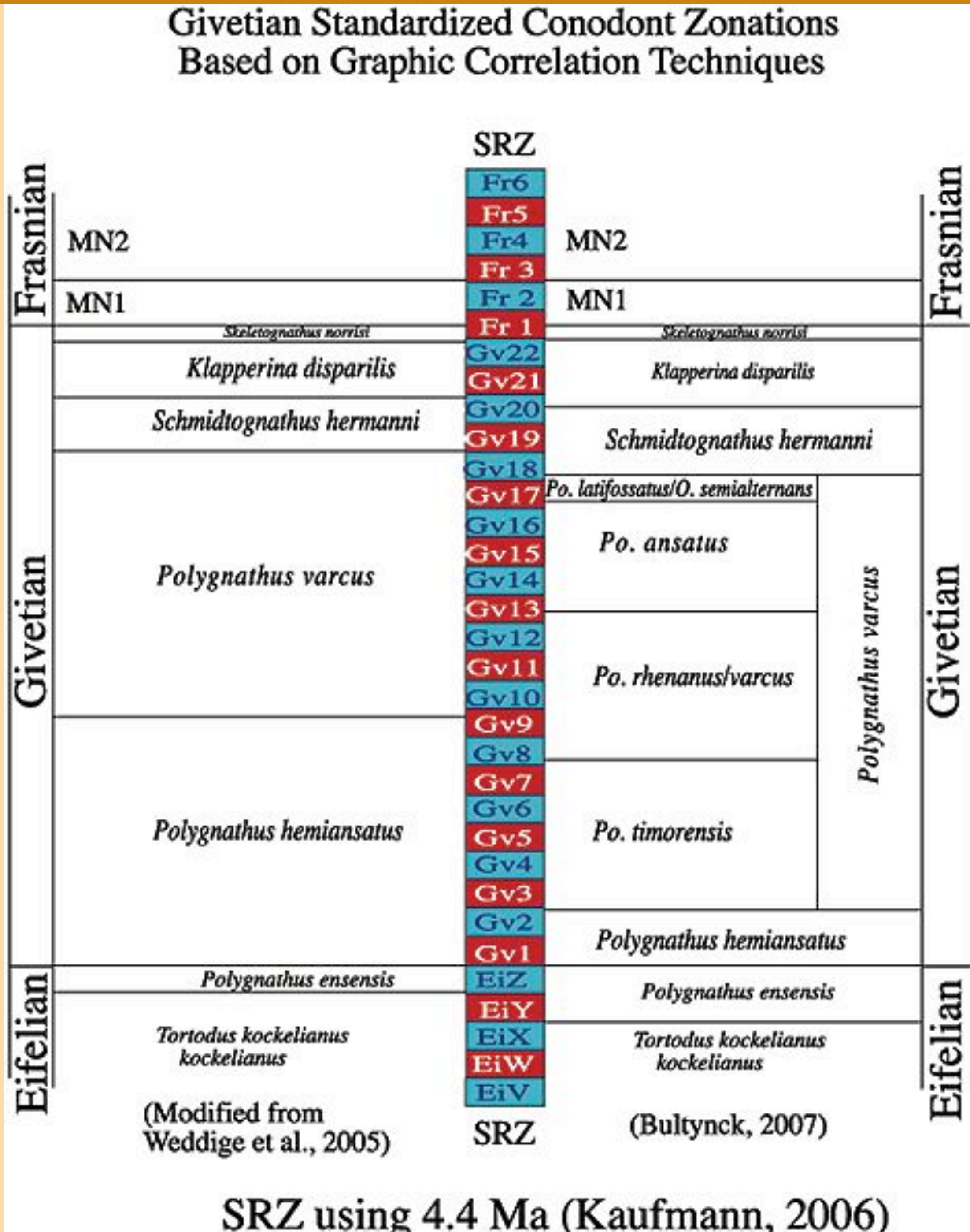


(Voigt et al., 2007)

Lower Cretaceous ~140 to 125 Ma; spectral character from carbon isotopic ($\delta^{13}C$) data; samples collected in Central Italy.



(Sproviei et al., 2006)



Step 1: Establish a climate model (SRZ) for the Givetian, and choose a time scale for the model

Here we use 400 kyr eccentricity cyclicity and Kaufmann's age

Step 2: Fit biostratigraphic zonation to the model

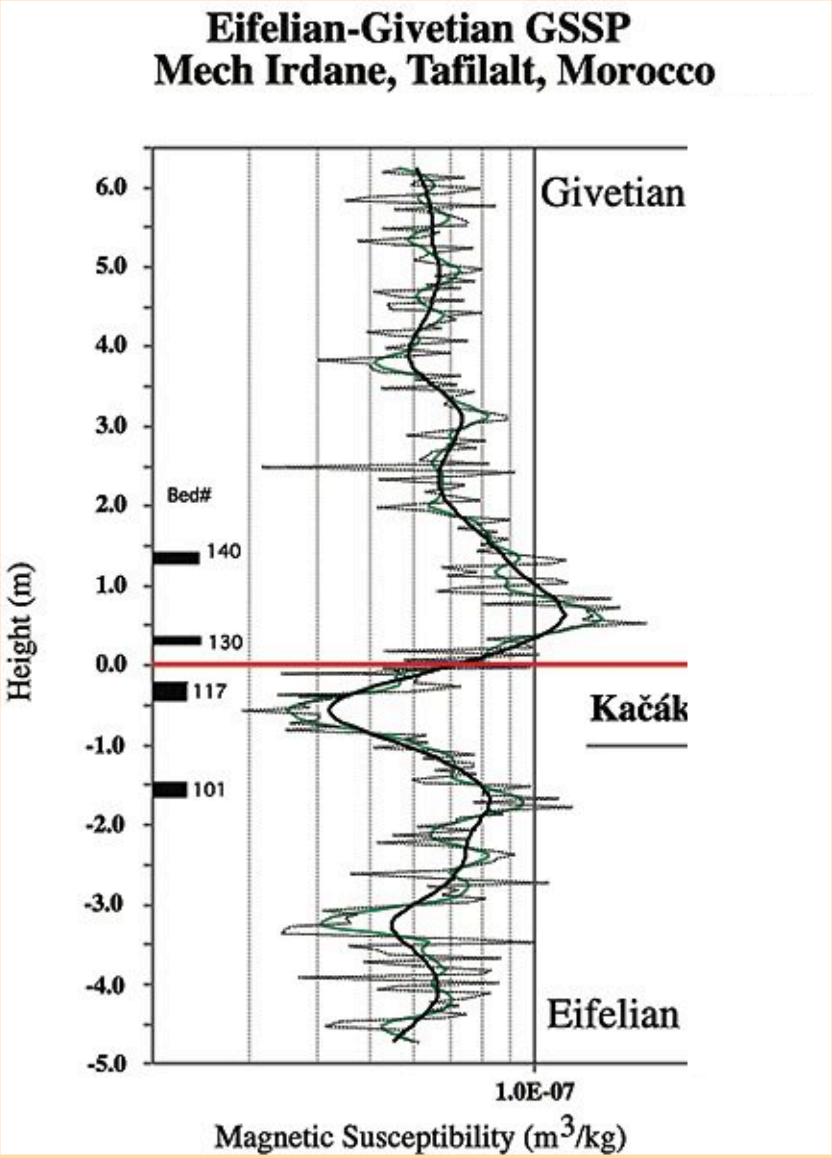
Here we use two conodont zonations developed from graphic correlation

