Martian Geochronology from Meteorites and Crater Counts

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Acknowledgments:

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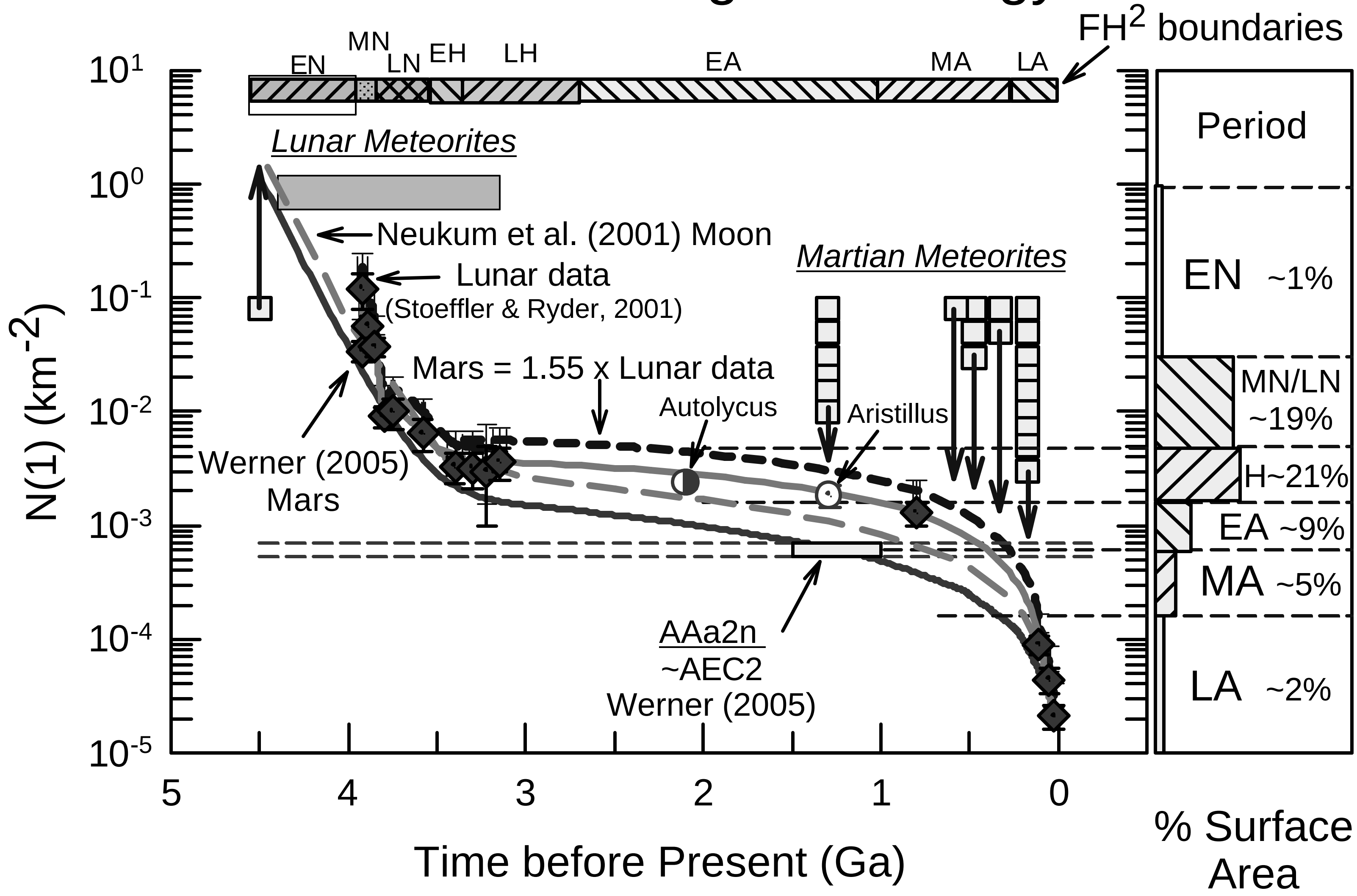
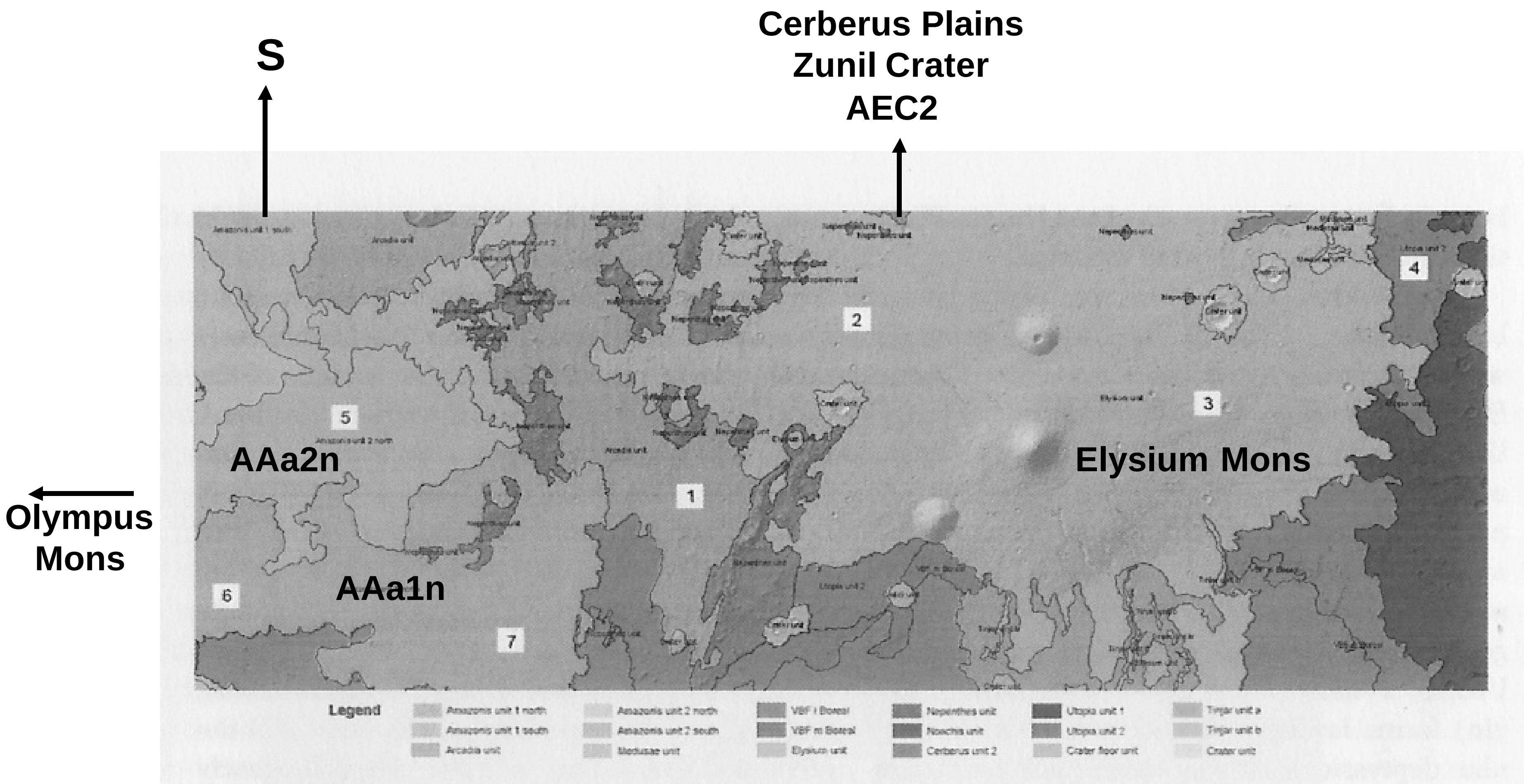
Introduction and Overview

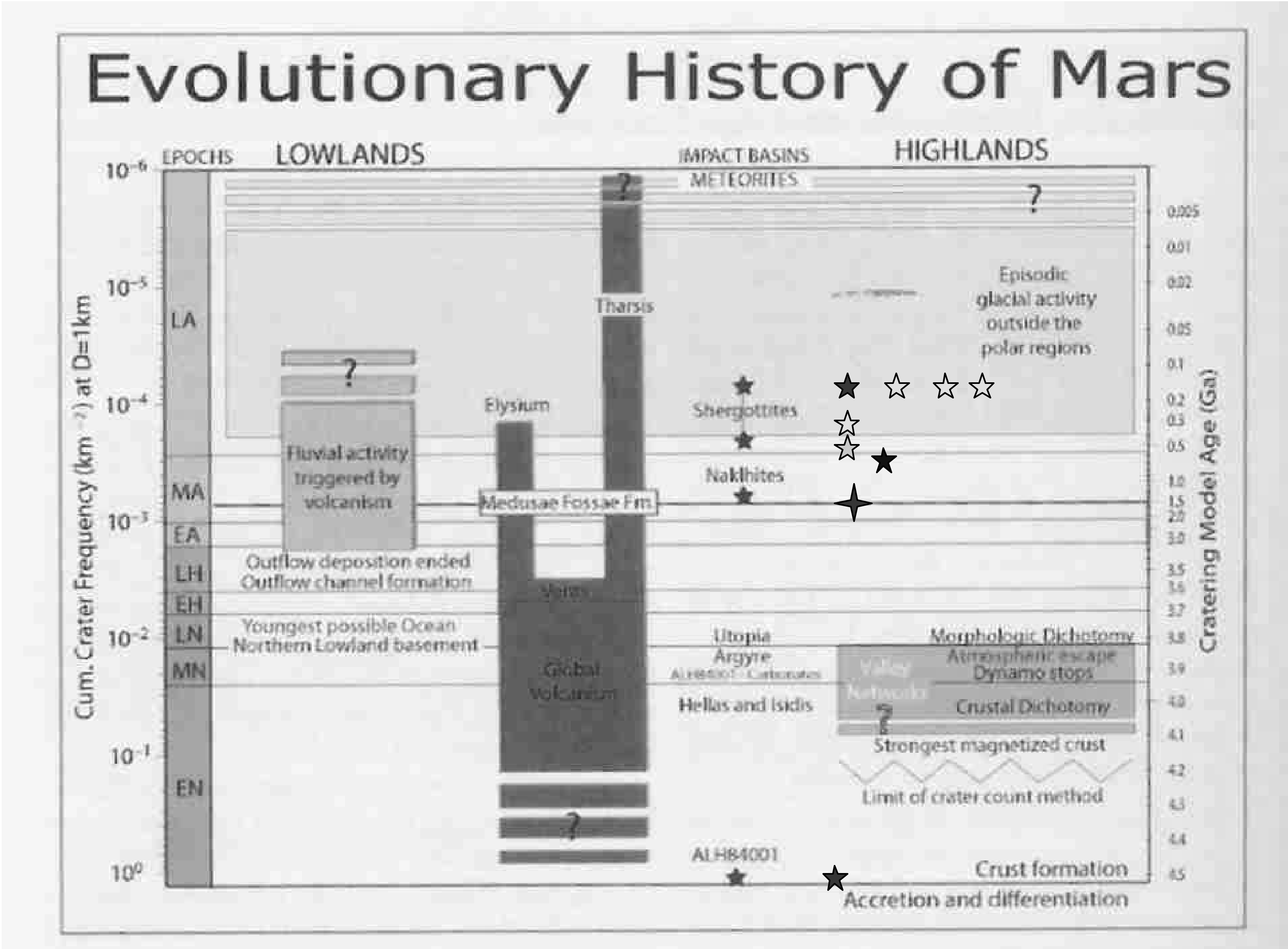
- Current status of Martian meteorite (MM) ages
  - Methods, examples, and factors
  - No “old” shergottites
- Comparisons to cratering chronologies
  - Hartmann/Neukum
    - S. Werner’s 2005 Ph. D. thesis
  - Stöffler-Ryder derived curve
    - Implications for meteorite source regions
- Possibilities for calibrating the cratering curve
- Possibilities for dating secondary mineralization
  - Example: Nakhlite iddingsite.
    - VERY preliminary Rb-Sr studies of sulfates
- Some analytical requirements for *in situ* age dating
  - Mostly for Rb-Sr, Sm-Nd

Martian and Lunar Meteorite Ages and Cratering Chronology

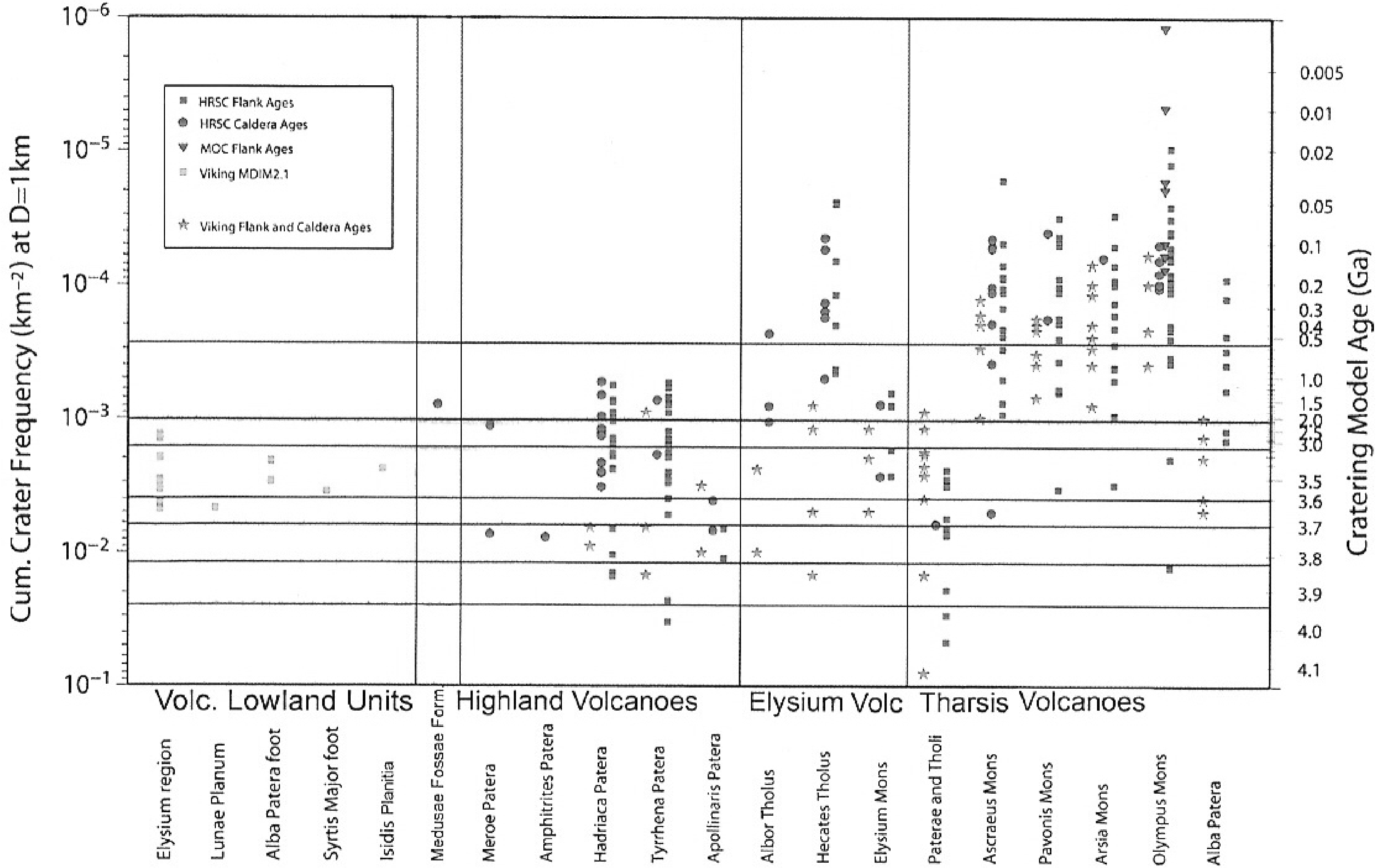




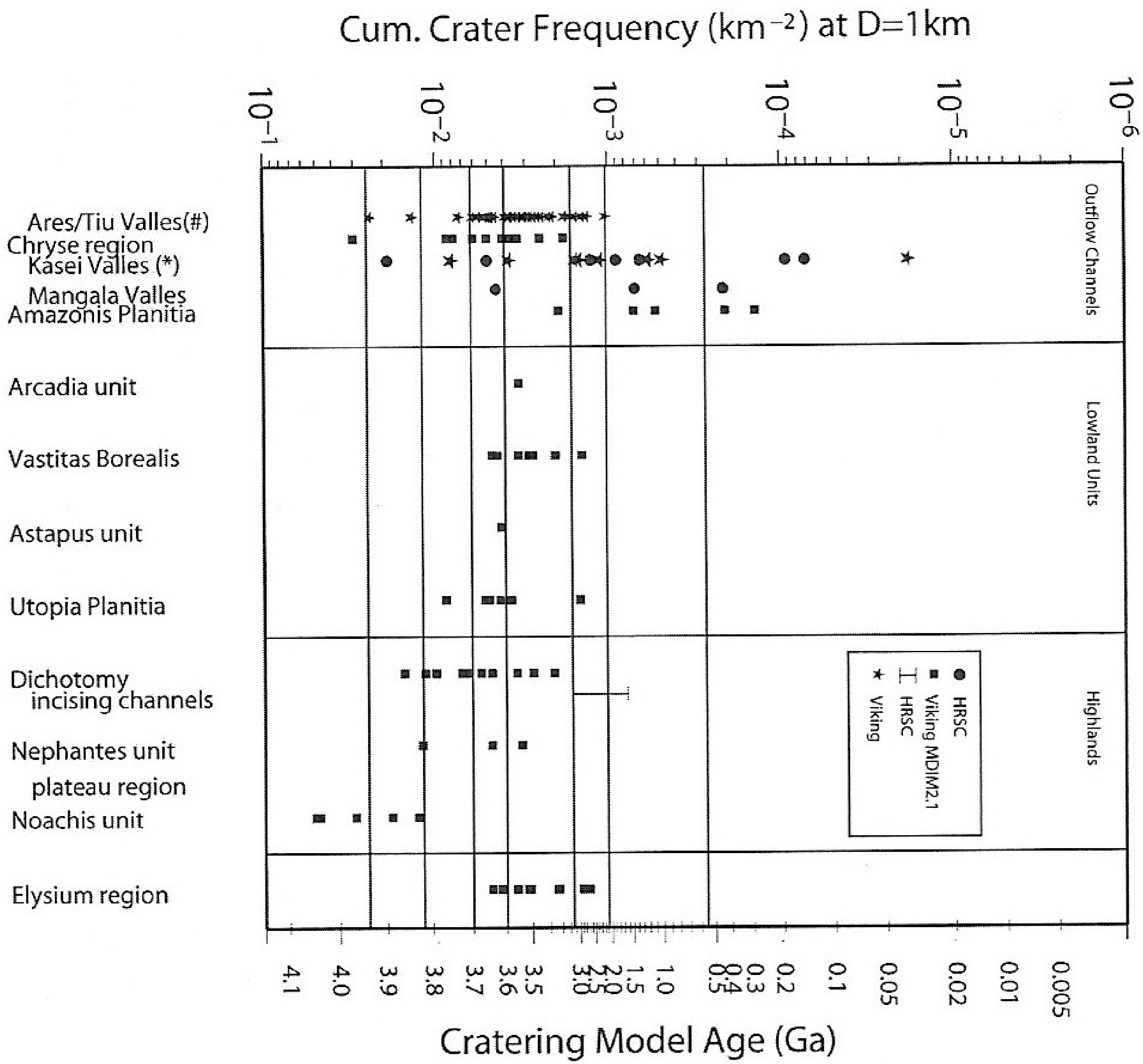
Werner (2005), Fig. 14.3. Geologic map from Tanaka et al. (2005) with numbered units for crater size-frequency distribution measurements by Werner.



