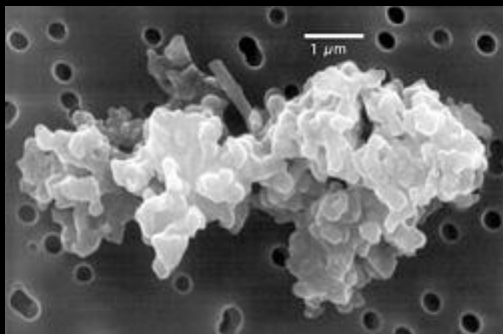
[redacted]

[6] 天体衝突イベント

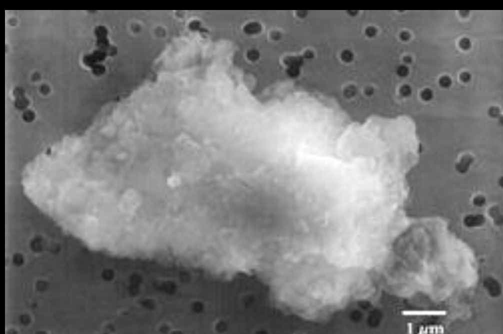
[redacted]

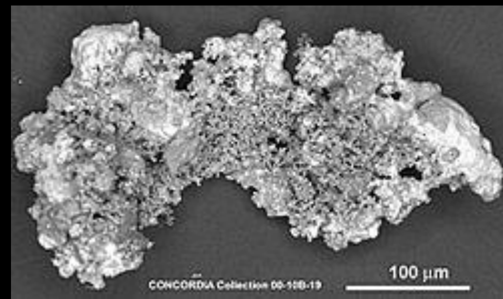
1. 天体衝突の普遍性

宇宙に開かれた地球

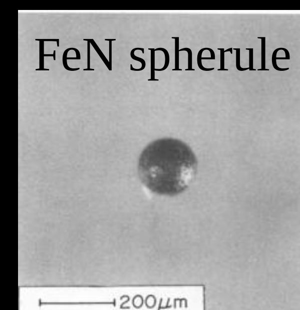


Interplanetary dust particle





Micrometeoroid



http://meteorite.weebly.com/meteorite-identification.htm

地球への衝突

ツングースカ大爆発

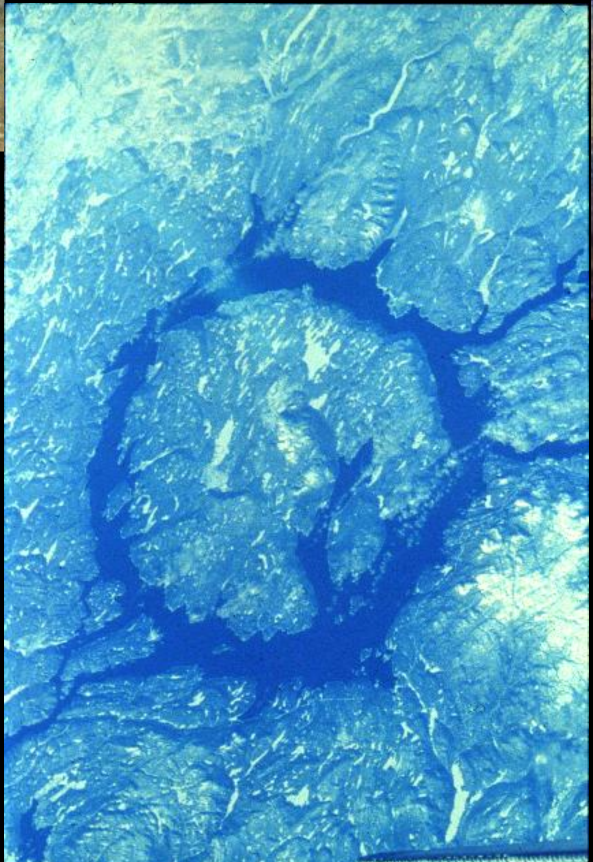
[http://ja.wikipedia.org/wiki]

1908年

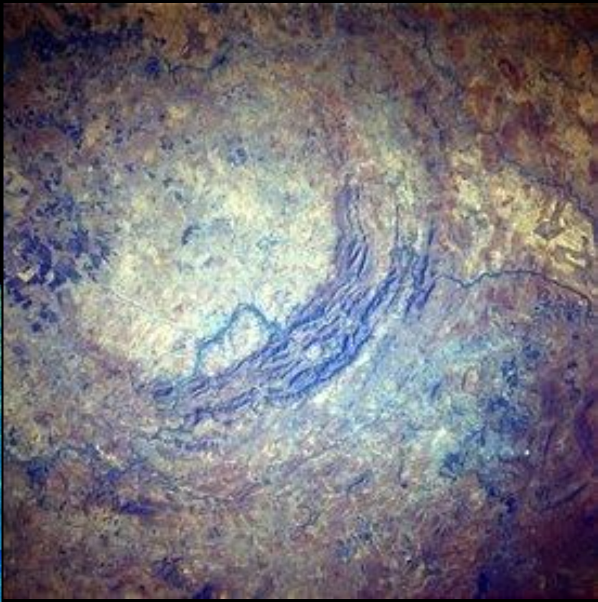
1972年

地球上の衝突クレーター

バリンジャー・クレーター
(メテオ・クレーター)
アメリカ合衆国
直径：1.2km
年代：5万年前
http://www.sandia.gov/geo/research.html



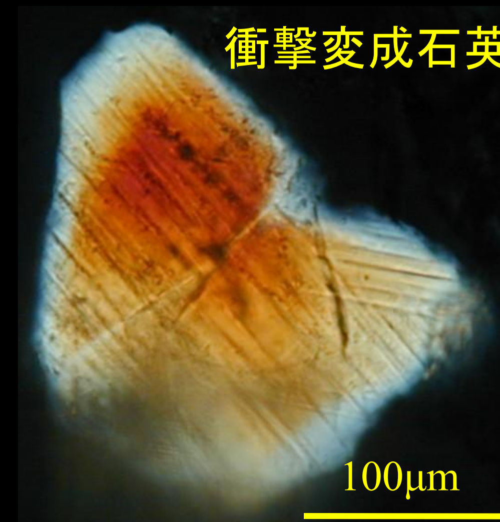
マニコーガン
カナダ
直径：100km
年代：2億1200万年前



フレデフォート
南アフリカ共和国
直径：190km
年代：20億2300万年前
http://lollofx.blogspot.com/2011/01/quais-sao-as-maiores-crateras-de.html

衝突の証拠

- 衝突クレーター
- 衝突起源物質・組織
  - シャッターコーン
  - 高圧鉱物
  - 衝撃変成鉱物 (PDFs)
  - テクタイト
- 地球外天体起源物質
  - 白金属元素の濃集
  - など