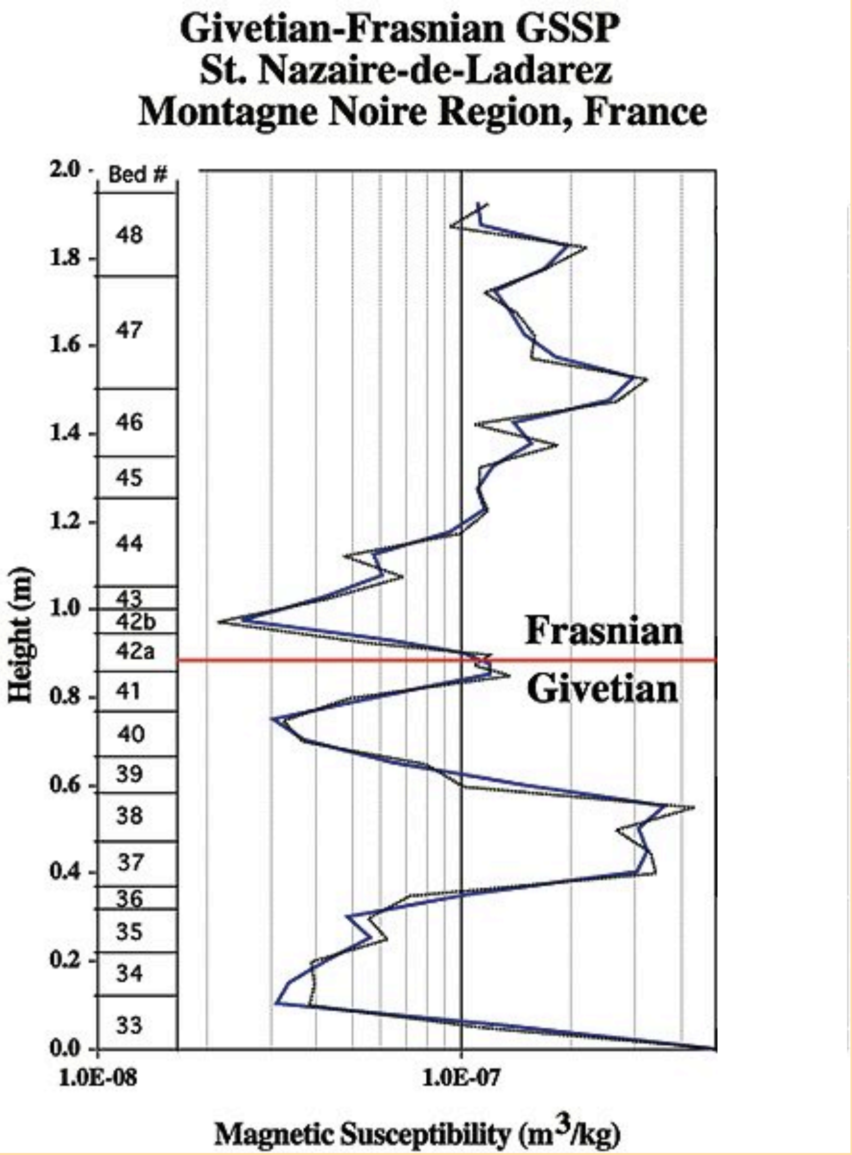
Eifelian-Givetian GSSP, Morocco

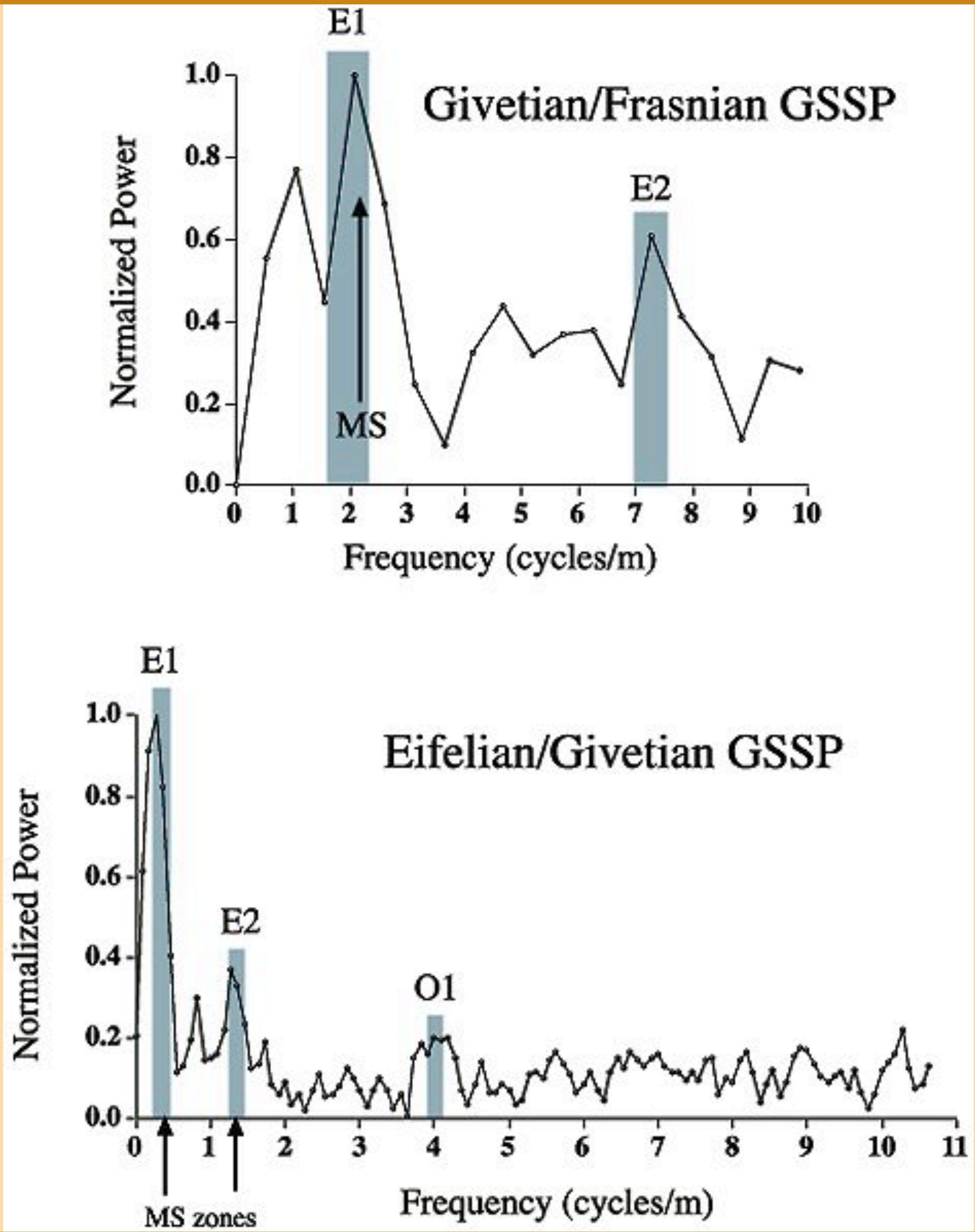
Givetian-Frasnian GSSP, Southern France

Givetian-Frasnian GSSP, Southern France

Step 4: Measure the MS for the Two GSSPs





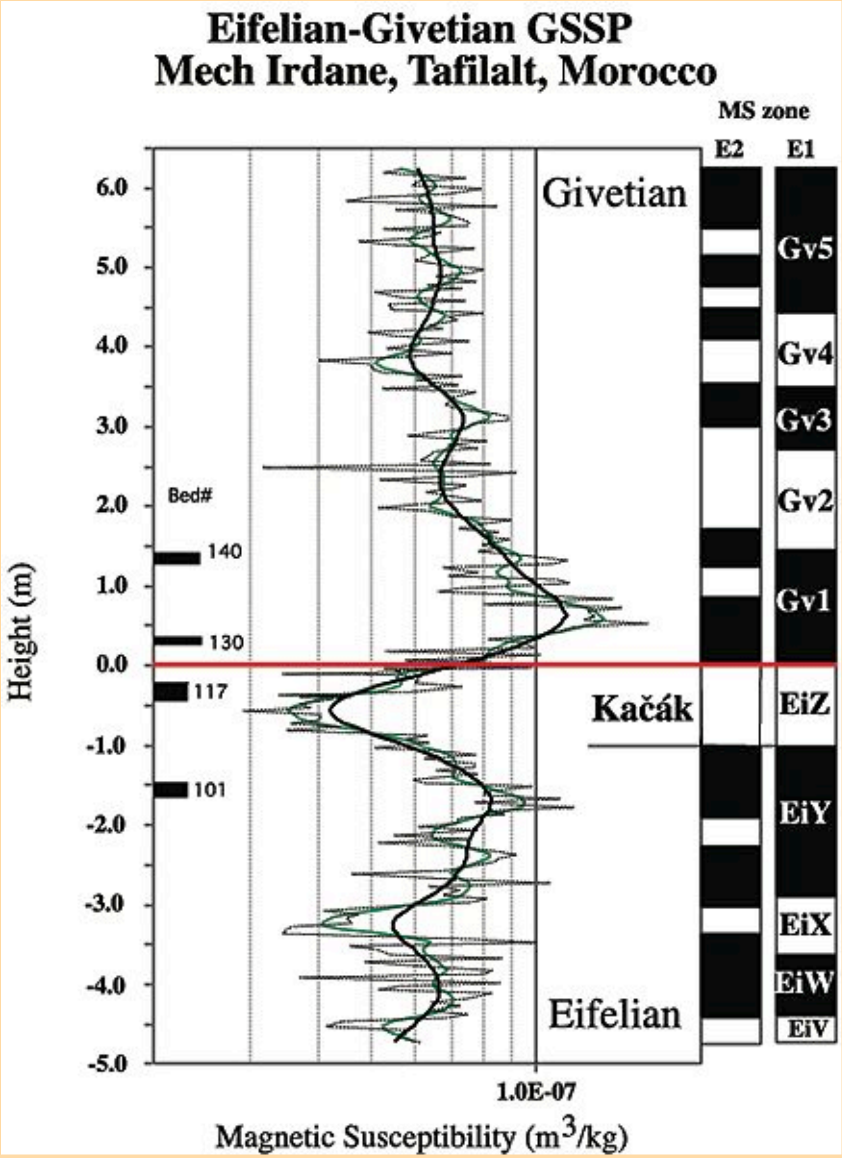