Adapted from S. Werner (Thesis, 2005)

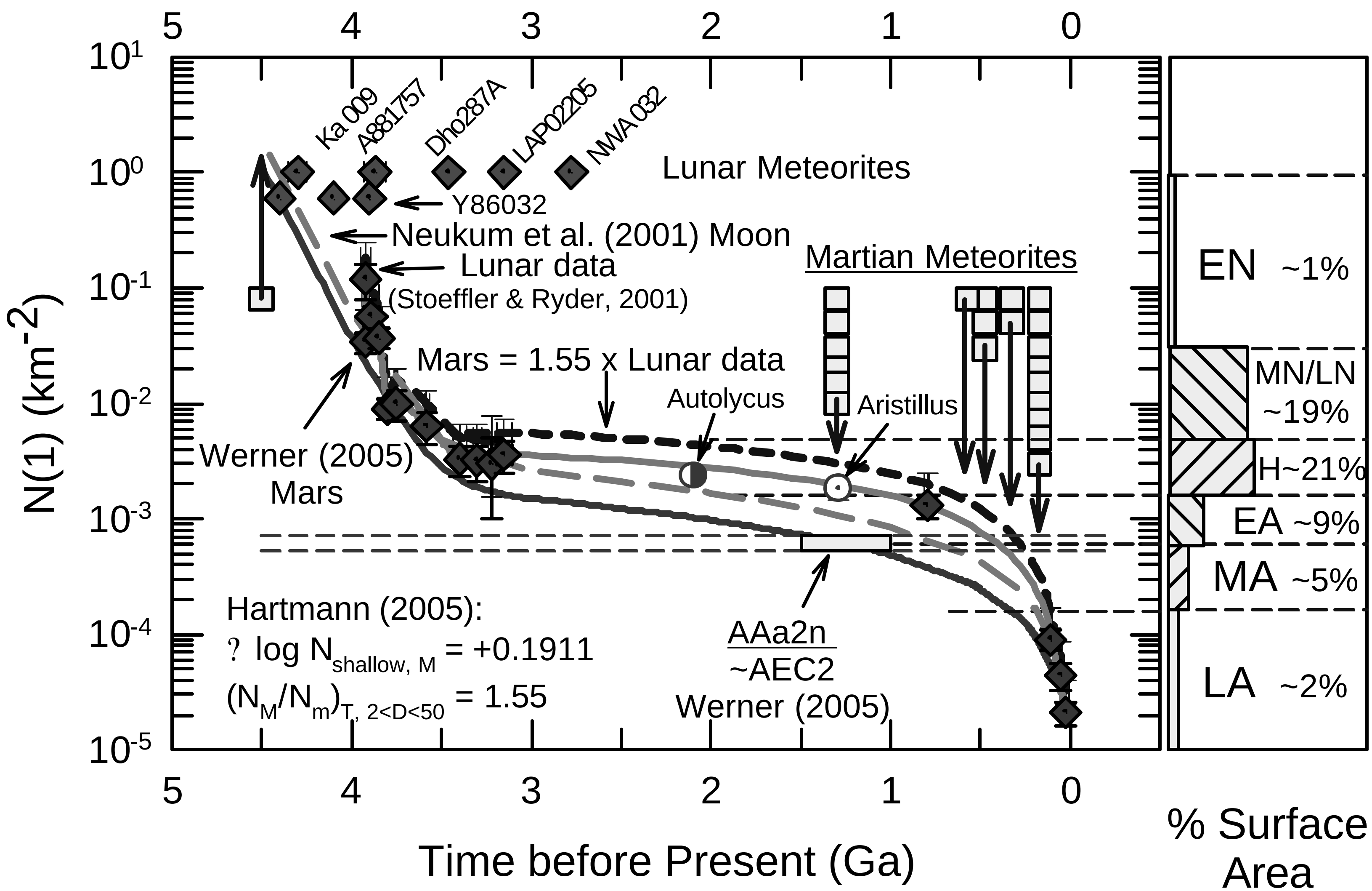


Adapted from Ph. D. Thesis of S. Werner (2005; Fig. 15.13)

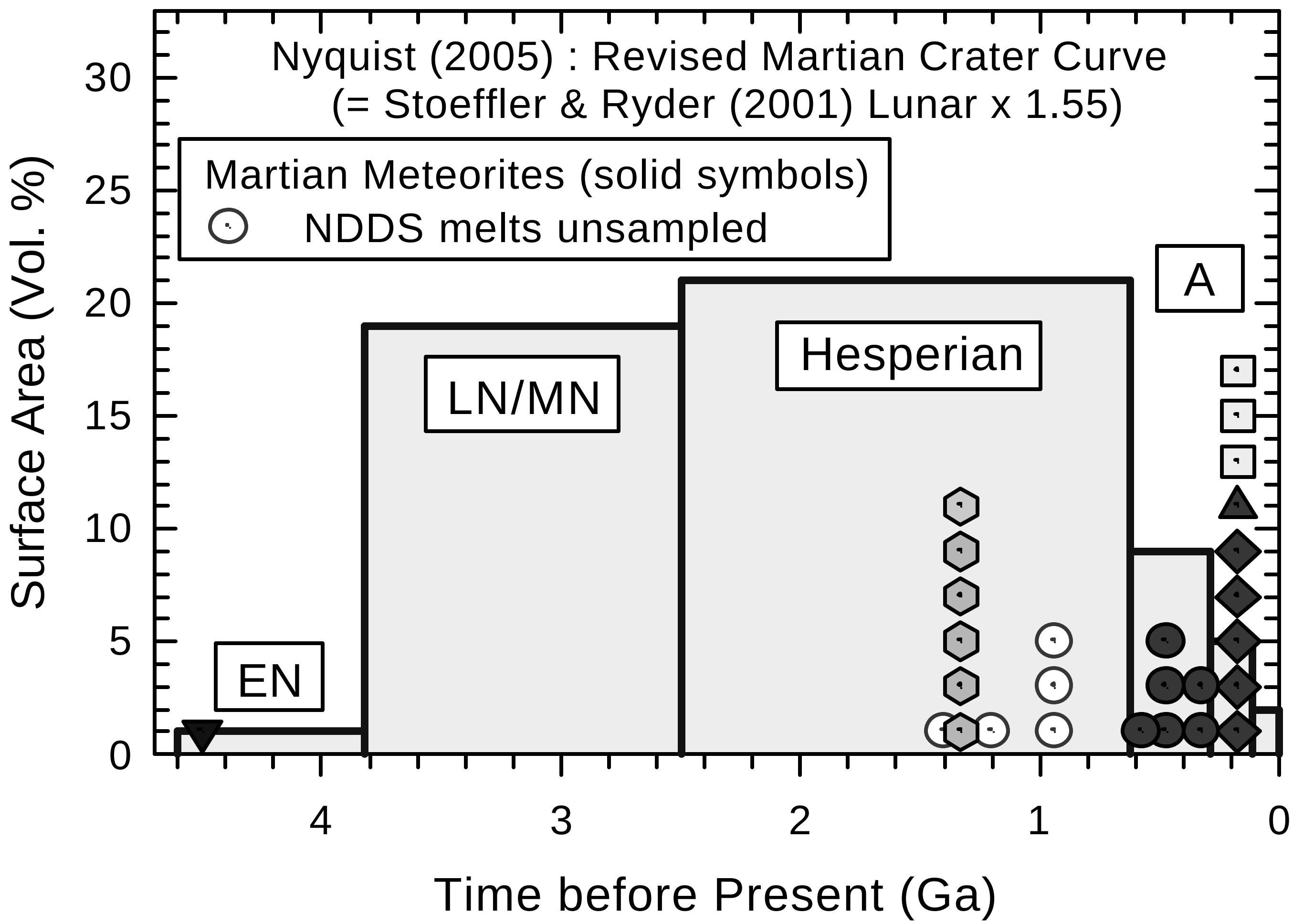


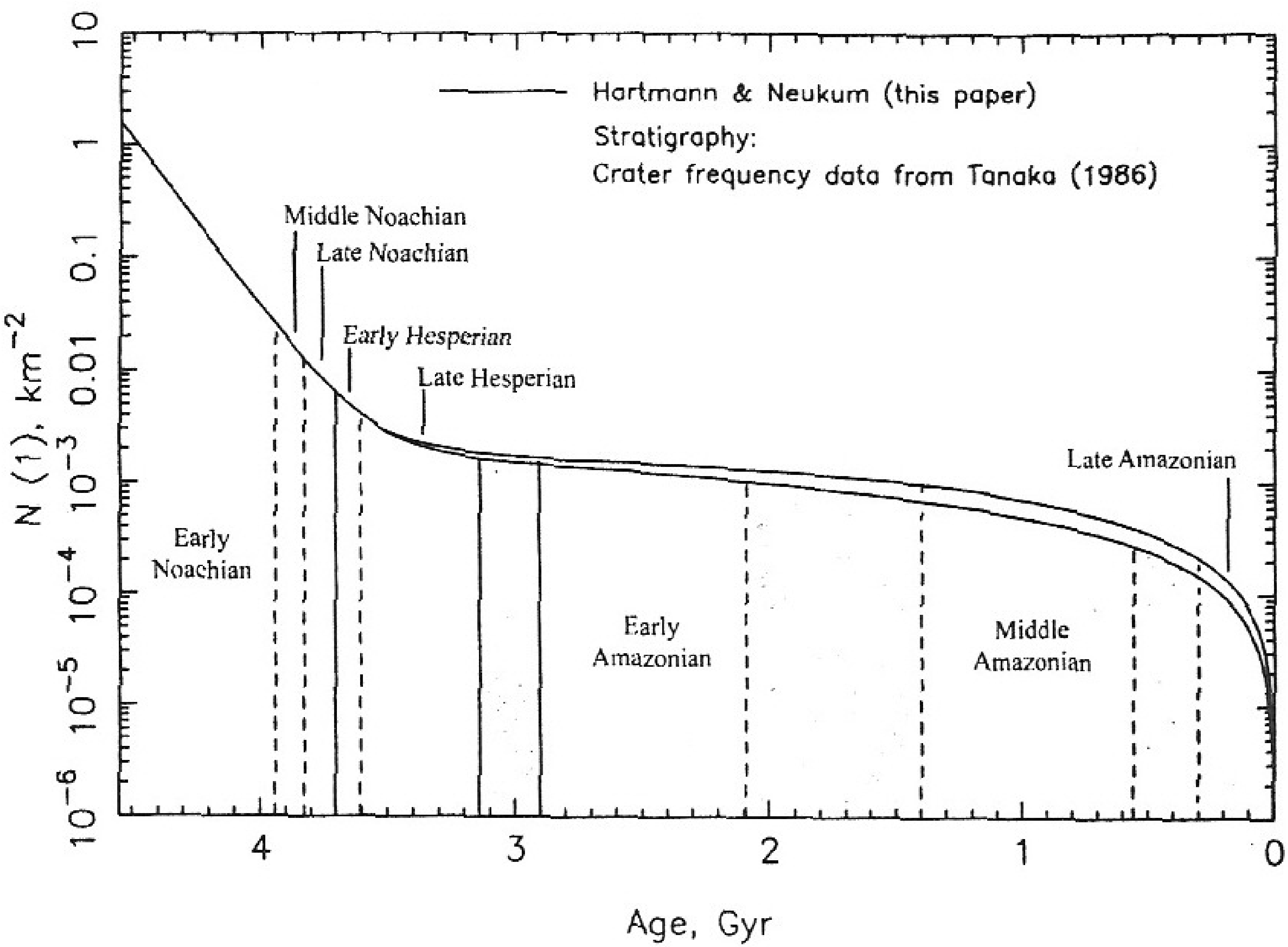
From S. Werner (Thesis, 2005, Fig. 14.11)

Radiometric Lunar and Martian Surface Ages and Impact Chronology

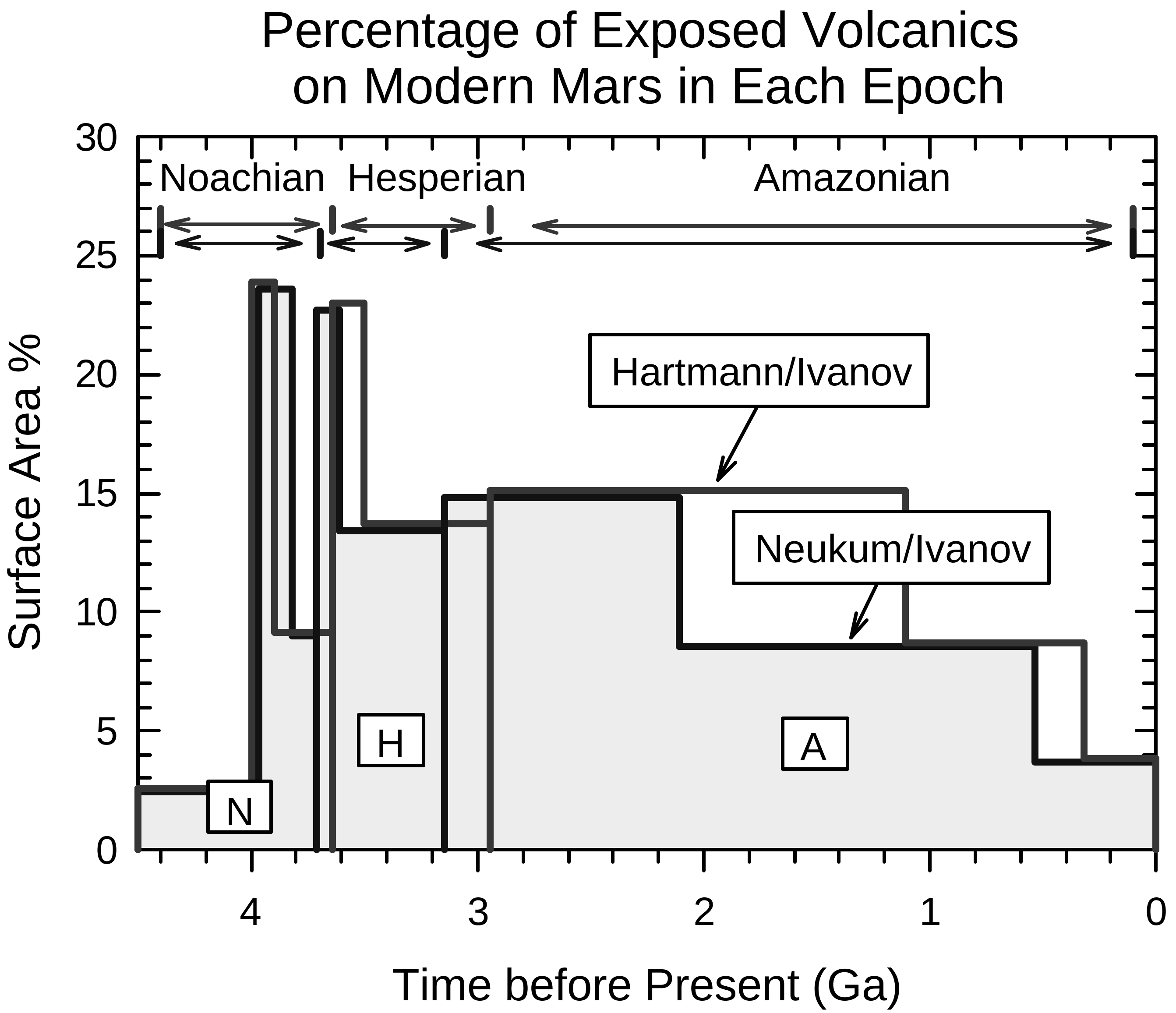


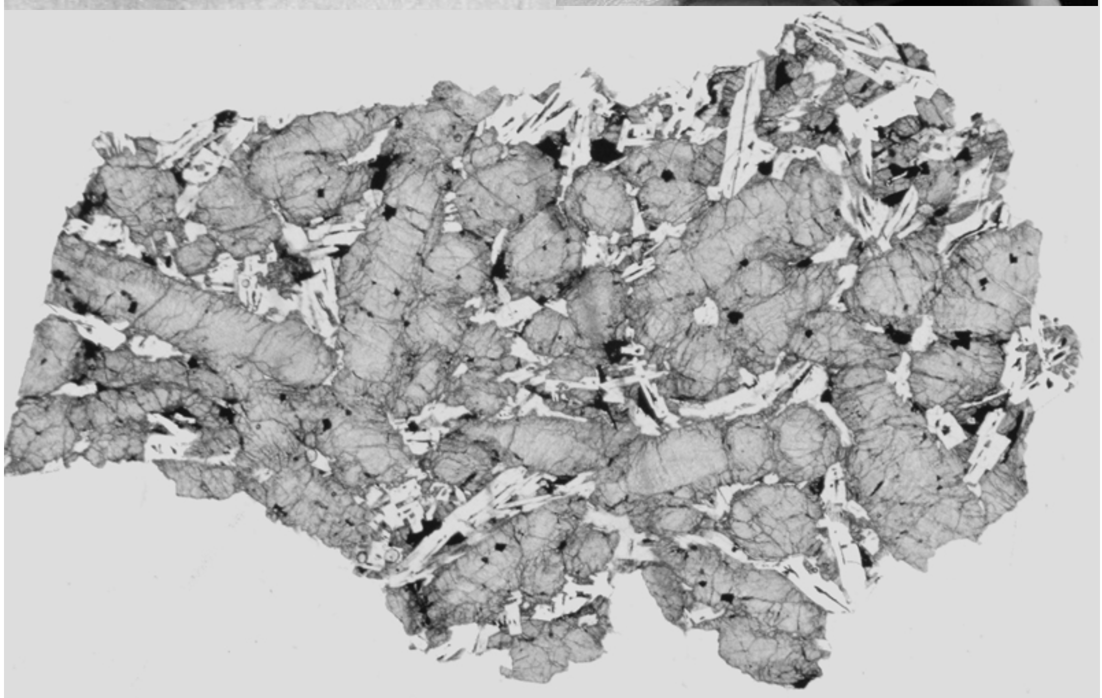
Impact Chronology of Mars



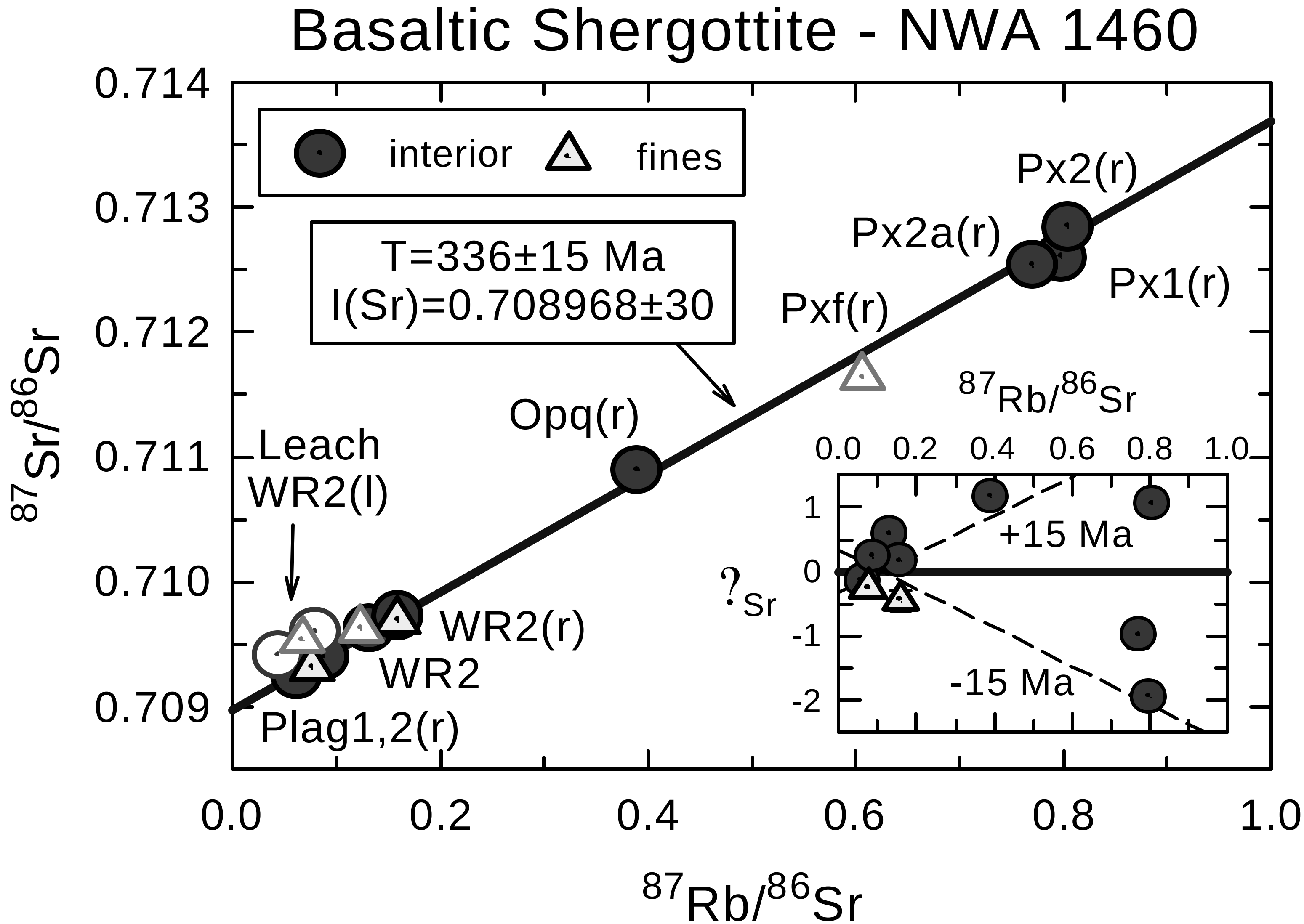


Hartmann & Neukum (this paper)
Stratigraphy:
Crater frequency data from Tanaka (1986)
Middle Noachian
Late Noachian
Early Hesperian
Late Hesperian
Late Amazonian
Early Noachian
Early Amazonian
Middle Amazonian
N (1), km^{-2}
10
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
4
3
2
1
0
Age, Gyr

