「クレータ年代学」を高校生と楽しむ

-Hartmann Diagramを用いた火星表面年代測定-

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概要

1. クレータ年代学とは（**Crater Chronology**）**:**
2. 用いた衛星画像について**:**
3. 年代解析結果**:**
4. 関連する話題**:**

※本講演は**2011**年７月「天文高校生集まれ！」（近畿地区高校生天文活動発表会実行委員会主催）での講演内容を簡略化し，新たな知見を加えたものである.

方法と関連する事項

1 “Crater Chronology”(Hartmann, 1998)

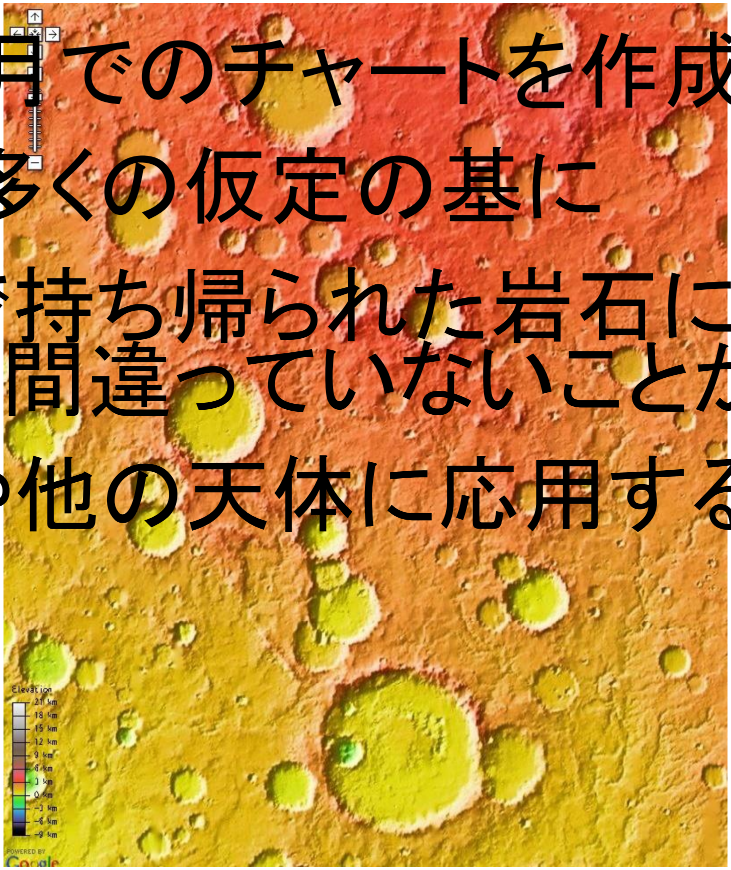
* 隕石(彗星)衝突レートを仮定(35億年以降ほぼ一定)
* 古い表面ほど多くの隕石痕

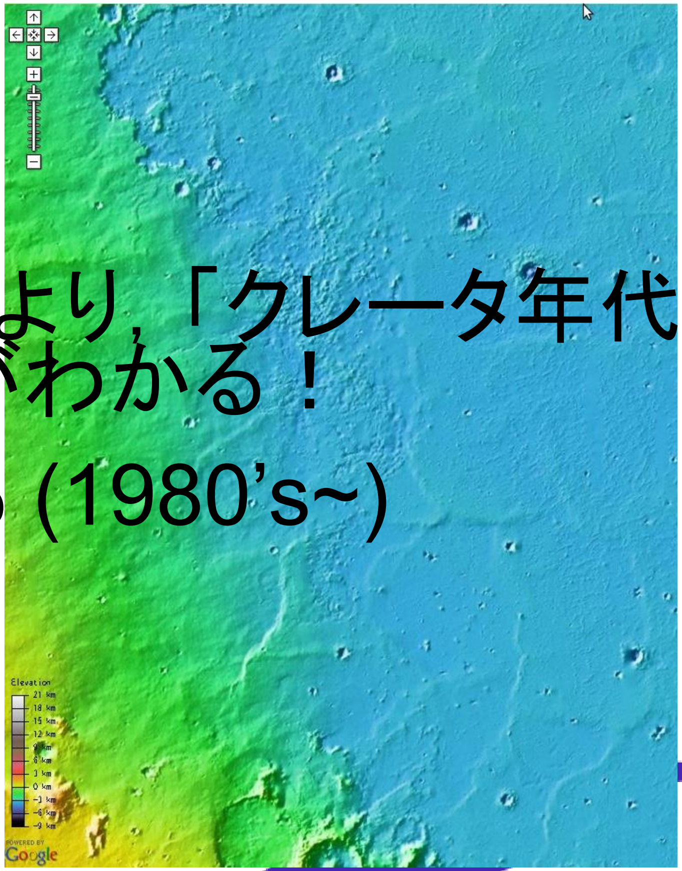
2　最近の話題

* Giant Impact Theory (Hartmann & Davis,1975)
* Late Heavy Bombardment (Cohen,et.al. 2000)

クレータ年代学

- William K. Hartmannが1960年代に開発
- 原理はめっちゃ簡単！（**表面年代∝クレータ密度**）
  ->多くのクレータがあるのは表面が古い証拠
- 1960年代に月でのチャートを作成
  ⇒もちろん多くの仮定の基に
- アポロ計画で持ち帰られた岩石により，「クレータ年代学」の大筋は間違っていないことがわかる！
- これを火星や他の天体に応用する (1980’s~)





実習1: 月の写真のクレータカウント

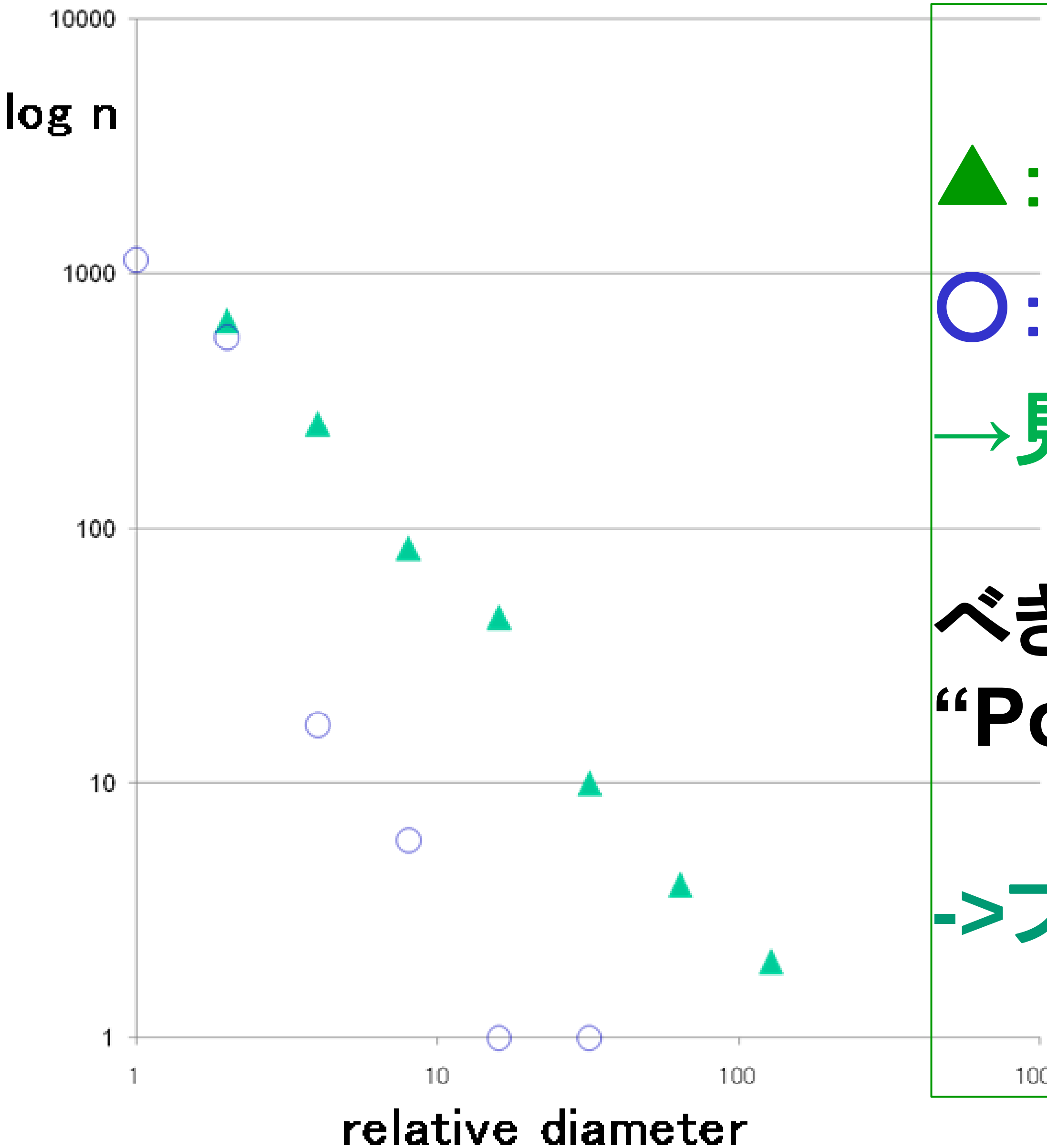
- “Google Moon”の写真
- “正” の字でサイズごとの個数を集計

透明尺を使用

http://kakijun.main.jp/ →

高校2年生によるカウント実習

両対数グラフ（log-log）上での結果



▲: 月の高地

○: 月の海

→見事な直線関係

べき分布
“Power law distribution”

->フラクタル分布ともいう

月から火星へ：火星特有の問題

* 月と火星の隕石衝突レートの違い
  隕石分布：　火星＞月　（小惑星帯までの距離）
  表面重力：　火星＞月
* 薄い大気と水の存在，砂嵐など
  ⇒小径のクレータほど先に消される
*2次クレータの問題　など

しかし，うまく使えば，
クレータ年代学を用いて，火星の表面発達史を再構成できる：海？河川，断層，溶岩流など

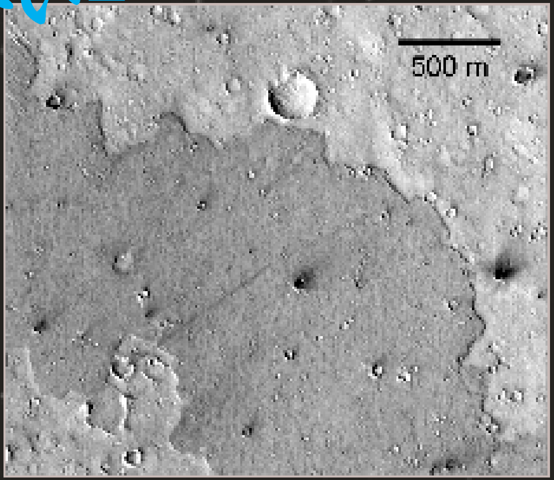
−Hartmann Diagramとの出会い−

Isochrons for Martian Crater Populations of Various Ages

Publications | Geologic Mapping | Geosciences Lab | Interns

ISOCHRONS FOR MARTIAN CRATER POPULATIONS OF VARIOUS AGES

William K. Hartmann



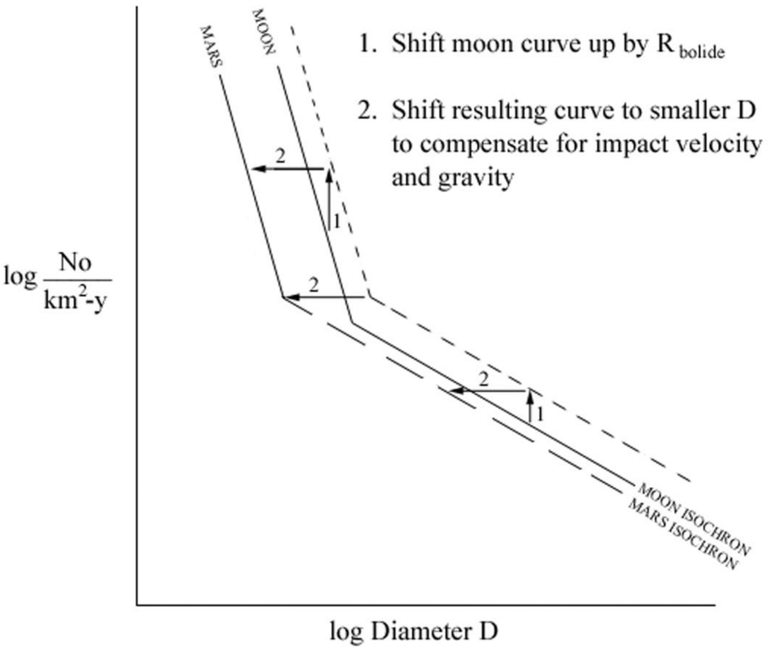
The Isochron System: Derivation of 2004 Iteration

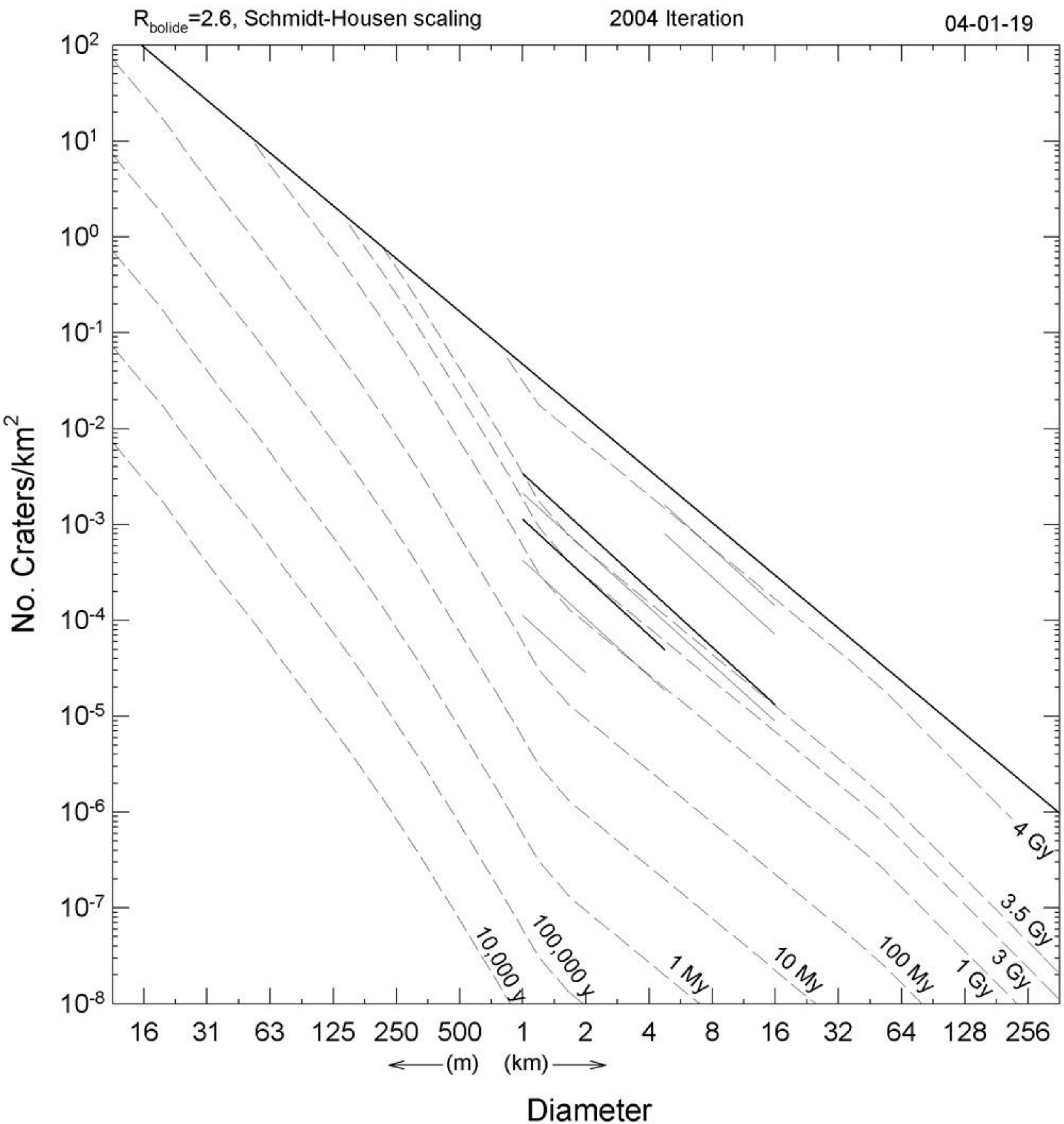
Improvements can still be made by using better estimates of the ratio R_{bolide} and the gravity and impact velocity scaling relations, and by adding the effects of loss of small meteoroids in the Martian atmosphere. To understand our approach to these improvements, think (for a moment) of the size distribution as constructed of power law segments (giving straight lines in the log *N* vs. log *D* plots used here). Virtually all work before MGS dealt with only one of these segments, the shallow or so-called primary branch, involving craters in the diameter range roughly 2 km < *D* < 64 km, where good statistics were available at that time. How do we use the lunar data from this diameter range to estimate the number of craters formed in that size range in a given time period on Mars? Imagine this diameter segment plotted for the number of craters formed in lunar maria in the last 3.5 Ga. To get the number of craters formed on Mars in the same period, Hartmann (1999) used the Mars/Moon cratering rate correction factor R_{crater} to shift this segment vertically, because of a higher estimated cratering rate on Mars. In addition, impact velocity and scaling corrections altered the diameter of a crater produced by a given meteoroid, hence sliding the curve horizontally (to the left, to smaller sizes, because of lower Mars impact velocity and higher gravity). Taking into account the slope of the single power law segment, these two shifts were combined into an effective single vertical shift. *Thus, that work assumed there was a single effective* R_{crater} *ratio that shifted the curve vertically by a fixed amount along the whole diameter segment*, and Hartmann (1999) applied it to the whole curve (11m < *D* < 100,000 m), deriving a single effective R_{crater} value and