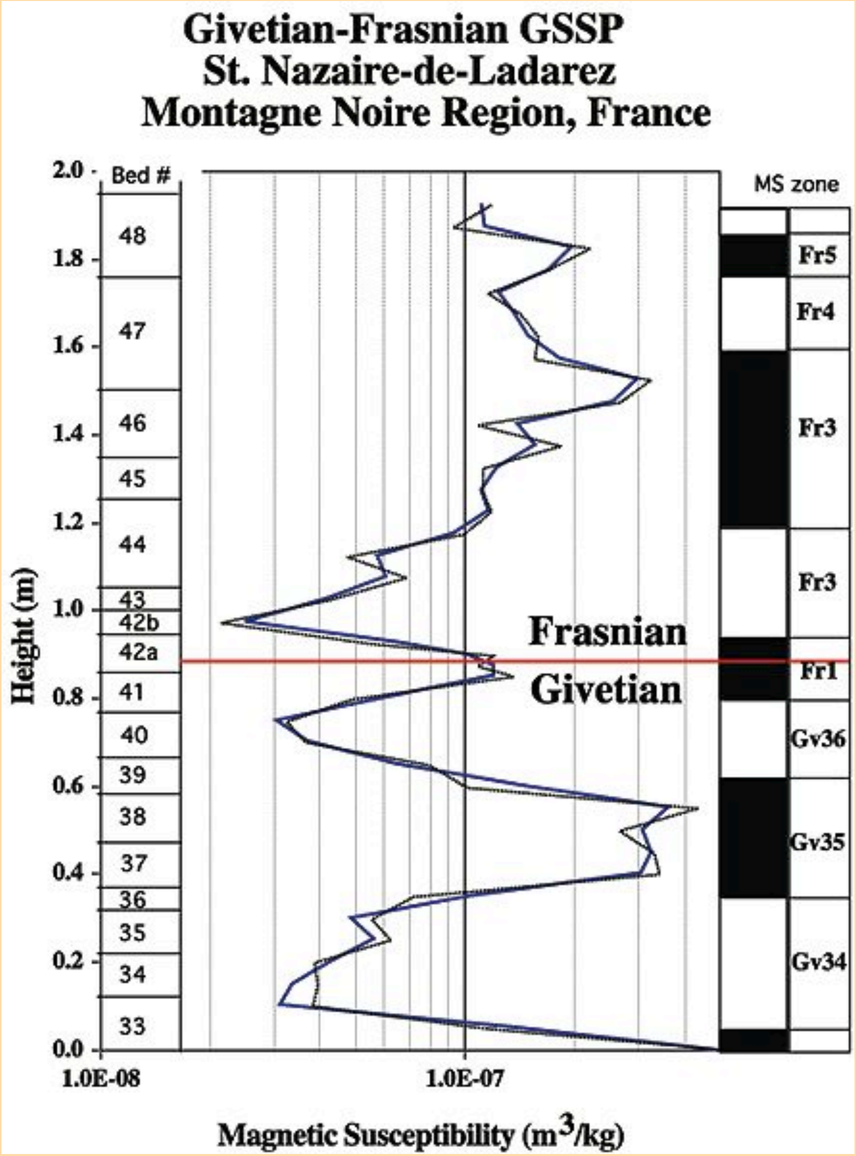
Step 5: Calculate the FT for the GSSPs

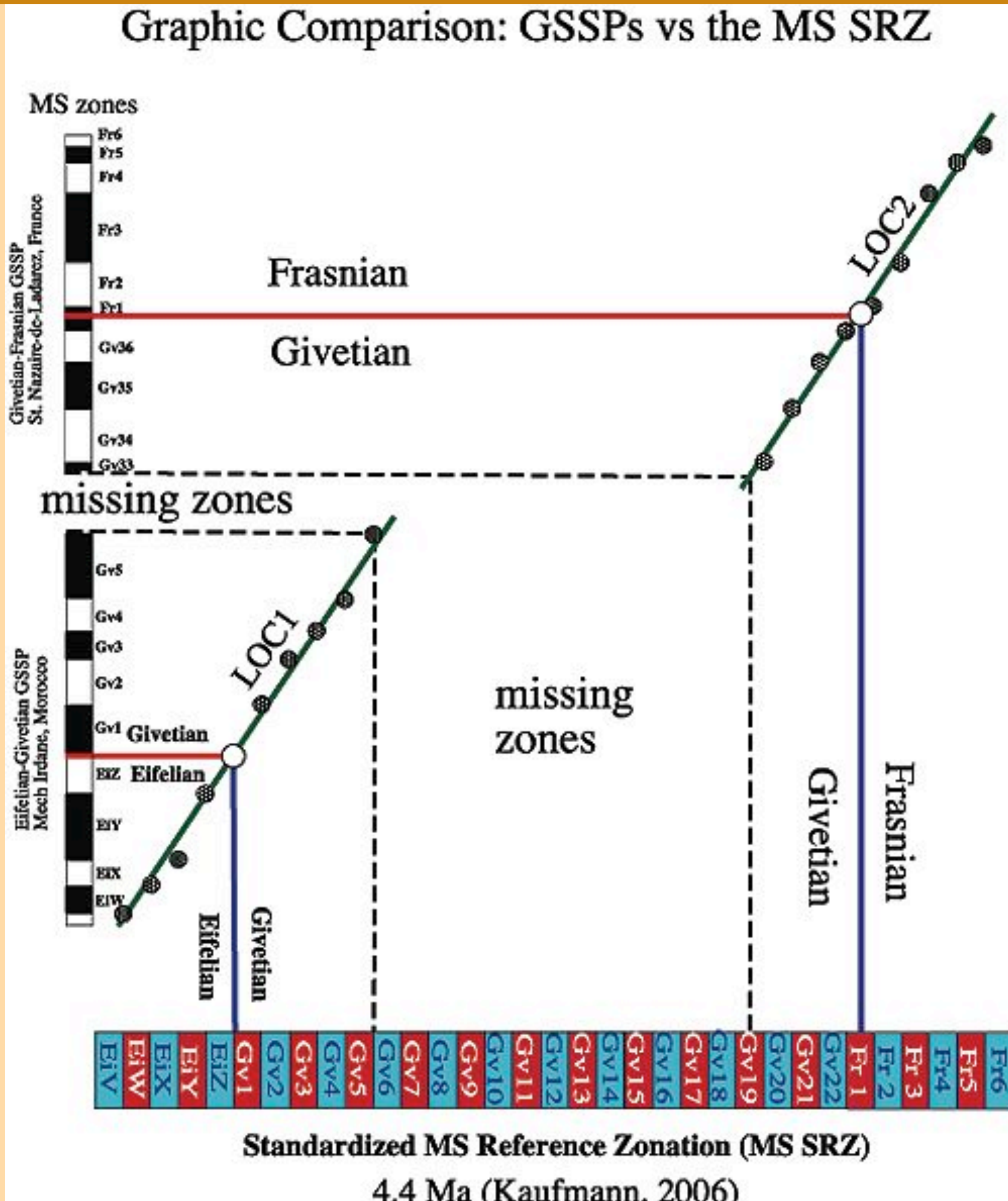
Comment: In correlating curve segments, simple visual curve matching does not work - need to quantify your approach - and support that with other methods, e.g., regression, time-series approaches, etc.