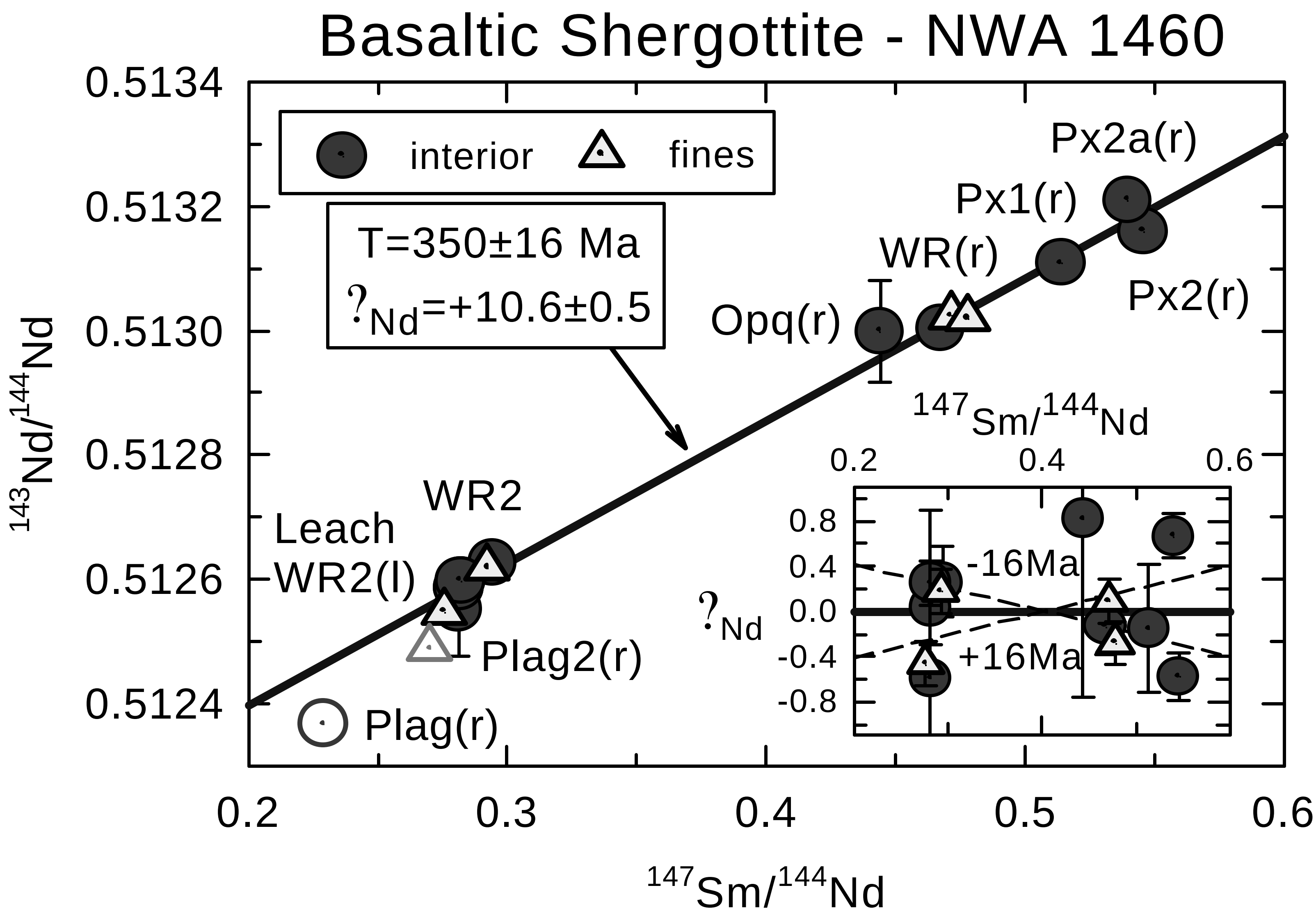

Percentage of Exposed Volcanics
on Modern Mars in Each Epoch
Surface Area %
Time before Present (Ga)
Noachian
Hesperian
Amazonian
Hartmann/Ivanov
Neukum/Ivanov
N
H
A
30
25
20
15
10
5
0
4
3
2
1
0

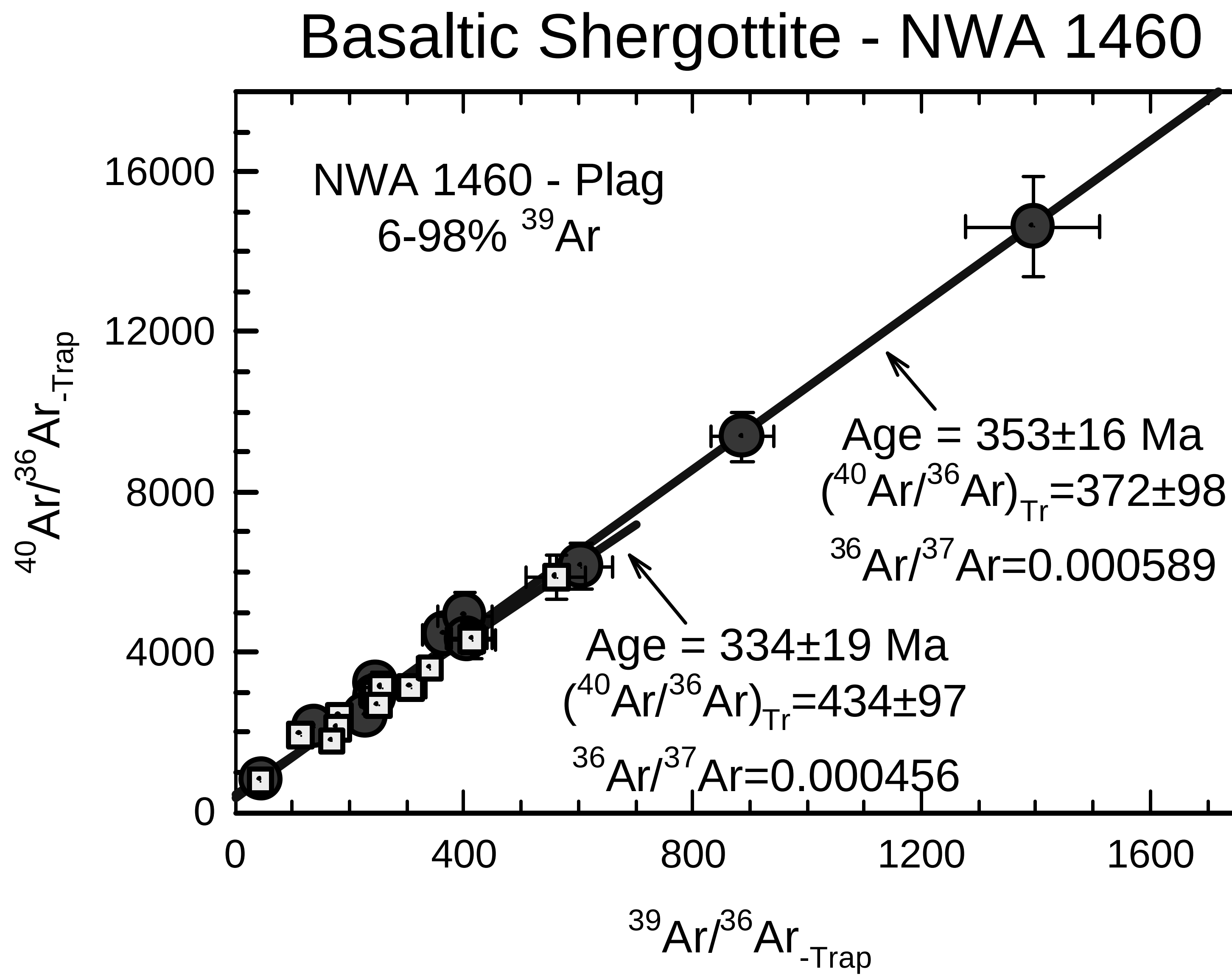


NWA 1460 Basaltic Shergottite

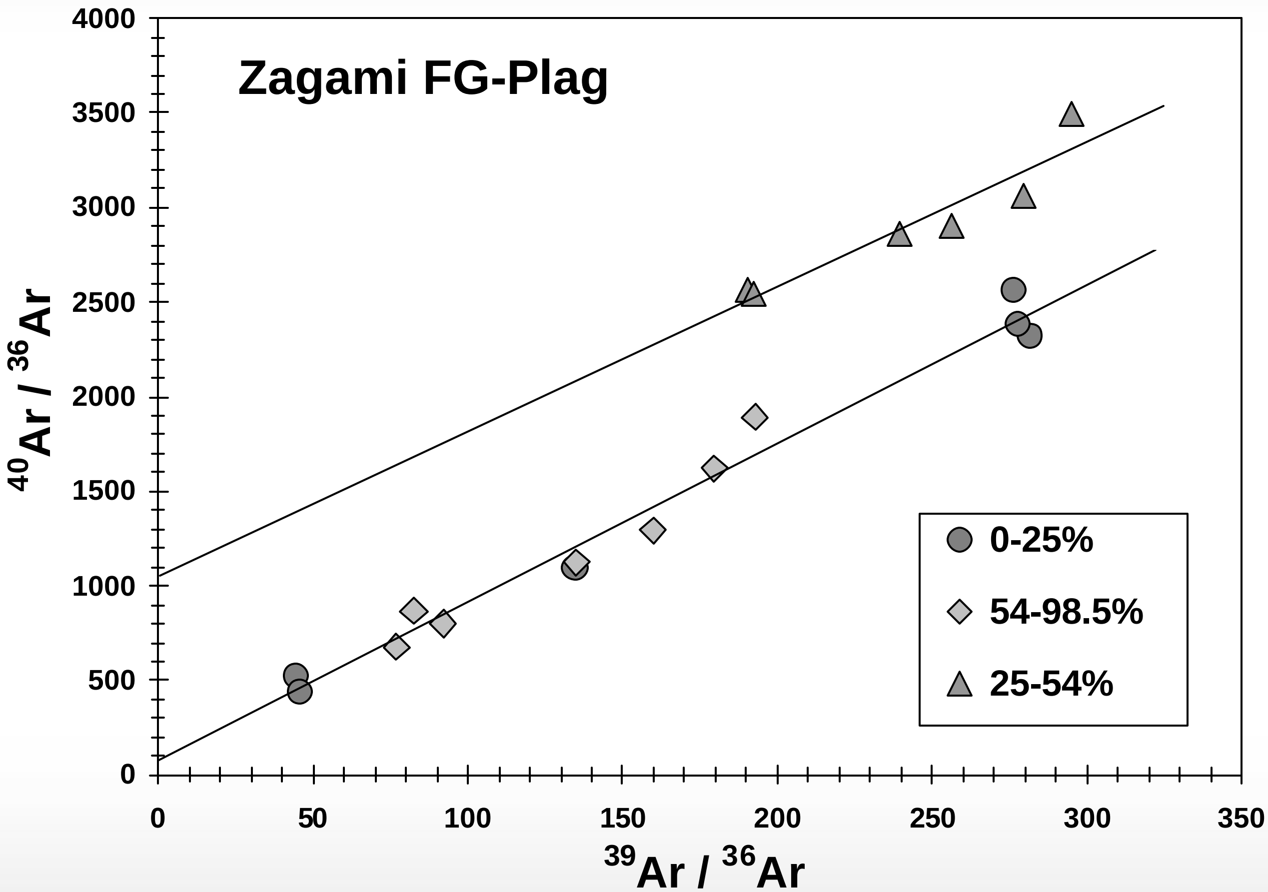


Basaltic Shergottite - NWA 1460
interior
fines
T=336±15 Ma
I(Sr)=0.708968±30
Px2(r)
Px2a(r)
Px1(r)
Pxf(r)
Opq(r)
Leach
WR2(l)
WR2(r)
WR2
Plag1,2(r)
+15 Ma
-15 Ma
0.714
0.713
0.712
0.711
0.710
0.709
0.0
0.2
0.4
0.6
0.8
1.0
$^{87}Sr/^{86}Sr$
$^{87}Rb/^{86}Sr$


Basaltic Shergottite - NWA 1460
0.5134
0.5132
0.5130
0.5128
0.5126
0.5124
143Nd/144Nd
interior
fines
T=350±16 Ma
?Nd=+10.6±0.5
Px2a(r)
Px1(r)
WR(r)
Px2(r)
Opq(r)
WR2
Leach
WR2(l)
Plag2(r)
Plag(r)
147Sm/144Nd
0.2
0.4
0.6
0.8
0.4
0.0
-0.4
-0.8
?Nd
-16Ma
+16Ma
0.2
0.3
0.4
0.5
0.6
147Sm/144Nd


Basaltic Shergottite - NWA 1460
NWA 1460 - Plag
6-98% ^{39}Ar
Age = 353±16 Ma
(^{40}Ar/^{36}Ar)$_{Tr}$=372±98
^{36}Ar/^{37}Ar=0.000589
Age = 334±19 Ma
(^{40}Ar/^{36}Ar)$_{Tr}$=434±97
^{36}Ar/^{37}Ar=0.000456
^{40}Ar/^{36}Ar$_{-Trap}$
^{39}Ar/^{36}Ar$_{-Trap}$
0
4000
8000
12000
16000
0
400
800
1200
1600

Isochron plot of 40Ar/36Ar vs 39Ar/36Ar



Bogard & Park (2008)

Slide courtesy of J. Park

Isochron Age

= ?300 Myr

$40Ar_{xs}$ is distributed through the lattice

Larger $40Ar_{xs}$ (at intermediate temp extractions 23-54% of 39Ar)

“hump” :

40Ar/36Ar= ?1000 (could be Martian atm in a shock produced phase)

Excess 40Ar in Zagami meteorite

Excess 40Ar in Zagami Mineral Separates

Phase	$40Ar_{xs}$	% total
CG-Plag	15.7x 10^{-7} cm^3	32
FG-Plag*	23.4 (17.9)x 10^{-7} cm^3	54
CG-Px2	10.8x 10^{-7} cm^3	85
FG-Px 2	9.2x 10^{-7} cm^3	86
FG-Px 1	15.3x 10^{-7} cm^3	89

Values calculated by subtracting from measured 40Ar, the amount of 40Ar* in situ, assuming Zagami formation age of 170 Myr.

No significant difference between CG & FG, nor between Plag & Pyx

(*Second value for FG-Plag subtracts the trapped component with 40Ar/36Ar=1000.)

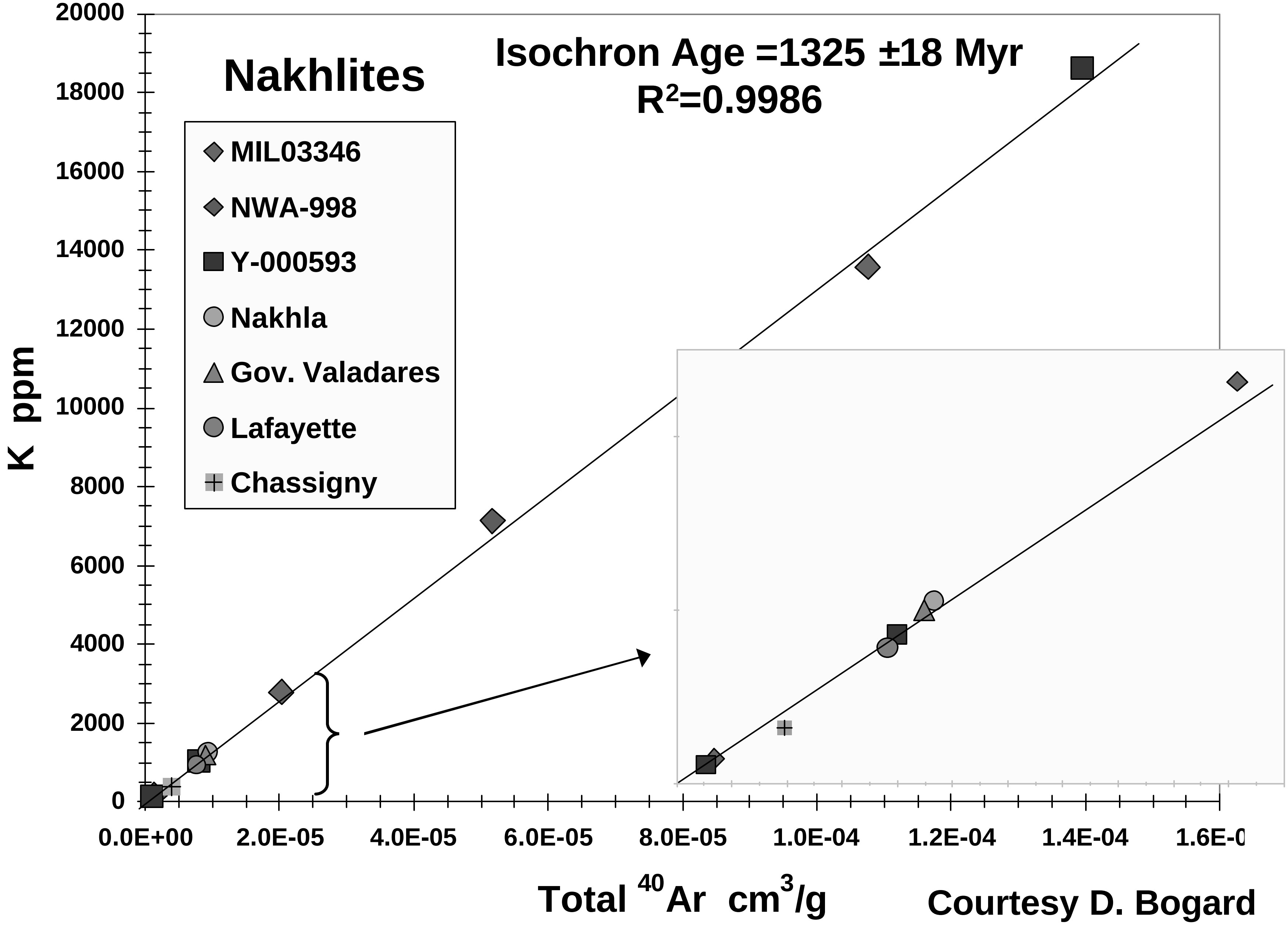
Bogard & Park (2008) suggest

$40Ar_{xs}$= ? 1-2x10^{-6}

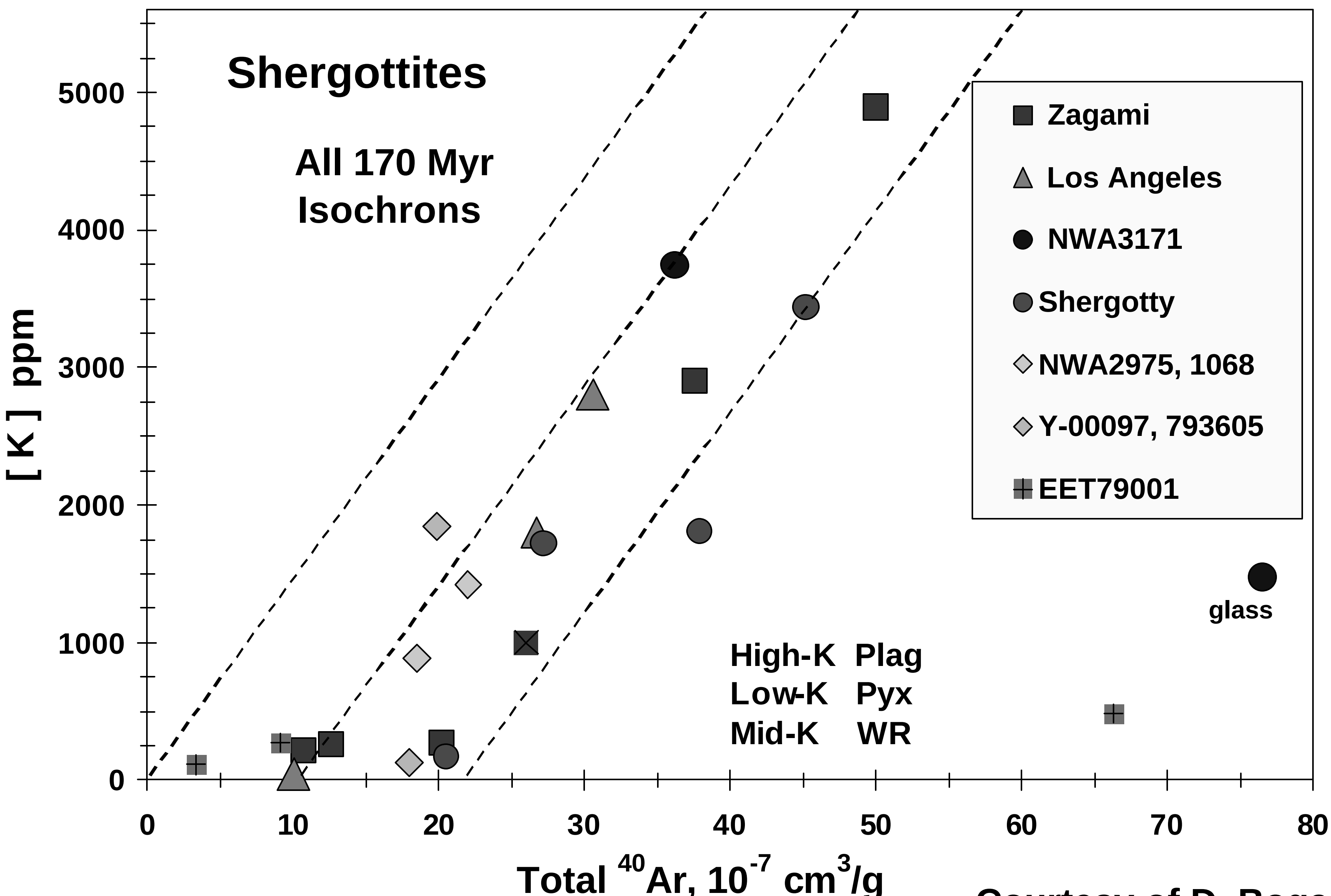
(in cm^3STP/g)

Similar 40Ar excesses are also observed in other shergottites (Bogard, Park & Garrison, 2008, submitted. Courtesy of J. Park)