Hartmann の新しいDiagram

From http://www.psi.edu/research/isochrons/chron04a.html

月から火星へ



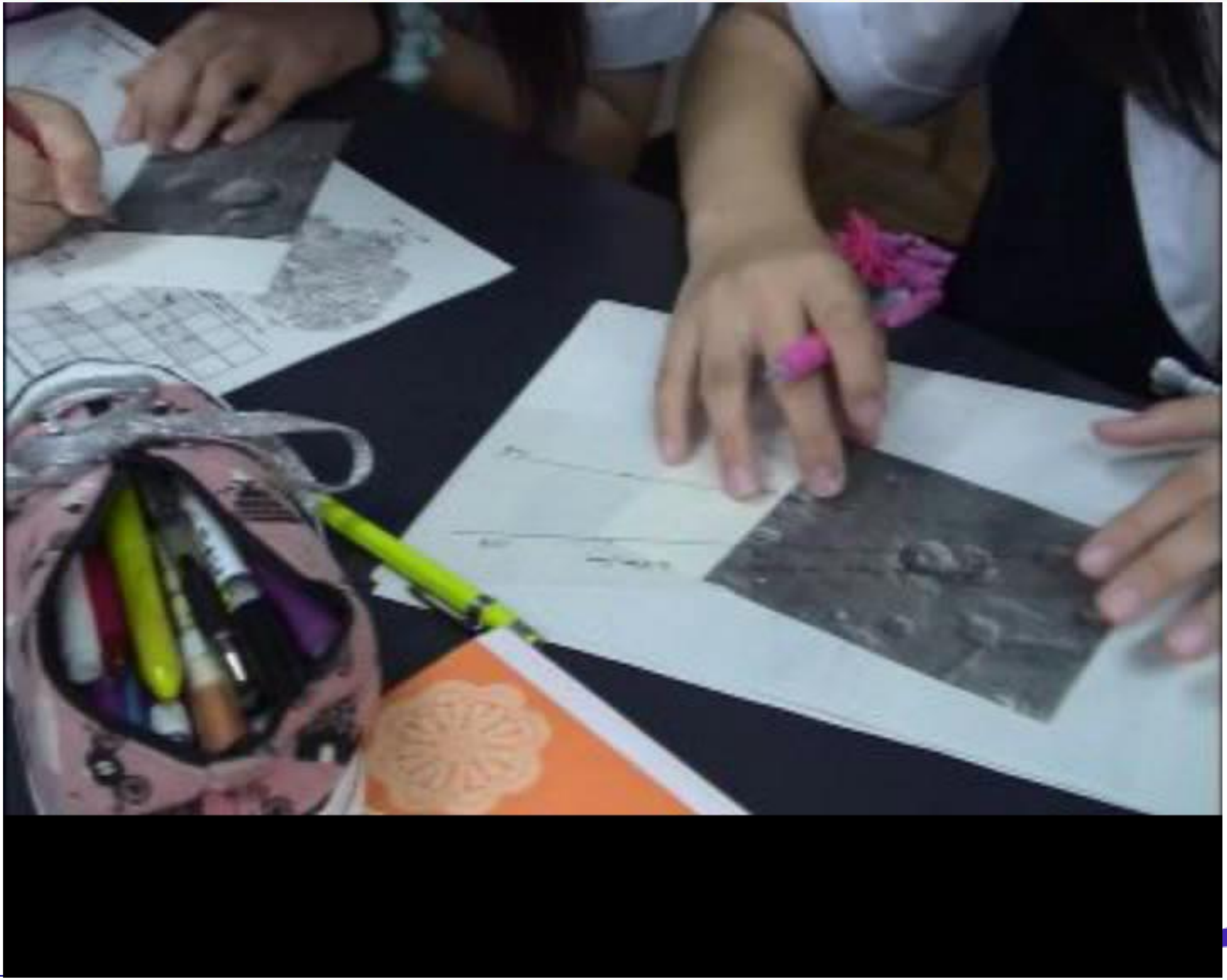


クレータサイズの度数分布から形成年代を推定する．書かれている線はアイソクロン（等年代線）

太い実線はクレータ密度が飽和を意味する．

完全なべき（フラクタル）ではない⇒２次クレータ，元の隕石サイズ

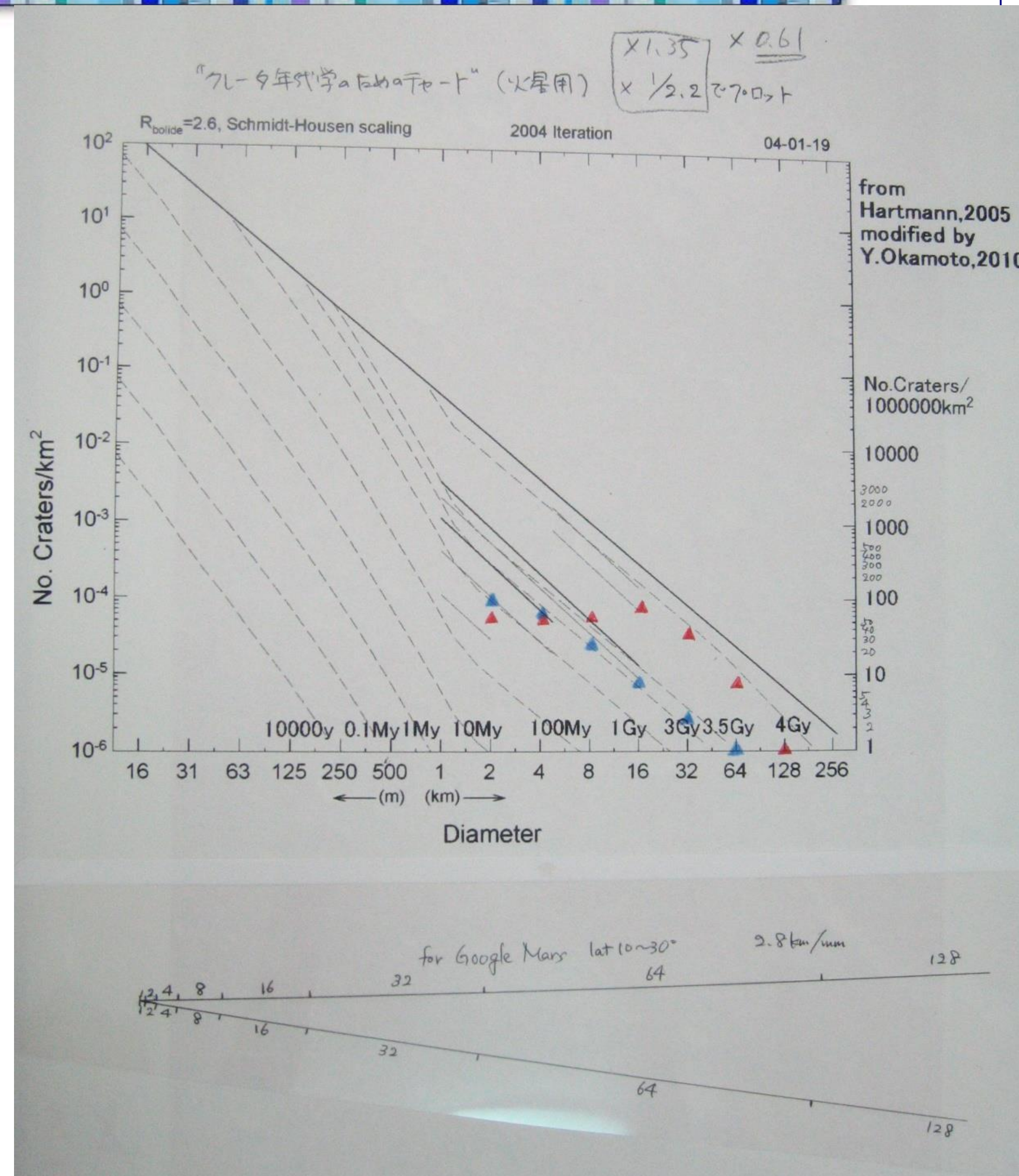
火星のクレータカウンティング（授業で）



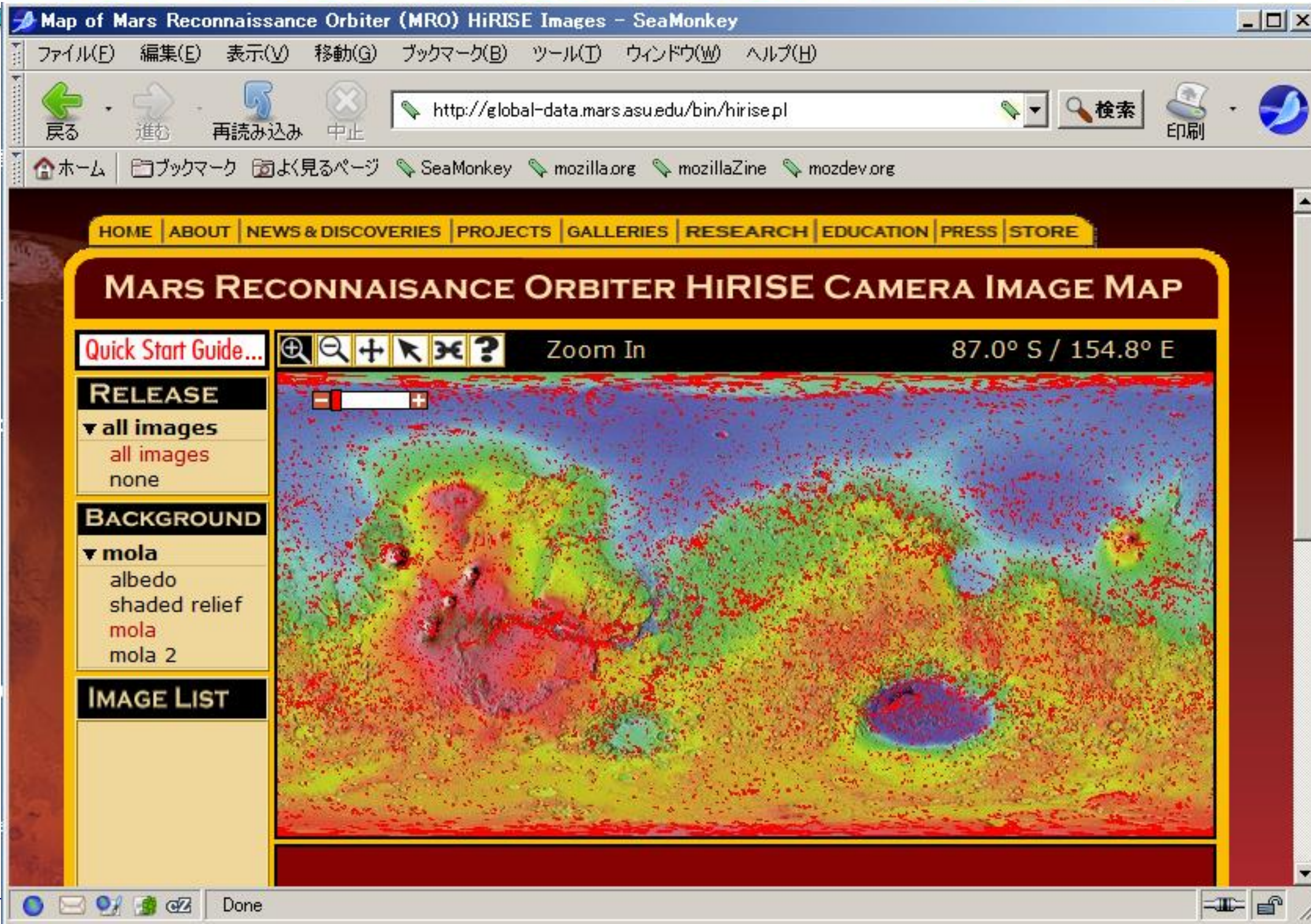
実習の進化

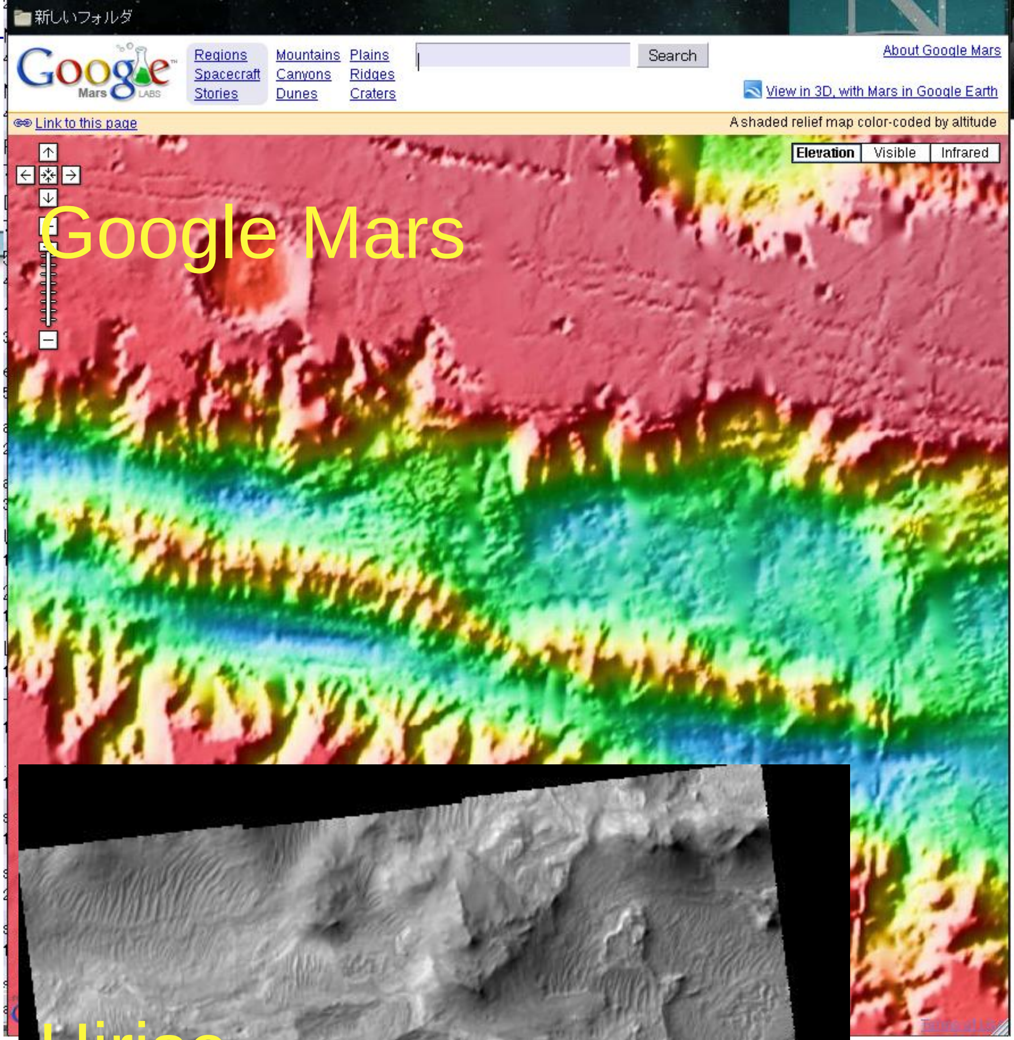
当初:“Google Mars”
大口径（100km超）～
中口径（2km<）
しか判読できない.