Many curves represent regional-global T-R cycles on which are superimposed multiple time series cycles that can be extracted

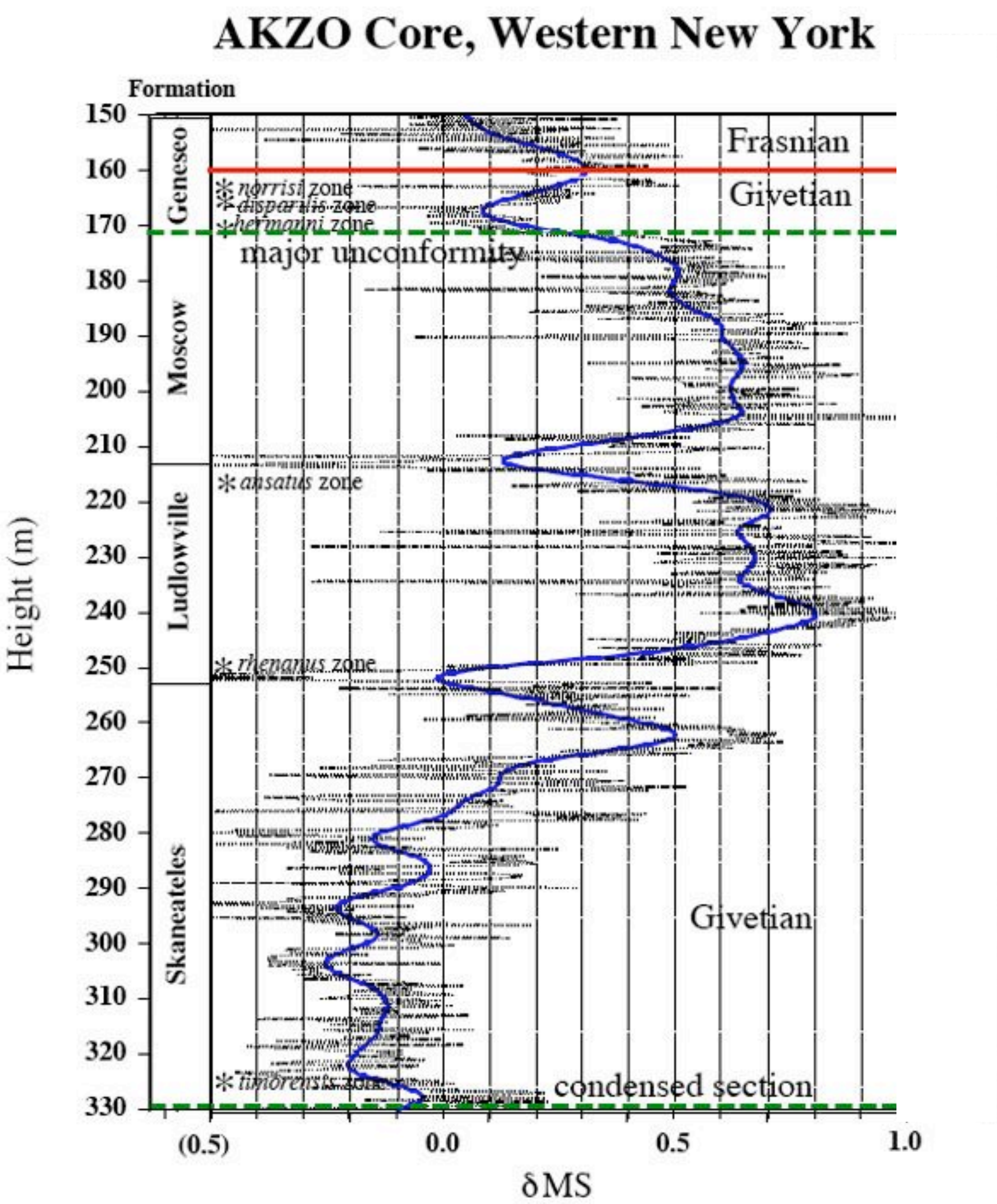
Step 6: If the 400 kyr cyclicity is represented, then smooth the MS data to conform to that cyclicity and build bar-logs







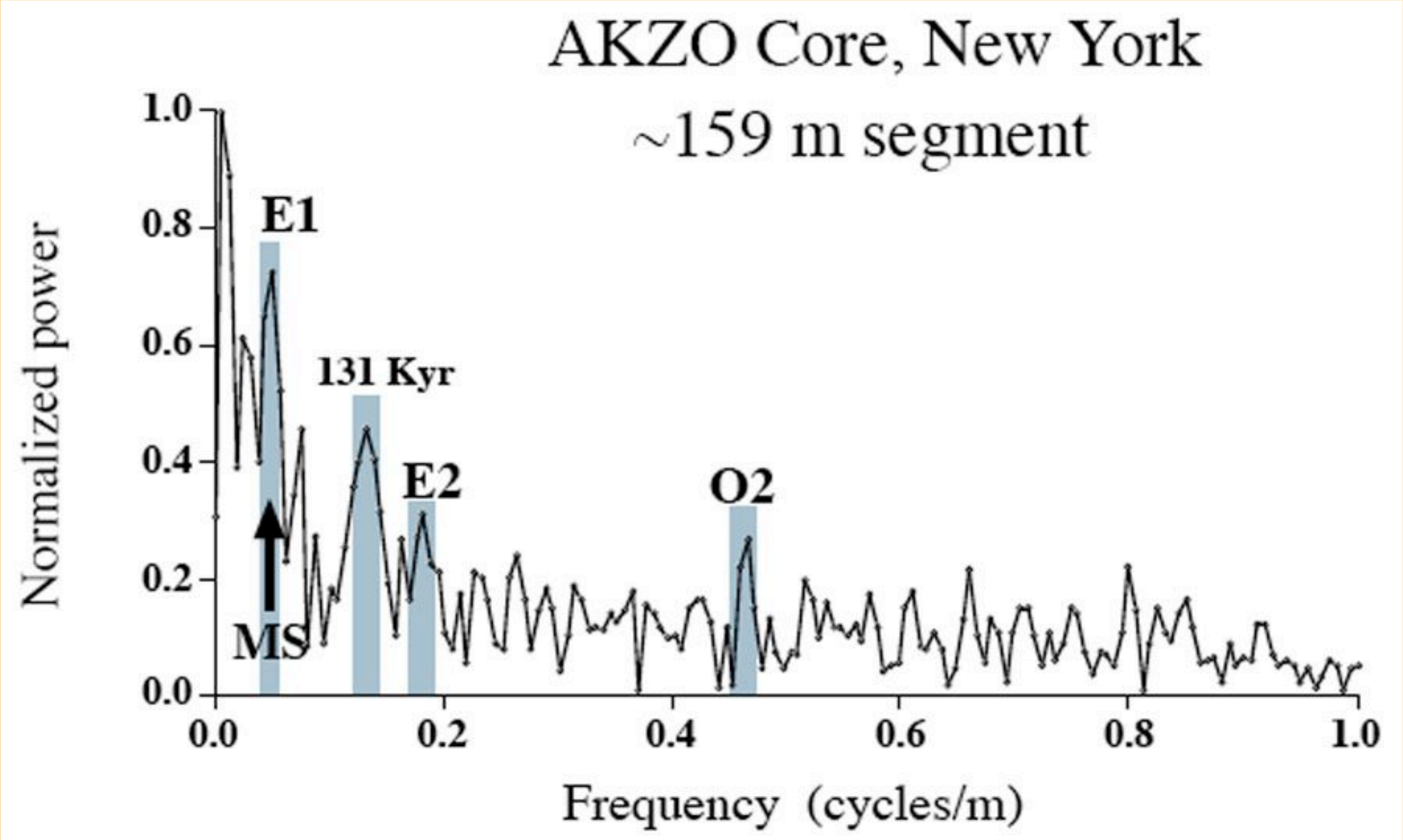
Step 7: Graphically compare the GSSP MS and 400 kyr climate zones