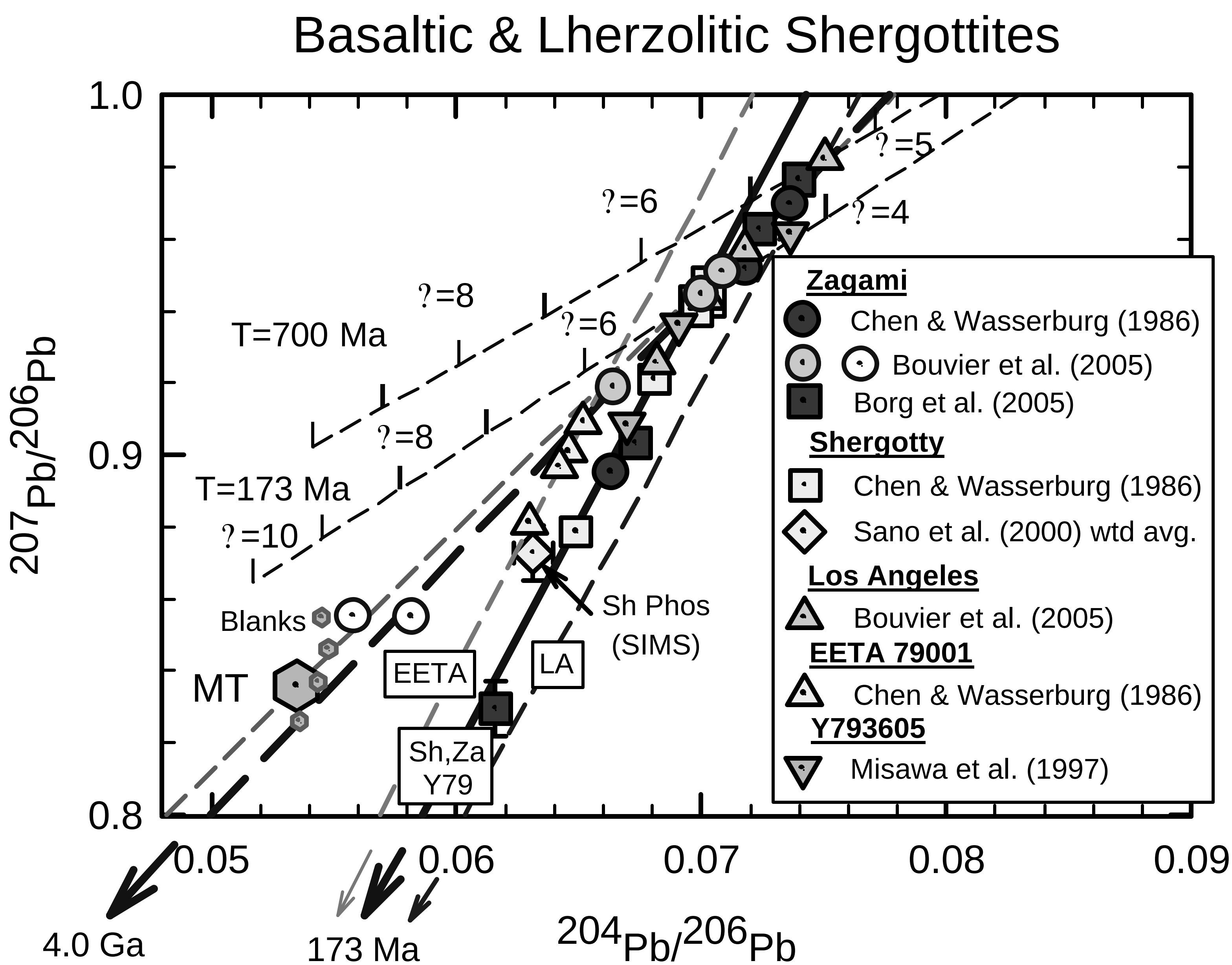
For Nakhlites: Common Age; No Evidence of Significant Excess ^{40}Ar

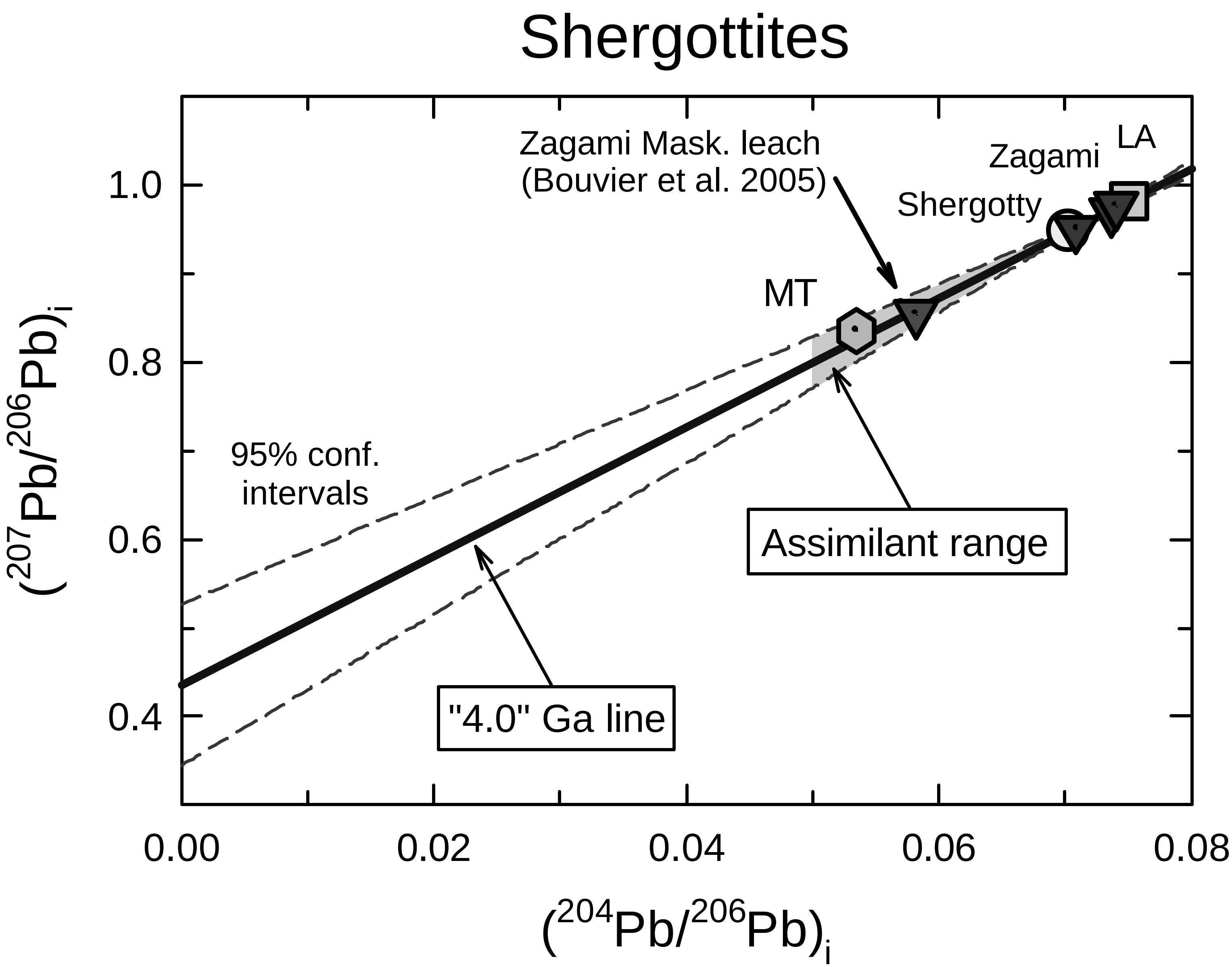


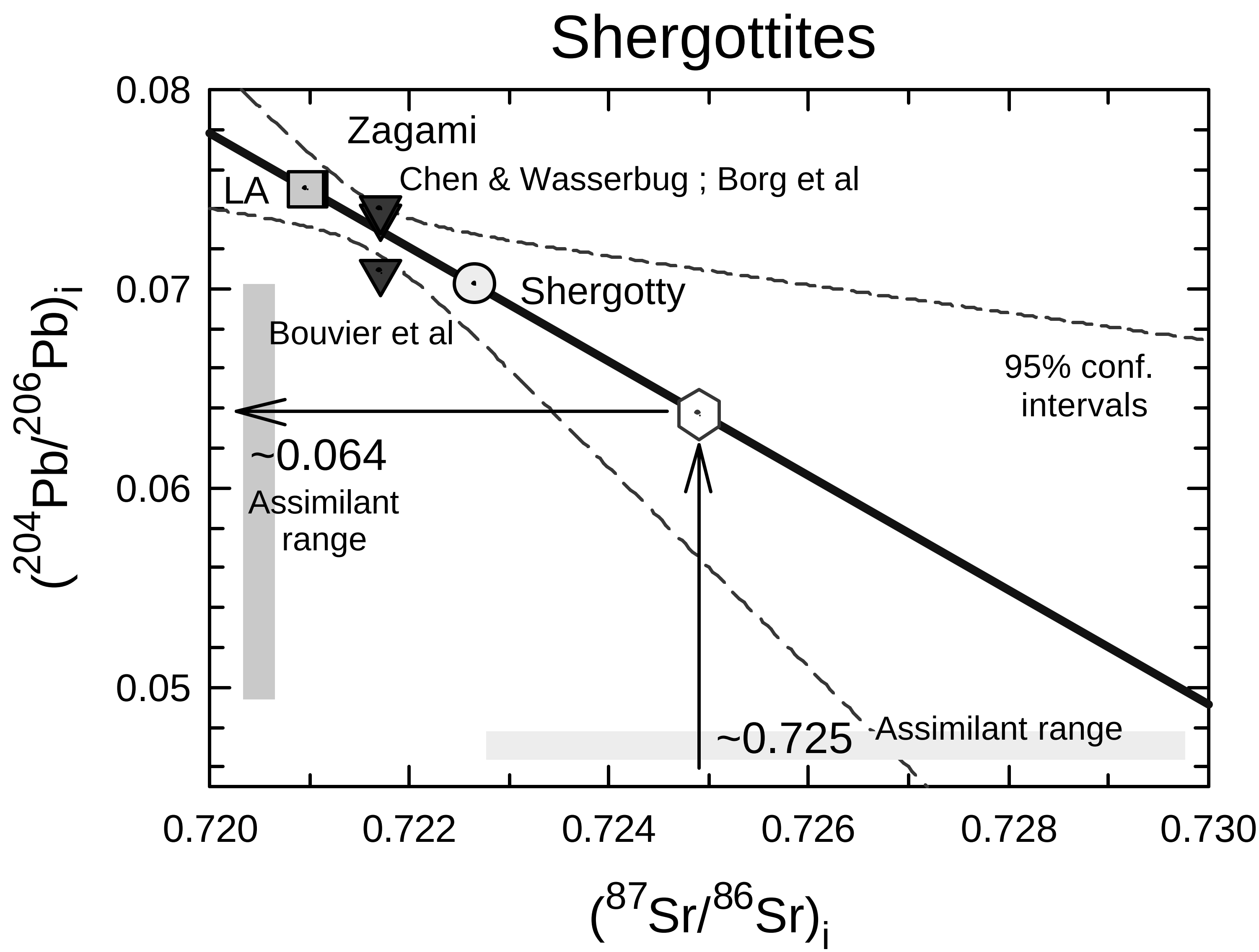
Common Age and 10-22 x10^{-7} cm^3/g Magma-Derived ^{40}Ar



Courtesy of D. Bogard


Basaltic & Lherzolitic Shergottites
1.0
0.9
0.8
0.05
0.06
0.07
0.08
0.09
207Pb/206Pb
204Pb/206Pb
?=5
?=4
?=6
?=8
?=6
T=700 Ma
?=8
T=173 Ma
?=10
Blanks
MT
EETA
LA
Sh Phos
(SIMS)
Sh,Za
Y79
4.0 Ga
173 Ma
Zagami
Chen & Wasserburg (1986)
Bouvier et al. (2005)
Borg et al. (2005)
Shergotty
Chen & Wasserburg (1986)
Sano et al. (2000) wtd avg.
Los Angeles
Bouvier et al. (2005)
EETA 79001
Chen & Wasserburg (1986)
Y793605
Misawa et al. (1997)


Shergottites
Zagami Mask. leach
(Bouvier et al. 2005)
LA
Zagami
Shergotty
MT
95% conf.
intervals
Assimilant range
"4.0" Ga line
1.0
0.8
0.6
0.4
0.00
0.02
0.04
0.06
0.08
(207Pb/206Pb)i
(204Pb/206Pb)i


Shergottites
Zagami
Chen & Wasserbug ; Borg et al
LA
Shergotty
Bouvier et al
95% conf. intervals
~0.064
Assimilant range
~0.725
Assimilant range
0.08
0.07
0.06
0.05
0.720
0.722
0.724
0.726
0.728
0.730
$(^{204}Pb/^{206}Pb)_i$
$(^{87}Sr/^{86}Sr)_i$

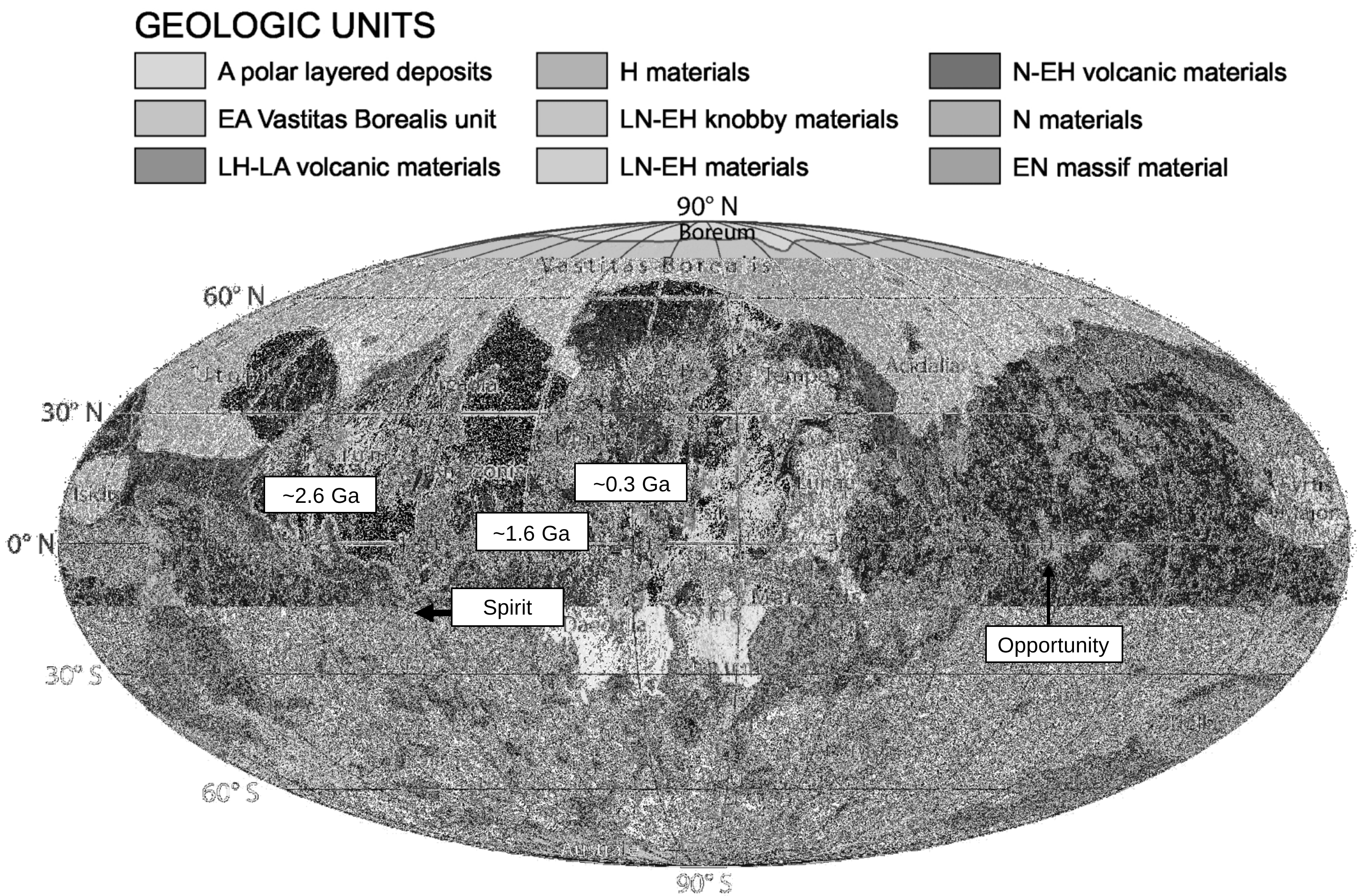
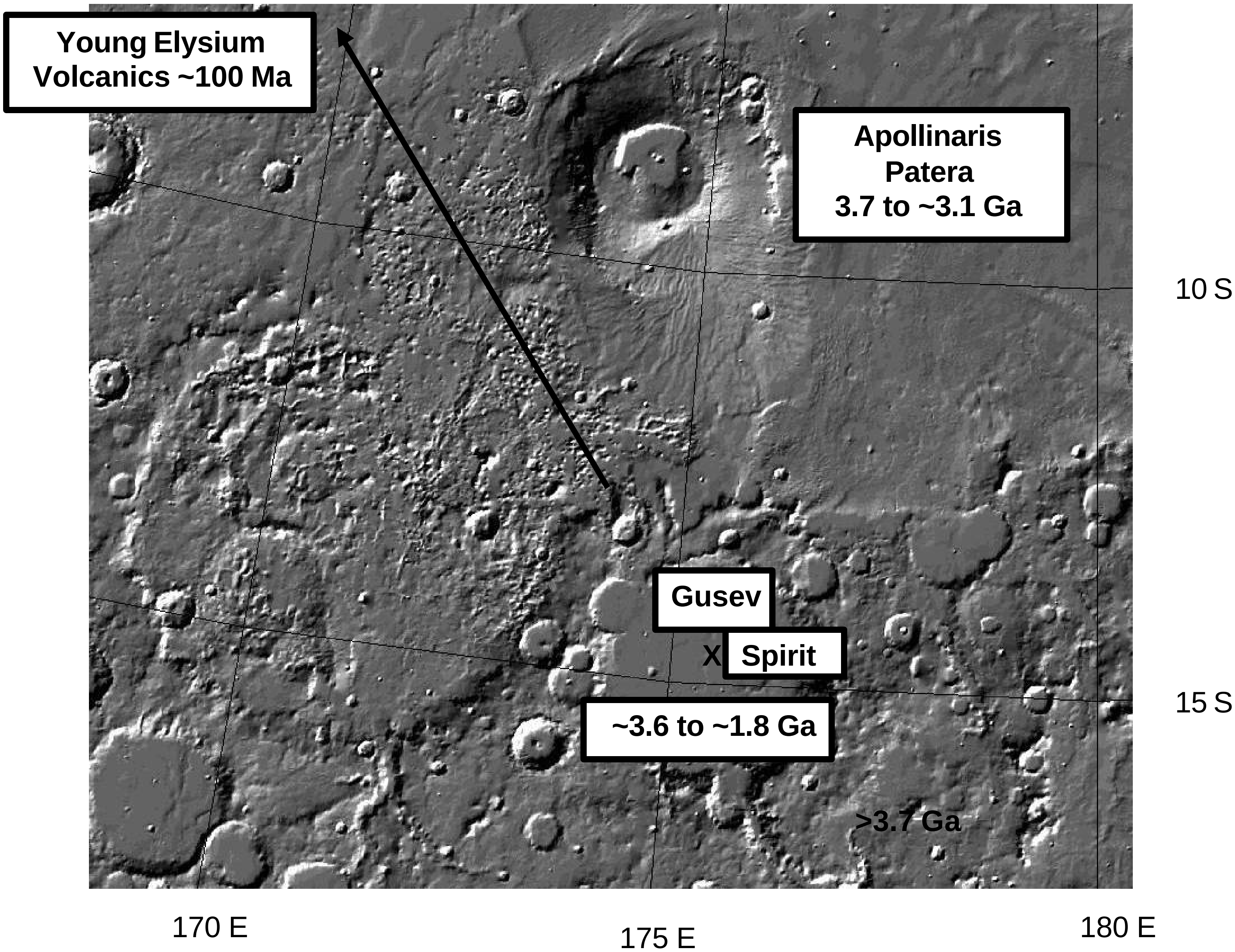
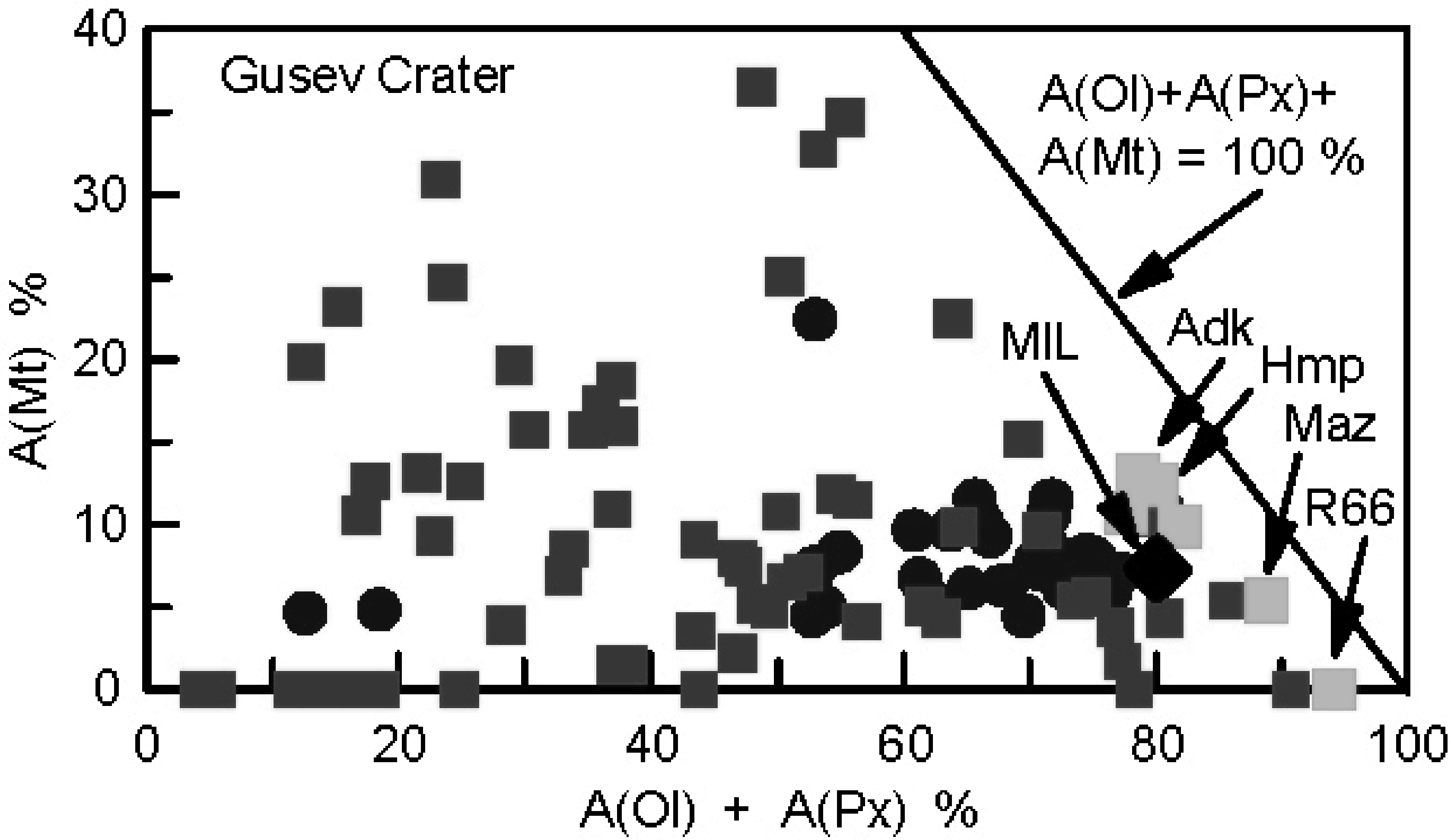