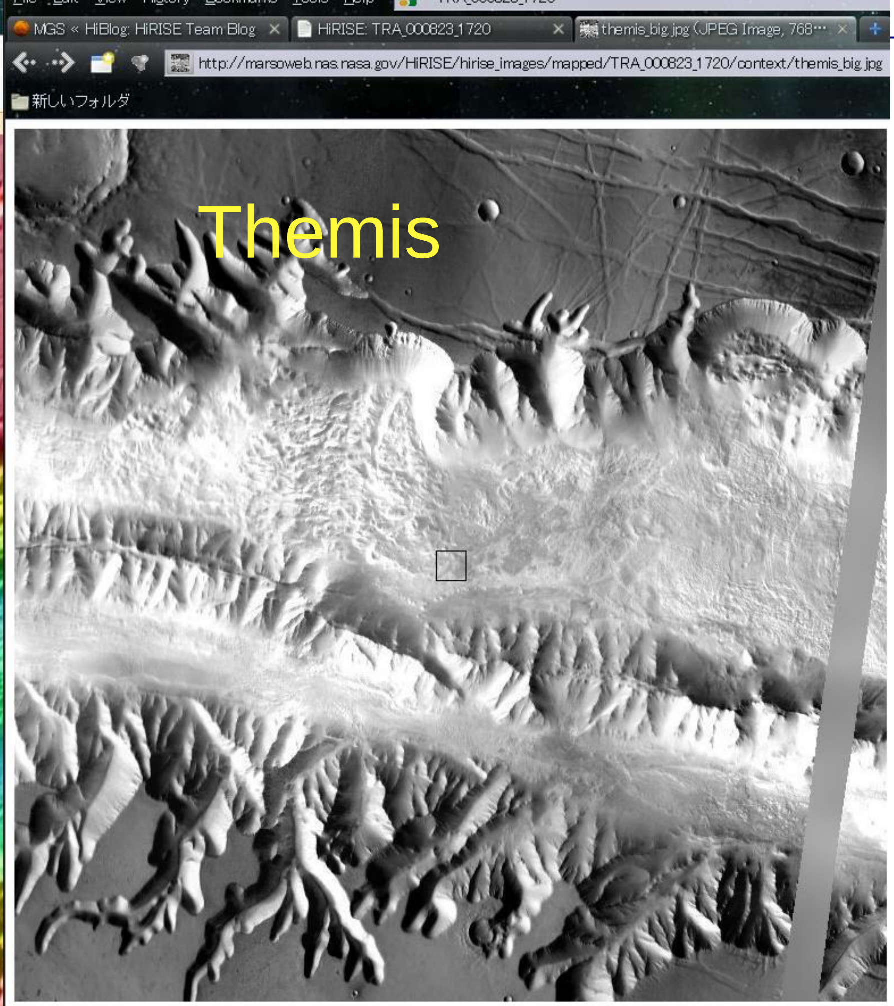
もっと詳しい画像はないか？

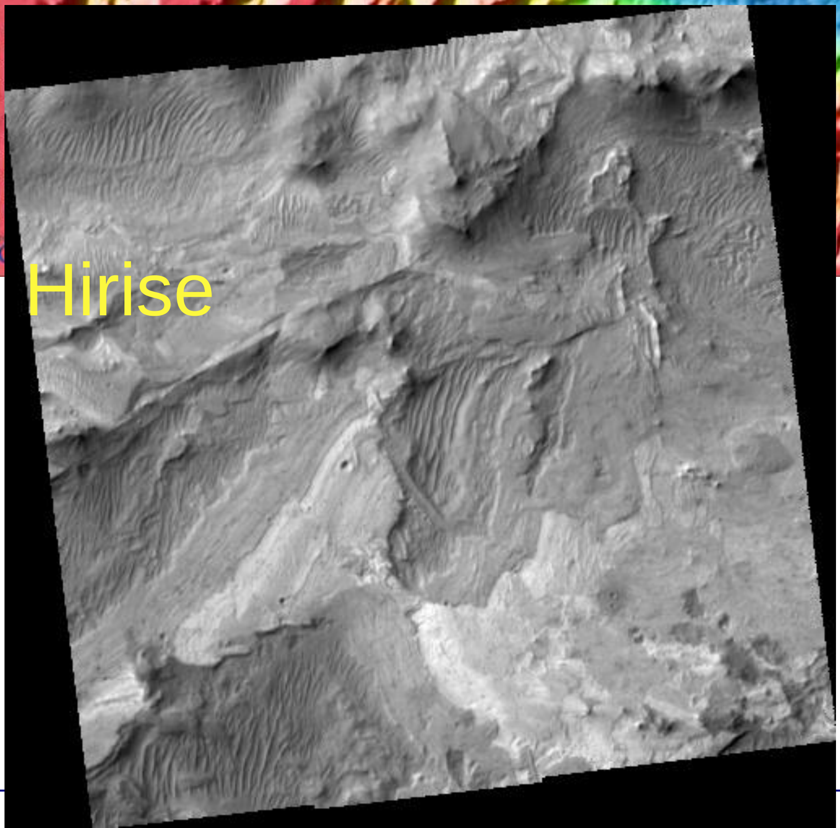


火星周回衛星MROに搭載　Hiriseカメラ

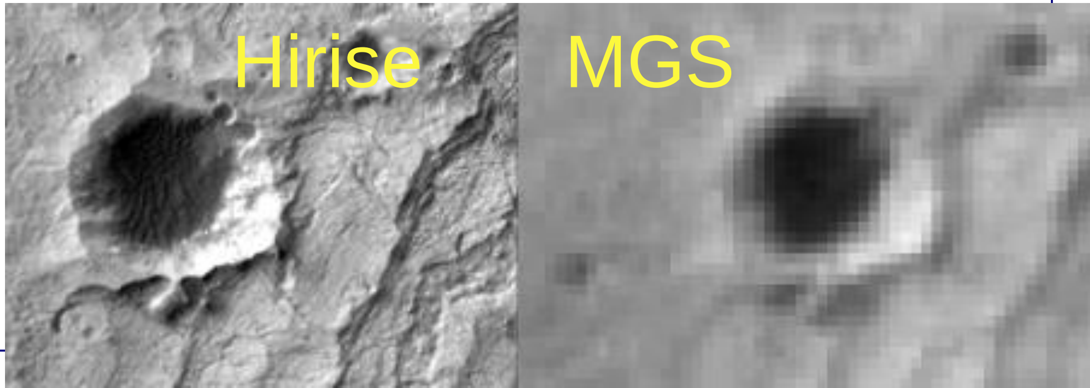




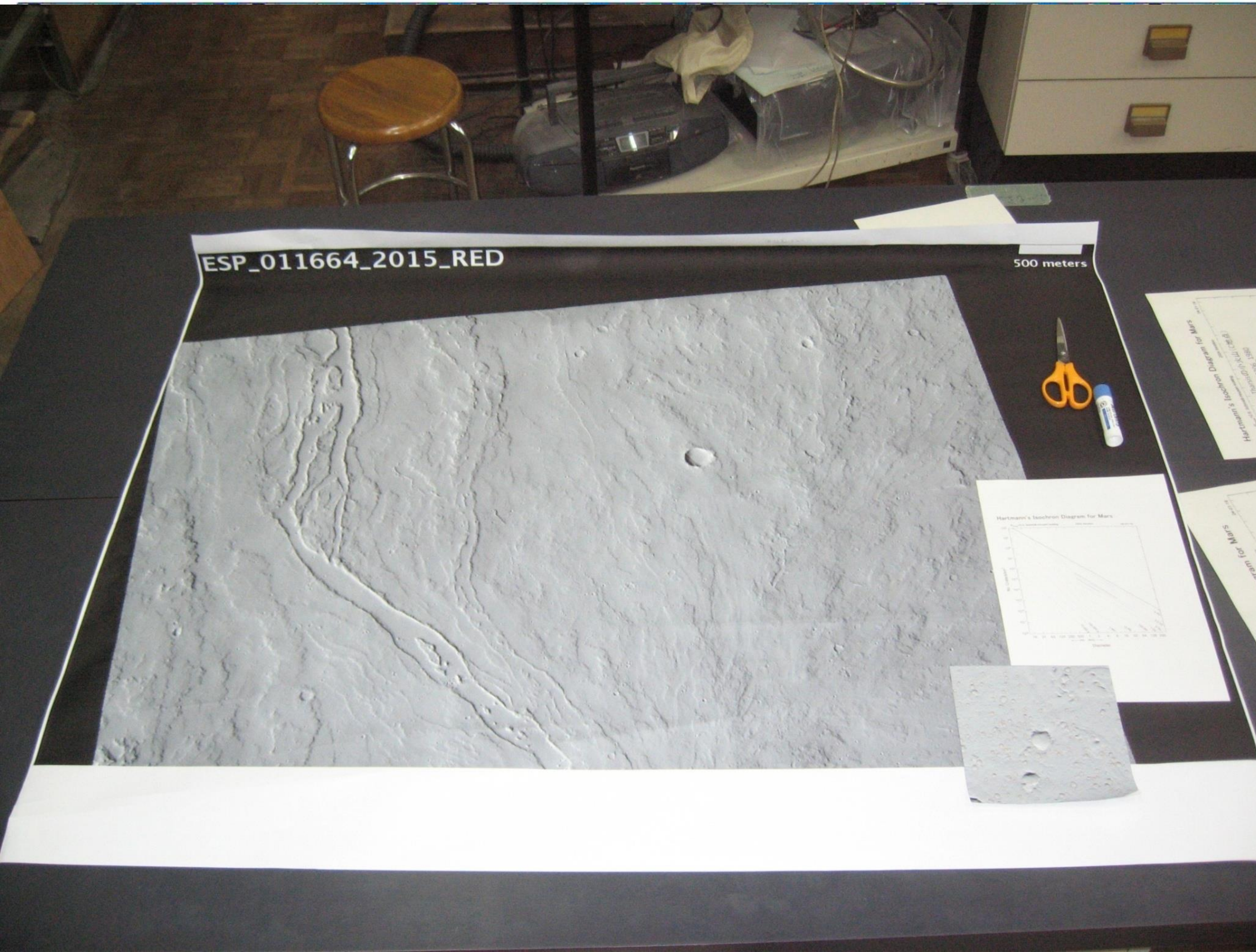




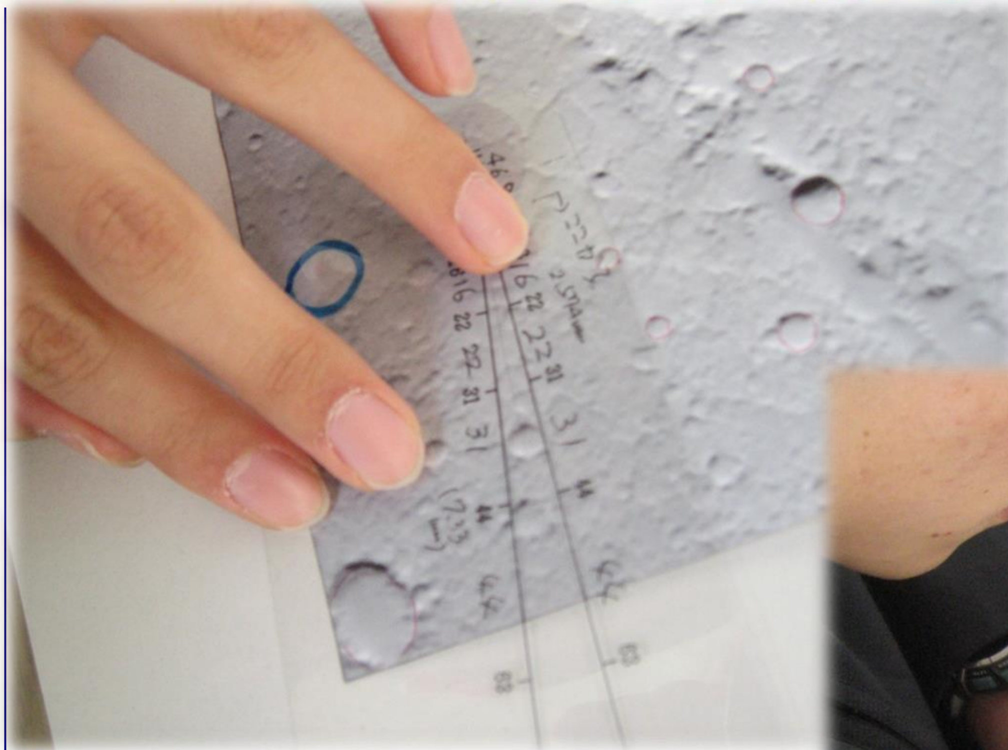
画像の解像度比較~30cm/px



読み取りに用いたA0判の印刷シート

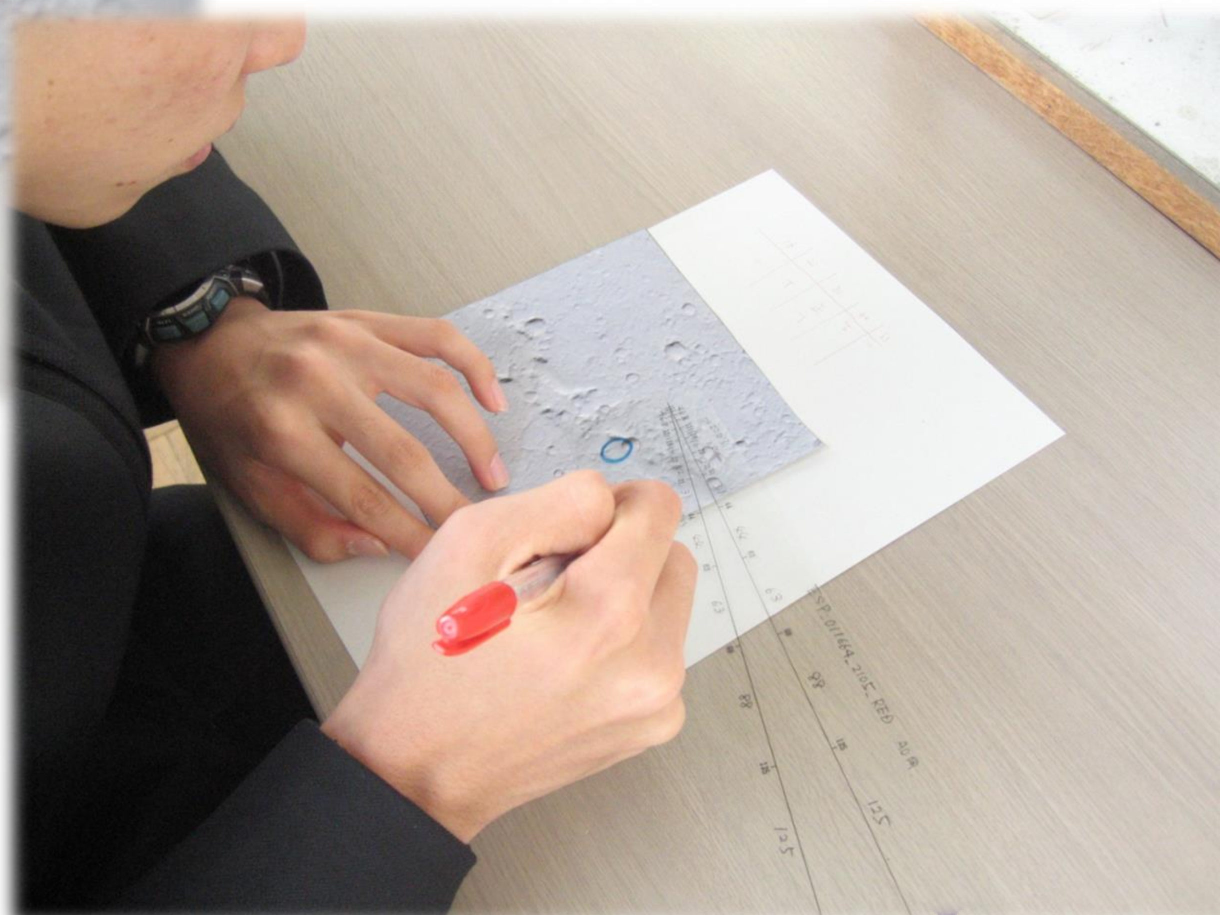


地学部による読み取り作業

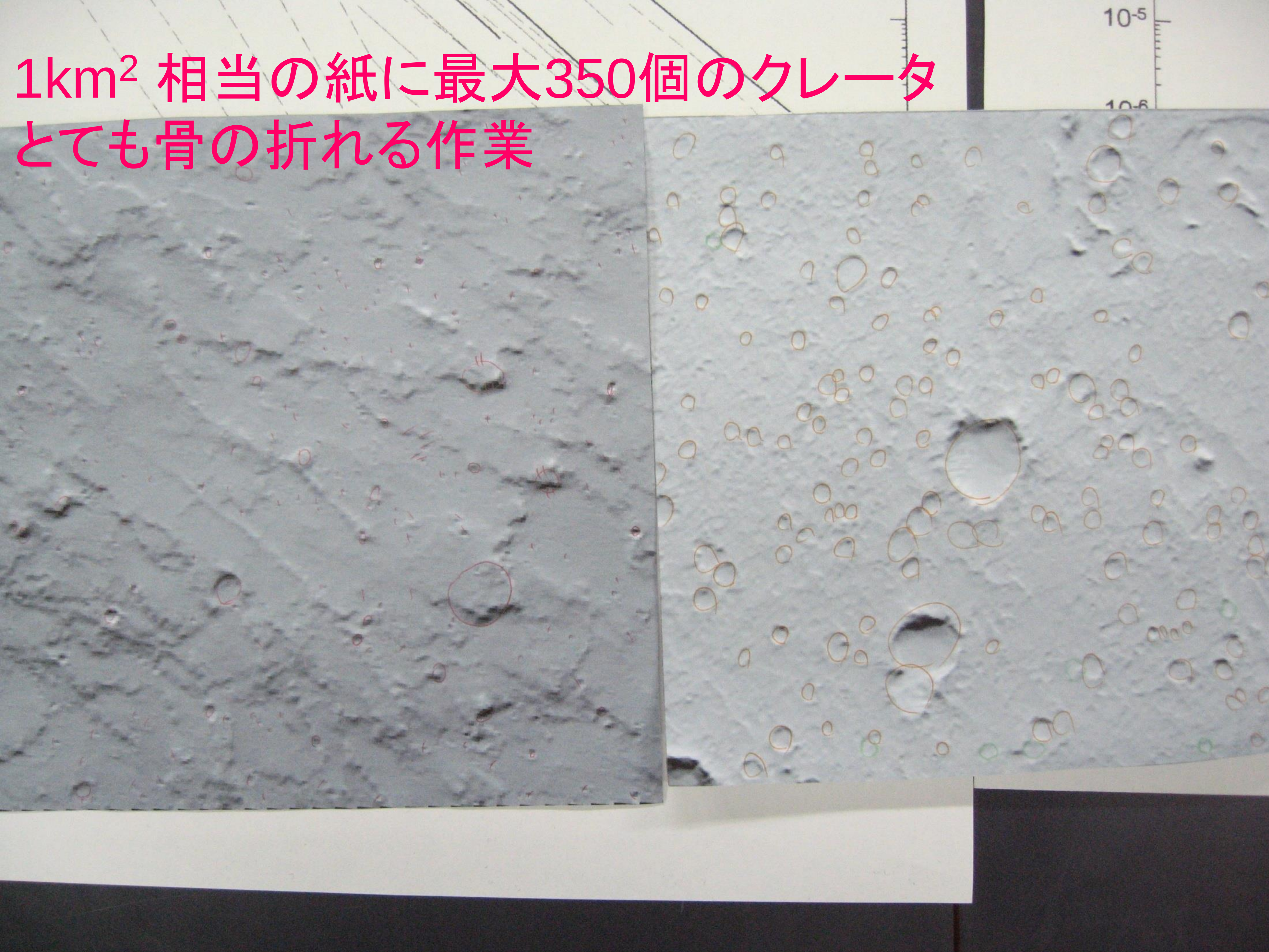


サイズを測定して，

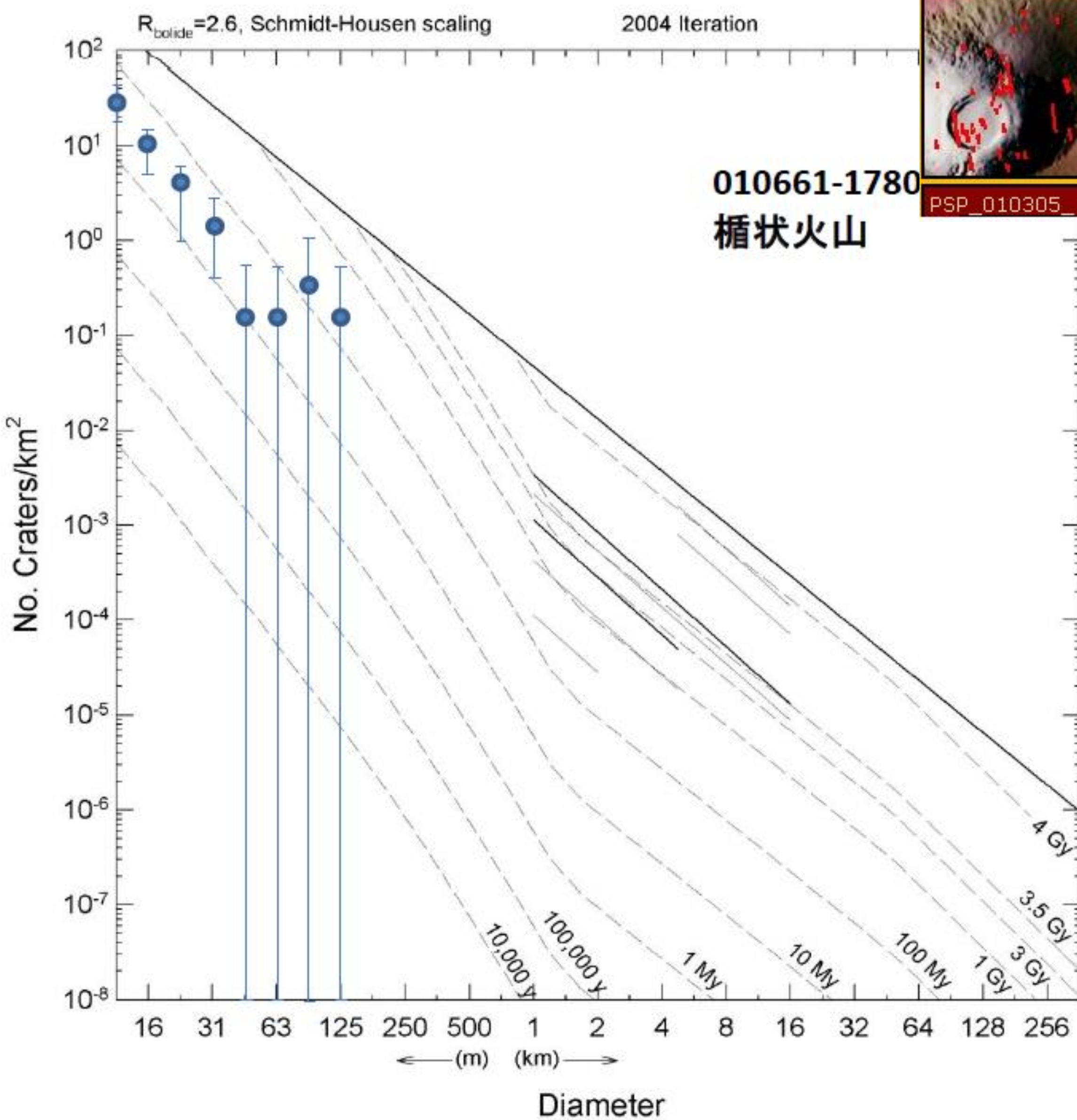
度数分布を作る



1km^2 相当の紙に最大350個のクレータ
とても骨の折れる作業