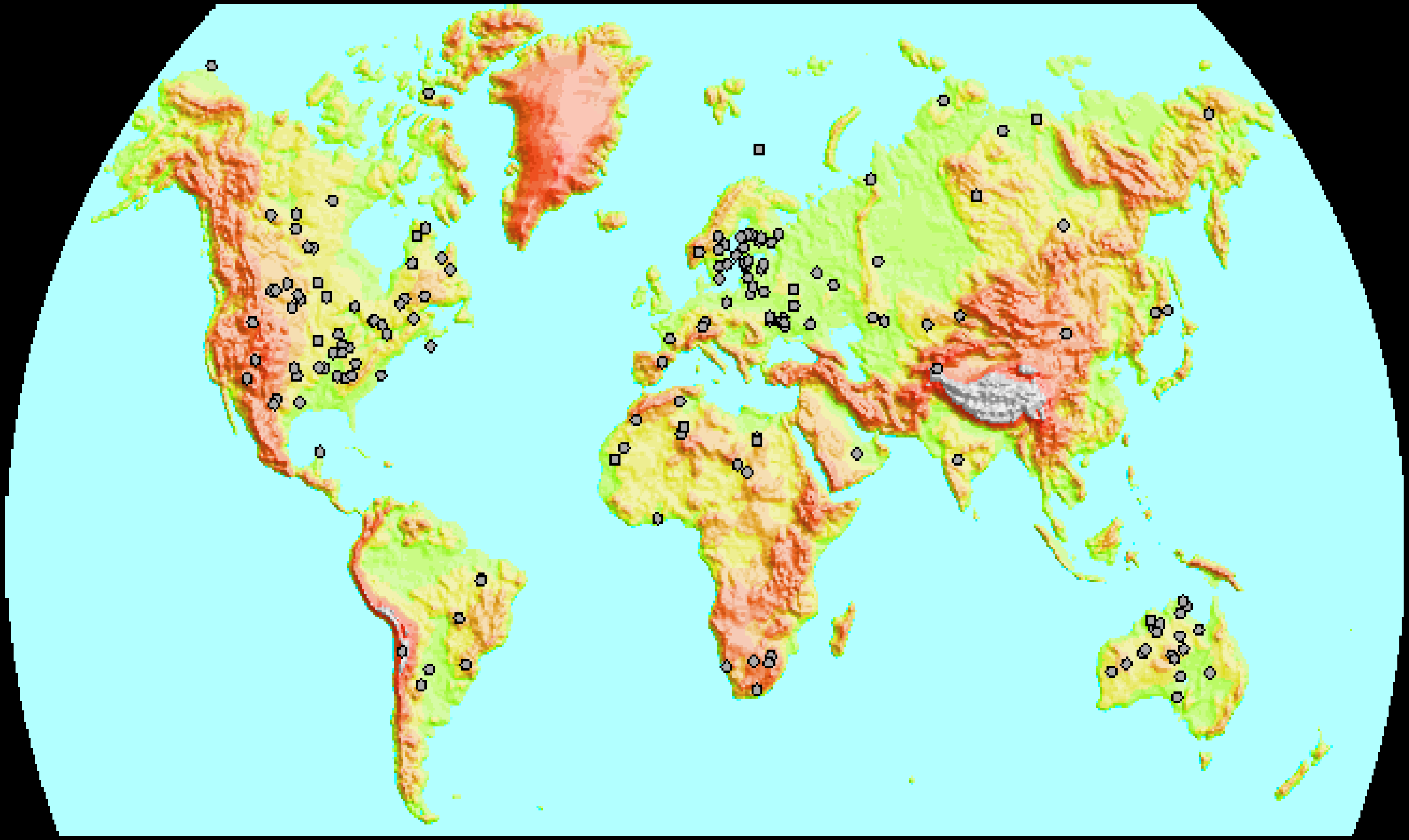


http://www.geocities.jp/tjboundary/research/impact/re1.htm

テクタイト

スフェルール

地球上の衝突クレーター分布

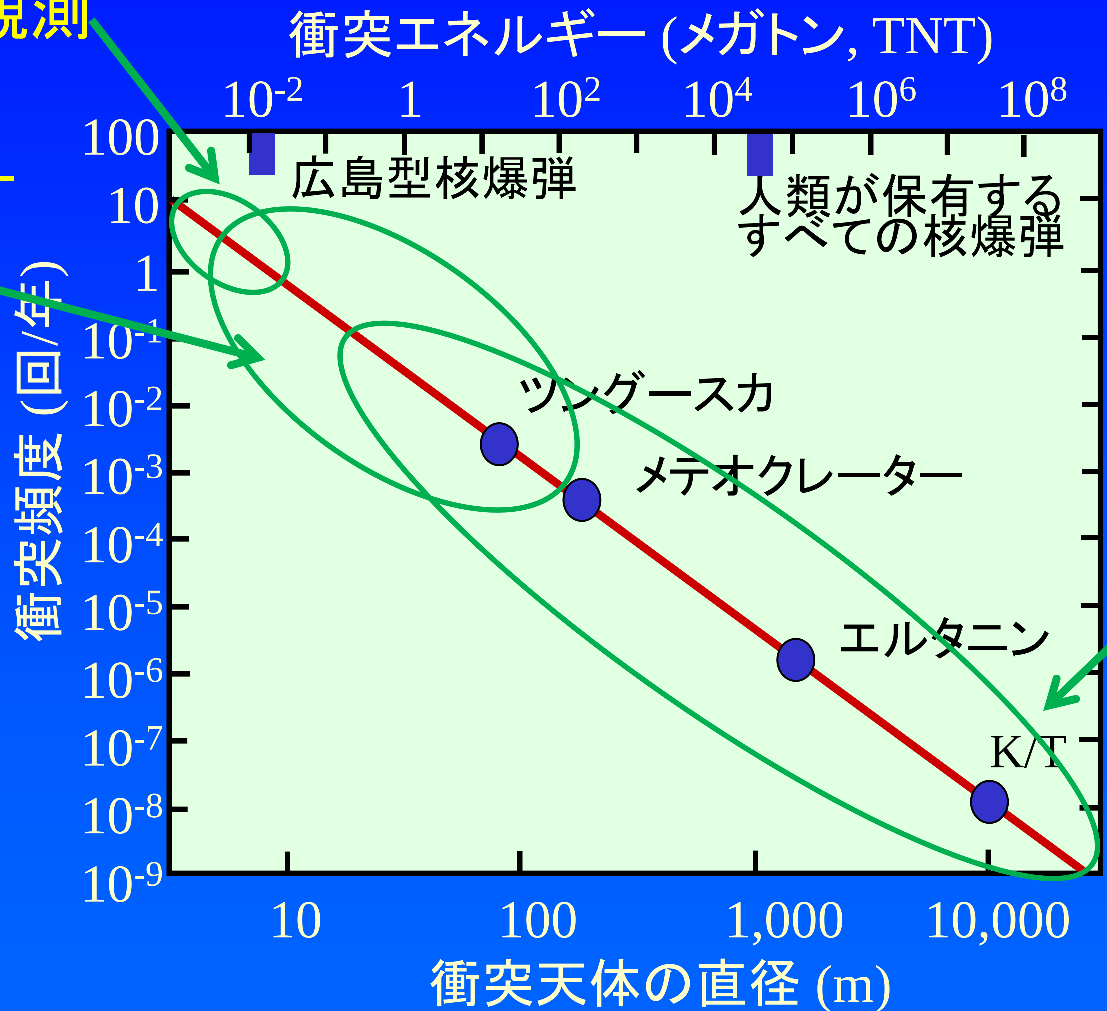


[http://gdcinfo.agg.nrcan.gc.ca/crater/world_craters_e.html]

衝突頻度

大気圏
レーダー観測

NEOs観測＋
数値計算
衛星観測

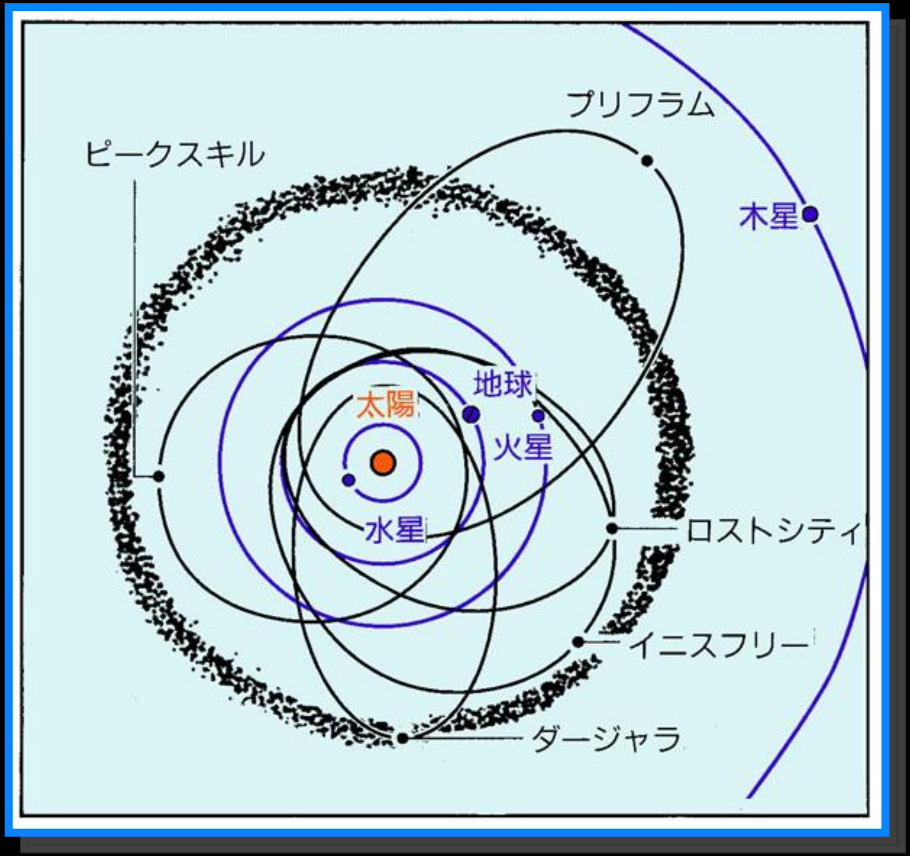


月のクレーター
統計

＊広島型爆弾級の衝突エネルギー(15±3 キロトン)を持つ天体が年間数回大気圏に突入!

[Based on Spacewatch, Shoemaker (1990), Chapman and Morrison (1994)]

隕石と小惑星

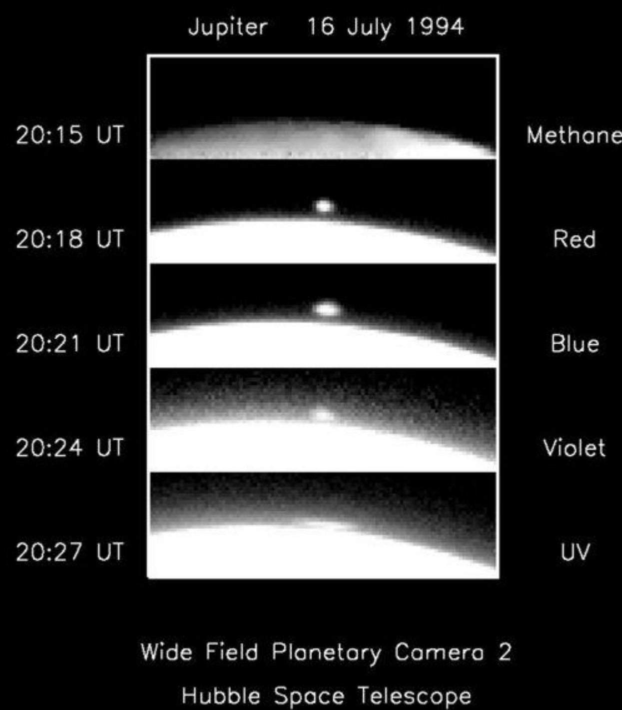


Peekskill 隕石 (1992/10/9落下)
12.4kg H6 monomict breccia

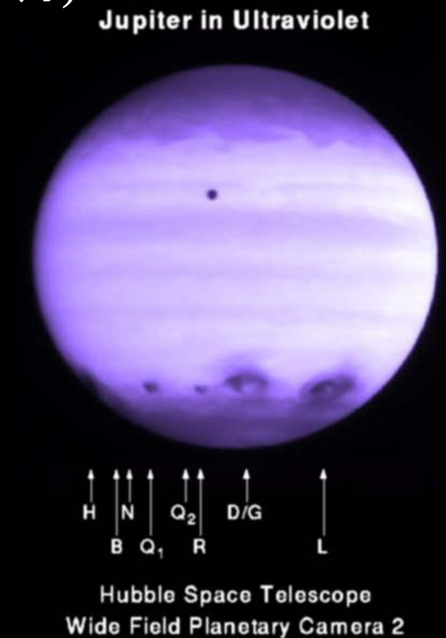
隕石のもとの軌道
→小惑星帯から飛来

衝突現象の“観測”

Shoemaker-Levy 9 の木星への衝突 (1994年7月)