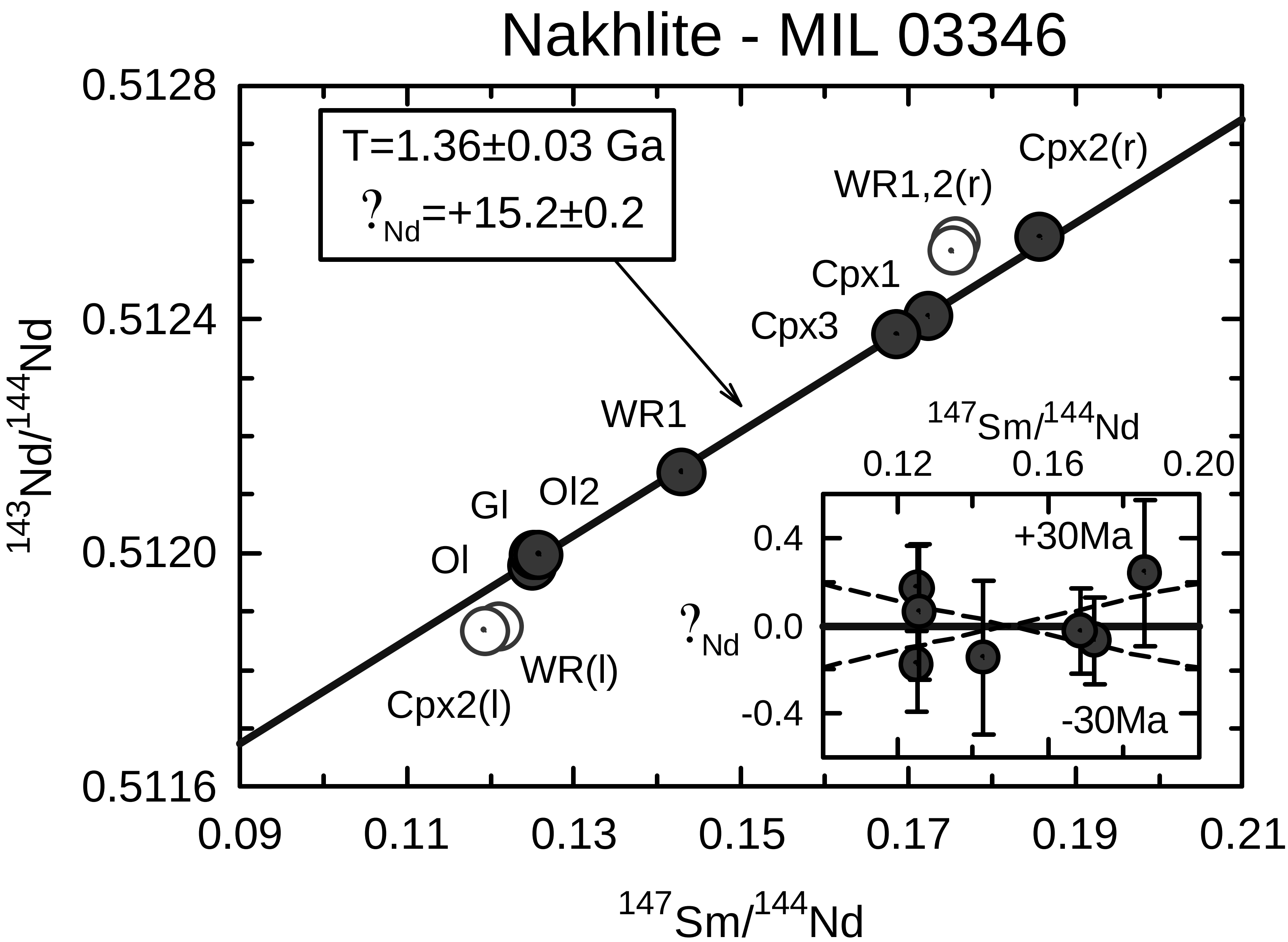
Figure 1 from Nimmo and Tanaka (2005)
Ann. Rev. Earth Planet. Sci., 33, 133-161
Surface ages from Hartmann et al. (1981)



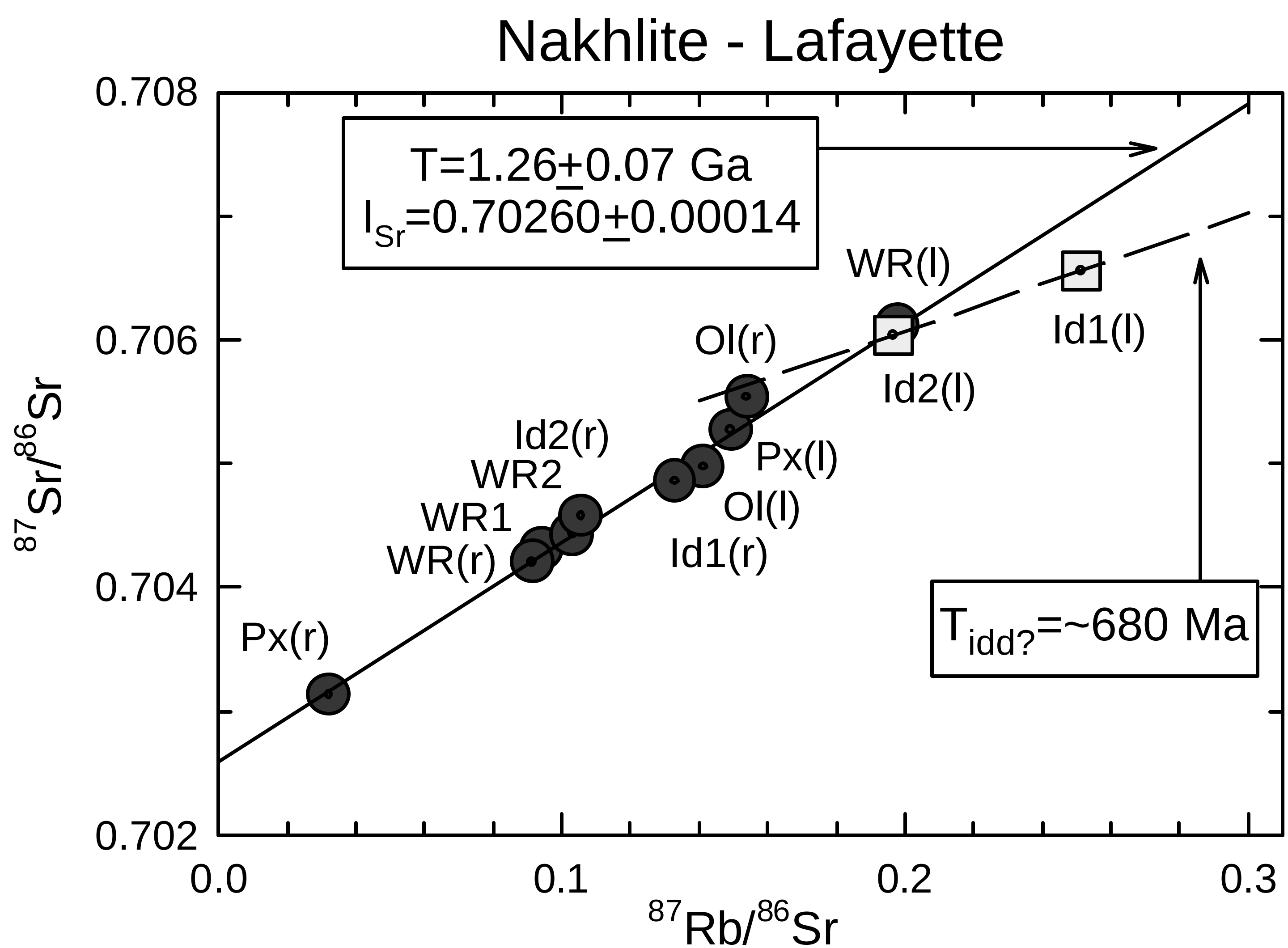
Gusev Crater with Apollinaris Patera
Image and Age Ranges Courtesy of K. Tanaka



Gusev Crater
A(Ol)+A(Px)+
A(Mt) = 100 %
MIL
Adk
Hmp
Maz
R66
A(Mt) %
A(Ol) + A(Px) %
0
10
20
30
40
0
20
40
60
80
100

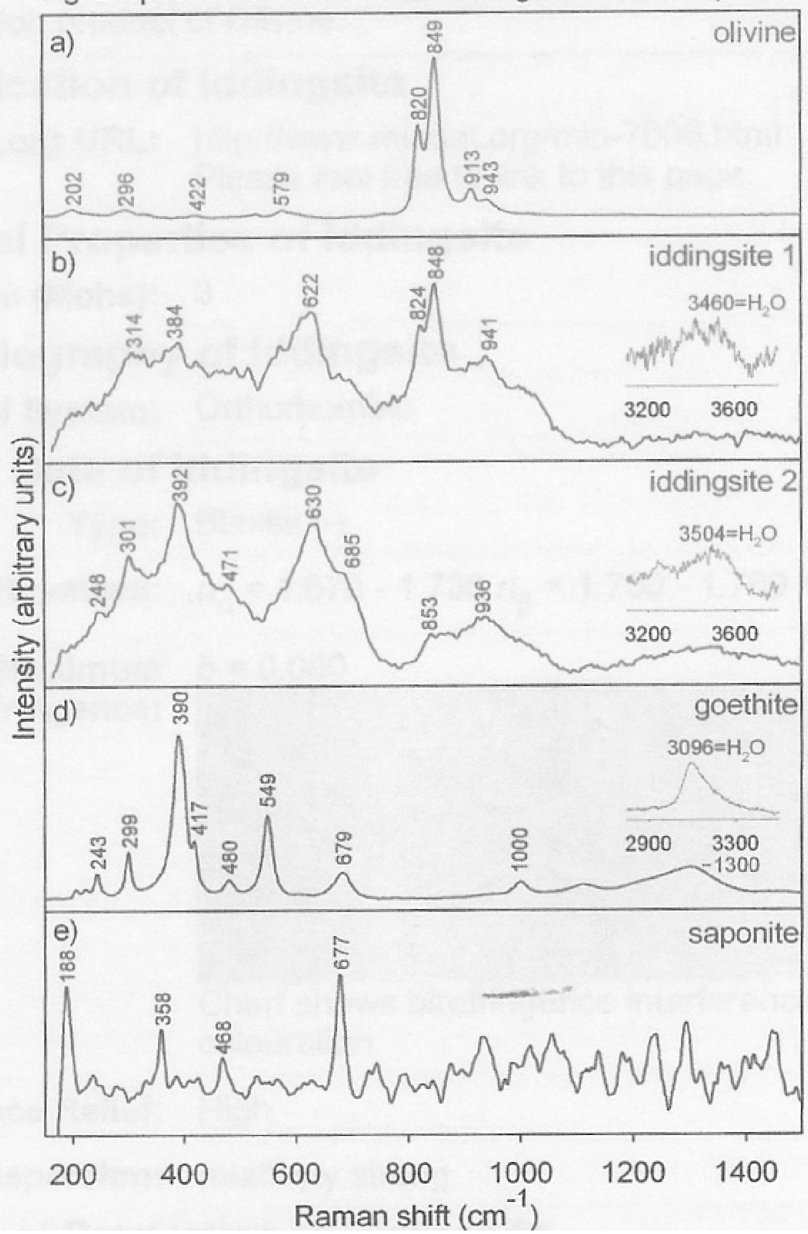


Nakhlite - MIL 03346
T=1.36±0.03 Ga
?Nd=+15.2±0.2
Cpx2(r)
WR1,2(r)
Cpx1
Cpx3
WR1
Ol2
Gl
Ol
WR(l)
Cpx2(l)
0.5128
0.5124
0.5120
0.5116
143Nd/144Nd
0.09
0.11
0.13
0.15
0.17
0.19
0.21
147Sm/144Nd
0.12
0.16
0.20
0.4
0.0
-0.4
?Nd
+30Ma
-30Ma



Shih et al. (1998)

Fig. 2 Spectra from QBV & standard goethite and saponite.

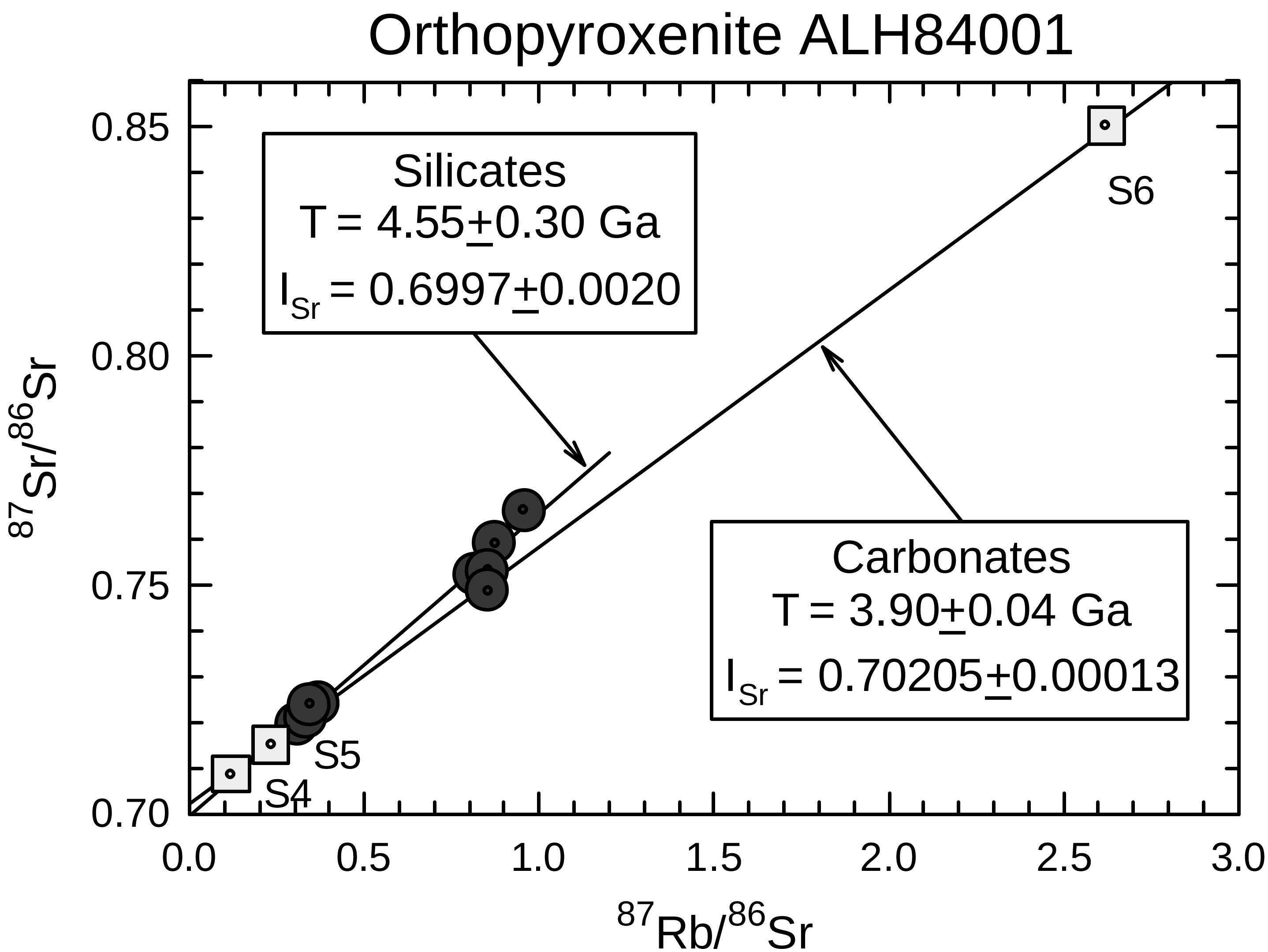


Kuebler et al. (2003), Fig. 2.

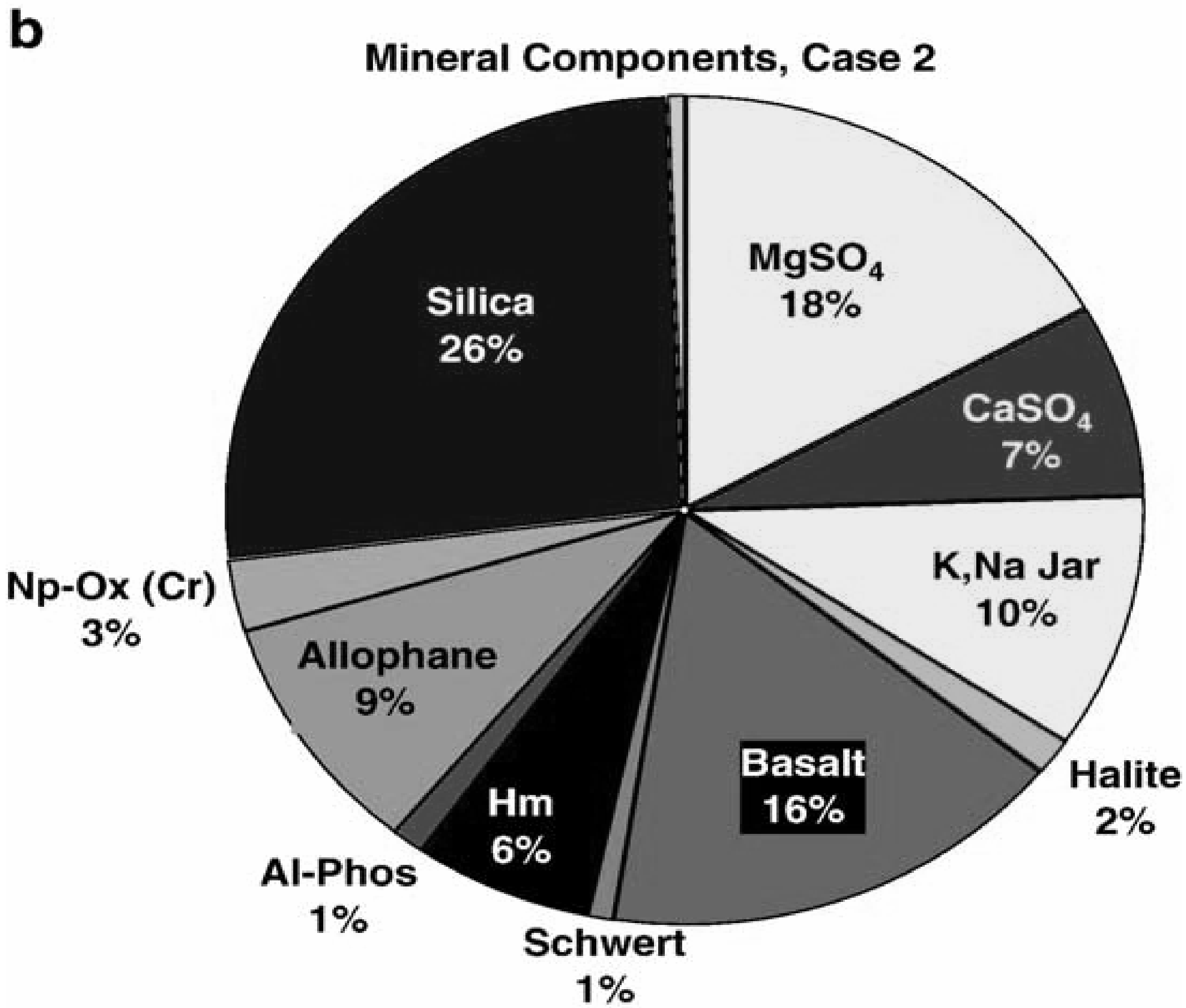
Kuebler et al. (2003) A study of olivine alteration to iddingsite using Raman spectroscopy. LPSC34.

"Iddingsite...a catch-all term to describe reddish alteration products of olivine...an Å-scale intergrowth of goethite and smectite (saponite)...

"Alteration conserves Fe (albeit oxidized), but requires addition of Al and H_2O and removal of Mg and Si."



Borg et al. (1999) The age of the carbonates in Martian Meteorite ALH84001. Science, 286, 90-94.



Clark et al. (2005) Chemistry and mineralogy of outcrops at Meridiani Planum. EPSL 240, 73-94. Fig. 12 showing the modeled mineral components of outcrops at Endurance, Fram, and Eagle Craters from the APXS and MB instruments. Modeled total sulfate abundance is 35 % for SO_3 = 20%.