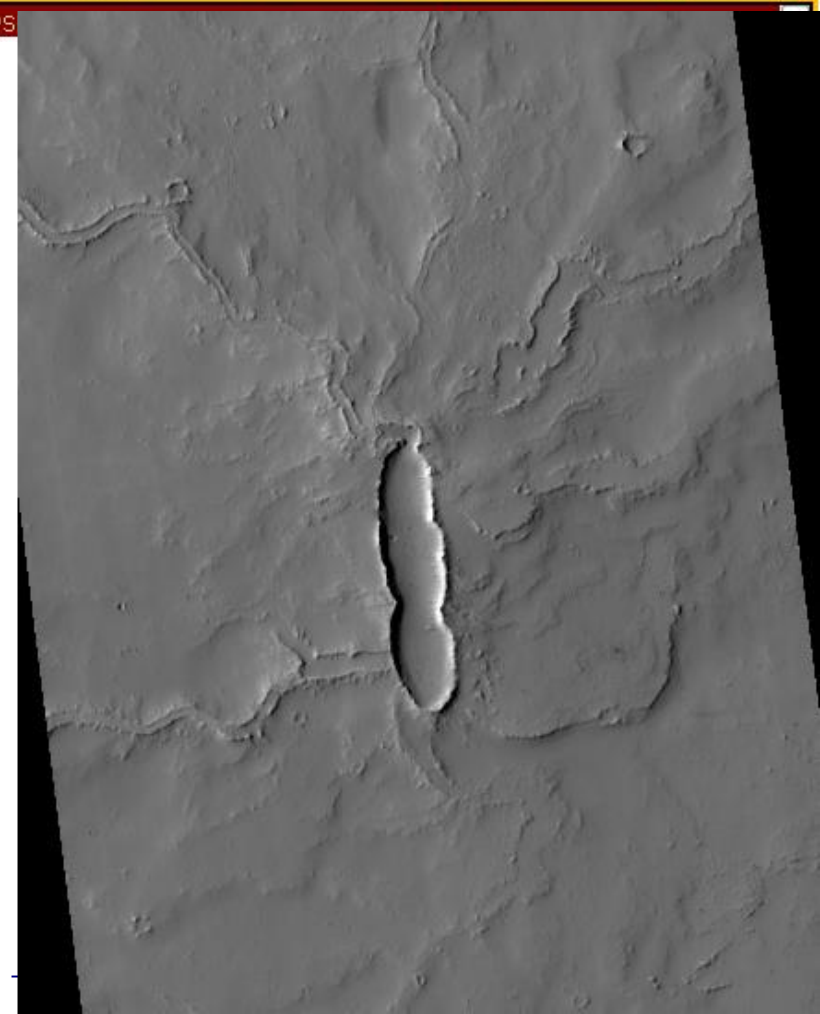


7000万年

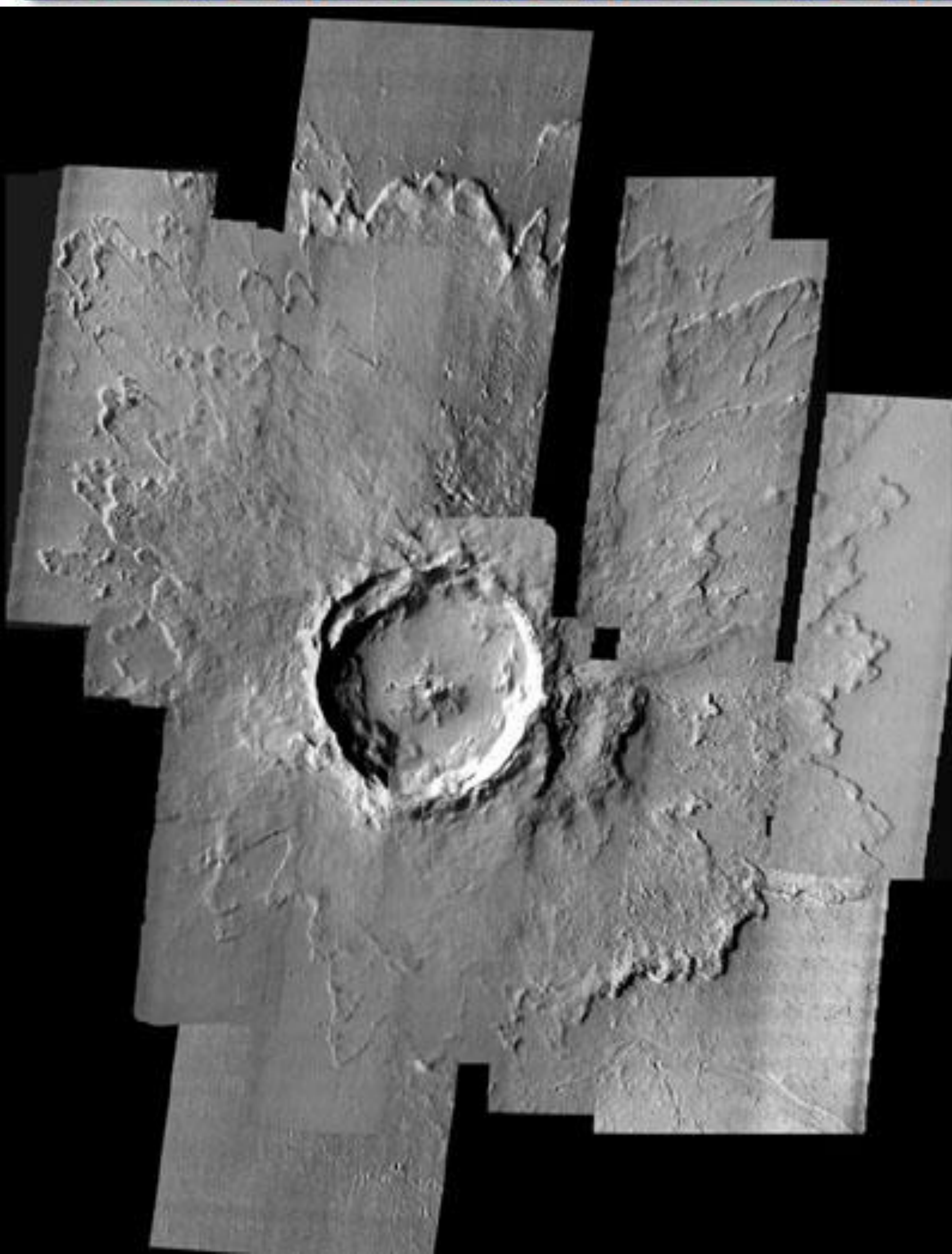


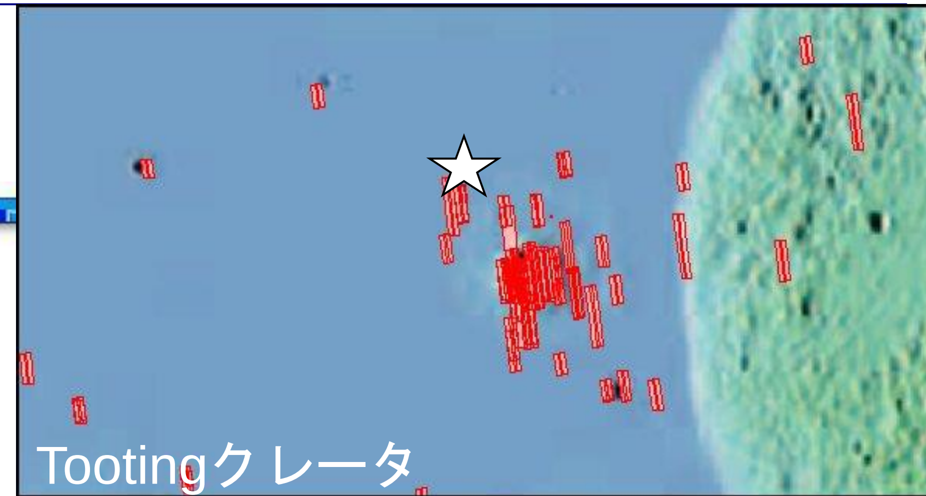
R$_{bolide}$=2.6, Schmidt-Housen scaling
2004 Iteration
010661-1780
楯状火山
No. Craters/km^2
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
16 31 63 125 250 500 1 2 4 8 16 32 64 128 256
(m) (km)
Diameter
10,000 y
100,000 y
1 My
10 My
100 My
1 Gy
3 Gy
3.5 Gy
4 Gy

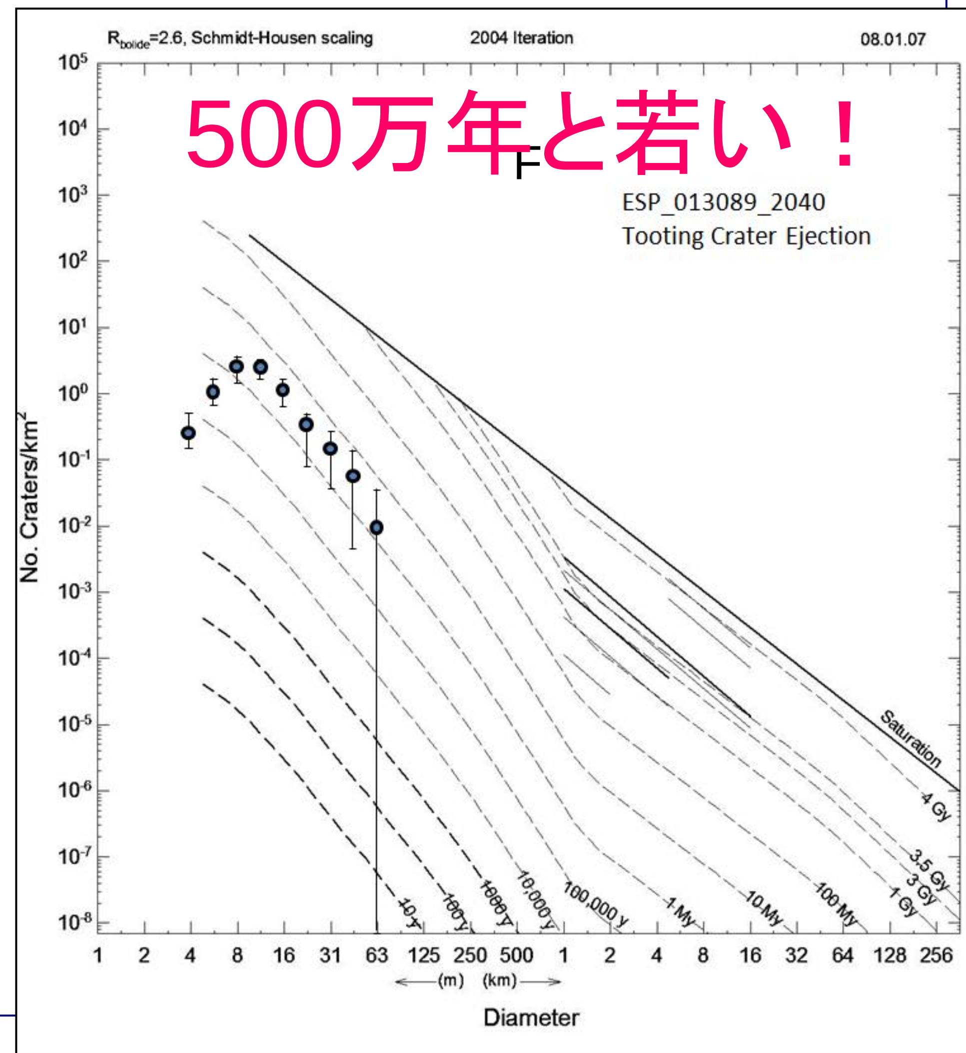
Select
2.0° S / 256.2° E
PSP_010305_1780 PS