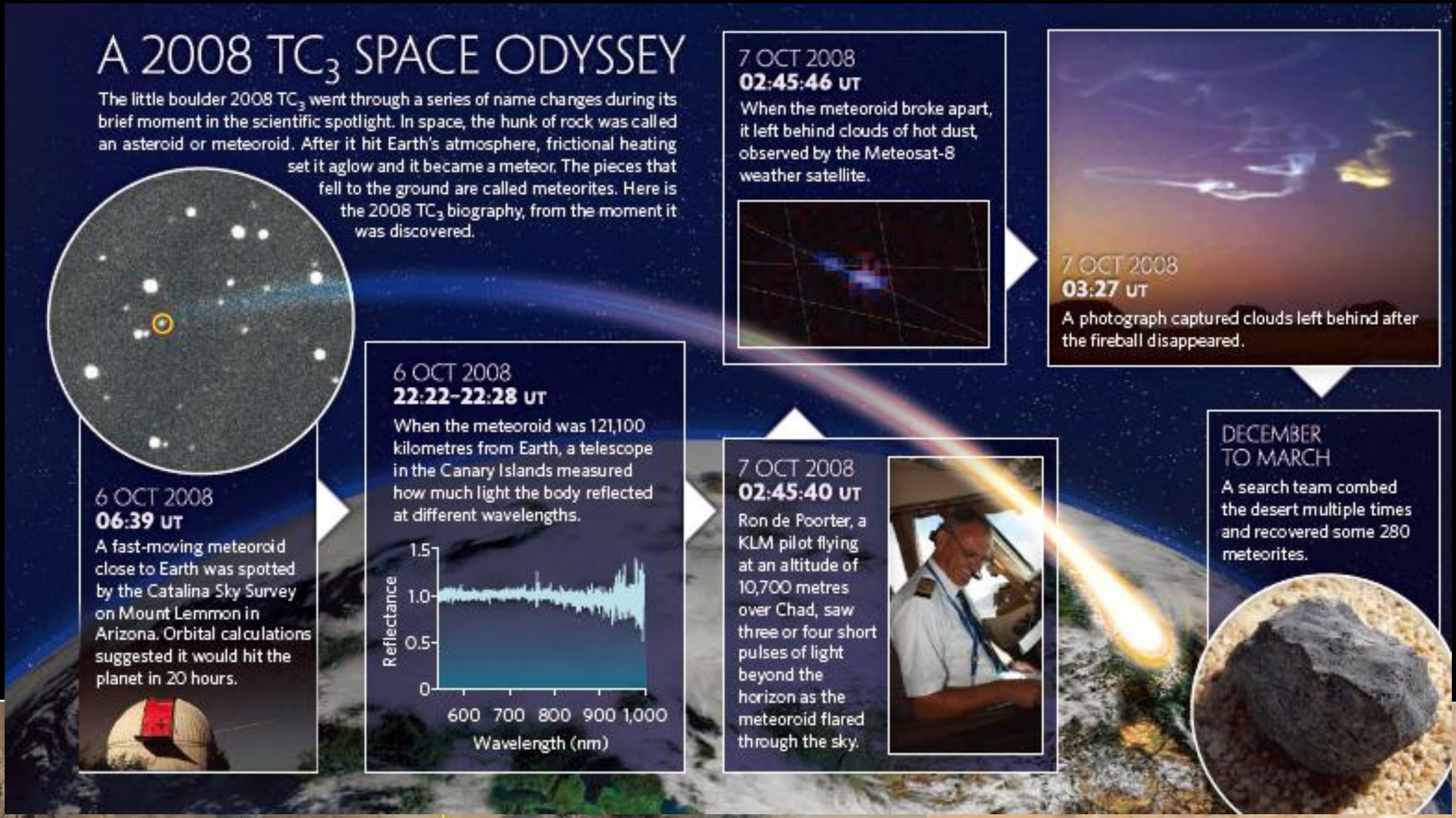
http://hubblesite.org/newscenter/archive/releases/1994/30/image/a/



http://www2.jpl.nasa.gov/sl9/image129.html

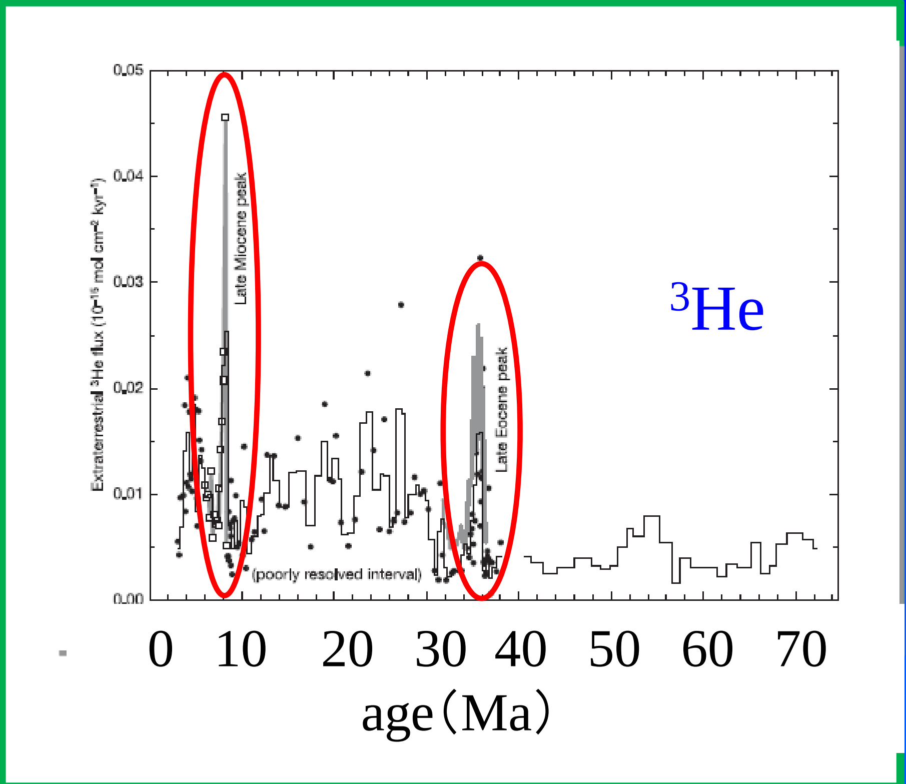
地球へ衝突する小惑星の発見

2008 TC_3の落下 (2008年10月7日)

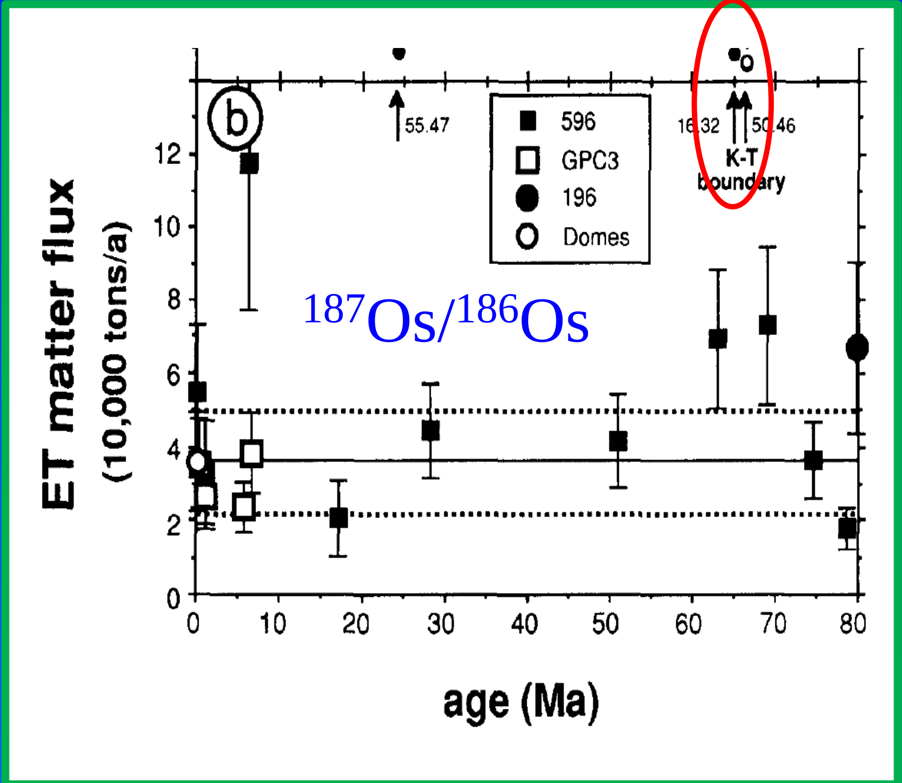


回収 3.95kg
>280個
ユレイライト

集積フラックスの時代変化



[Farley et al., 2006]