Outcrop sulfates at the Opportunity Site, Meridiani Planum

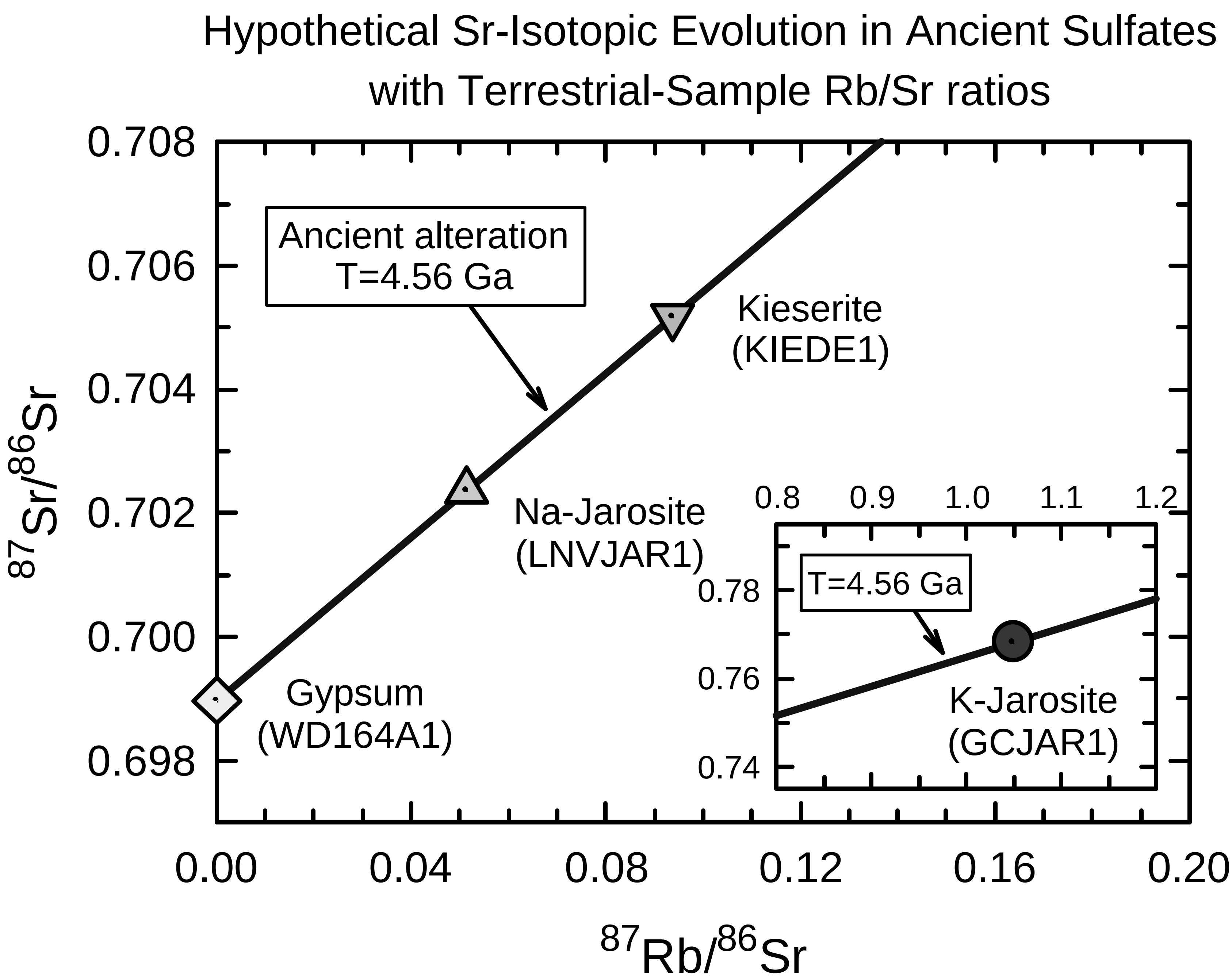
(Mini-TES; Glotch et al. (2006) JGR 111, E12SO3)

Mineral	"Base Model"	Terr. Rb-Sr	Sample
Na-jarosite			
$NaFe_3(SO_4)_2(OH)_6$	10% (5% ?)	Y	LNVJAR1-FP
K-jarosite			
$KFe_3(SO_4)_2(OH)_6$	(5% ?)	Y	GCJAR1-FP
Kieserite			
$MgSO_4 \cdot H_2O$	20%	Y	KIEDEI
Anhydrite			
$CaSO_4$	10 %		
Gypsum			
$CaSO_4 \cdot 2H_2O$		Y	WD164A1

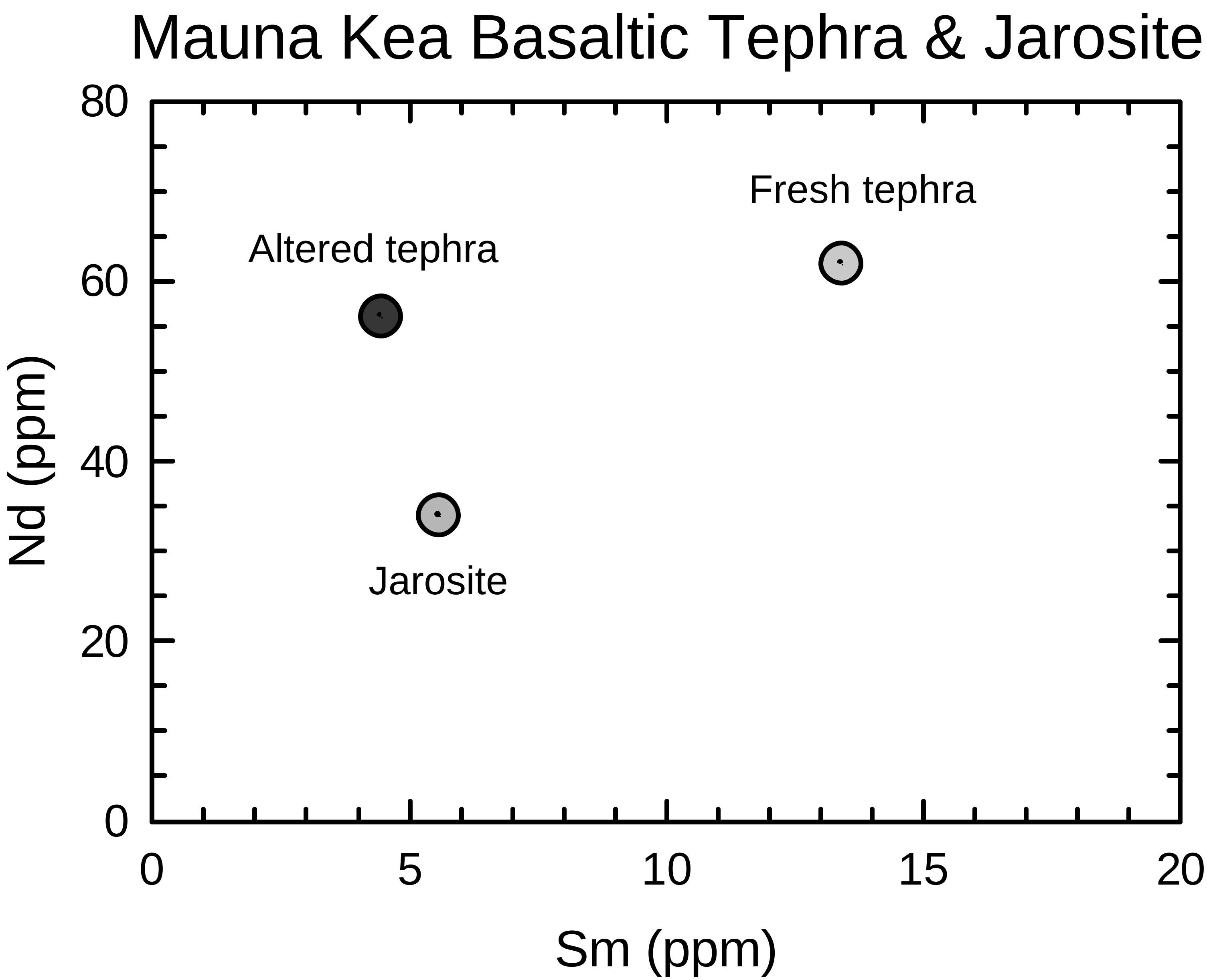
Terrestrial sulfate samples courtesy of R. Morris

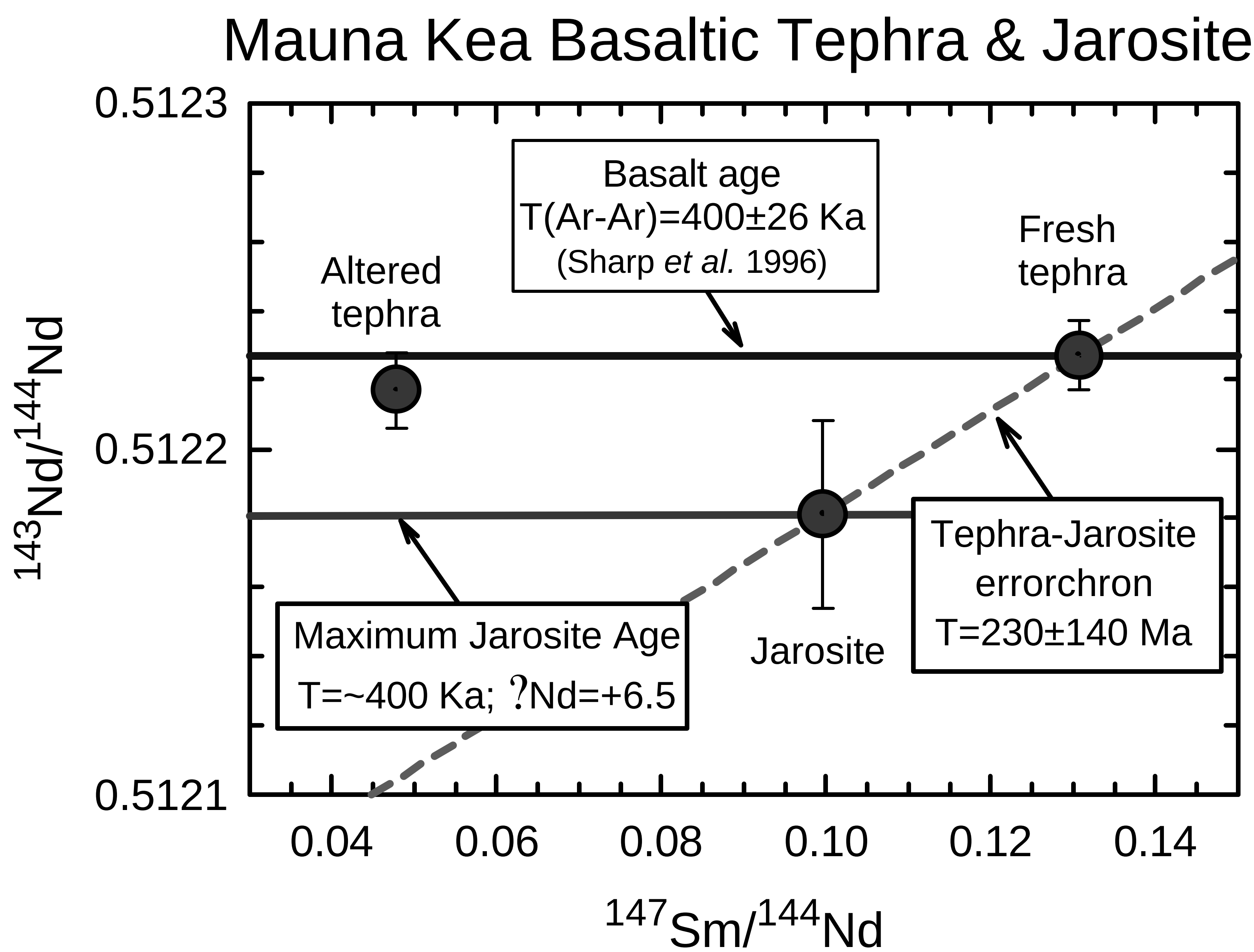
Preliminary Rb-Sr Study of Terrestrial Sulfates

- **K-Jarosite – $KFe_3(OH)_6(SO_4)_2$ (15 mg)**
  - GCJAR1-FP (New Mexico)
  - Readily soluble in $HF+HNO_3$
- **Na-Jarosite – $NaFe_3(OH)_6(SO_4)_2$ (16 mg)**
  - LNVJAR1-FP (Nevada)
  - Readily soluble in $HF+HNO_3$
- **Gypsum – $CaSO_4 \cdot 2H_2O$ (16 mg)**
  - WD164A1 (Italy)
  - Insoluble in hot water, soluble in 1N HCl
- **Kieserite – $MgSO_4 \cdot H_2O$ (26 mg)**
  - KIEDEI (Germany)
  - Insoluble in room temperature H_2O (15 min)
  - Soluble in hot H_2O (1 hr)

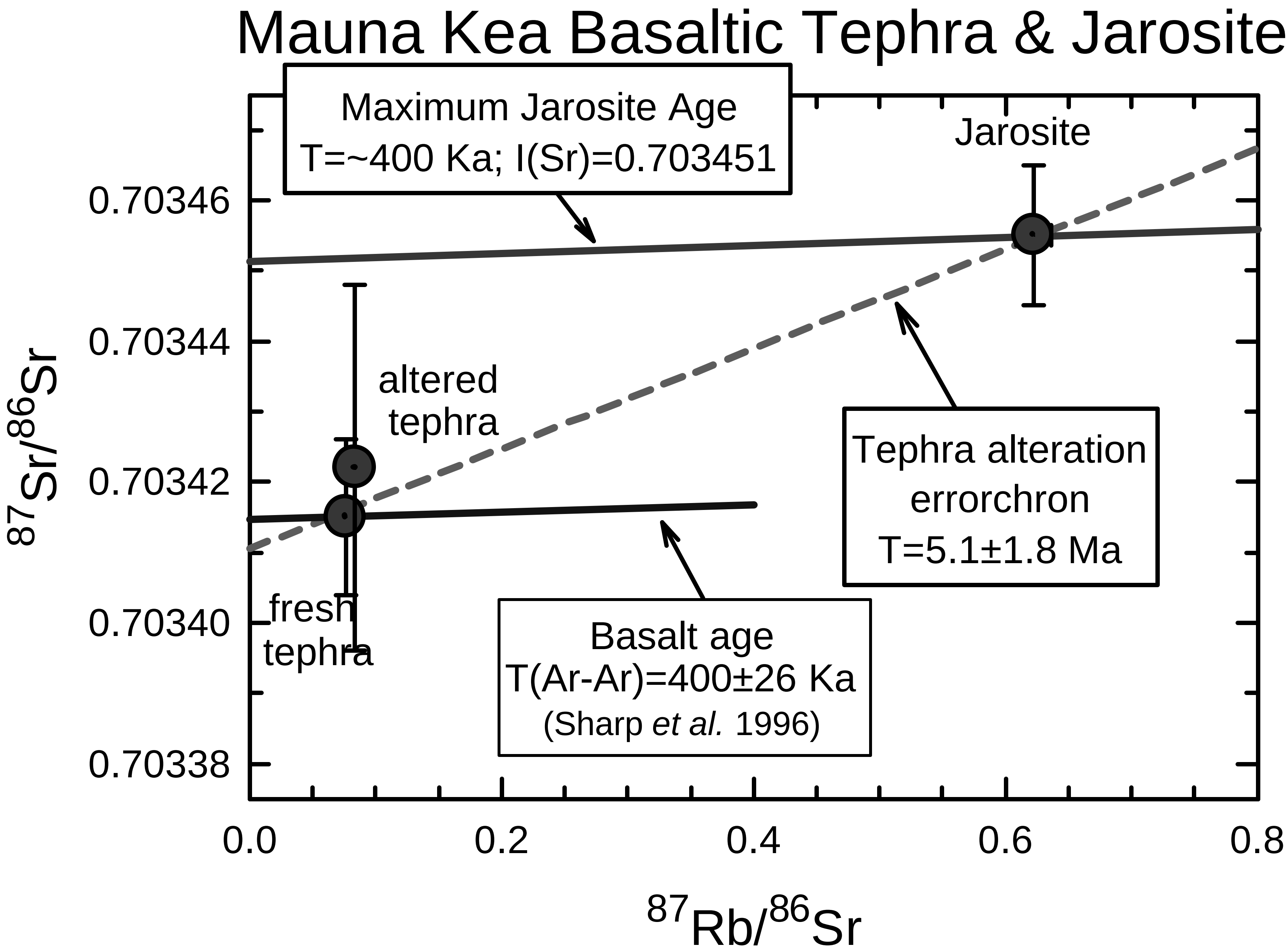


Hypothetical Sr-Isotopic Evolution in Ancient Sulfates
with Terrestrial-Sample Rb/Sr ratios
0.708
0.706
0.704
0.702
0.700
0.698
87Sr/86Sr
Ancient alteration
T=4.56 Ga
Kieserite
(KIEDE1)
Na-Jarosite
(LNVJAR1)
Gypsum
(WD164A1)
0.8
0.9
1.0
1.1
1.2
0.78
0.76
0.74
T=4.56 Ga
K-Jarosite
(GCJAR1)
0.00
0.04
0.08
0.12
0.16
0.20
87Rb/86Sr

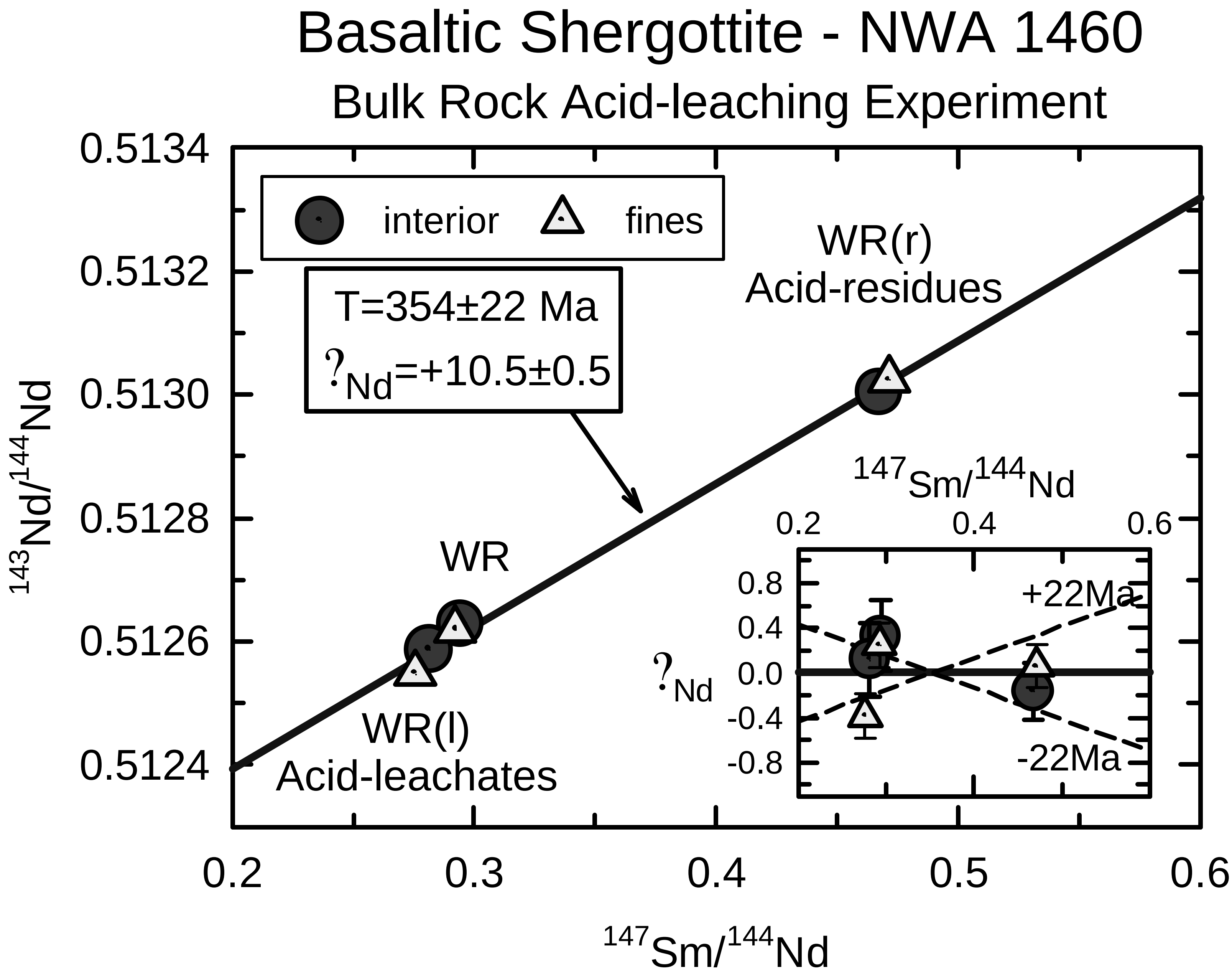

Mauna Kea Basaltic Tephra & Jarosite
Fresh tephra
Altered tephra
Jarosite
Nd (ppm)
Sm (ppm)
0
20
40
60
80
0
5
10
15
20