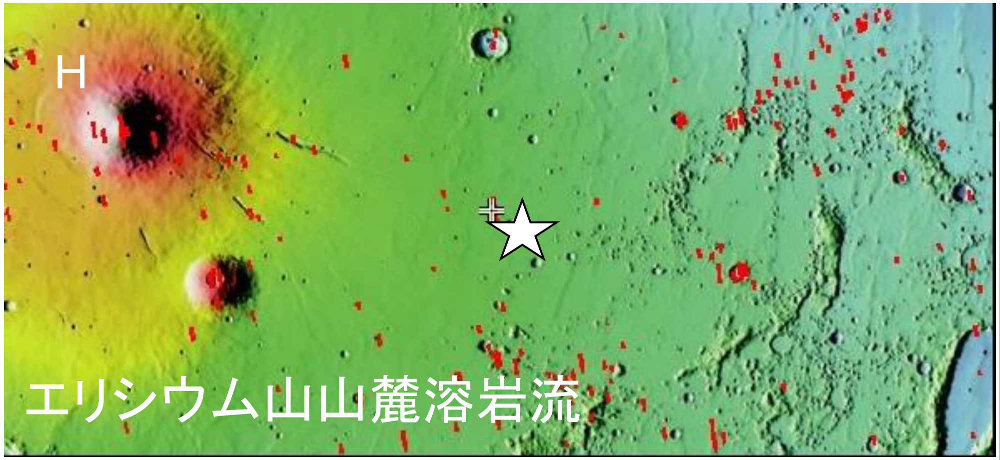
ランパート型クレータ



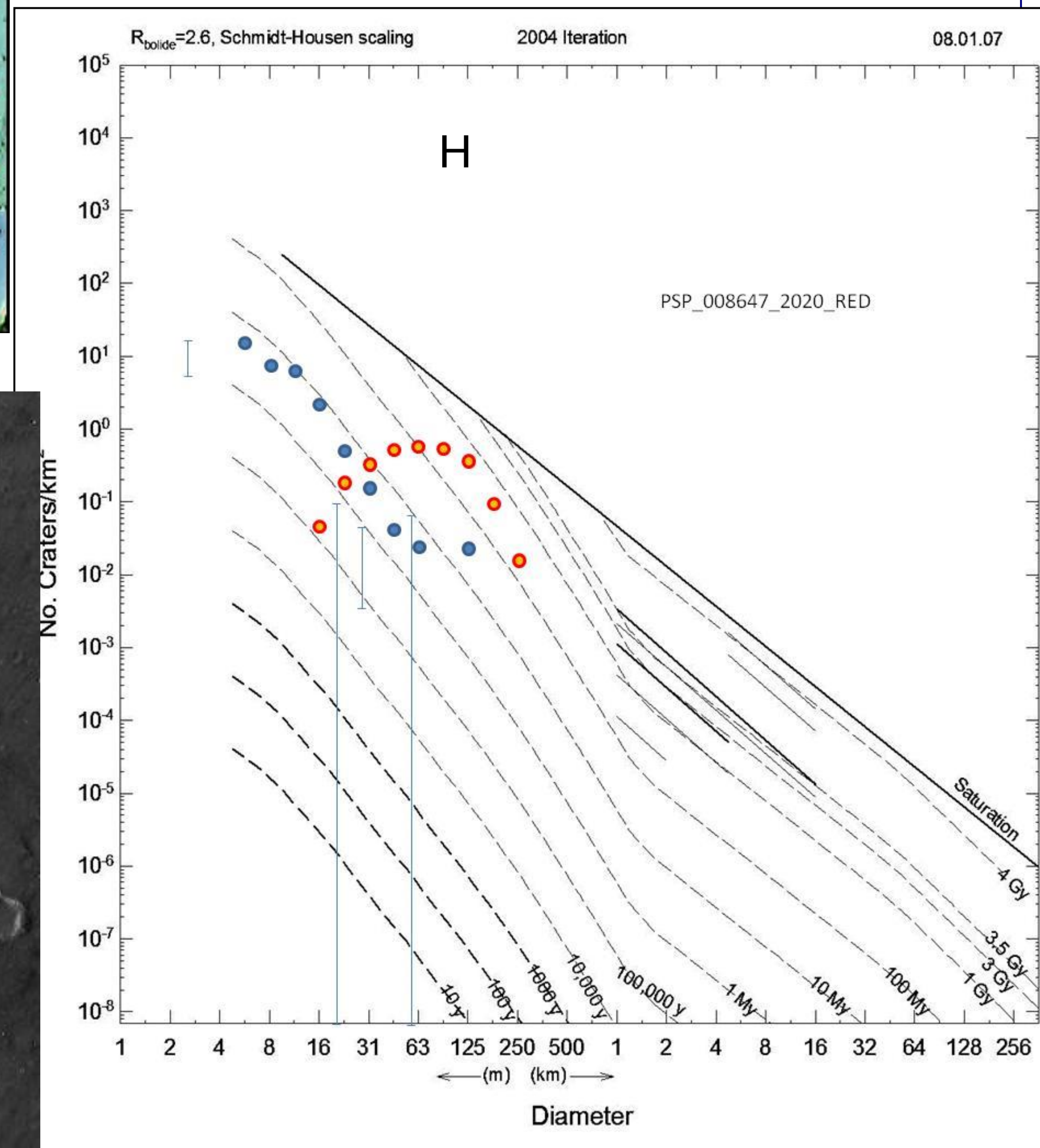

Tootingクレータ


R_bolide=2.6, Schmidt-Housen scaling
2004 Iteration
08.01.07
500万年と若い！
ESP_013089_2040
Tooting Crater Ejection
No. Craters/km²
10⁵
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
Saturation
4 Gy
3.5 Gy
3 Gy
1 Gy
100 My
10 My
1 My
100,000 y
10,000 y
1000 y
100 y
10 y
1
2
4
8
16
31
63
125
250
500
1
2
4
8
16
32
64
128
256
(m)
(km)
Diameter

新・旧2種類の年代：2層の溶岩流？



赤：7億年　青：9千万年



カウント実習結果

- 溶岩流や火山山麓の年代推定結果は専門家の結果と大変調和的である. (例えば Hartmann,2005)
- カウント実習そのものは高校生でも，それほどの準備なしに結構たやすく実行できる.
- クレータの読み取り時代は結構大変な作業であるが，データをプロットしてすぐに興味深い年代測定の結果が出ることは，大変生徒の興味を引く.
- この作業を通じて，地味な統計が，実は最新の科学の最先端の研究や科学論争につながることを実感できる. いつもハイテク＝最新科学ではない！

実習を通してわかったこと

- 画像の選定が大事.
- 読み取った結果が直線にならぶような場所を選ぶ.
- 小径クレータまで鮮明な地域の画像を選ぶ.
- あまり古い年代の表面を選ばない⇒クレータが多すぎてカウントに苦労する.
- あらかじめ推定年代のデータが出ている場所をまず選定してカウントの妥当性を評価するとよい.
- 逆に, カウントして直線に乗らない場所はオリジナルな研究として発展する可能性がある.

高校地学Ⅰ，Ⅱでの紹介

高校地学Ⅰ，Ⅱの授業でもクレータカウント実習を行ったり，内容を紹介することがある．

特にこの手法と関連する内容（次スライド以降）の紹介を兼ねて行うと生徒の関心が極めて高まる．

クレータ年代学の火星での応用（C.Fassett et.al.,2008）

Caleb I. Fassett, James W. Head III :The timing of martian valley network activity:

Constraints from buffered crater counting, Icarus 195 (2008) 61–89

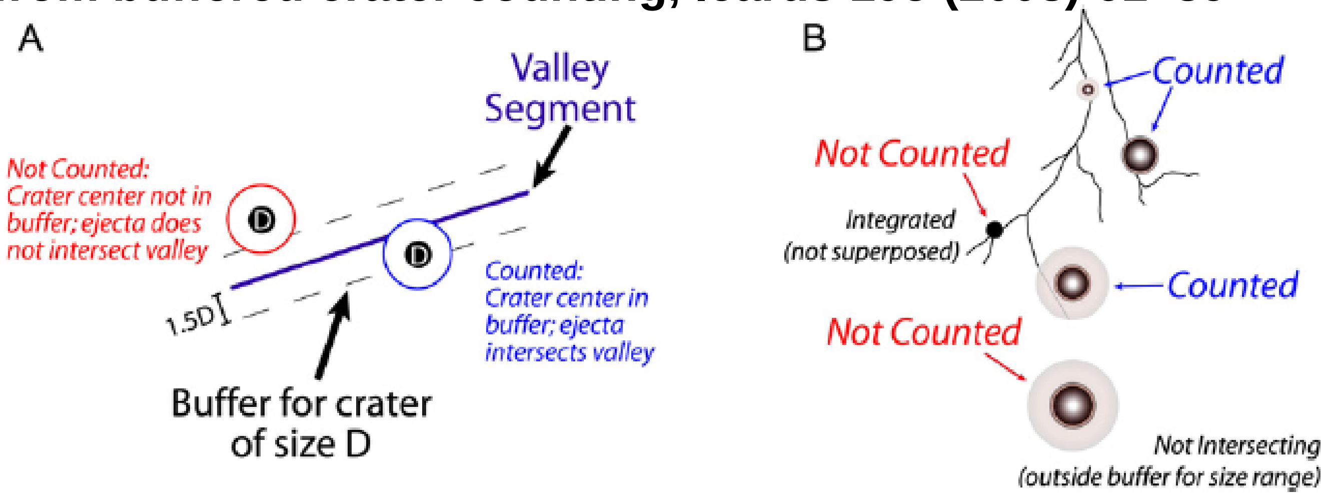


Fig. 3. Schematic diagrams illustrating the buffer crater counting methodology. (A) A buffer is established for a given crater size, and craters are counted which (1) have their centers in the buffer, and (2) intersect the valley segment. For each buffer, a count area is then calculated (which thus allows for size–frequency determination). (B) A schematic of buffer creation at a variety of crater sizes. Craters are not included if they are not superposed on the valley network (e.g., integrated), or outside the buffer appropriate for its crater size.

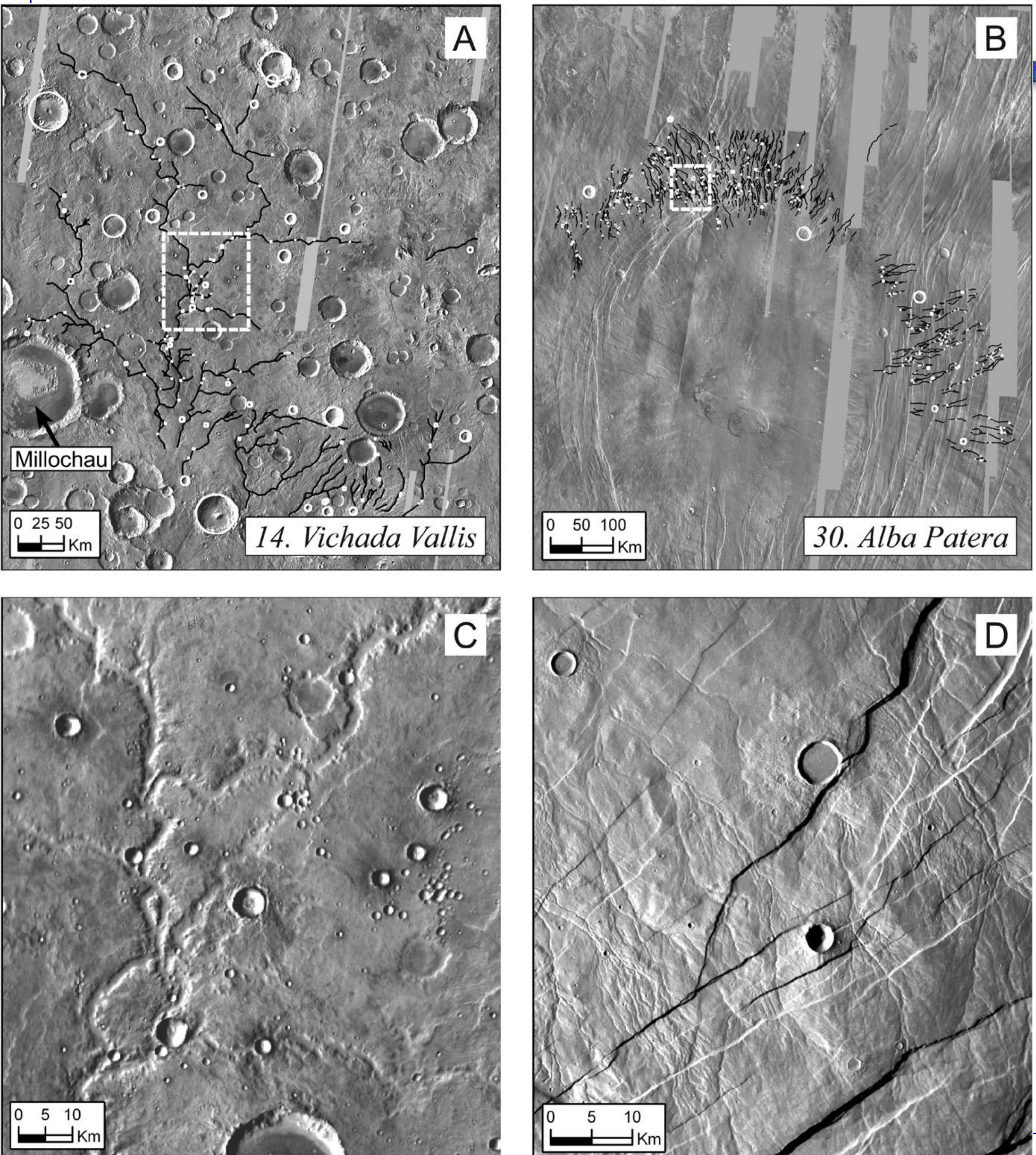
Good example of cross-cutting relationship!

in other words, there are no apparent systematic errors resulting from our choice of a buffer size.