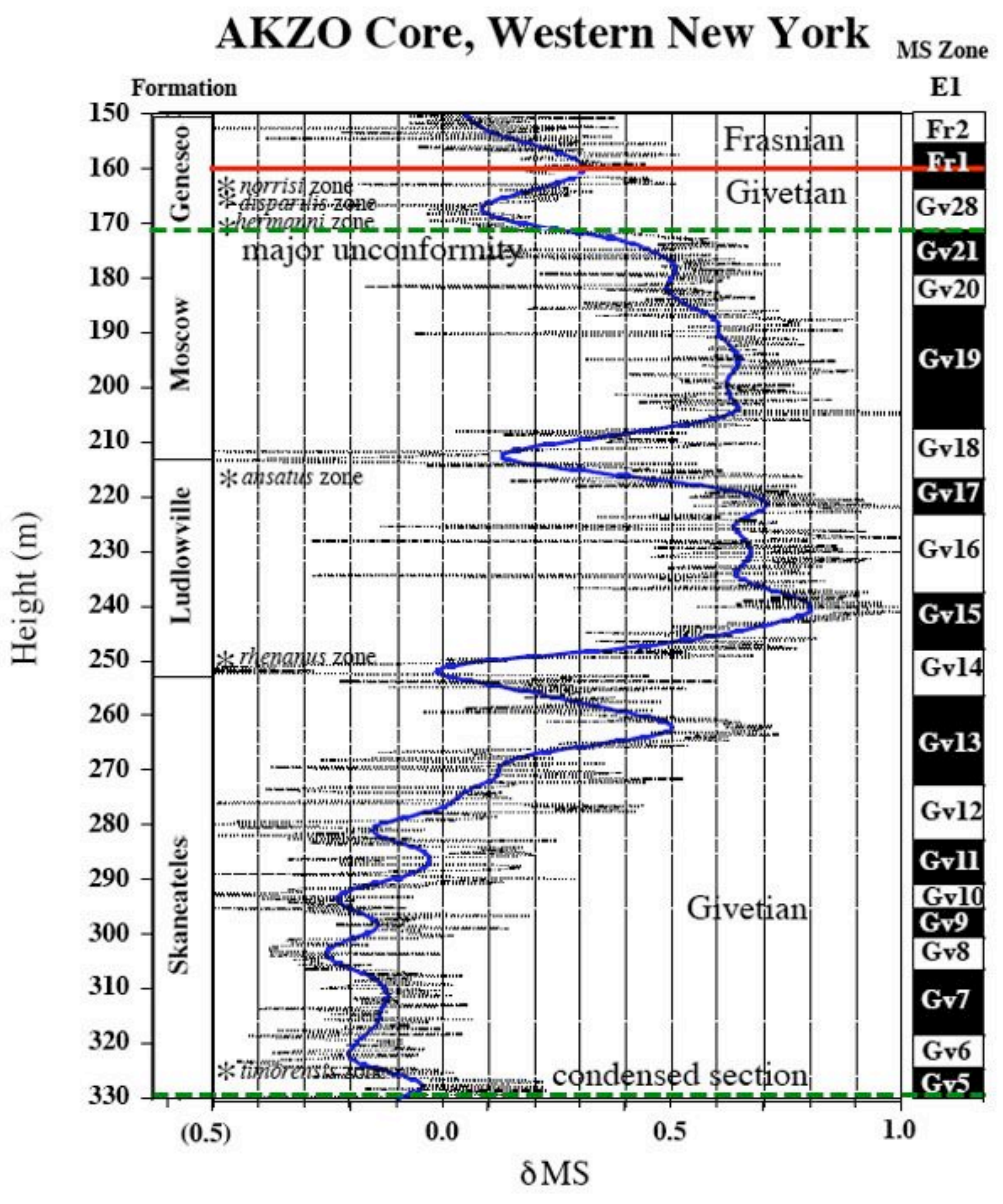


Step 8: Fill in the gap between GSSPs to complete the Givetian Stage zonation

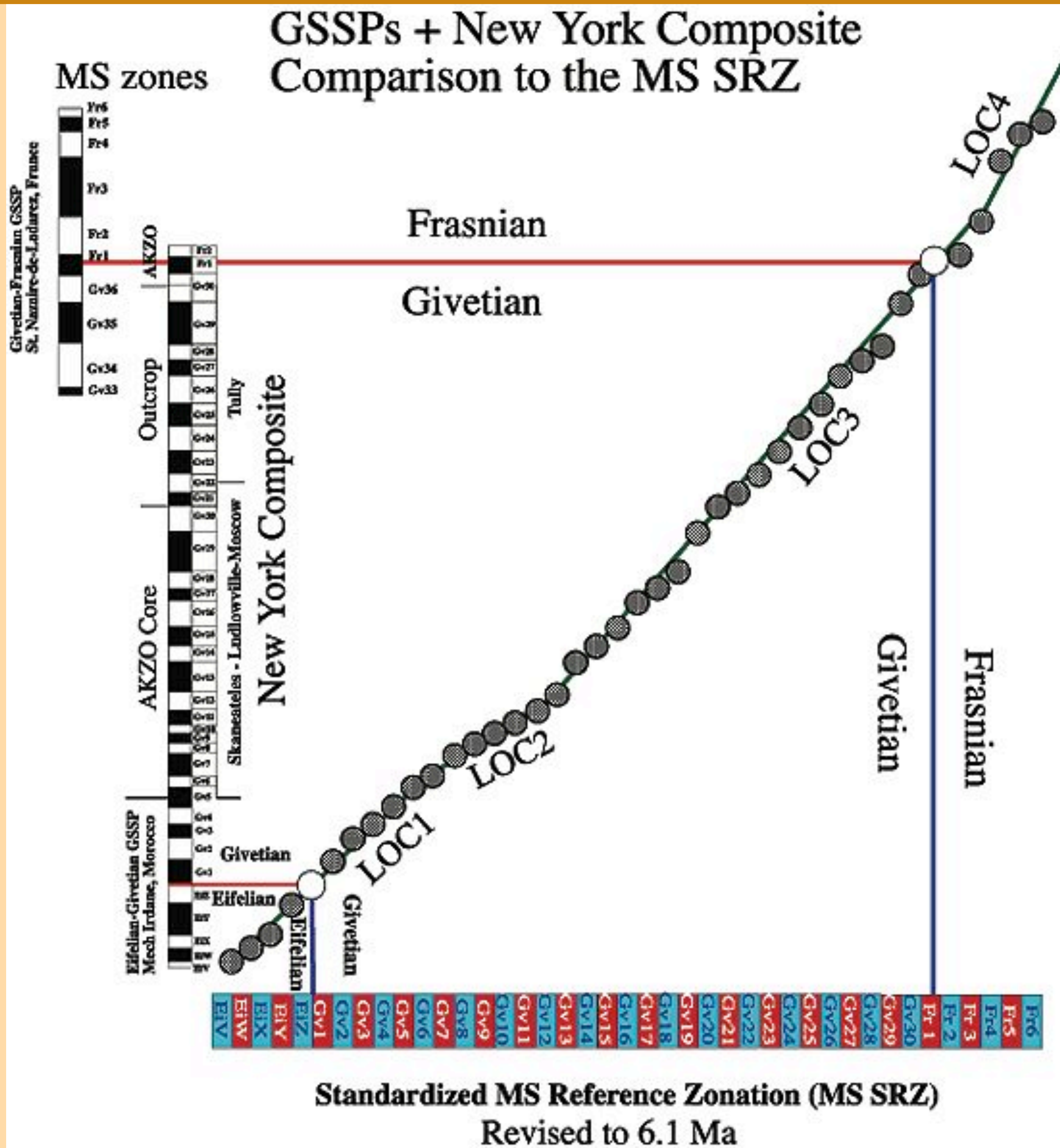
Example from New York

Step 9: Calculate the FT for the filling sequemce

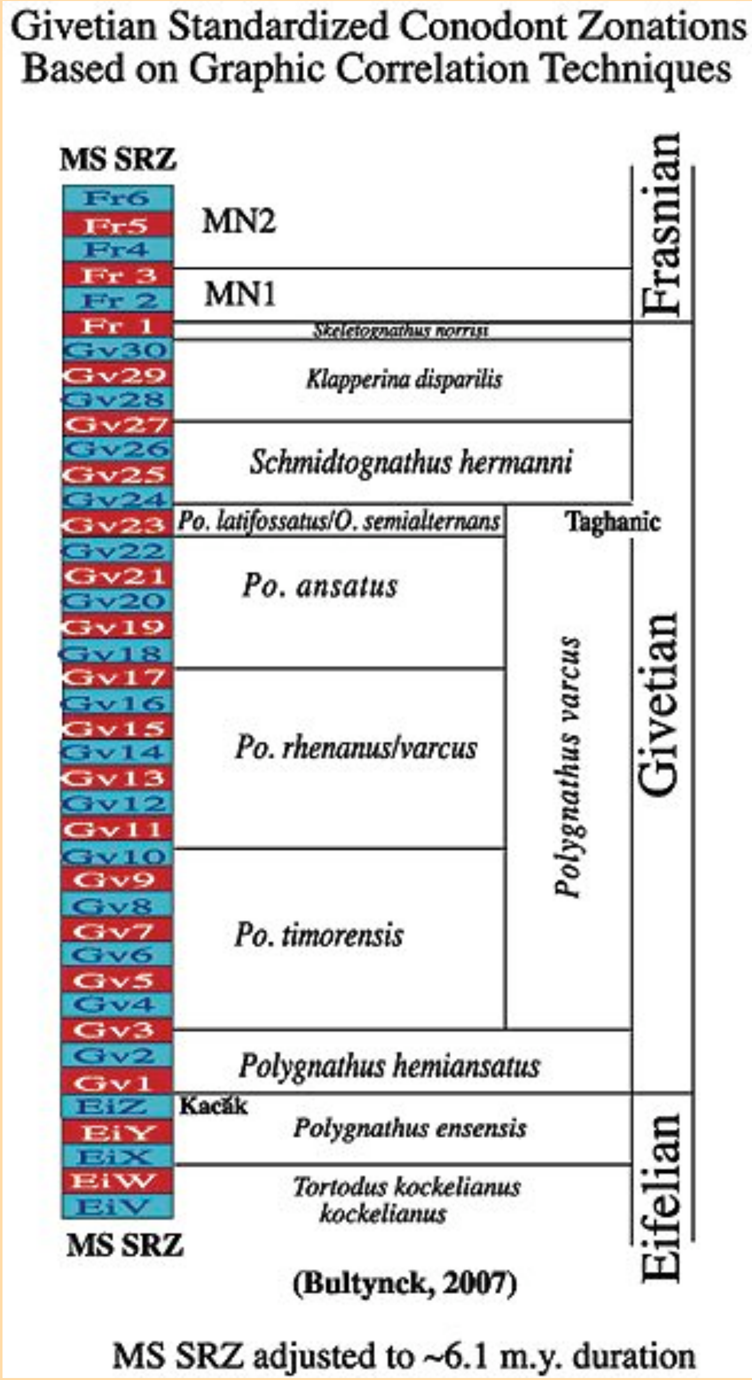




Step 10: If the 400 kyr cyclicity is represented, then smooth the MS data to conform to that cyclicity and build bar-logs



Step 11: Add the new data set to the graphic comparison

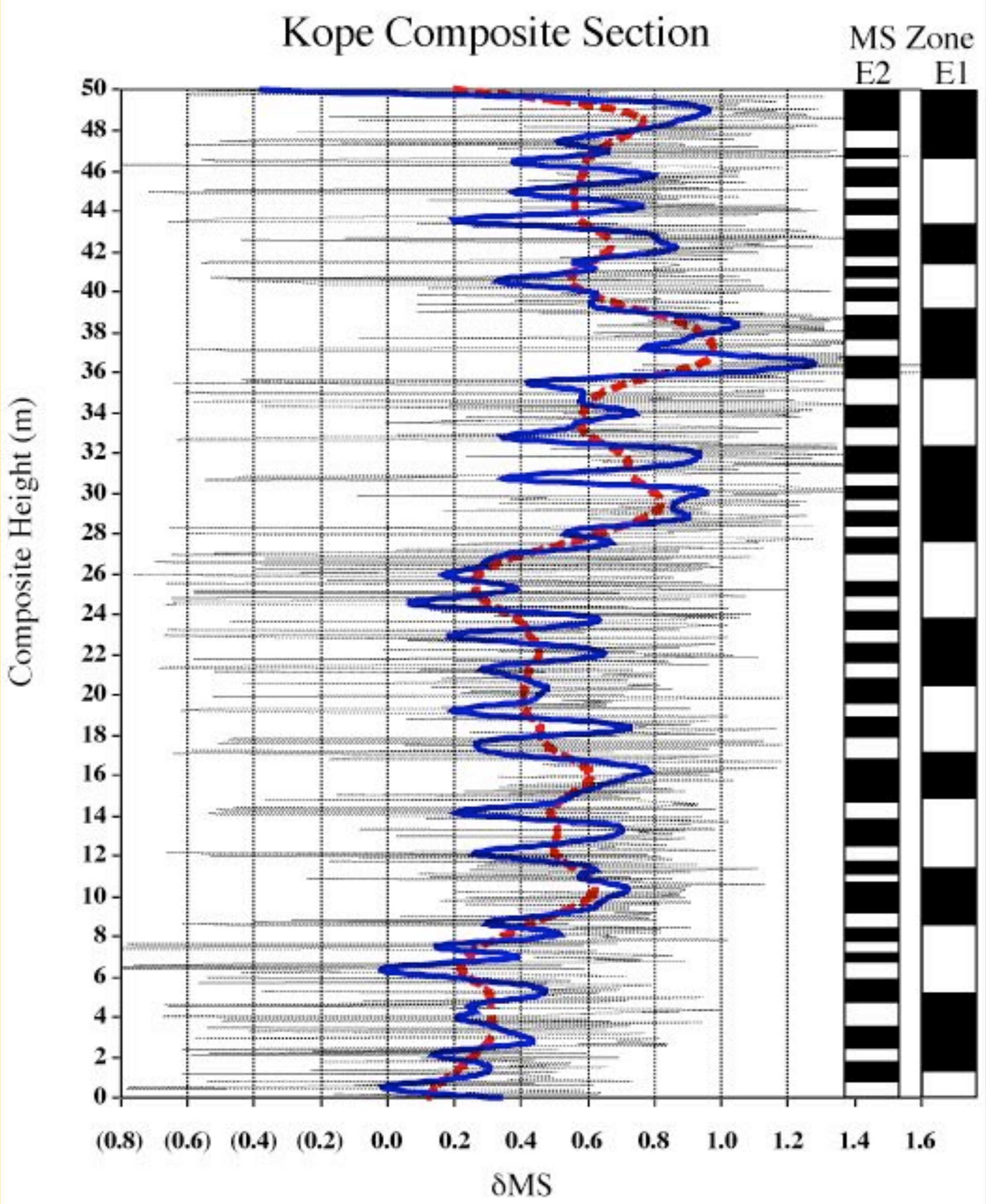