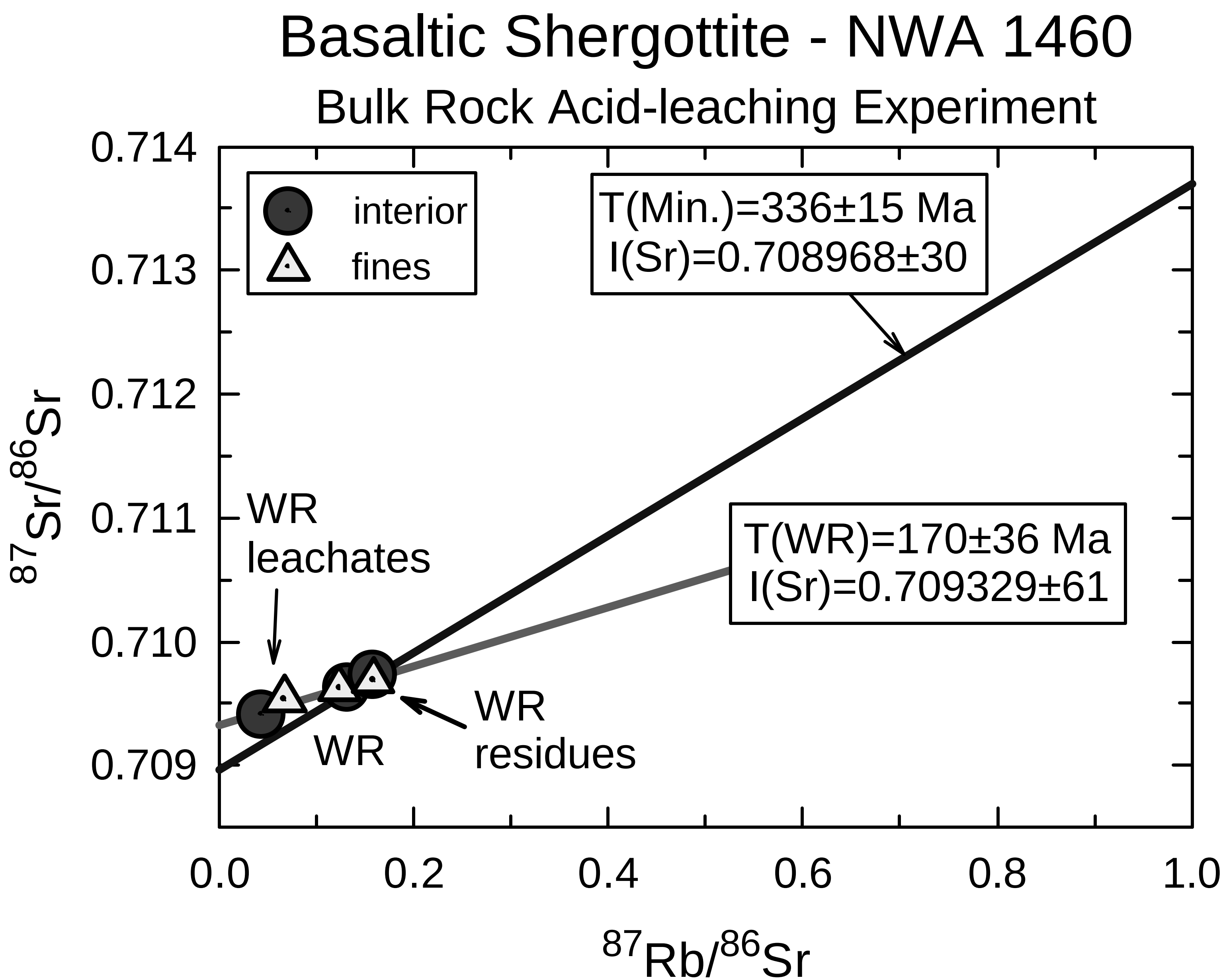


Mauna Kea Basaltic Tephra & Jarosite
0.5123
0.5122
0.5121
143Nd/144Nd
Basalt age
T(Ar-Ar)=400±26 Ka
(Sharp et al. 1996)
Altered tephra
Fresh tephra
Jarosite
Maximum Jarosite Age
T=~400 Ka; ?Nd=+6.5
Tephra-Jarosite errorchron
T=230±140 Ma
0.04
0.06
0.08
0.10
0.12
0.14
147Sm/144Nd

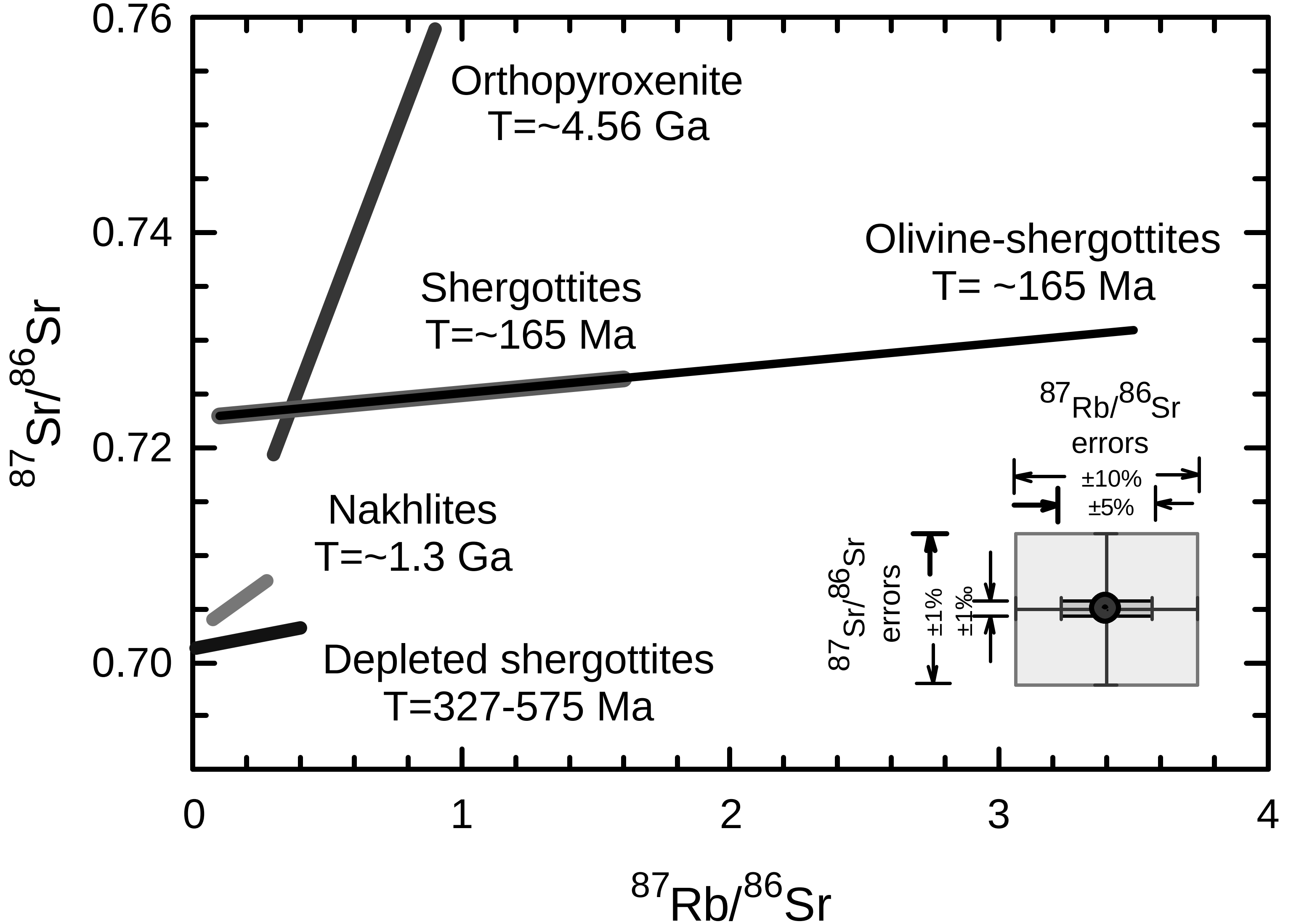


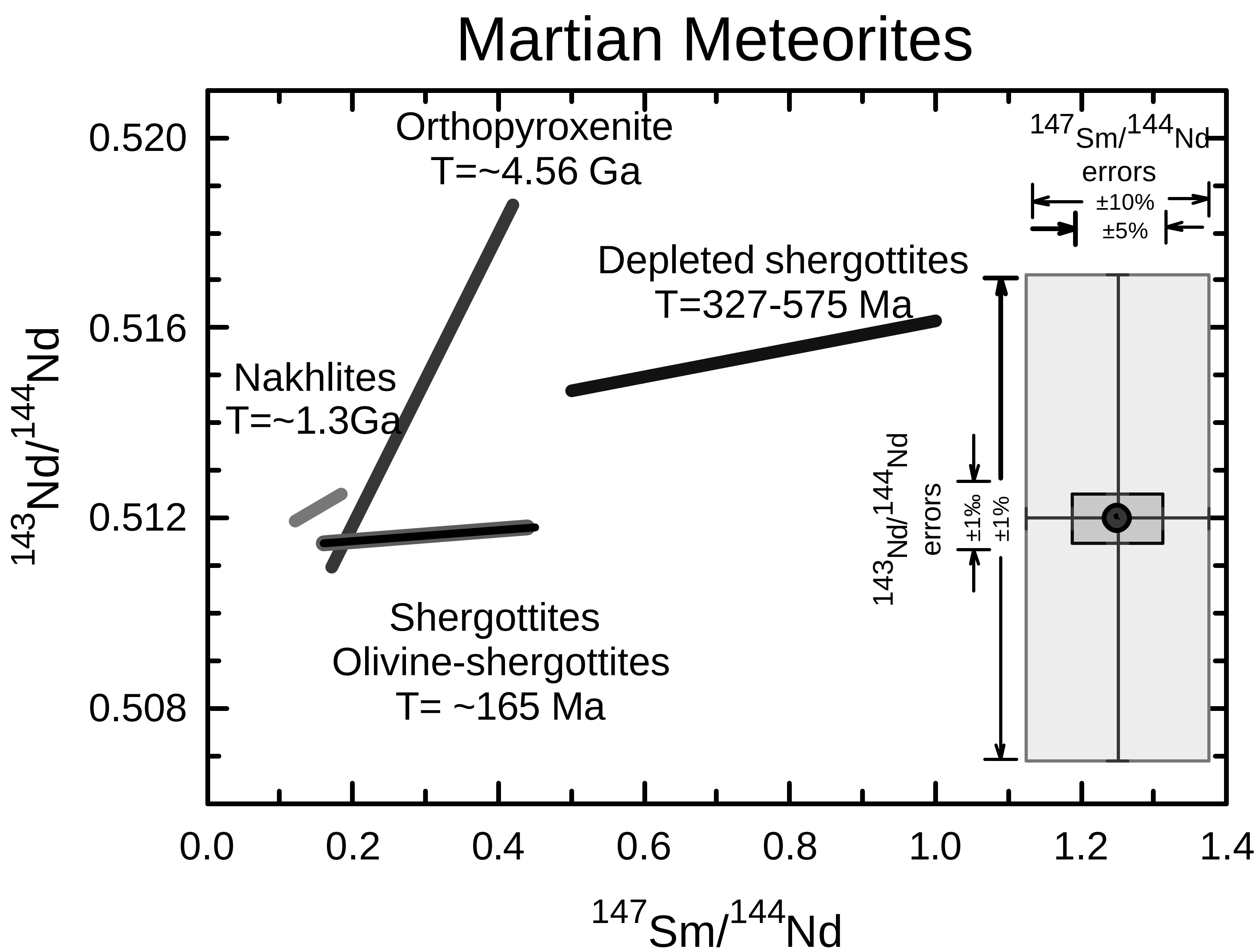
Mauna Kea Basaltic Tephra & Jarosite
Maximum Jarosite Age
T=~400 Ka; I(Sr)=0.703451
Jarosite
altered tephra
fresh tephra
Tephra alteration errorchron
T=5.1±1.8 Ma
Basalt age
T(Ar-Ar)=400±26 Ka
(Sharp et al. 1996)
0.70338
0.70340
0.70342
0.70344
0.70346
0.0
0.2
0.4
0.6
0.8
87Sr/86Sr
87Rb/86Sr


Basaltic Shergottite - NWA 1460
Bulk Rock Acid-leaching Experiment
interior
fines
T=354±22 Ma
?Nd=+10.5±0.5
WR(r)
Acid-residues
WR
WR(l)
Acid-leachates
147Sm/144Nd
143Nd/144Nd
0.5134
0.5132
0.5130
0.5128
0.5126
0.5124
0.2
0.3
0.4
0.5
0.6
+22Ma
-22Ma
?Nd
0.8
0.4
0.0
-0.4
-0.8


Basaltic Shergottite - NWA 1460
Bulk Rock Acid-leaching Experiment
0.714
0.713
0.712
0.711
0.710
0.709
interior
fines
T(Min.)=336±15 Ma
I(Sr)=0.708968±30
T(WR)=170±36 Ma
I(Sr)=0.709329±61
WR
leachates
WR
WR
residues
0.0
0.2
0.4
0.6
0.8
1.0
87Rb/86Sr
87Sr/86Sr

Martian Meteorites





Martian Meteorites
Orthopyroxenite
T=~4.56 Ga
Depleted shergottites
T=327-575 Ma
Nakhlites
T=~1.3Ga
Shergottites
Olivine-shergottites
T= ~165 Ma
147Sm/144Nd
errors
±10%
±5%
143Nd/144Nd
errors
±1‰
±1%
0.520
0.516
0.512
0.508
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
147Sm/144Nd
143Nd/144Nd

Summary and Conclusions

- Large inherent uncertainty in cratering chronologies
  - Date an Early-Mid Amazonian (~1-3 Ga) surface to calibrate.
    - Gusev-like site probably OK
  - Absolute dating of the Hesperian/Noachian also desirable.
    - Better for “life”, “late heavy bombardment” issues.
    - Meridiani-like site may be OK
- Dating aqueous activity/secondary minerals/life habitats
  - Hard, even for laboratory-based geochronology.
    - Isochron methods (esp. Rb-Sr) look promising
    - Ar-Ar techniques also should be investigated.
  - Micro-beam techniques available for a returned sample.
    - SIMS: shergottite phosphates, baddeleyite; nakhlite phos.
- *In Situ* Dating
  - Hard to impossible by traditional methods
  - Best bet: redundant methods
    - K-Ar with gas source mass spectrometer
    - Automated chemistry lab for simple leaching, etc., with solids source mass spec (TIMS)

Outcrop sulfates at the Opportunity Site, Meridiani Planum

(Mini-TES; Glotch et al. (2006) JGR 111, E12SO3)

Mineral	**“Base Model”**	**Terr. Rb-Sr**	**Sample**
Na-jarosite			
$NaFe_3(SO_4)_2(OH)_6$	10% (5% ?)	Y	LNVJAR1-FP
K-jarosite			
$KFe_3(SO_4)_2(OH)_6$	(5% ?)	Y	GCJAR1-FP
Kieserite			
$MgSO_4 \cdot H_2O$	20%	Y	KIEDEI
Anhydrite			
$CaSO_4$	10 %		
Gypsum			
$CaSO_4 \cdot 2H_2O$		Y	WD164A1