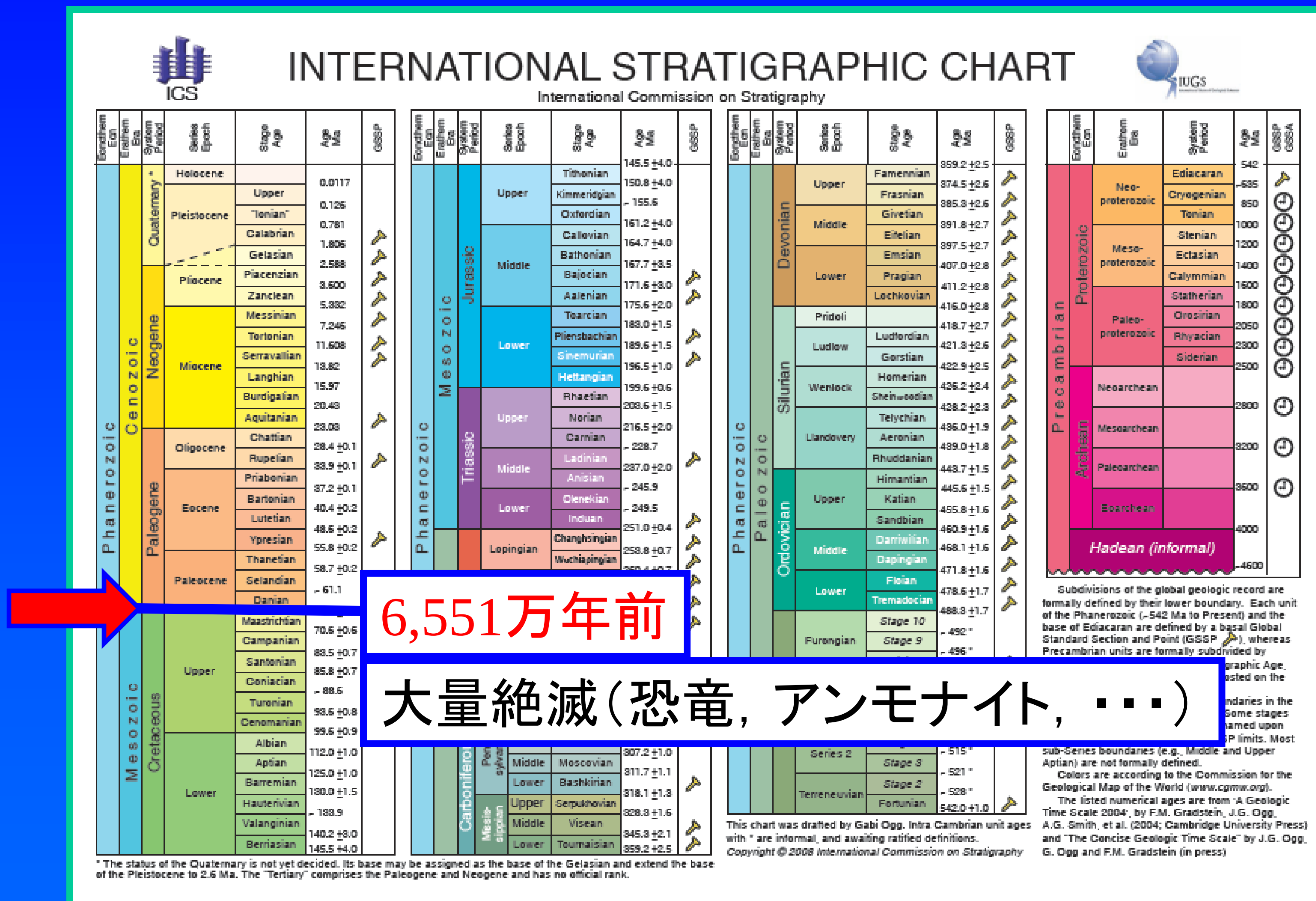
[Peucker-Ehrenbrink, 1996]

フラックスの増加 → 天体衝突イベント

→ 太陽系内における大衝突イベントの記録！

2. K/T境界における衝突

白亜紀/第三紀(K/T)境界とは



K/T (Cretaceous/Tertiary) → K/Pg (Cretaceous/Paleogene)

http://www.stratigraphy.org/upload/ISChart2009.pdf

K/T境界粘土 (boundary clay)層

Gubbio, Italy

Stevns Klint, Denmark

天体衝突の証拠 (1)

6 June 1980, Volume 208, Number 4448

SCIENCE

Extraterrestrial Cause for the Cretaceous-Tertiary Extinction

Experimental results and theoretical interpretation

Luis W. Alvarez, Walter Alvarez, Frank Asaro, Helen V. Michel

Summary. Platinum metals are depleted in the earth's crust relative to their cosmic abundance; concentrations of these elements in deep-sea sediments may thus indicate influxes of extraterrestrial material. Deep-sea limestones exposed in Italy, Denmark, and New Zealand show iridium increases of about 30, 160, and 20 times, respectively, above the background level at precisely the time of the Cretaceous-Tertiary extinctions, 65 million years ago. Reasons are given to indicate that this iridium is of extraterrestrial origin, but did not come from a nearby supernova. A hypothesis is suggested which accounts for the extinctions and the iridium observations. Impact of a large earth-crossing asteroid would inject about 60 times the object's mass into the atmosphere as pulverized rock; a fraction of this dust would stay in the stratosphere for several years and be distributed worldwide. The resulting darkness would suppress photosynthesis, and the expected biological consequences match quite closely the extinctions observed in the paleontological record. One prediction of this hypothesis has been verified: the chemical composition of the boundary clay, which is thought to come from the stratospheric dust, is markedly different from that of clay mixed with the Cretaceous and Tertiary limestones, which are chemically similar to each other. Four different independent estimates of the diameter of the asteroid give values that lie in the range 10 ± 4 kilometers.

In the 570-million-year period for which abundant fossil remains are available, there have been five great biological crises, during which many groups of organisms died out. The most recent of the great extinctions is used to define the boundary between the Cretaceous and Tertiary periods, about 65 million years ago. At this time, the marine reptiles, the flying reptiles, and both orders of dinosaurs died out (*1*), and extinctions occurred at various taxonomic levels among the marine invertebrates. Dramatic extinctions occurred among the microscopic floating animals and plants; both the calcareous planktonic foraminifera and the calcareous nannoplankton were nearly exterminated, with only a few species surviving the crisis. On the other hand, some groups were little affected, including the land plants, crocodiles, snakes, mammals, and many kinds of invertebrates. Russell (*2*) concludes that about half of the genera living at that time perished during the extinction event.

Many hypotheses have been proposed to explain the Cretaceous-Tertiary (C-T) extinctions (*3, 4*), and two recent meetings on the topic (*5, 6*) produced no sign of a consensus. Suggested causes include gradual or rapid changes in oceanographic, atmospheric, or climatic conditions (*7*) due to a random (*8*) or a cyclical (*9*) coincidence of causative factors; a magnetic reversal (*10*); a nearby supernova (*11*); and the flooding of the ocean surface by fresh water from a postulated arctic lake (*12*).

A major obstacle to determining the cause of the extinction is that virtually all the available information on events at the time of the crisis deals with biological changes seen in the paleontological record and is therefore inherently indirect. Little physical evidence is available, and it also is indirect. This includes variations in stable oxygen and carbon isotopic ratios across the boundary in pelagic sediments, which may reflect changes in temperature, salinity, oxygenation, and organic productivity of the ocean water, and which are not easy to interpret (*13, 14*). These isotopic changes are not particularly striking and, taken by themselves, would not suggest a dramatic crisis. Small changes in minor and trace element levels at the C-T boundary have been noted from limestone sections in Denmark and Italy (*15*), but these data also present interpretational difficulties. It is noteworthy that in pelagic marine sequences, where nearly continuous deposition is to be expected, the C-T boundary is commonly marked by a hiatus (*3, 16*).

In this article we present direct physical evidence for an unusual event at exactly the time of the extinctions in the planktonic realm. None of the current hypotheses adequately accounts for this evidence, but we have developed a hypothesis that appears to offer a satisfactory explanation for nearly all the available paleontological and physical evidence.

Luis Alvarez is professor emeritus of physics at Lawrence Berkeley Laboratory, University of California, Berkeley 94720. Walter Alvarez is an associate professor in the Department of Geology and Geophysics, University of California, Berkeley. Frank Asaro is a senior scientist and Helen Michel is a staff scientist in the Energy and Environment Division of Lawrence Berkeley Laboratory.