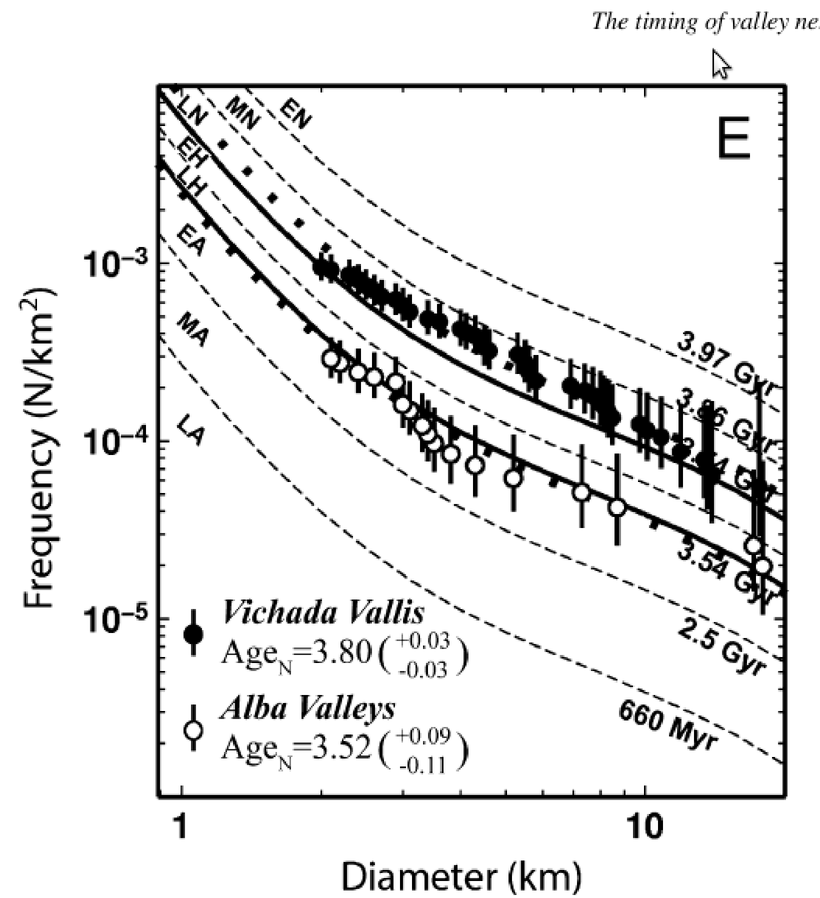
Our procedures for the count are as follows: (1) We first map the valley system being examined and determine its average width. (2) We then find all craters clearly superposed upon the valley that have a center within the buffer area appropriate for the specific crater diameter (so that its rim falls within a distance of one crater diameter of the valley). (3) A count area is

Lack of knowledge of the exact historical impact crater production rate on Mars leads to a systematic uncertainty in absolute ages of up to a factor of ~2–4, and the degree of uncertainty depends on the age of terrain being considered (e.g., Hartmann and Neukum, 2001). Along with this systematic uncertainty, there are also non-negligible differences in the ages that are derived using the Hartmann and Neukum production functions. For example, calculating the

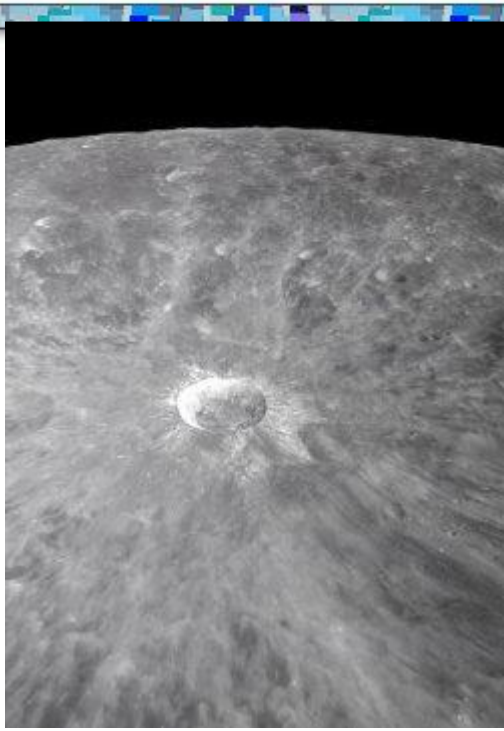
河谷の形成年代⇒意外と古い！



C.Fassett et.al.,2008

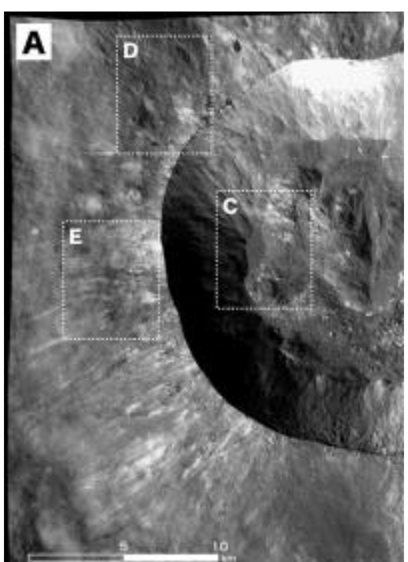


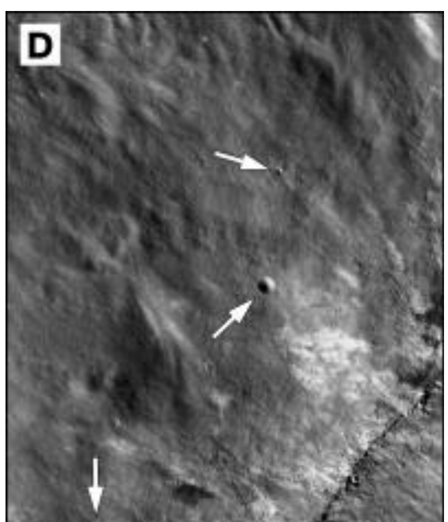
本家の月でも:「かぐや」のデータを使って

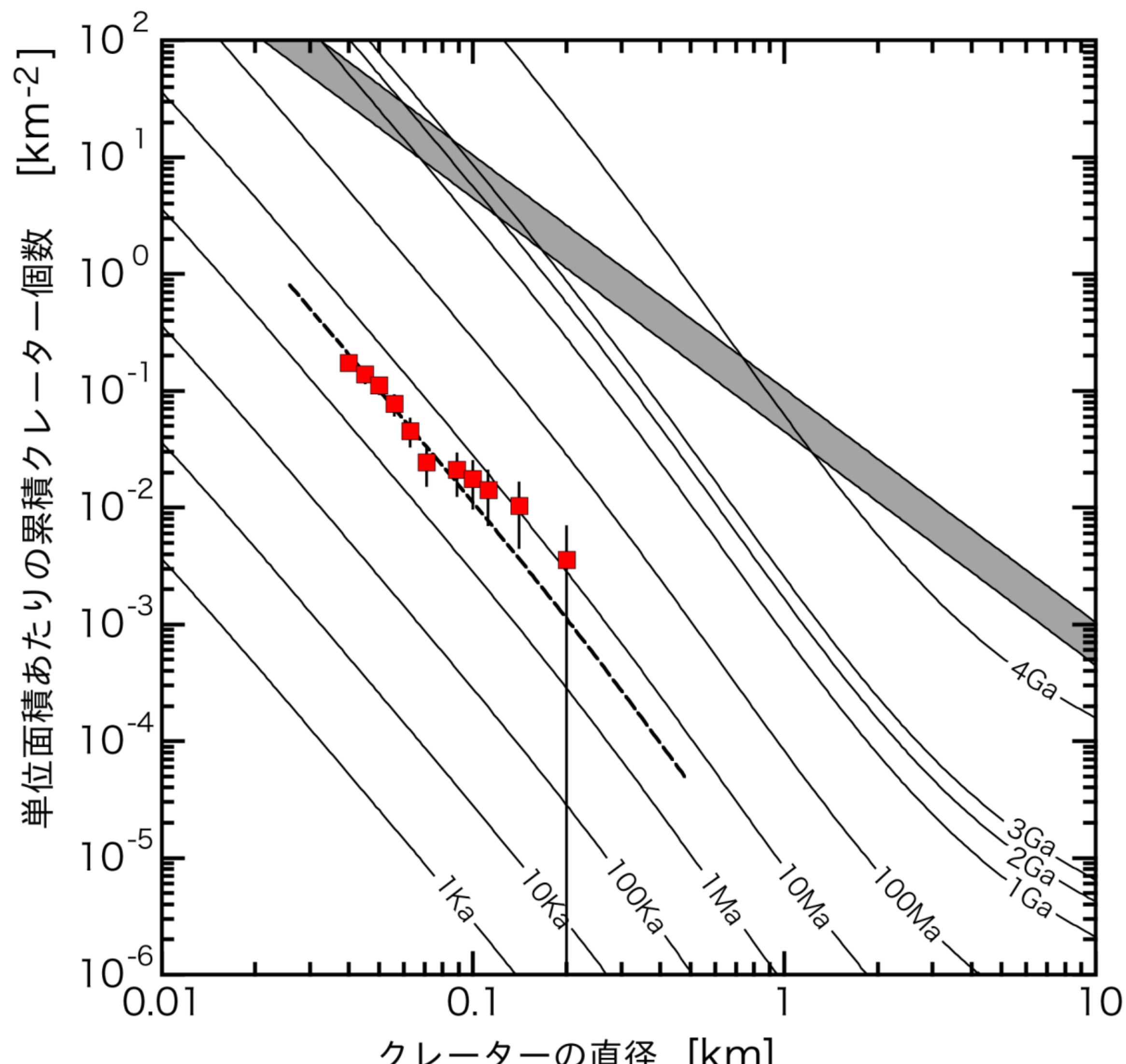


ジョルダーノ･ブルーノは歴史時代にできたものか？

http://moonstation.jp/ja/history/Kaguya/Giordano_Bruno/index.html
より







この手法は本当に妥当なのか？

1. **火星表面の岩石が手に入ればよい！**
2. **それは2030年まで無理なのか？**

-----？

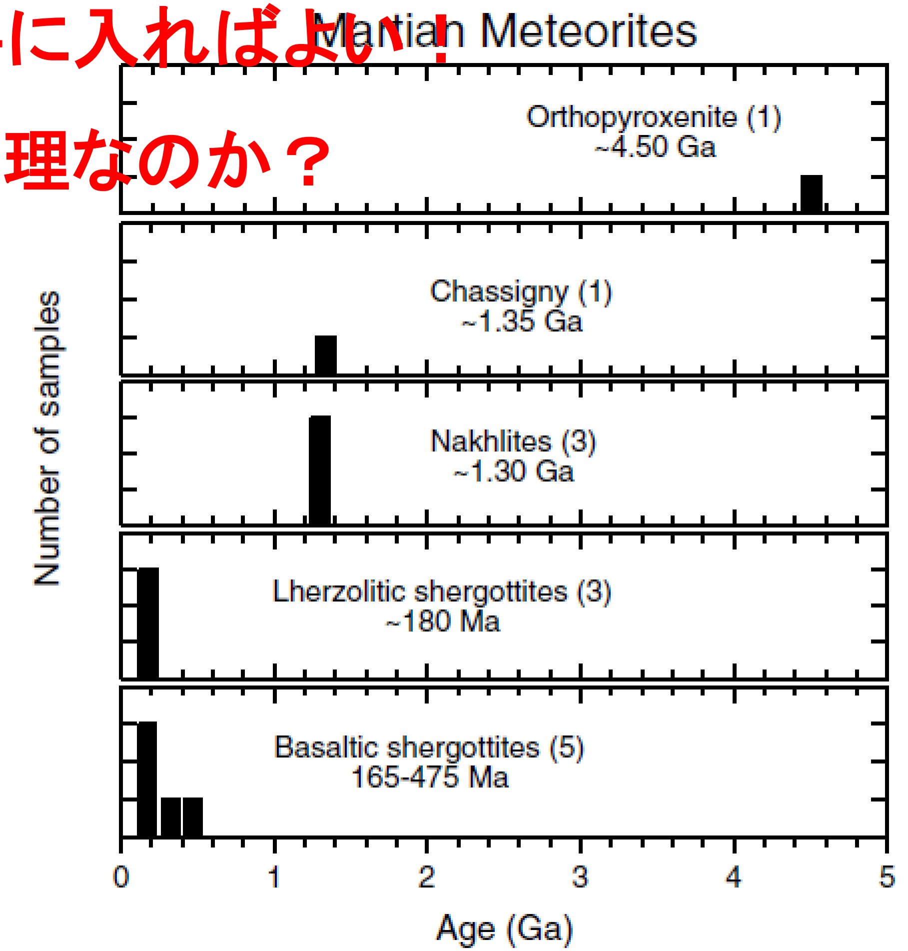


Figure 2. The crystallization ages of Martian meteorites separated by compositional group. The values plotted are the "preferred ages" from Tables II and III. The oldest meteorite in the Martian clan is ~4.5 Gyr old, and the youngest ~180 Myr old. Thus, Martian magmatism appears to have extended over most of solar system history, a conclusion that agrees with the time span of crater retention ages (Hartmann and Berman, 2000). The thirteen meteorites fall into only five age groups, leaving large gaps in Martian chronology as recorded by the meteorites.

14個の火星起源の

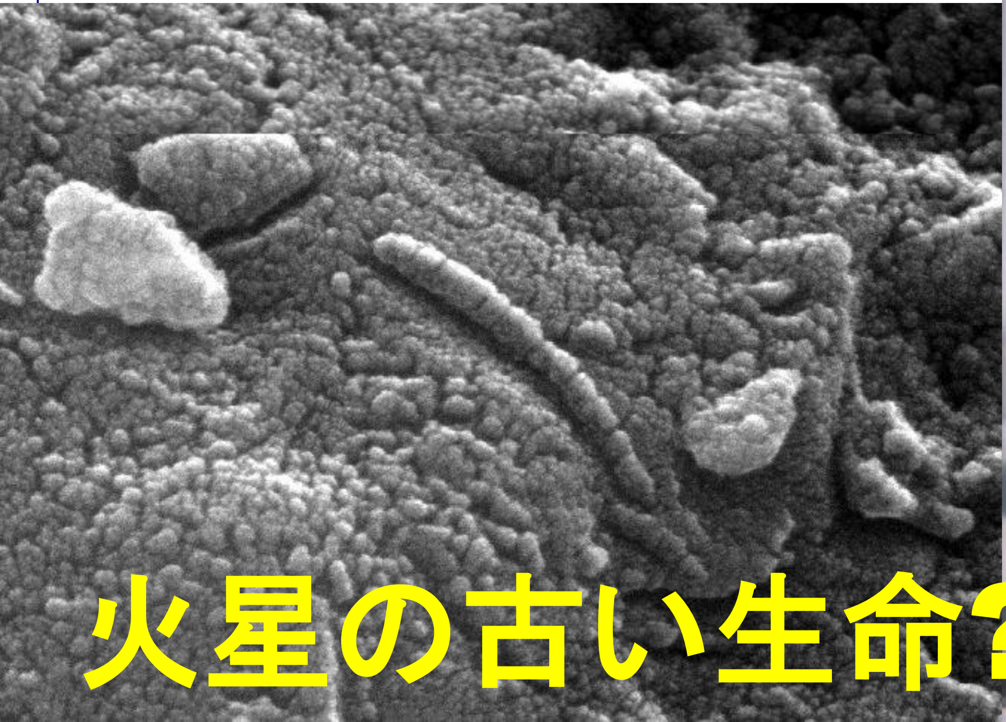
隕石の年代測定

Nyquist et al.,2001

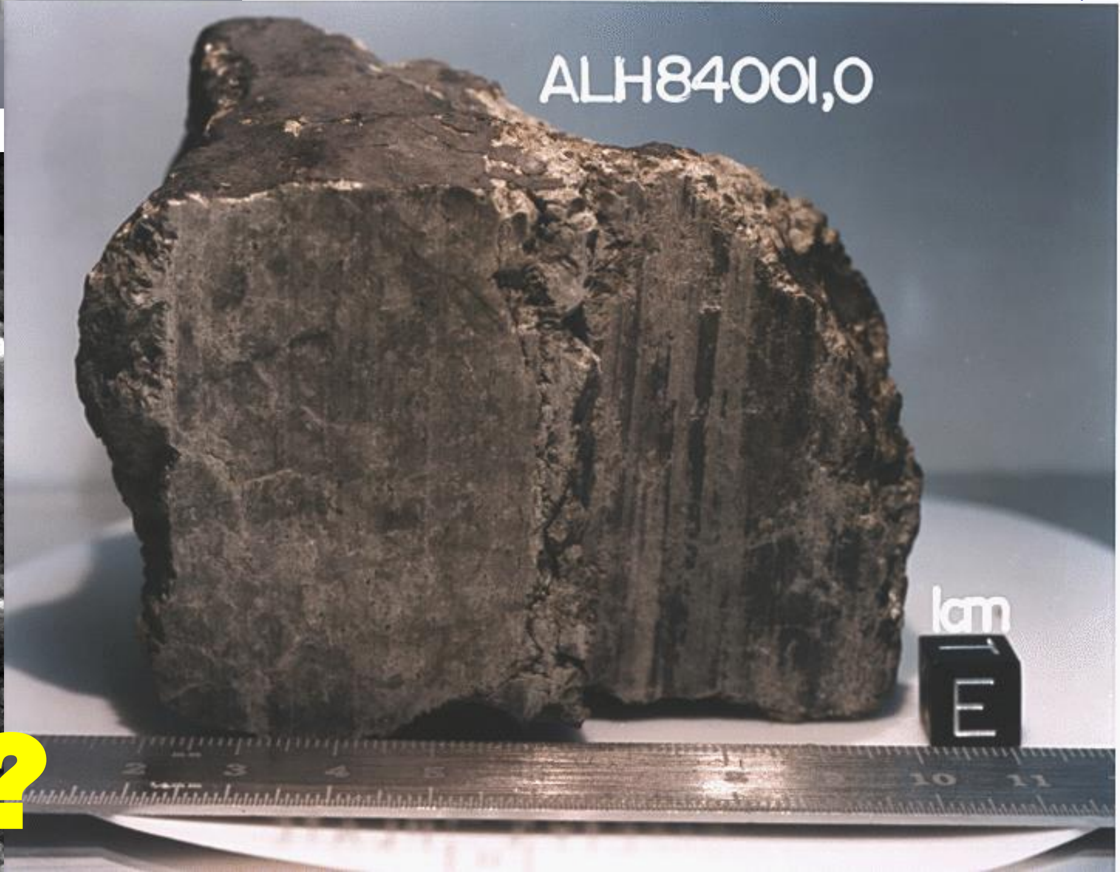
火星からの隕石

ALH84001

McKay, David S., *et al.* (1996). “Search for Past Life on Mars: Possible Relic Biogenic Activity in Martian Meteorite ALH84001”. *Science* **273** (5277): 924–930.