Step 12: Given the biostratigraphy in all sections used - and the constraints placed on the data sets by the 400 kyr zonation - adjust the original SRZ model to accommodate the new zonation and recalculate the duration for the Givetian Stage - this requires slightly adjusting the conodont zonations as well

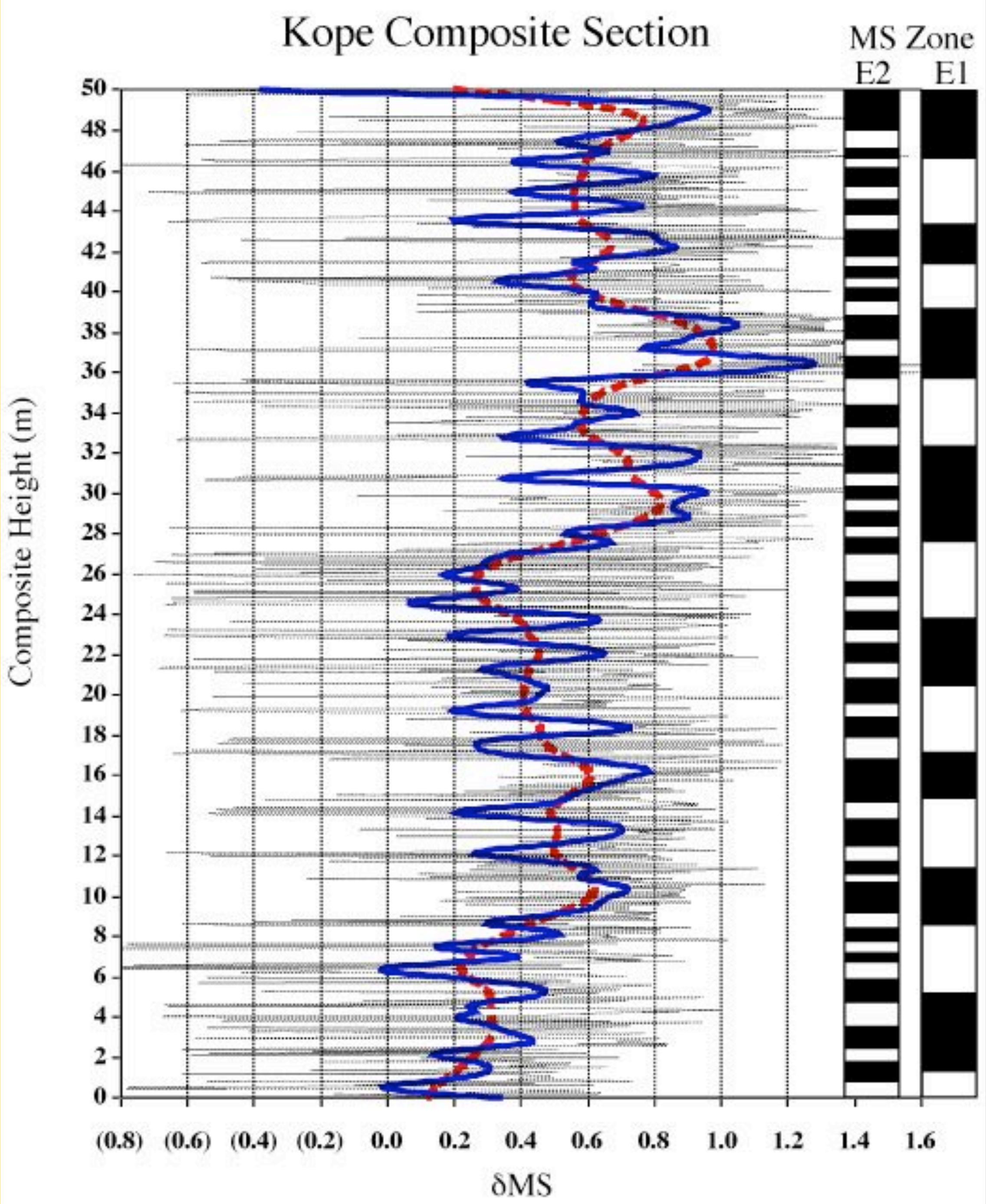
Example of how the MS in well-constrained composite sections can be useful in visualizing outcrops

Kope Formation Outcrop, Northern Kentucky

Ordovician rocks with clear cycles but what is the cyclicity?