0036-8075/80/0606-1095$02.00/0

■白金属元素の異常濃集

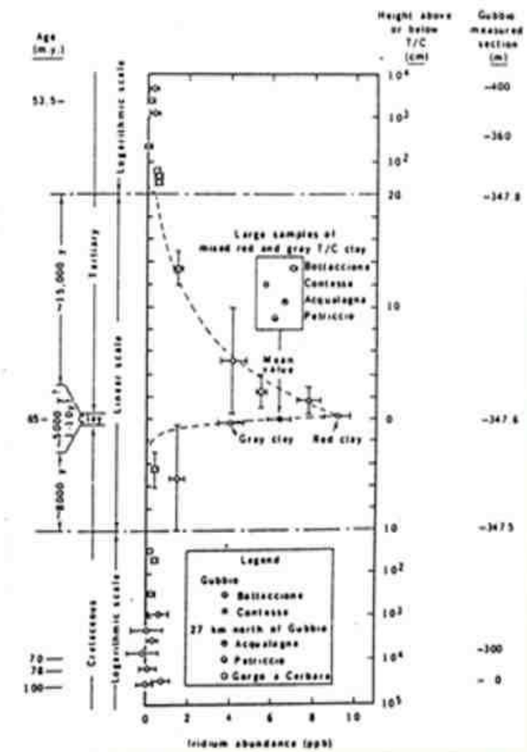
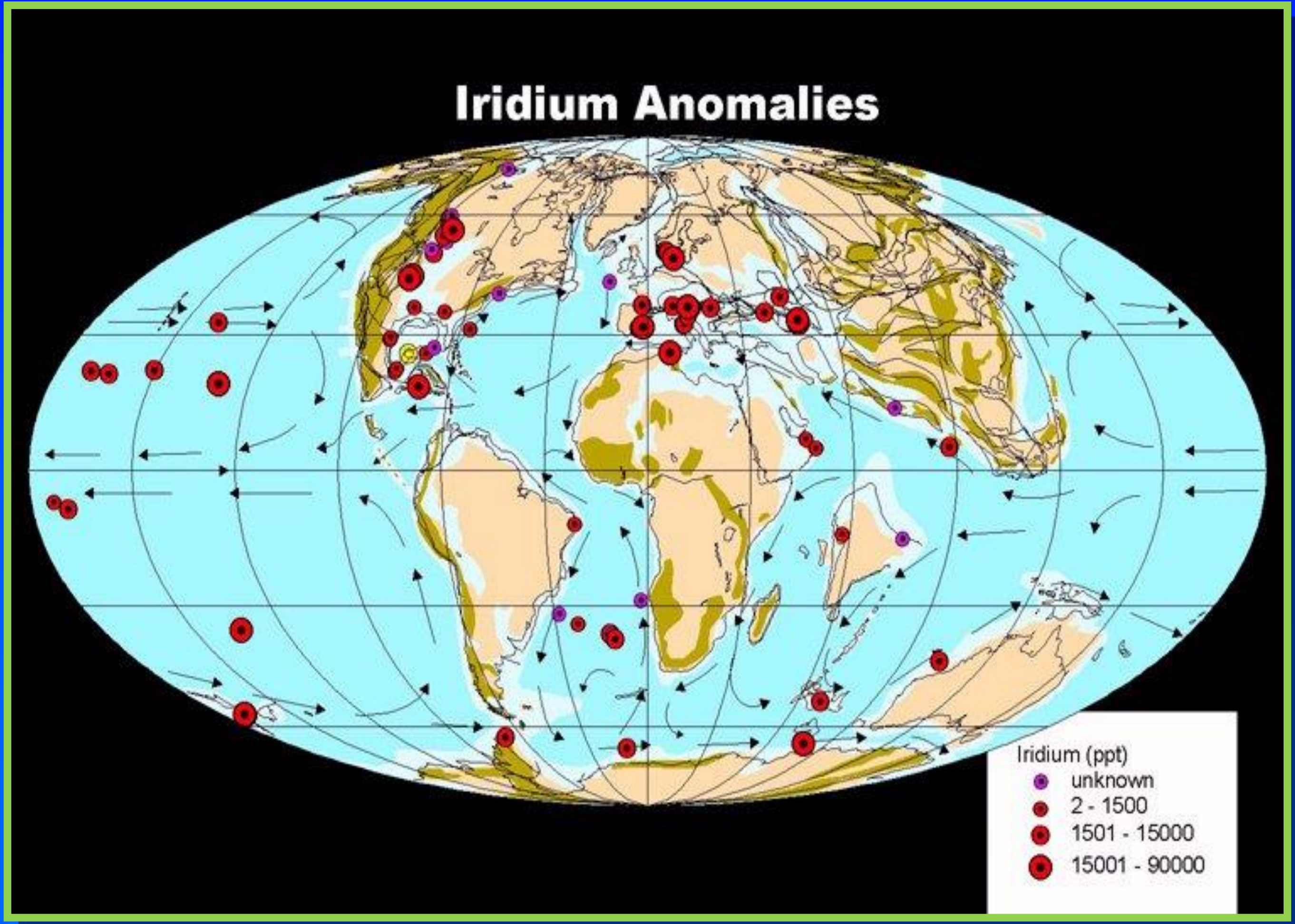


Fig. 5. Iridium abundances per unit weight of 2N HNO_3 acid-insoluble residues from Italian limestones near the Tertiary - Cretaceous boundary. Error bars on abundances are the standard deviations in counting radioactivity. Error bars on stratigraphic position indicate the stratigraphic thickness of the sample. The dashed line above the boundary is an "eyeball fit" exponential with a half-height of 4.6 cm. The dashed line below the boundary is a best fit exponential (two points) with a half-height of 0.43 cm. The filled circle and error bar are the mean and standard deviation of Ir abundances in four large samples of boundary clay from different locations.

[Alvarez et al., 1980]

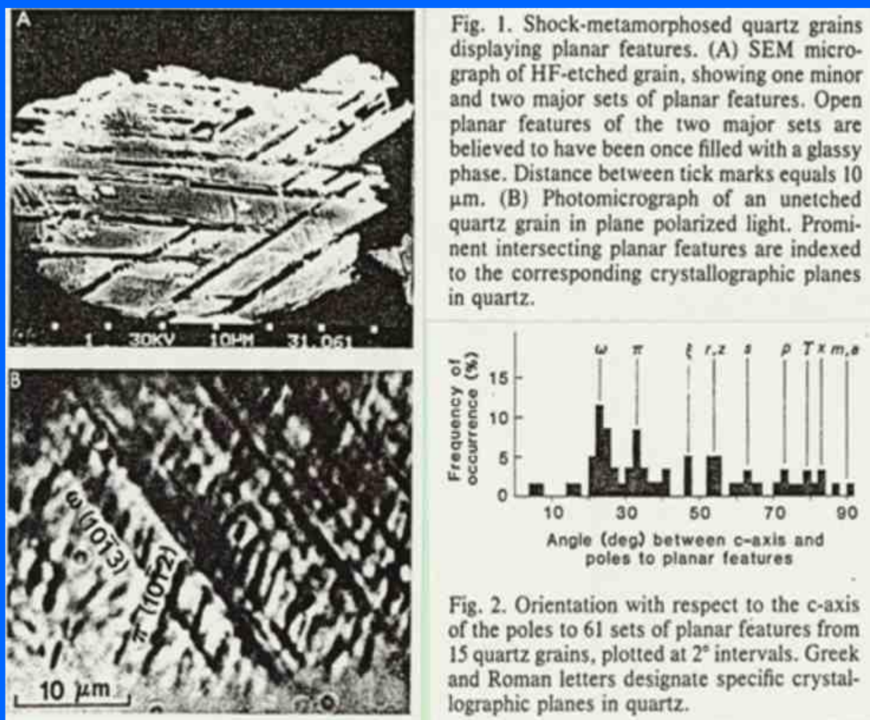
天体衝突の証拠 (1)

■イリジウム異常濃集



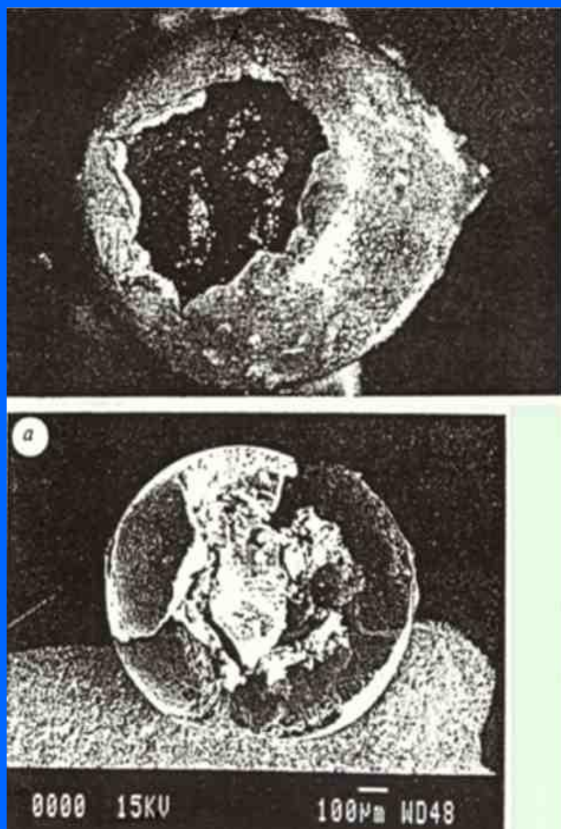
天体衝突の証拠 (2)

■ 衝撃変成石英



Montana, USA [Bohor et al., 1984]

■ スフェルール

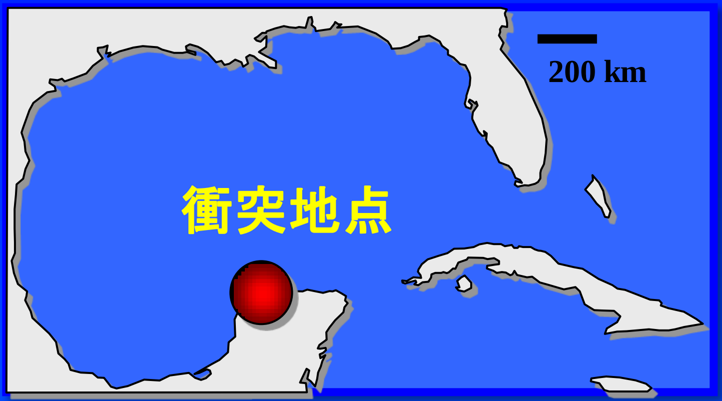


Beloc, Haitti [Sigurdsson et al., 1991]

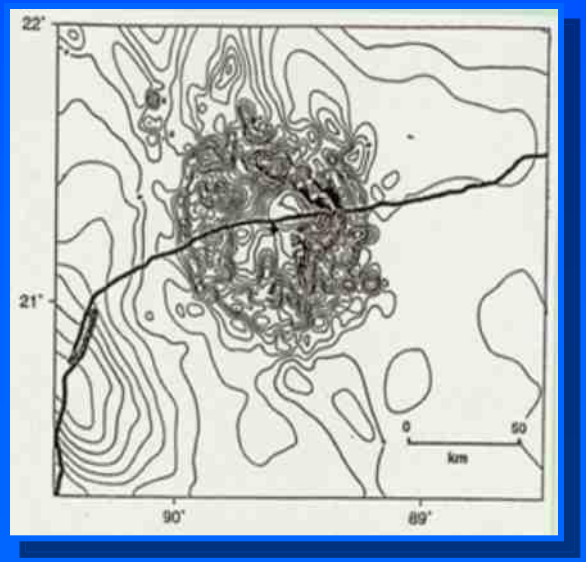
天体衝突の証拠 (3)