火星の古い生命?



さしあたっての問題

1. 隕石衝突の頻度は歴史上一定なのか ？

-> No:The Late Heavy Bombardment Period(LHB)

2. 火星表面では砂嵐などによる風化がないのか？

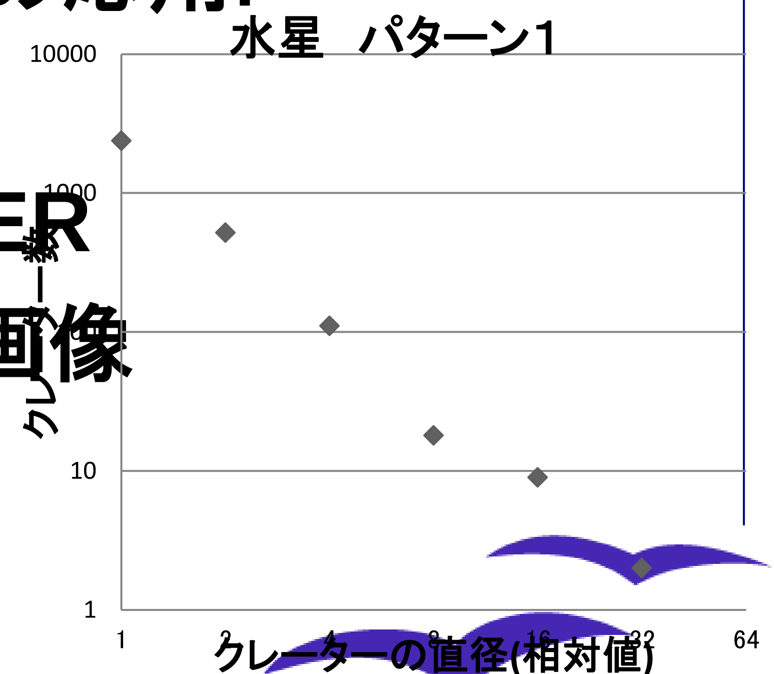
-> Yes: 古いクレータが埋もれたり，再度掘られたりする.

3.他の惑星や小惑星さらに衛星への応用.

→　水星における試行

※さらに現在NASAのMESSENGER
というミッションが水星表面の精彩画像
を送付中.

はやぶさなどの小惑星では？



クレータ年代学にまつわる話題

- ジャイアントインパクト仮説

  月の起源（45億年ころ生成？）

  火星くらいの惑星が地球に斜め衝突

- 後期重爆撃期説（LHB）

  太陽系の隕石衝突にはClimax Stageがあった.

  月の海や盆地の生成

  地球への影響は？とりわけ生命の起源？

後期重爆撃期説:39億年前隕石衝突のピーク

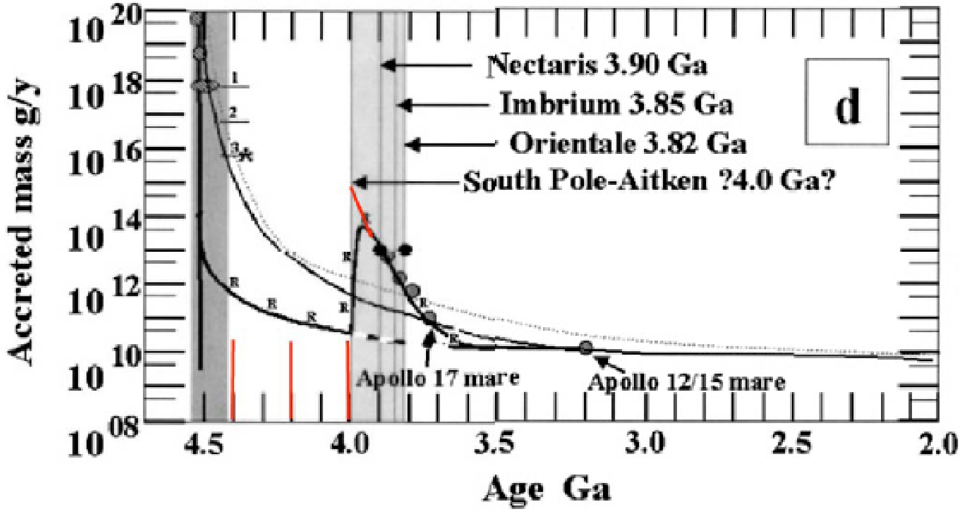
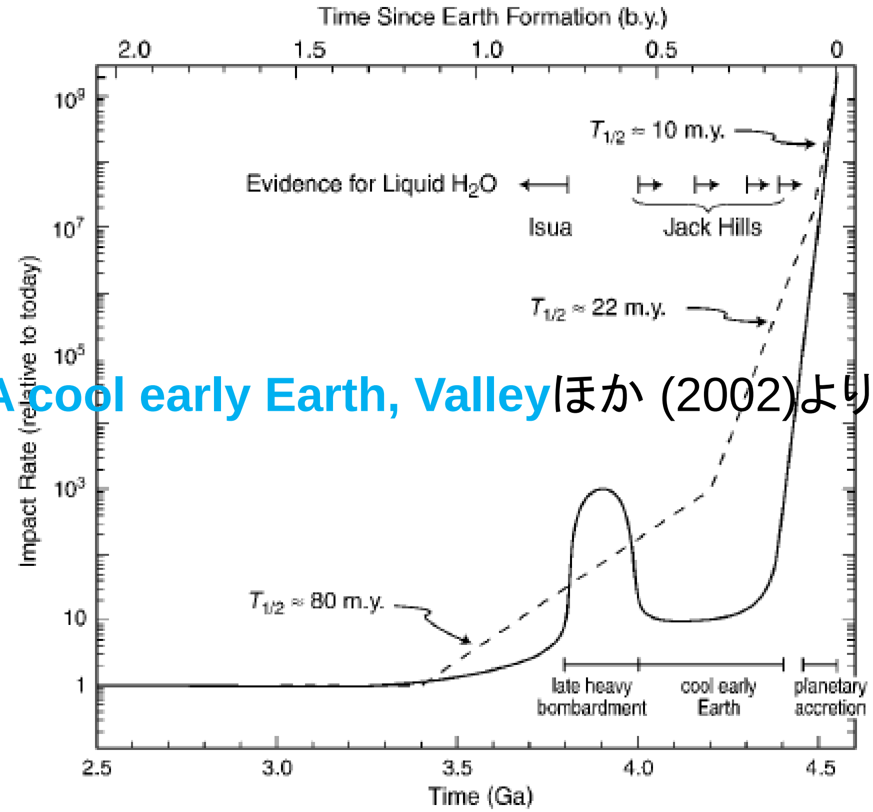


Fig. 6. Ryder's (2002) preferred model of the LHB, adapted from his Fig. 4d which he described as a "cataclysmic impact episode that includes all the observed basins, preceded by a long period of relative impact quiescence. The curve does not have to be so extremely low in the period 4.4 - 4.0 Ga..." Ryder's cataclysm occurs at $t_{LHB} = 3.9 \pm 0.1$. Three vertical red lines in the lower left indicate the 4.2 ± 0.2 Ga estimate of the age of SPA used in the three models in Figure 3. Ryder has assumed that the age of SPA is 4.0. Even if we assume Ryder's $t_{SPA} = 4.0$ Ga, Fig. 3 indicates that there is no increase in the impact rate after t_{SPA} (as postulated by Ryder) since the slope of the cumulative curve is steepest at t_{SPA} and does not steepen appreciably after t_{SPA}, which is required by Ryder's model. This is true independent of the value of t_{SPA}. In the $t_{SPA} = 4.0$ Ga model, Fig. 3 suggests that if we accept the decrease in the impact rate from 3.9 to 3.7, then the data suggests that the earlier impact rate is even higher shown by the diagonal red line....which is strongly inconsistent with the pre-Nectarian



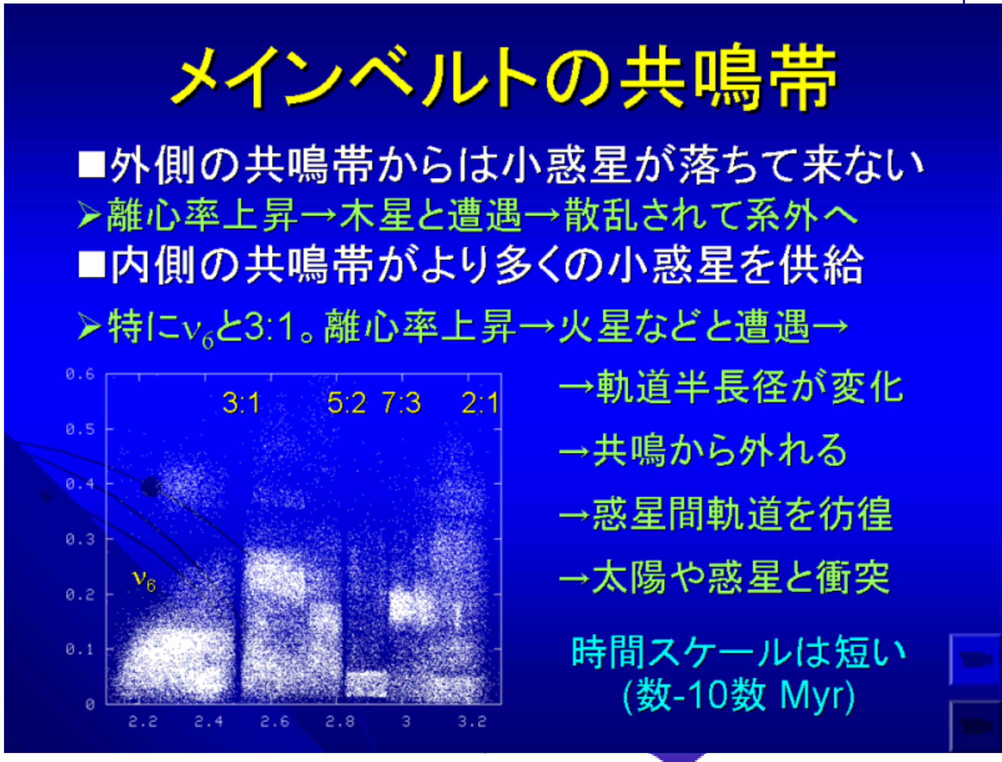
A cool early Earth, Valleyほか (2002)より

Figure 3. Estimates of meteorite-impact rate for first 2 b.y. of Earth history. Two hypotheses are shown: exponential decay of impact rate (dashes, Hartmann et al., 2000) and cool early Earth–late heavy bombardment (solid curve, this study). Approximate half-life is given in million years for periods of exponential decline in flux. In either model, spikes occurred owing to isolated large impacts. Evidence for liquid water comes from high-$\delta^{18}O$ zircons (>4.4 to >4.0 Ga) and sedimentary rocks (Isua, 3.8–3.6 Ga). The cool early Earth hypothesis (solid curve) suggests that impact rates had dropped precipitously by 4.4 Ga, consistent with relatively cool conditions and liquid water.

Ryder, G., (2002)をNorman（2008）が編集したもの

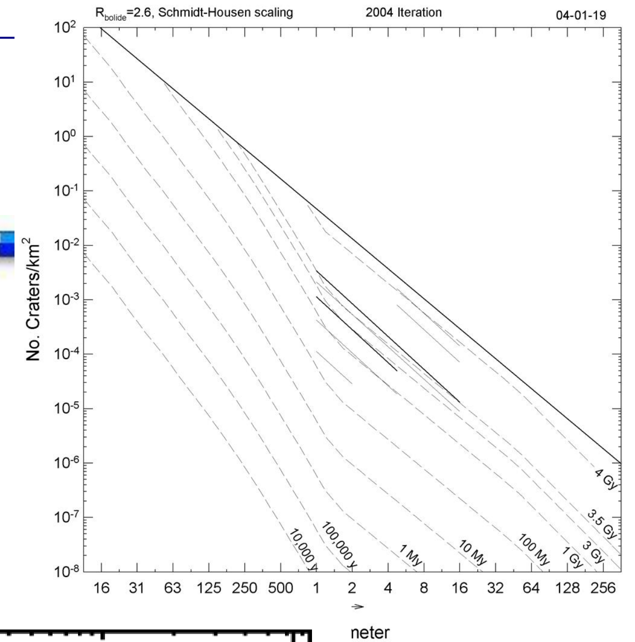
後期重爆撃期説 （Late Heavy Bombardment Period）

1. 月から採集した岩石の年代が39億年に集中．
（月，火星からの隕石も同様） →月の海の形成
2．月・地球上の岩石は40億年より古いものがない．
3．クレータ年代学
⇒38億年以降は過疎
4．隕石の供給過程の計算
（太陽系内の不安定要因：
数値シミュレーション）



伊藤孝士2007より

クレータサイズ分布：R-plot



２種類の異なった分布：衝突天体の違い？

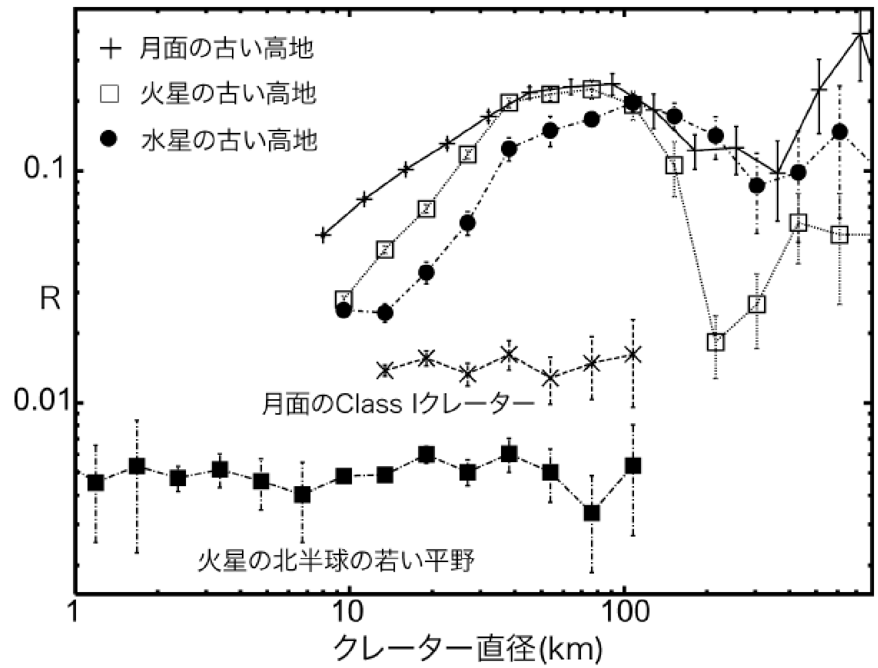


図 2　月，水星，火星のさまざまな領域でのクレーターのサイズ分布．縦軸はクレーターの数密度に対応する．

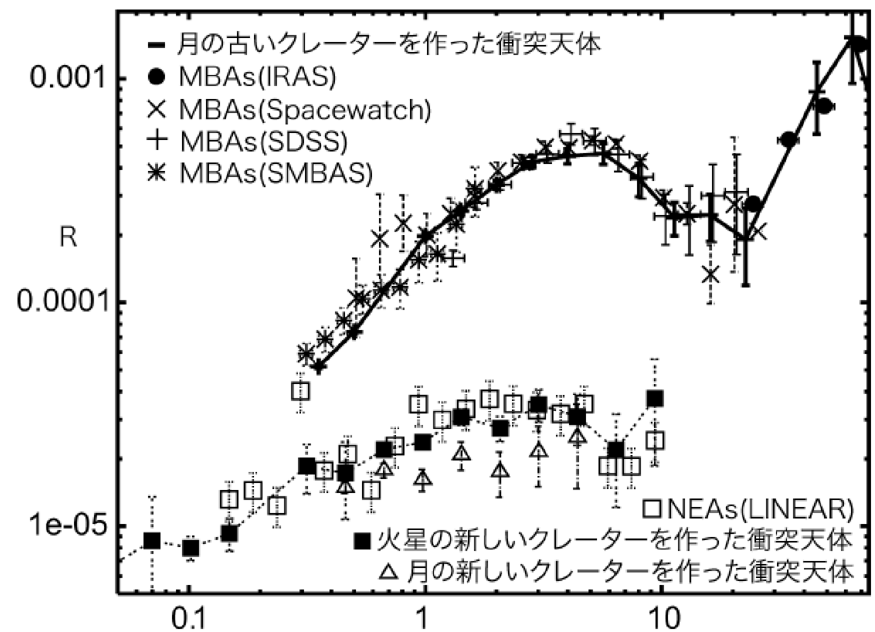


図 6　クレーターを作った衝突天体のサイズ分布と現在の小惑星のサイズ分布の比較．横軸は天体の直径（km），縦軸は天体の個数密度．ここでは小惑星的天体を仮定してクレーターから衝突体のサイズを導出した．