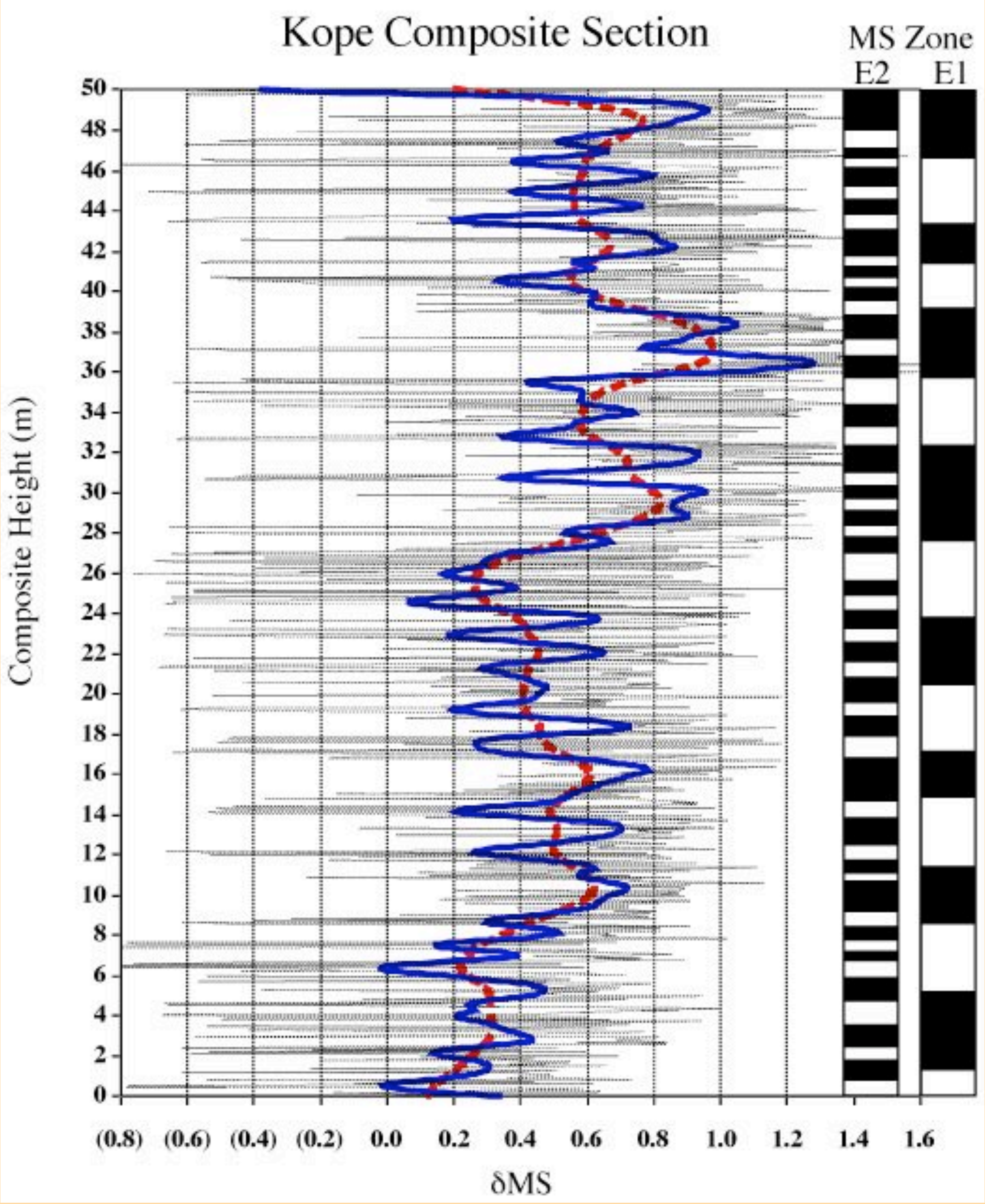


Begin with close interval (5 cm) samples in three different correlated sections to build a composite.



Begin with close interval (5 cm) samples in three different correlated sections to build a composite.

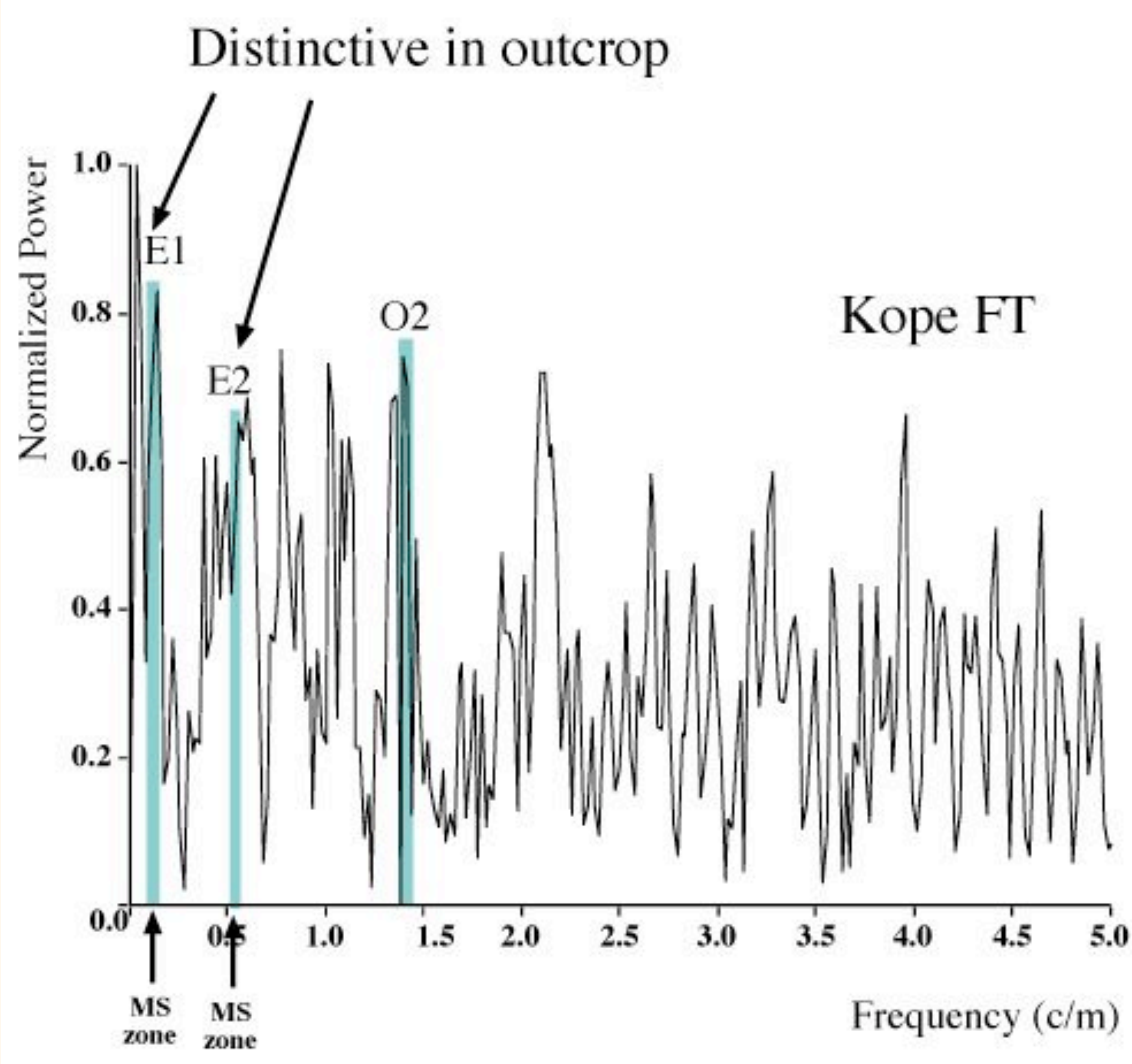
Smoothing using splines to conform to Fourier transform (FT) cycles.