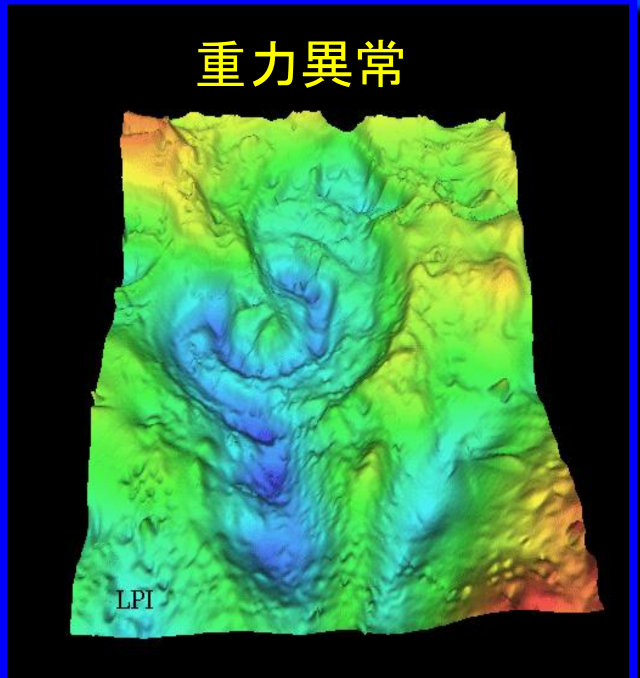
■ 衝突クレーターの発見　[Hildebrand et al. (1991) Geology]
(The Chicxulub Crater)

場所 : メキシコ，ユカタン半島北東部
(21°20’N, 89°30’W)
年代 : 6,551万年前
直径 : D = 195 km　[Gulick et al., 2008]



地磁気異常





天体衝突の証拠 (4)

■ 衝突天体の破片の発見 [Kyte (1998) Nature]
DSDP Hole 576 (328 21.49 N, 1648 16.59 E) 衝突地点からの距離9,000km
炭素質コンドライト

CV, CO, or CR type [Kyte, 1998] CM2 type [Bottke et al., 2007]

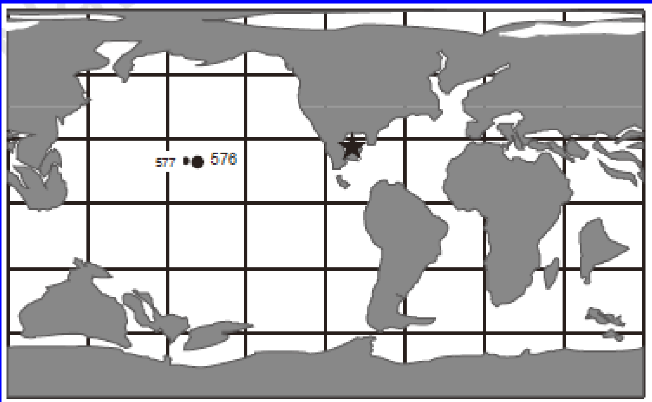


Figure 1 Palaeoreconstruction map. Shown are the locations of DSDP sites 576 and 577 (filled circles) and the Chicxulub impact structure (star) at the time of the K/T boundary impact (65 Myr ago).

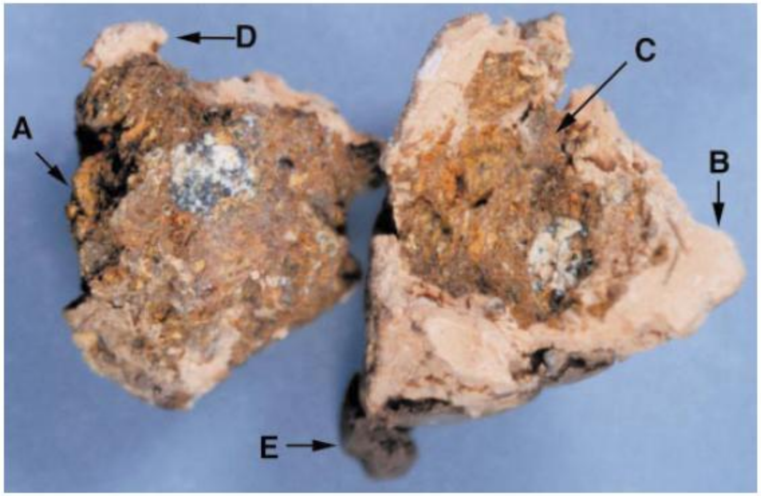


Figure 2 Photograph of separated meteorite and surrounding clays. A fossil meteorite (A) was found encased in light-brown clays (B). Portions of the meteorite still line the interior cavity of the light-brown clays (C), and the white spot in the cavity is a portion of the black and white inclusion at the centre of the meteorite surface. We note that some light-brown clays remain on the surface of the meteorite (D). Typical sediments from the K/T boundary at DSDP Site 576 are dark brown. Small pieces of dark-brown clay (E) can be seen on the bottom of the piece of light brown rim. Largest dimension of the meteorite is 2.5 mm.

＊小惑星Baptistinaが160My前の
衝突イベントで破壊された破片?
[Bottke et al. (2007) Nature]

衝突の冬仮説

■“衝突の冬”（impact winter）

衝突によって巻き上げられた塵が日射を遮ることによって，光合成活動が停止し，食物連鎖によって多くの生物種が絶滅した （恐竜が絶滅した原因）

＊ 核実験の観測によると，地面から巻き上げられたダストの他，蒸発または熔融した物質が凝結することによってもダストが生成される

＊サイズの大きな粒子はすみやかに大気から除去される

＊ サブミクロンサイズの粒子が長期間(半年～数年)にわたって大気中にとどまり，日射をさえぎる

→ 数ヶ月程度で雨で洗い流されると考えられるようになった

短期間過ぎる？ エアロゾル？

K/T境界における大量絶滅

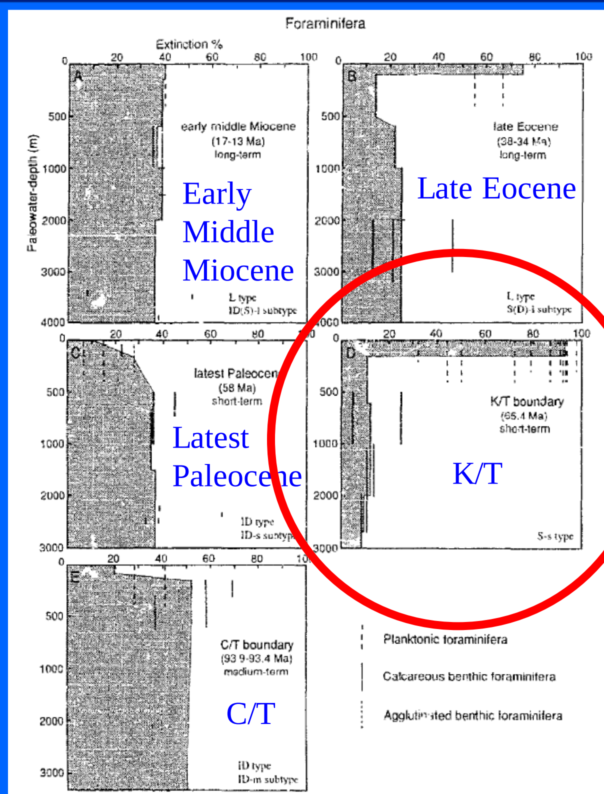
- 絶滅の規模 (科のレベルで20%, 属のレベルで50%)

  e.g., P/T境界の場合：科のレベルで50%, 属のレベルで83%, 種のレベルで96%

- 絶滅のパターン：海洋表層水型

  表層水に生息する浮遊性有孔虫の大部分(>90%)が絶滅

  中・深層水に生息する底生有孔虫はあまり絶滅していない

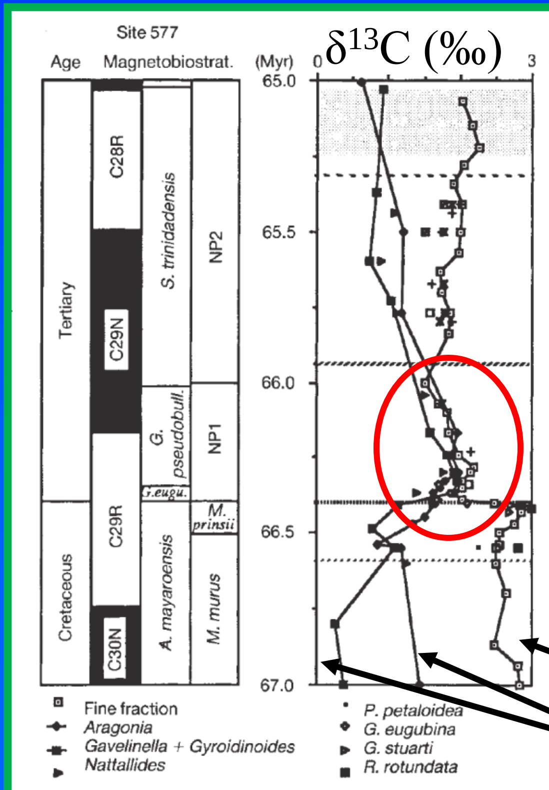


→ 衝突の冬仮説(光合成生物を一次生産者とする食物連鎖の崩壊で大量絶滅が生じたとする考え)と整合的

[Kaiho, 1994]

K/T境界における炭素同位体比変動

- 表層水と深層水の炭素同位体比が収束する
  → 海洋における炭素同位体比の鉛直分布が変化
- 底生有孔虫の炭素同位体比も収束
  → 有機物の埋没が減少し，間隙水中の炭素同位体比が底層水と一致
- 炭酸塩鉱物の沈澱フラックスが減少 (保存状態は良いので溶解ではない)



回復初期

～50万年間

K/T境界

浮遊性有孔虫（表層水）

底生有孔虫(深層水)

[Zachos et al., 1989]

“ストレンジラヴ･オーシャン”