Terrestrial sulfate samples courtesy of R. Morris

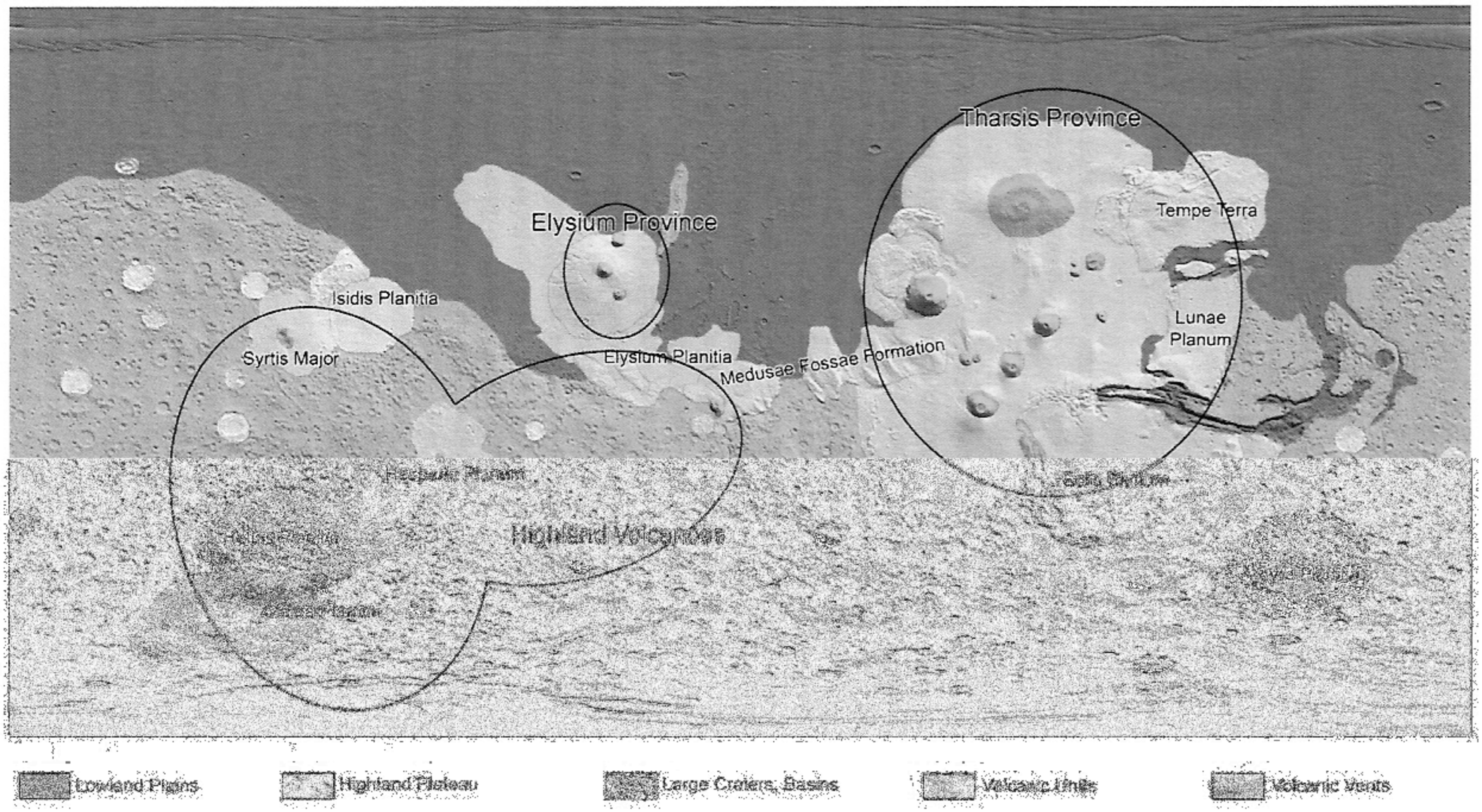
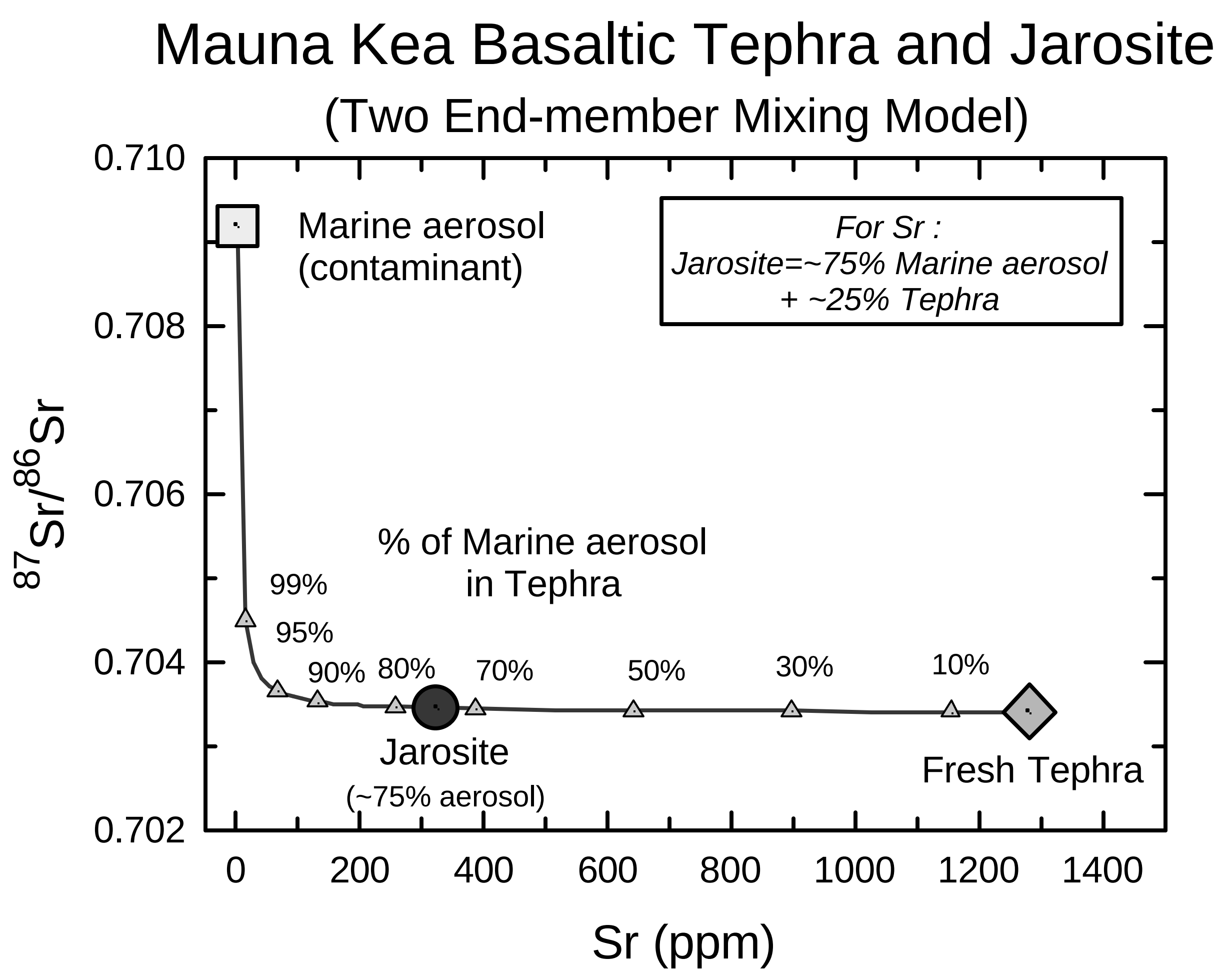
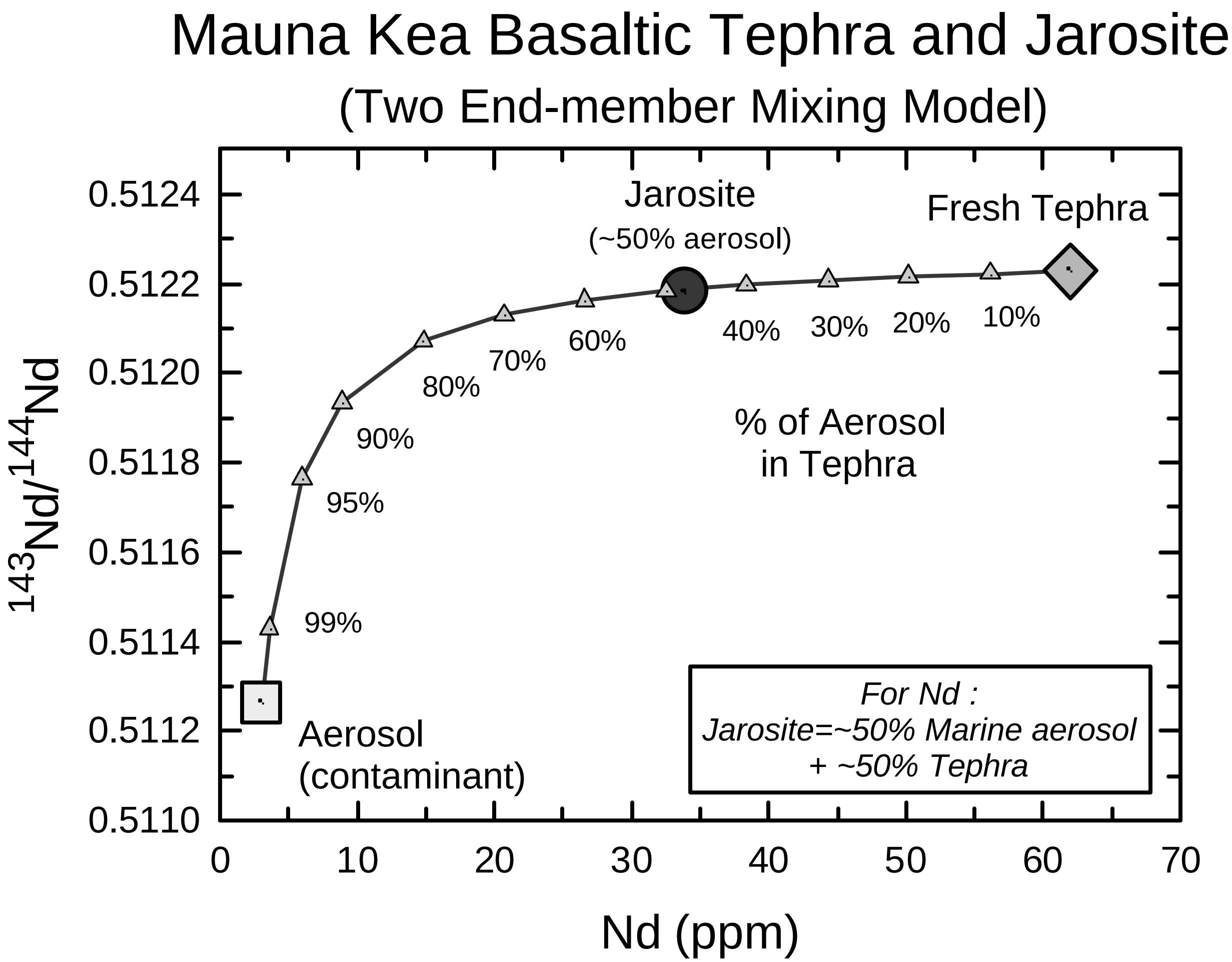
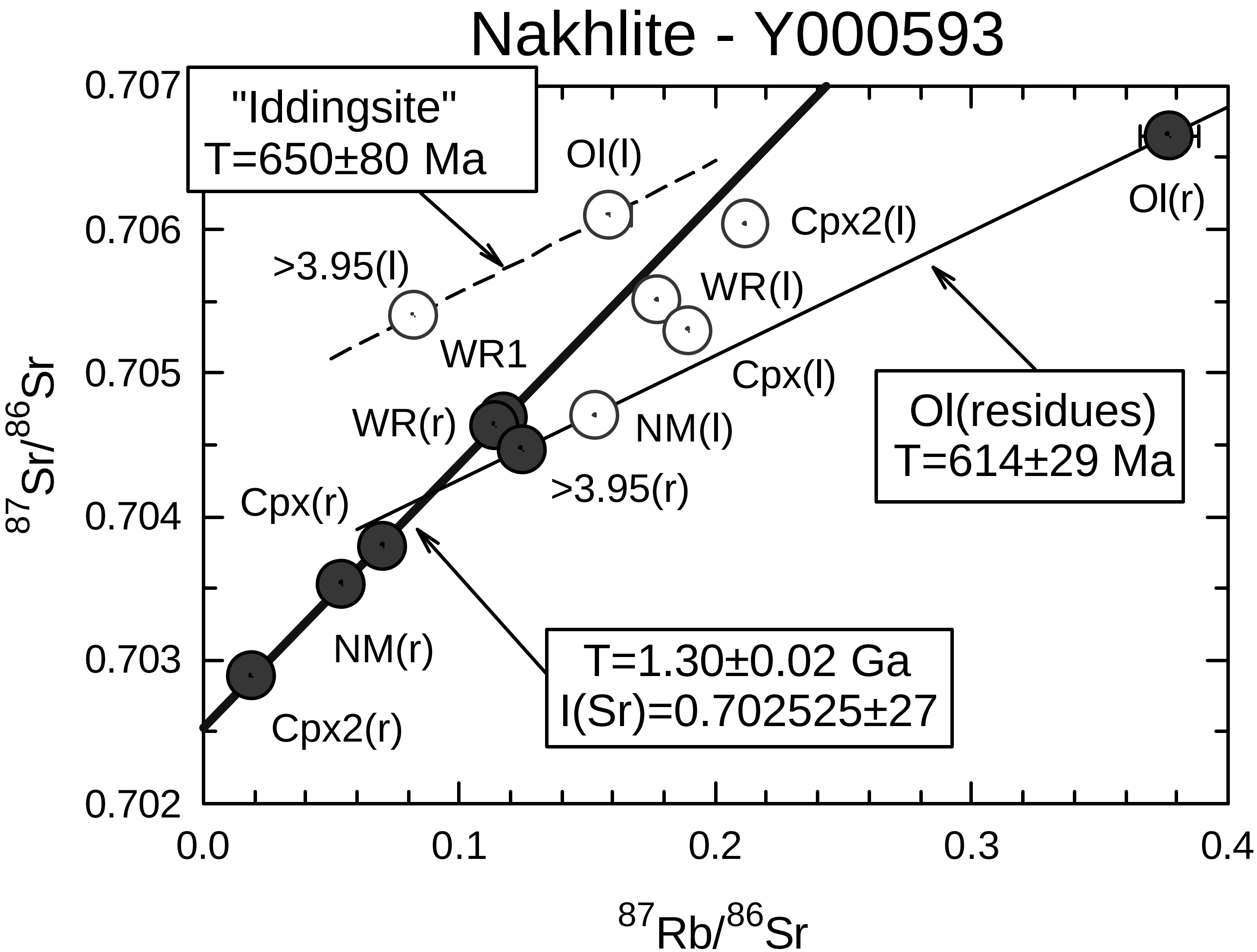


Figure 15.1.: The volcanic provinces of Mars are indicated in yellow. Known central vent constructs are displayed inred. The individual volcanoes are assigned in separate maps. The topographic dichotomy is shown in blue for the lowland parts and green for the highland parts. Large impact structures are shown in white. The background topography is given as a MOLA shaded- relief map.



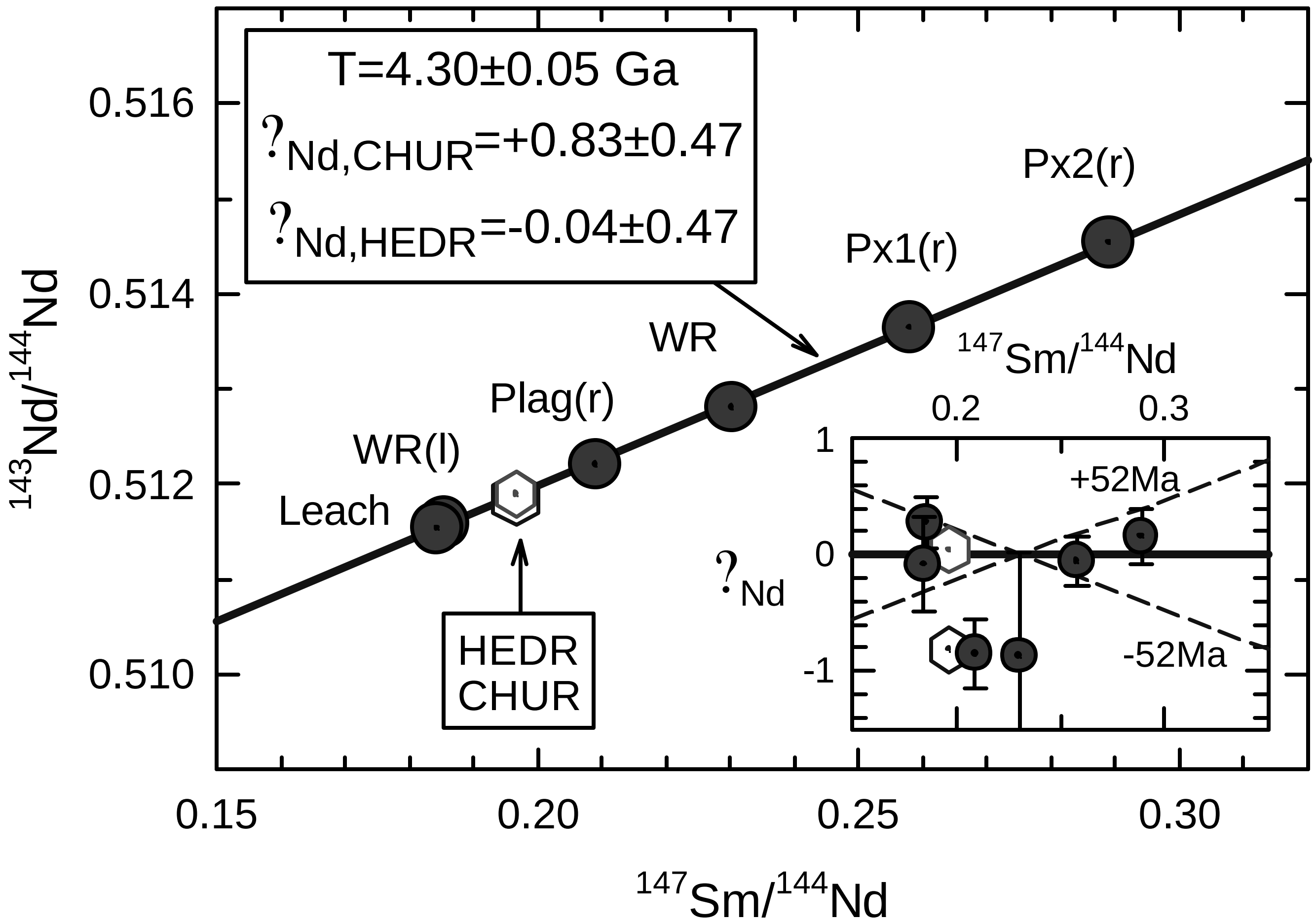
Mauna Kea Basaltic Tephra and Jarosite
(Two End-member Mixing Model)
0.710
0.708
0.706
0.704
0.702
87Sr/86Sr
0
200
400
600
800
1000
1200
1400
Sr (ppm)
Marine aerosol
(contaminant)
For Sr :
Jarosite=~75% Marine aerosol
+ ~25% Tephra
% of Marine aerosol
in Tephra
99%
95%
90%
80%
70%
50%
30%
10%
Jarosite
(~75% aerosol)
Fresh Tephra

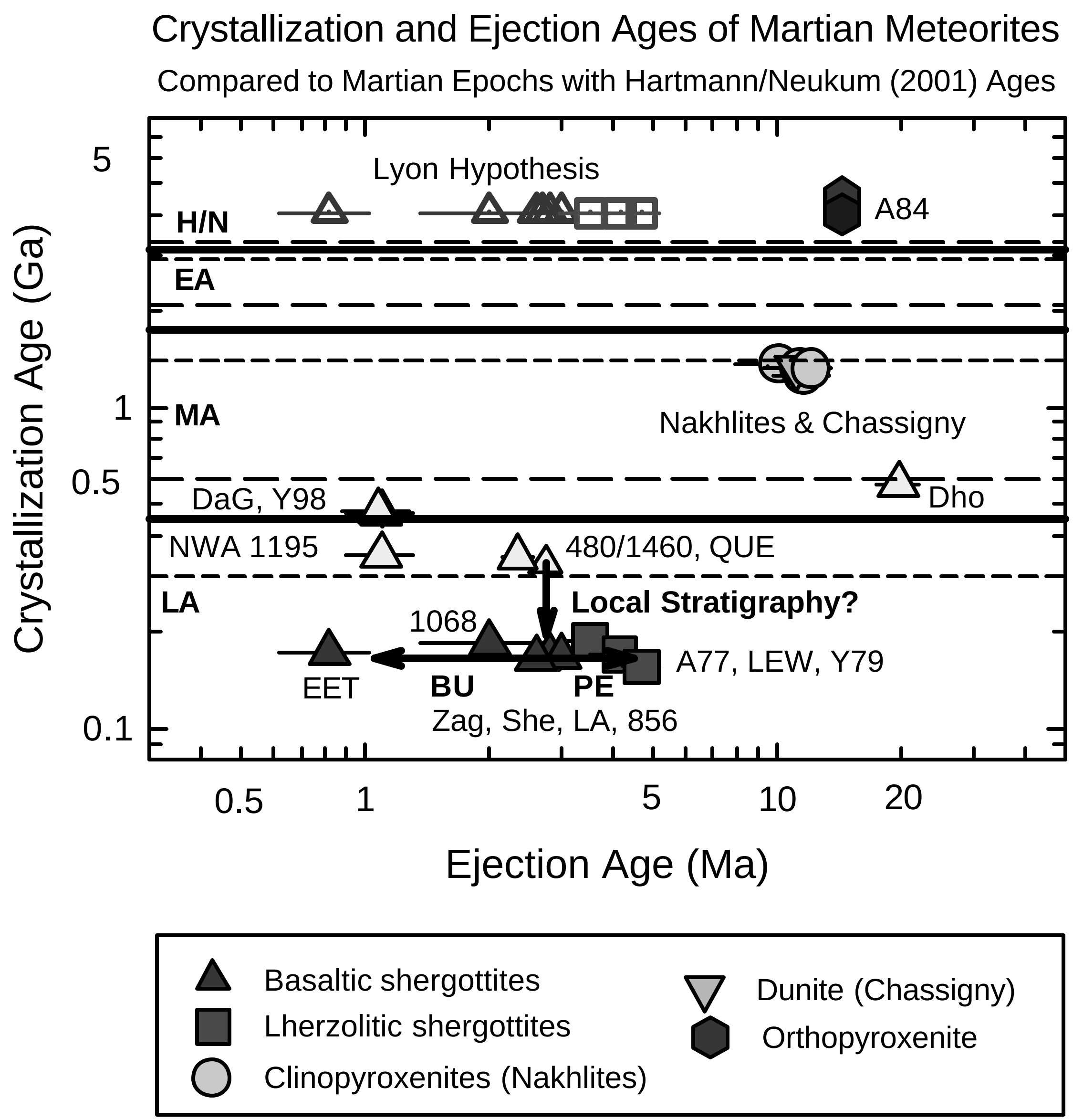

Mauna Kea Basaltic Tephra and Jarosite
(Two End-member Mixing Model)
Jarosite
(~50% aerosol)
Fresh Tephra
40%
30%
20%
10%
60%
70%
80%
90%
95%
99%
% of Aerosol
in Tephra
Aerosol
(contaminant)
For Nd :
Jarosite=~50% Marine aerosol
+ ~50% Tephra
0.5124
0.5122
0.5120
0.5118
0.5116
0.5114
0.5112
0.5110
0
10
20
30
40
50
60
70
Nd (ppm)
143Nd/144Nd



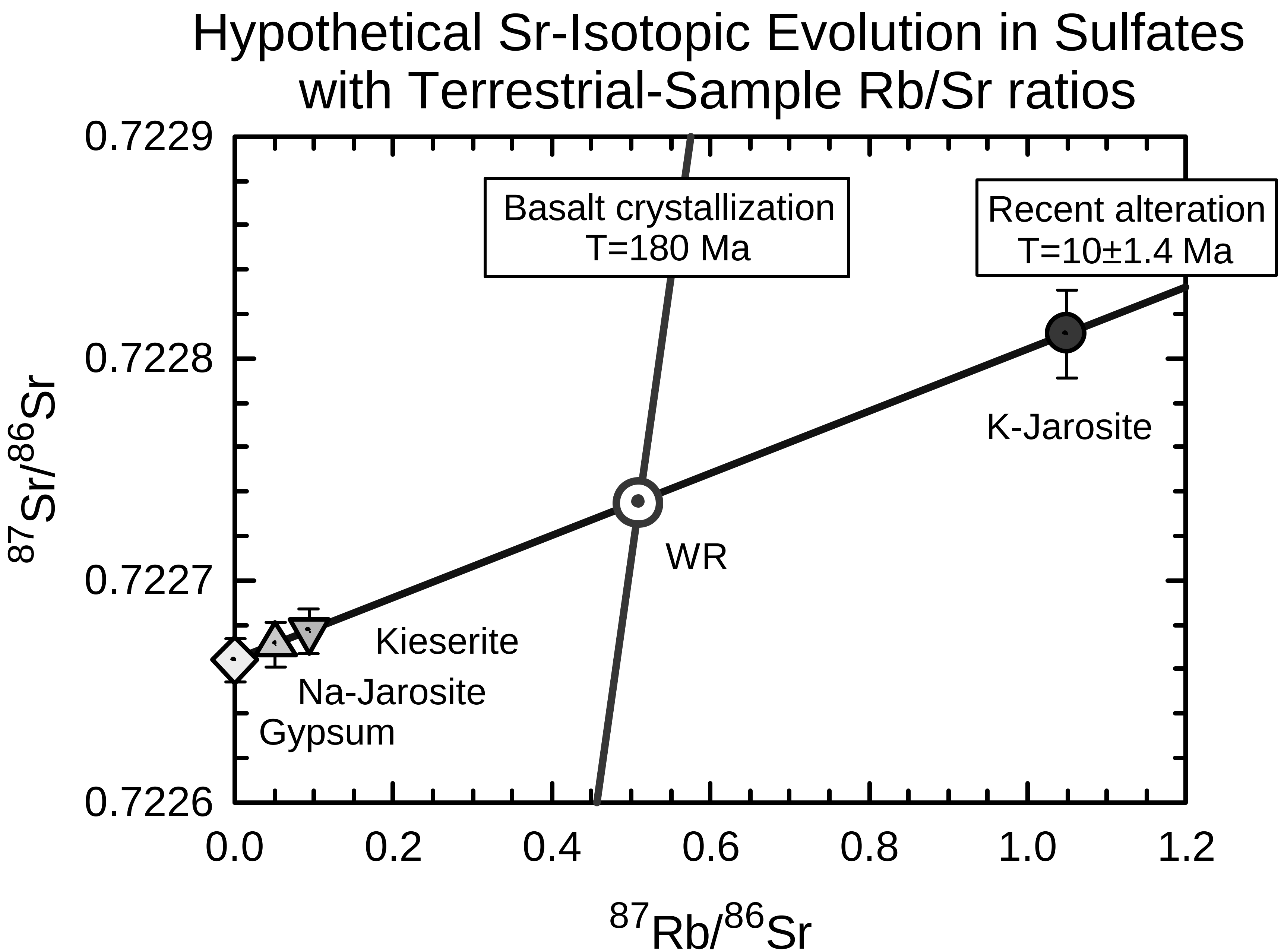
Misawa et al. (2005) Antarct. Met. Res., Fig. 3

Lunar Mare Basalt Meteorite - Kalahari 009





Crystallization and Ejection Ages of Martian Meteorites
Compared to Martian Epochs with Hartmann/Neukum (2001) Ages
Crystallization Age (Ga)
Ejection Age (Ma)
5
1
0.5
0.1
0.5
1
5
10
20
Lyon Hypothesis
A84
H/N
EA
MA
LA
Nakhlites & Chassigny
DaG, Y98
Dho
NWA 1195
480/1460, QUE
Local Stratigraphy?
1068
A77, LEW, Y79
EET
BU
PE
Zag, She, LA, 856
Basaltic shergottites
Lherzolitic shergottites
Clinopyroxenites (Nakhlites)
Dunite (Chassigny)
Orthopyroxenite



Hypothetical Sr-Isotopic Evolution in Sulfates
with Terrestrial-Sample Rb/Sr ratios
0.7229
0.7228
0.7227
0.7226
Basalt crystallization
T=180 Ma
Recent alteration
T=10±1.4 Ma
K-Jarosite
WR
Kieserite
Na-Jarosite
Gypsum
0.0
0.2
0.4
0.6
0.8
1.0
1.2
87Sr/86Sr
87Rb/86Sr