Begin with close interval (5 cm) samples in three different correlated sections to build a composite.

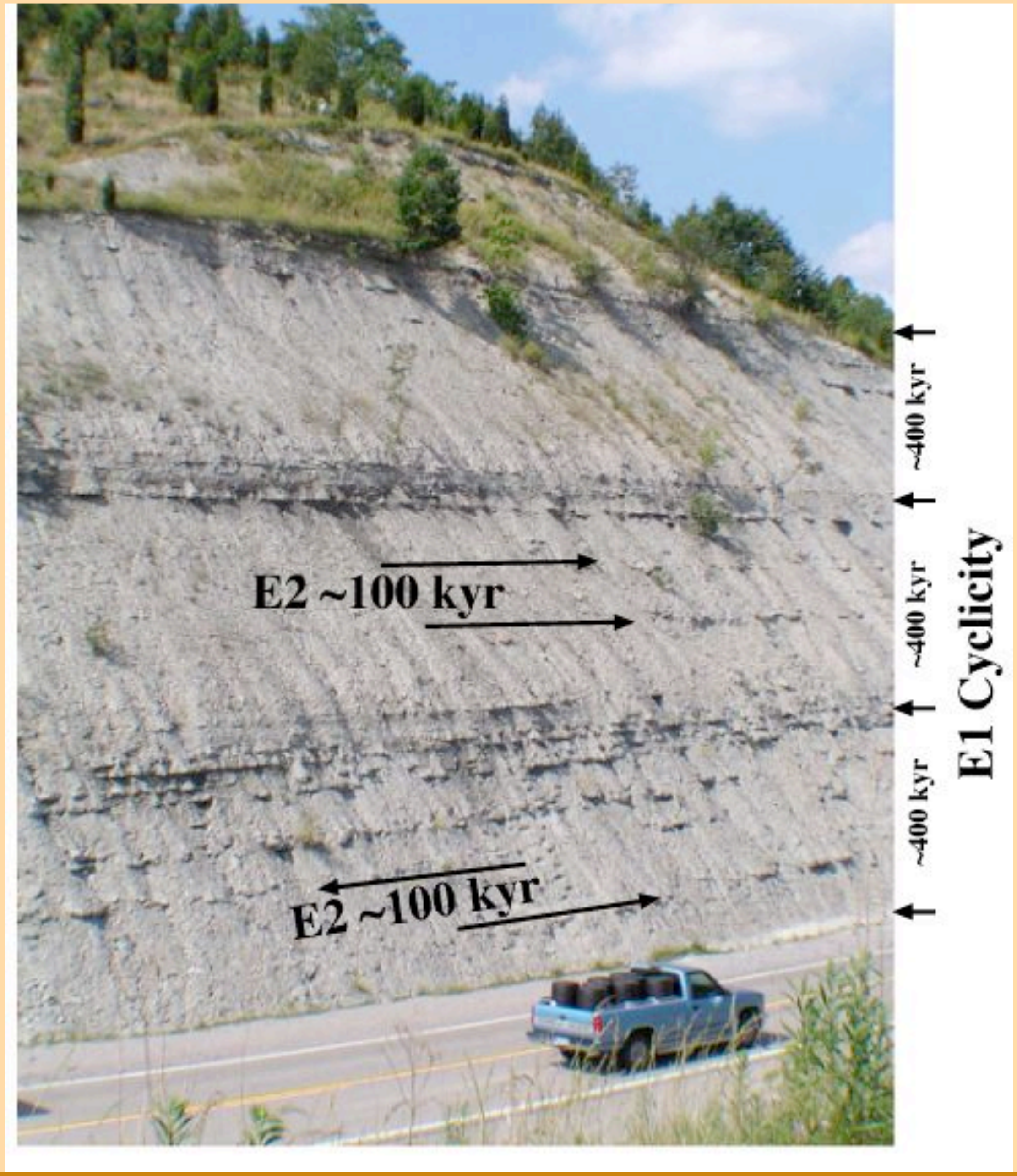
Smoothing using splines to conform to Fourier transform (FT) cycles.

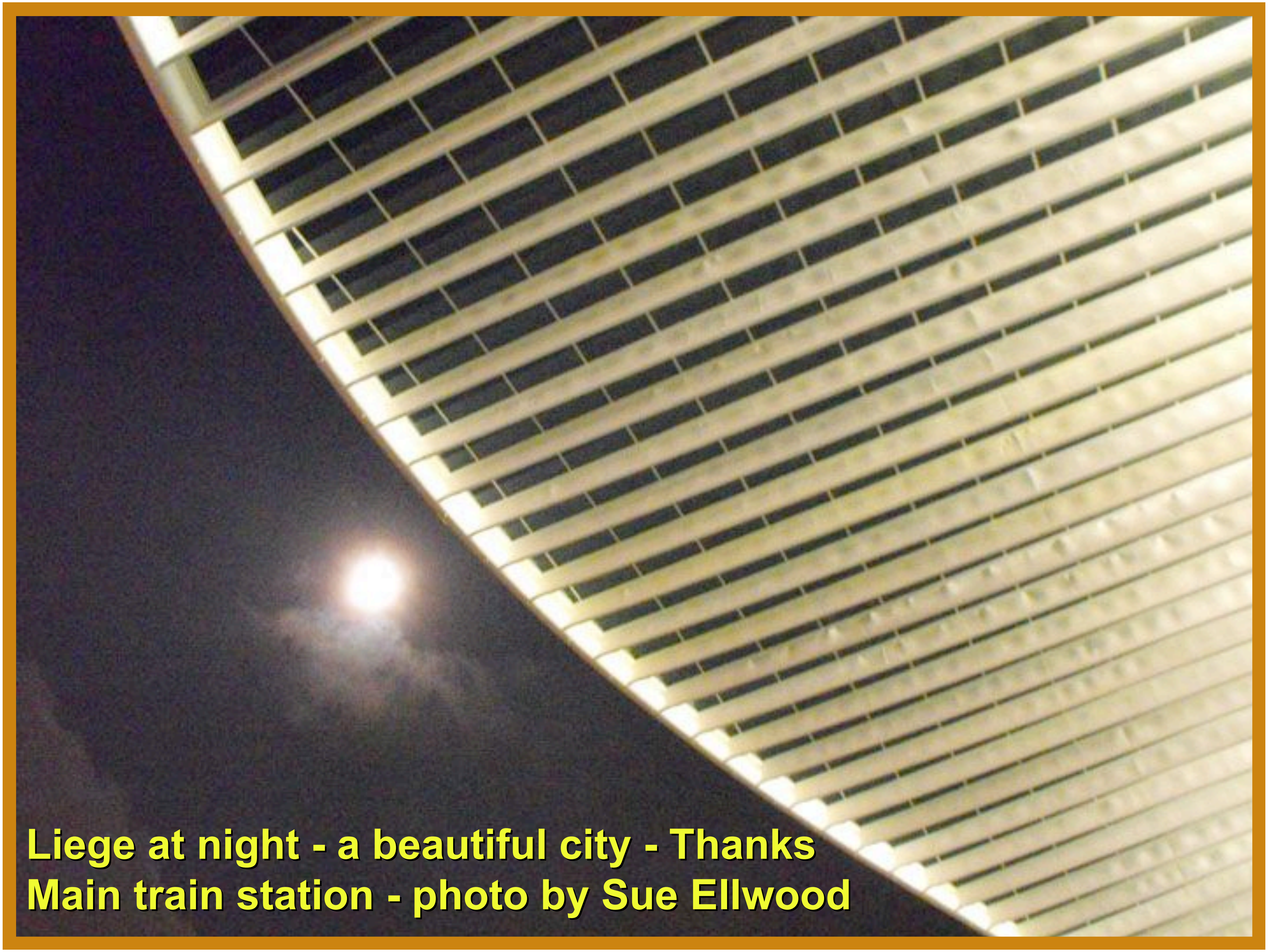
MS bar-logs represent these cycles.



Distinctive in outcrop
E1
E2
O2
Kope FT
Normalized Power
1.0
0.8
0.6
0.4
0.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
MS zone
MS zone
Frequency (c/m)

Kope Formation Outcrop, Northern Kentucky




Liege at night - a beautiful city - Thanks
Main train station - photo by Sue Ellwood