■ 生物生産の停止

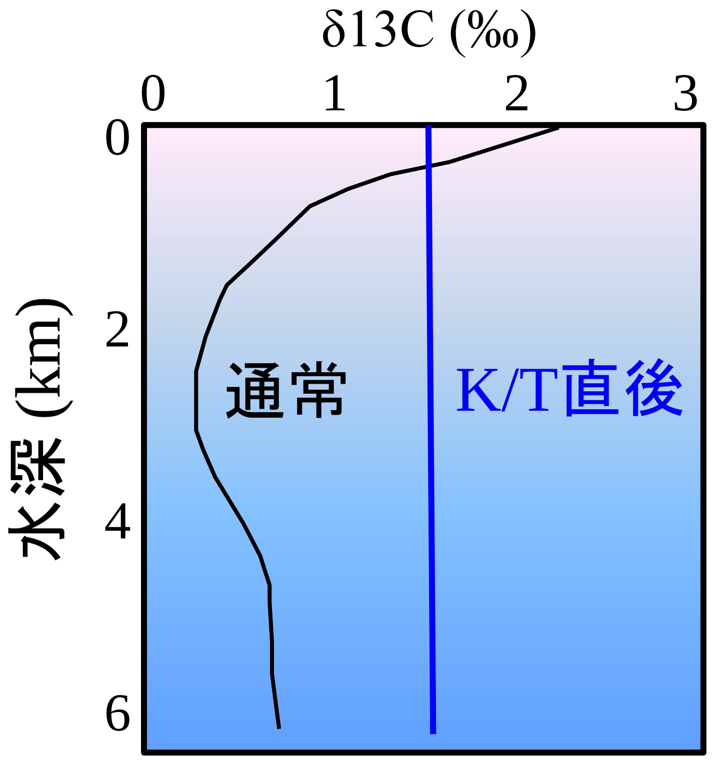
- 生物ポンプの停止によって，表層水と深層水の間での炭素同位体比の勾配は消失するはず [Broecker and Peng, 1982]

↓

K/T境界における炭素同位体比の挙動は，大量絶滅による生物生産 (光合成活動)の停止を意味するのではないか

[Hsu and McKenzie, 1985]

“ストレンジラヴ･オーシャン”
（*Strangelove Ocean*）



K/T直後も生物生産は続いていた?

- ■ もし完全に生物活動が停止したら，海洋の炭素同位体比は河川水や火山ガスとして流入する炭素の同位体比(～- 5‰)に漸近するはず
  ＊そうなっていないのは，生物活動が継続していたから?
- ■ 外洋域では有機物の埋没がほぼ完全に消滅したが，浅海域では白亜期末と同程度の生物活動があったとすれば，炭素同位体比の勾配がなくなったことと，海水の炭素同位体比の平均値が高いことを説明できる

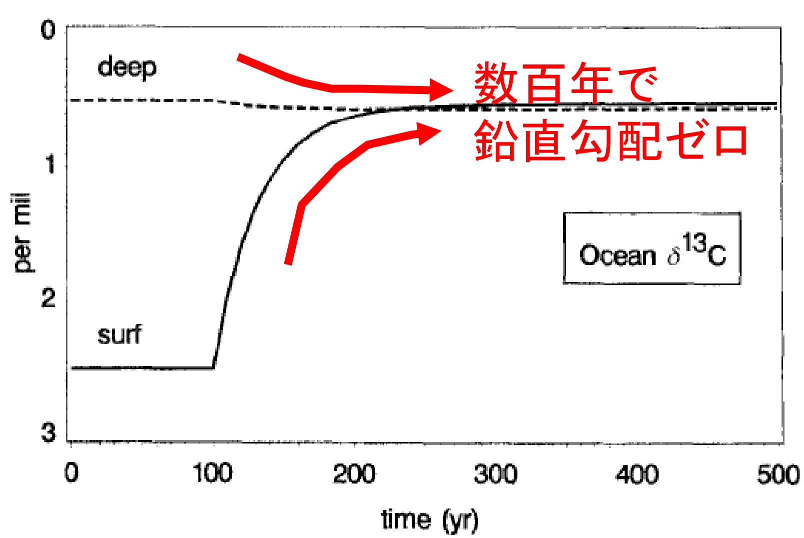


Figure 3. Short-term response of oceanic carbon-isotope system to instantaneous loss of net production and thus of flux of organic carbon to deep ocean.

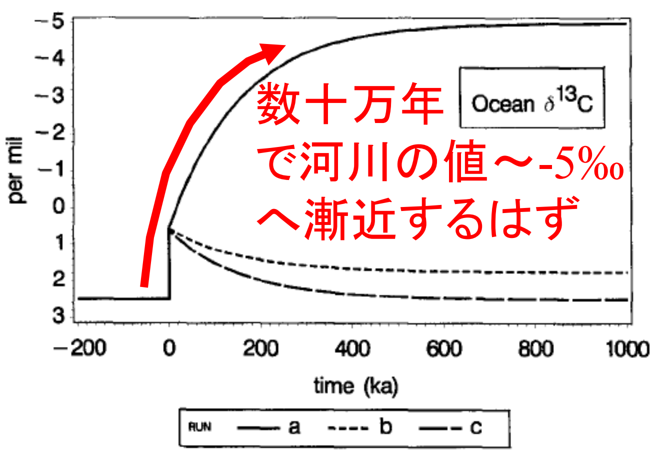


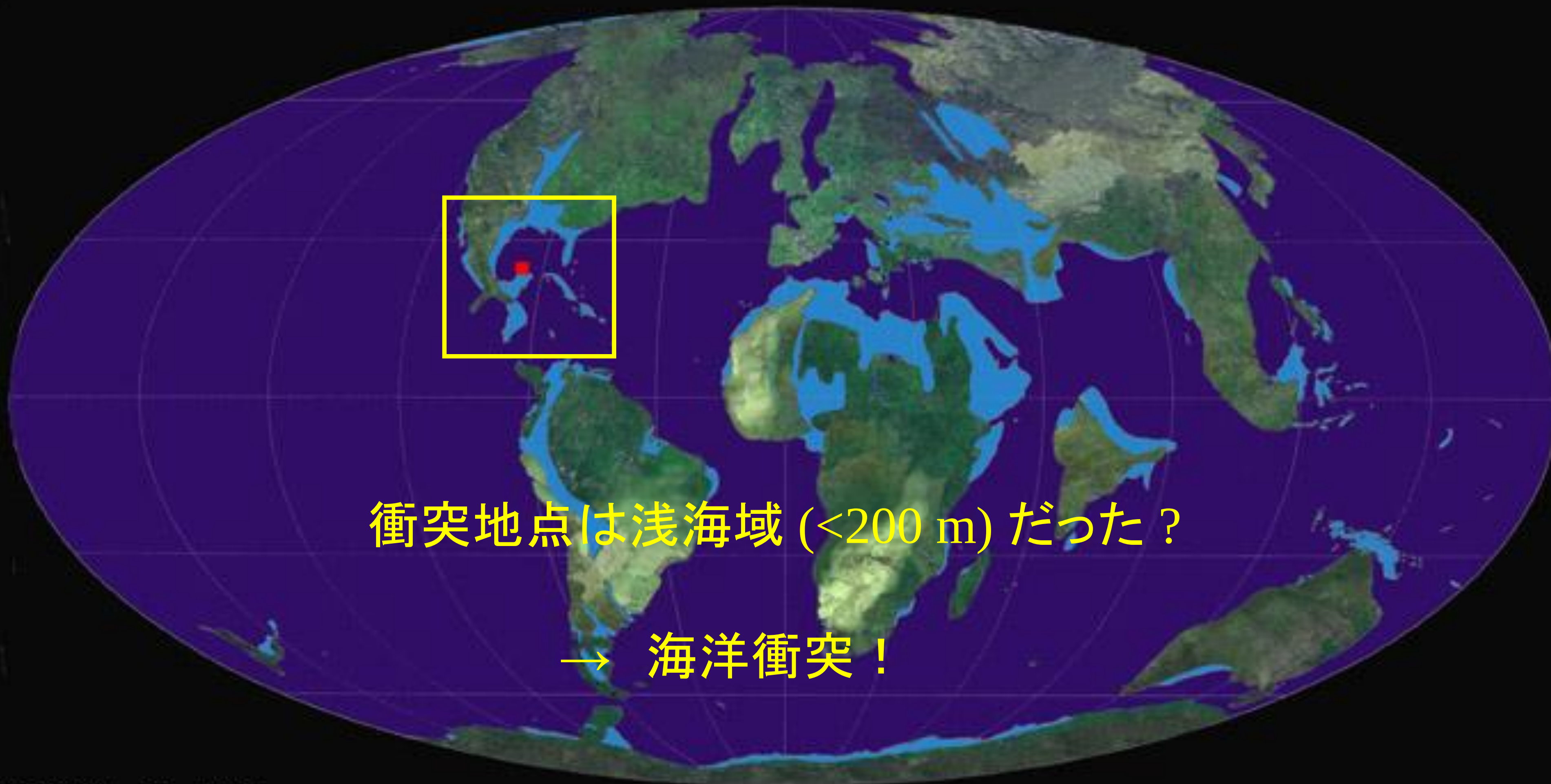
Figure 4. Long-term response of surface-ocean isotope composition to same perturbation as in Figure 3. Run a: organic carbon burial rate (F_b^o) = 0. Run b: F_b^o = 0.9 of Cretaceous steady-state value. Run c: F_b^o = Cretaceous steady-state value. Note that after time zero, these curves also reflect isotopic composition of deep ocean (i.e., ocean becomes isotopically homogeneous).