吉田二美 2006より

Giant Impact 説の検証

月が昔は近くて，段々遠くなって行ったことの検証
→古い時代の月の軌道の公転周期や地球の自転周期などがわかるとよい．

しかしどうすれば？------

潮汐を記録する古い地層

Williams,2000
Review of Geophysics

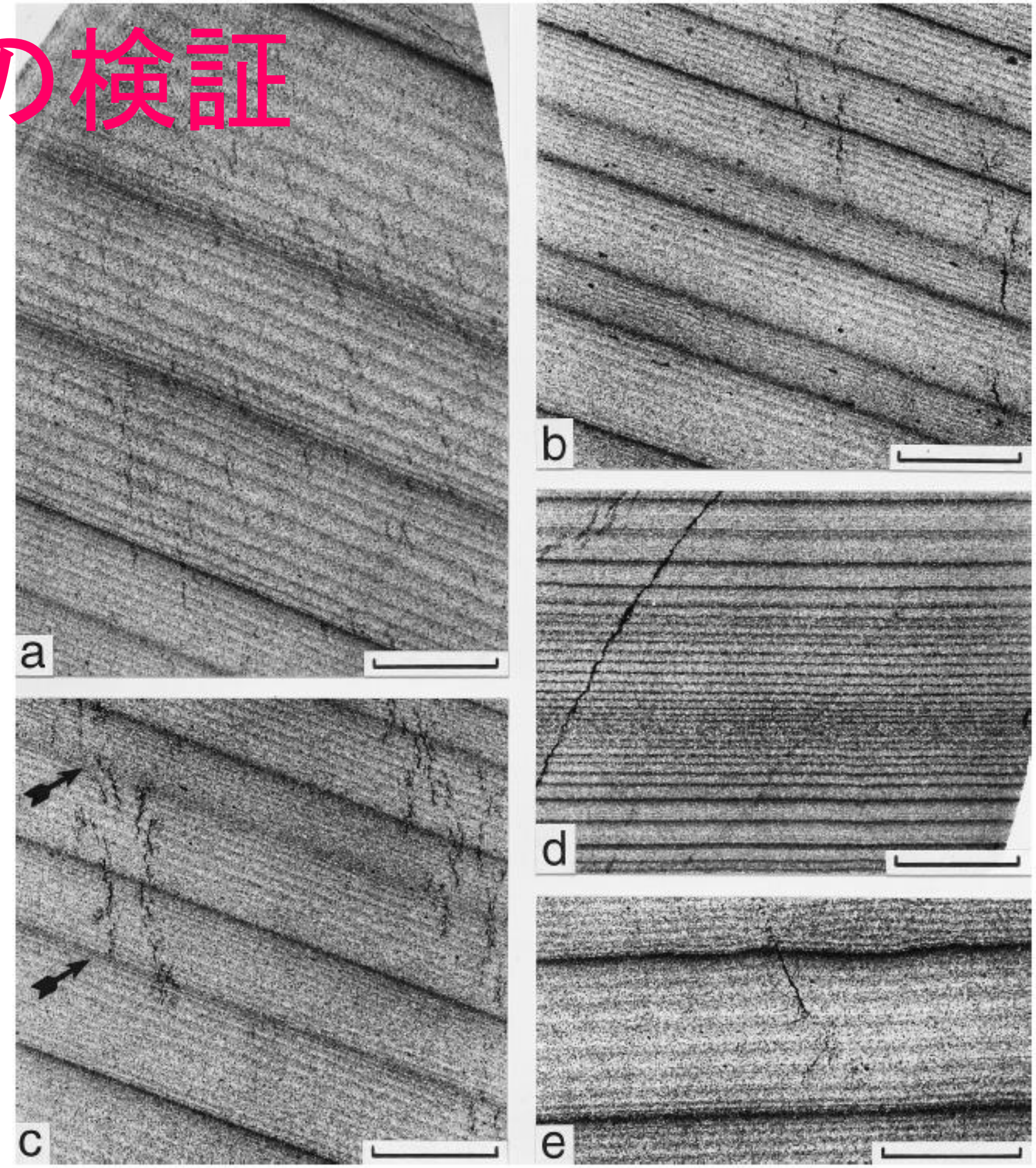


Figure 4. Thin sections of rhythmites from drill core of the late Neoproterozoic Elatina Formation, South Australia, viewed with transmitted light; opaque muddy material appears darker than translucent sandy and silty layers. Scale bars are 1 cm. (a) Four complete fortnightly neap-spring cycles of ~10–14 graded, diurnal laminae are bounded by conspicuous, dark, mud drapes deposited near times of neap tides. (b) Alternately thick and thin neap-spring cycles indicating the monthly inequality of paleo-spring tides. (c) Neap-spring cycles with alternate boundaries represented by very thin silty laminae (arrows) rather than mud drapes; such little abbreviated neap-spring cycles were deposited near solstices, when neap-tidal ranges were maximum (see section 3.1). (d) A group of thin (0.5–3.0 mm) neap-spring cycles representing just over 1 year's deposition; internal lamination between mud drapes is discernible only in a few places. (e) A neap-spring cycle comprising diurnal laminae as well as semidiurnal sublaminae. Reproduced from *Williams* [1991] with the permission of the Canadian Society of Petroleum Geologists, Calgary.

Moodies Group（32億年前）の浅い海の　tidal　rythmite その2

南アフリカ2010年
秋の地質巡検より

南アMoodies Group（32億年）潮汐縞の解析

・現在より早い月の公転（約20日弱）
・月の軌道が円軌道に近い

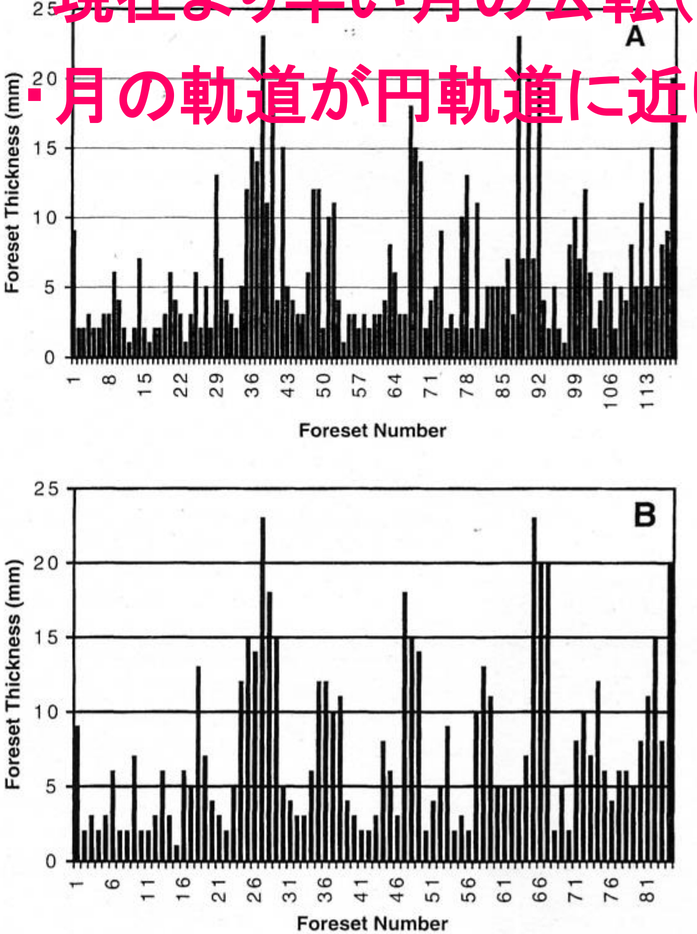


Figure 3. A: Traverse 2—all data. Histogram of sandstone foreset bundle thicknesses plotted against foreset number for traverse two through cross-bed set shown in Figure 2. Note variation in thickness of sandstone foresets and common presence of thick-thin pairs of foresets. B: Traverse 2—subordinates removed. Histogram of inferred dominant-tide foreset bundle thicknesses plotted against foreset number for traverse two through cross-bed set shown in Figure 2. Inferred subordinate flood-tide laminations were removed visually from data sets. Note that interpreted neap-spring-neap cycles are 9–10 days long and that alternate neap-spring-neap cycles are thicker and thinner, respectively.

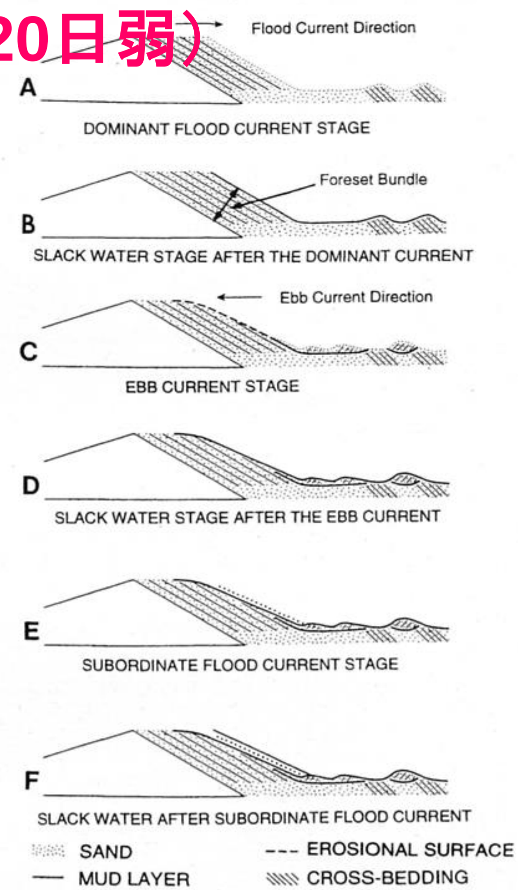


Figure 4. Migration of sand wave in tidal system characterized by strong flood current and weak ebb current (modified after Visser, 1980). Note that most sand is deposited on lee face of sand wave during dominant flood stage (A), whereas only thin sand layer is deposited on lee face during subordinate flood stage (E). Dominant and subordinate flood currents are typical of semidiurnal tidal systems. During ebb stage, sand deposition takes place only in trough of sand wave and is preserved in form of intrasets within toesets of cross-bed set (C). During stillstand associated with turning of tide, clay accumulates on lee face and within trough of sand wave and is preserved as mudstone drapes (B, D, F).

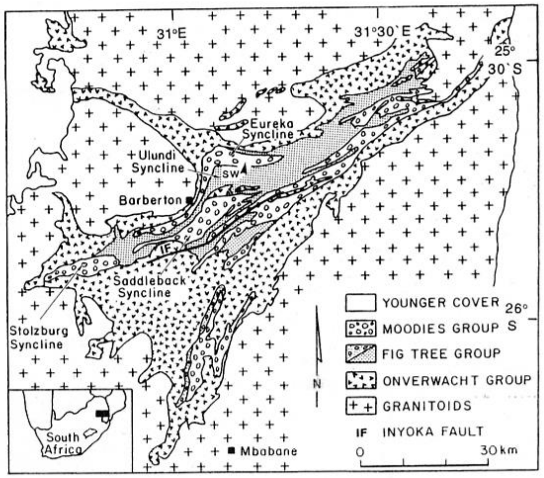
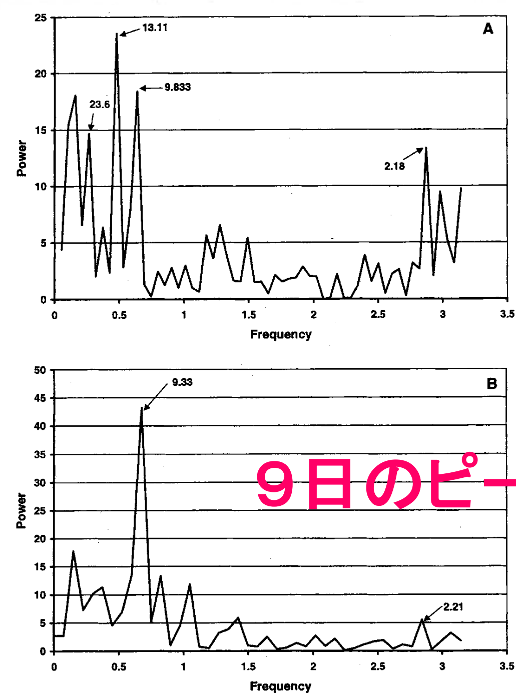


Figure 1. Simplified geological map of Barberton Greenstone Belt. Heavy arrowhead indicates location of sand-wave (sw) in Eureka syncline.



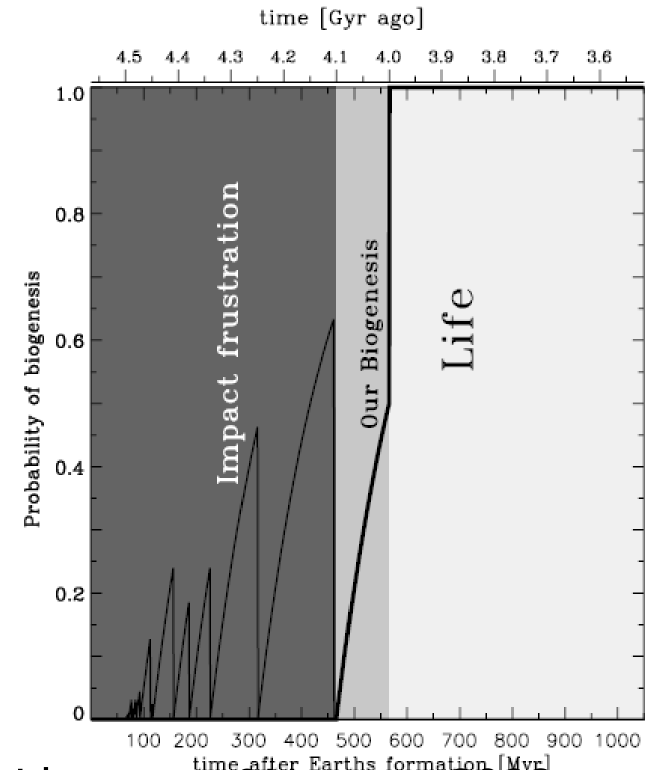
９日のピーク

Figure 5. A: Traverse two—all data. Power spectral plot of foreset bundle thicknesses measured along traverse two (see Fig. 3A). B: Traverse two—subordinates removed. Power spectral plots of dominant flood-tide foreset bundle thicknesses along traverse two (see Fig. 3B).

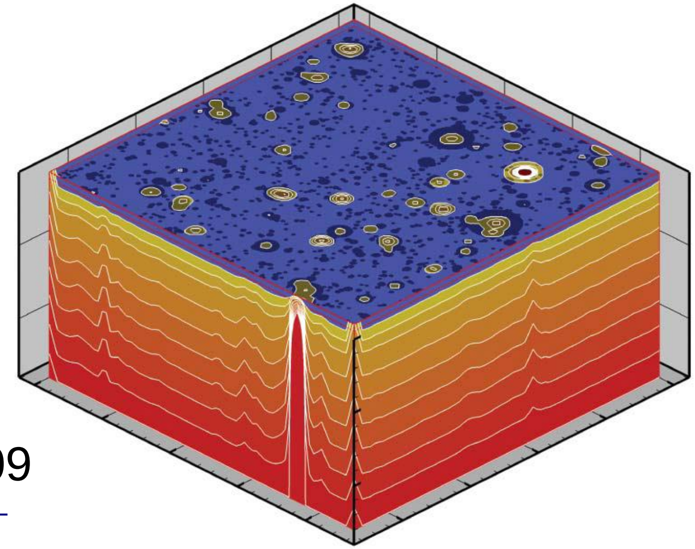
Eriksson 2000より

なぜ月があるのか？そして--

*月が地球の生命を育んだ？
“潮汐力のゆりかご”
*LHB以前に生命は生まれていた？
“殺菌”されていない初期地球？
*そもそも生命は宇宙から持ち込まれた！ “Panspermia仮説”
*そして夢は
“太陽系氷衛星” エウロパ
“太陽系外惑星”
へと果てしなく続く――――――



Lineweaver&Norman,2008



Abramov&Mojzsis,2009

クレータ年代学：その目標と今後

＊惑星表面の時代変遷を探る
＊太陽系の起源を探る
＊ひいてはわれわれ地球型生命の起源を探る
＊そして宇宙における生命の位置づけを探る
＊これらの仕事は，高校生の大きな動機となる！！
＊地味な統計にこそ，科学の手法の真髄？
＊一緒に始めませんか？

謝辞，参考文献

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ご清聴ありがとうございました.

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