←
実際は
そうなって
いない！

[Kump, 1991]

3. チチュルブ衝突

海洋衝突



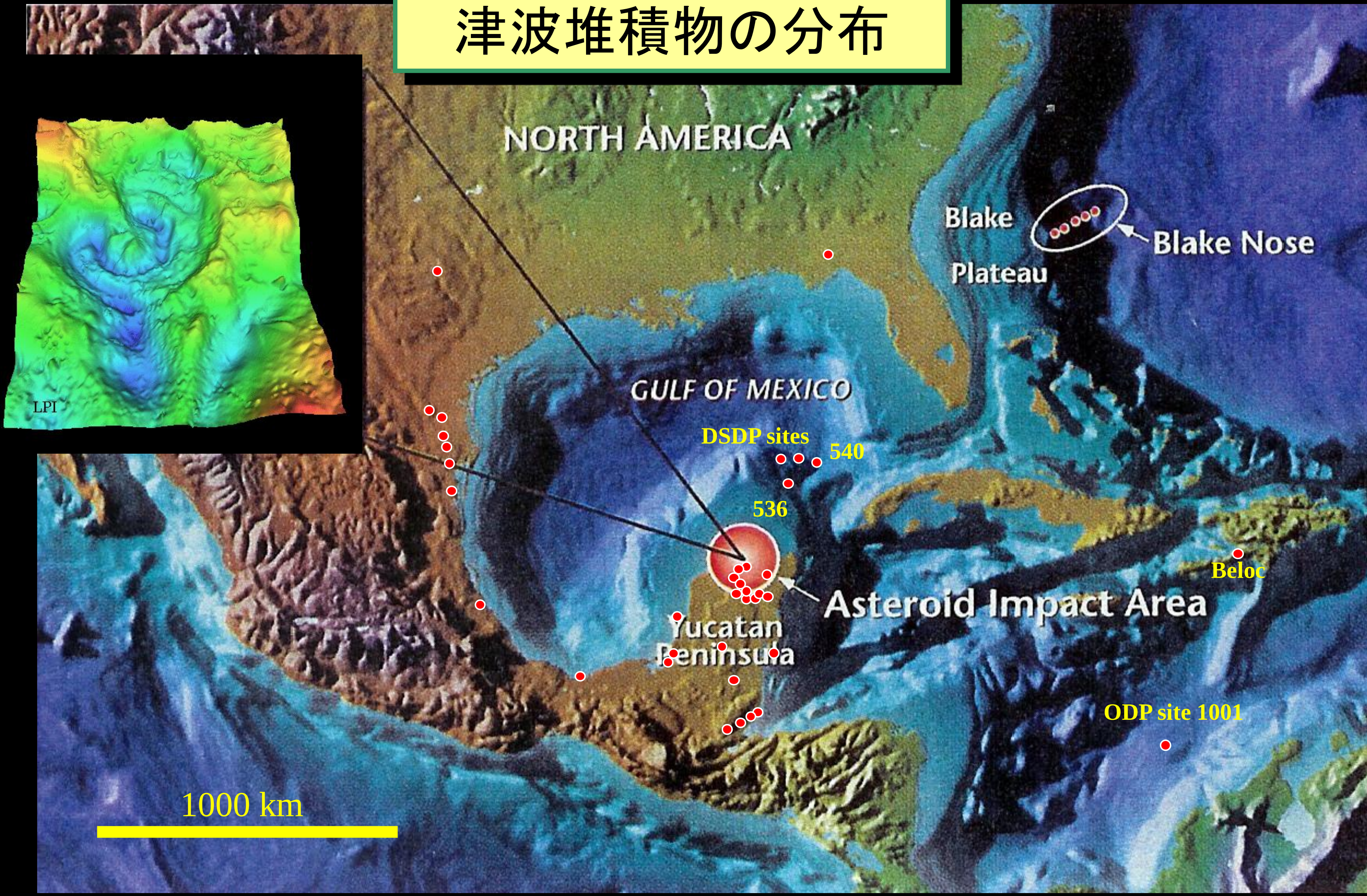
衝突地点は浅海域 (<200 m) だった？

→ 海洋衝突！

Paleogeographic map at 65 Ma

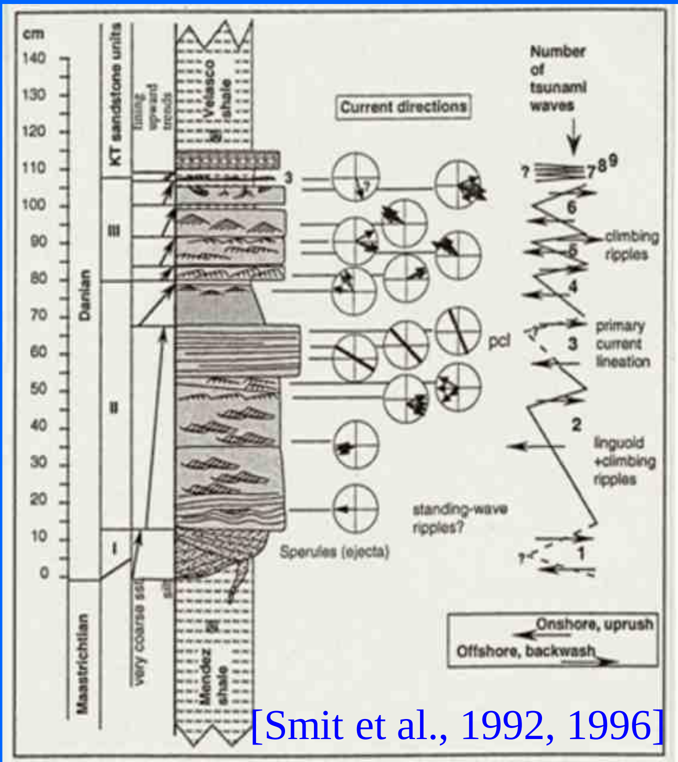
→ 衝突によって津波が発生した可能性

津波堆積物の分布



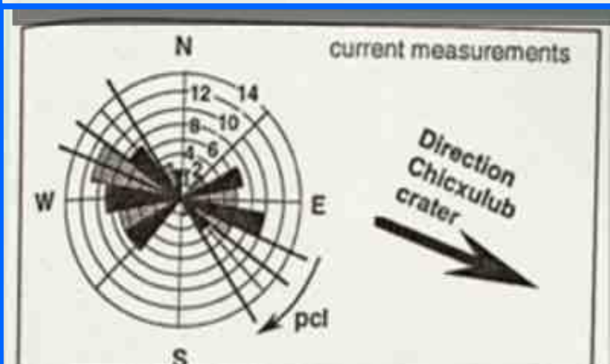
Norris et al. (1997)

メキシコ北東部にみられる津波堆積物

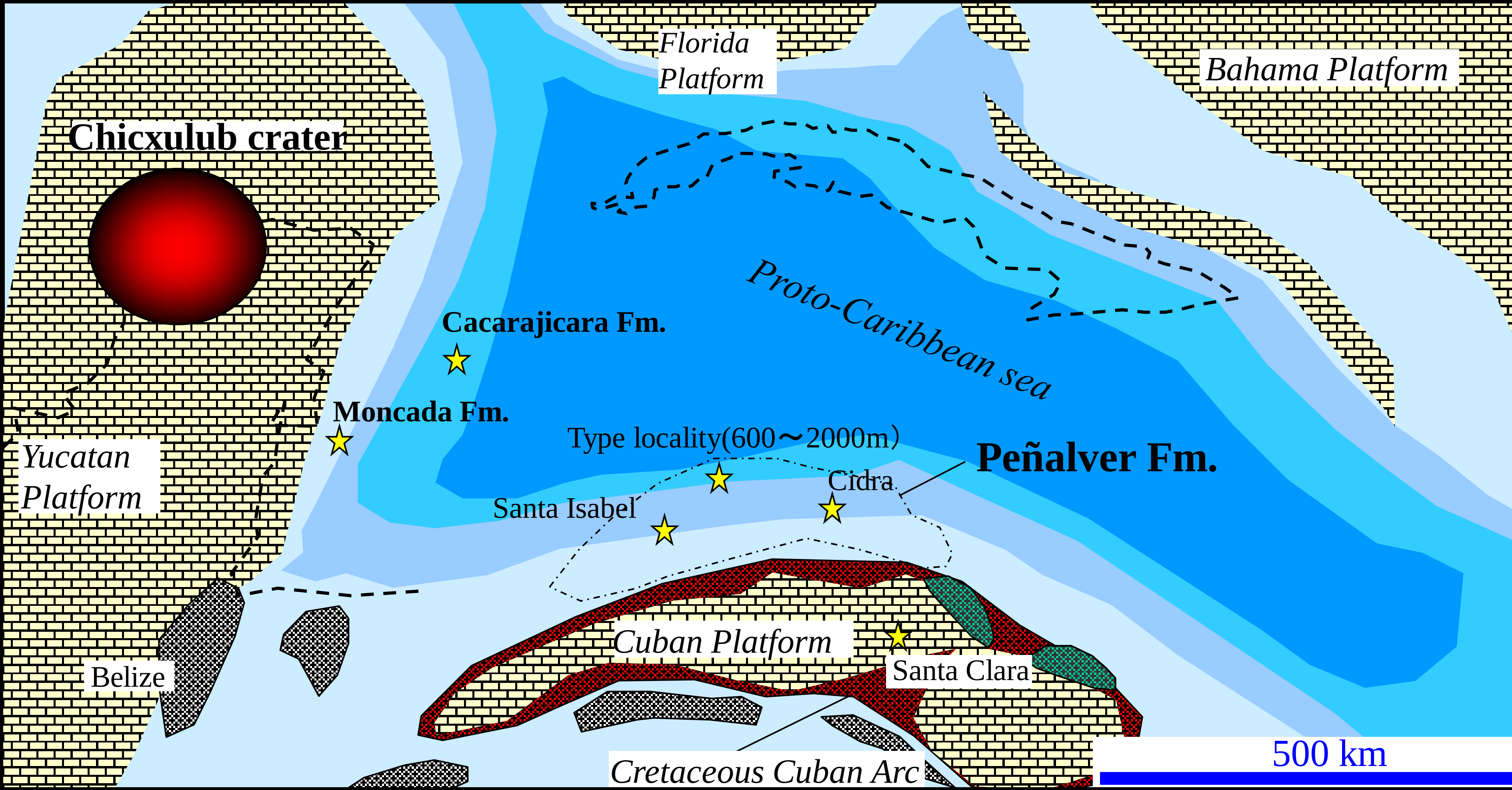


[Smit et al., 1992, 1996]

Figure 15. La Lajilla, Mexico. Stratigraphic column through the K/T sandstone complex at La Lajilla, Mexico. 40 km east of Ciudad Victoria. Measured paleocurrent directions are plotted next to the stratigraphic level. At right the total number of current reversals is indicated, inferred to indicate the number of passages of tsunami waves. Pcl = primary current lineation.



6,500万年前の古地理復元



層厚200メートルのK/T境界層

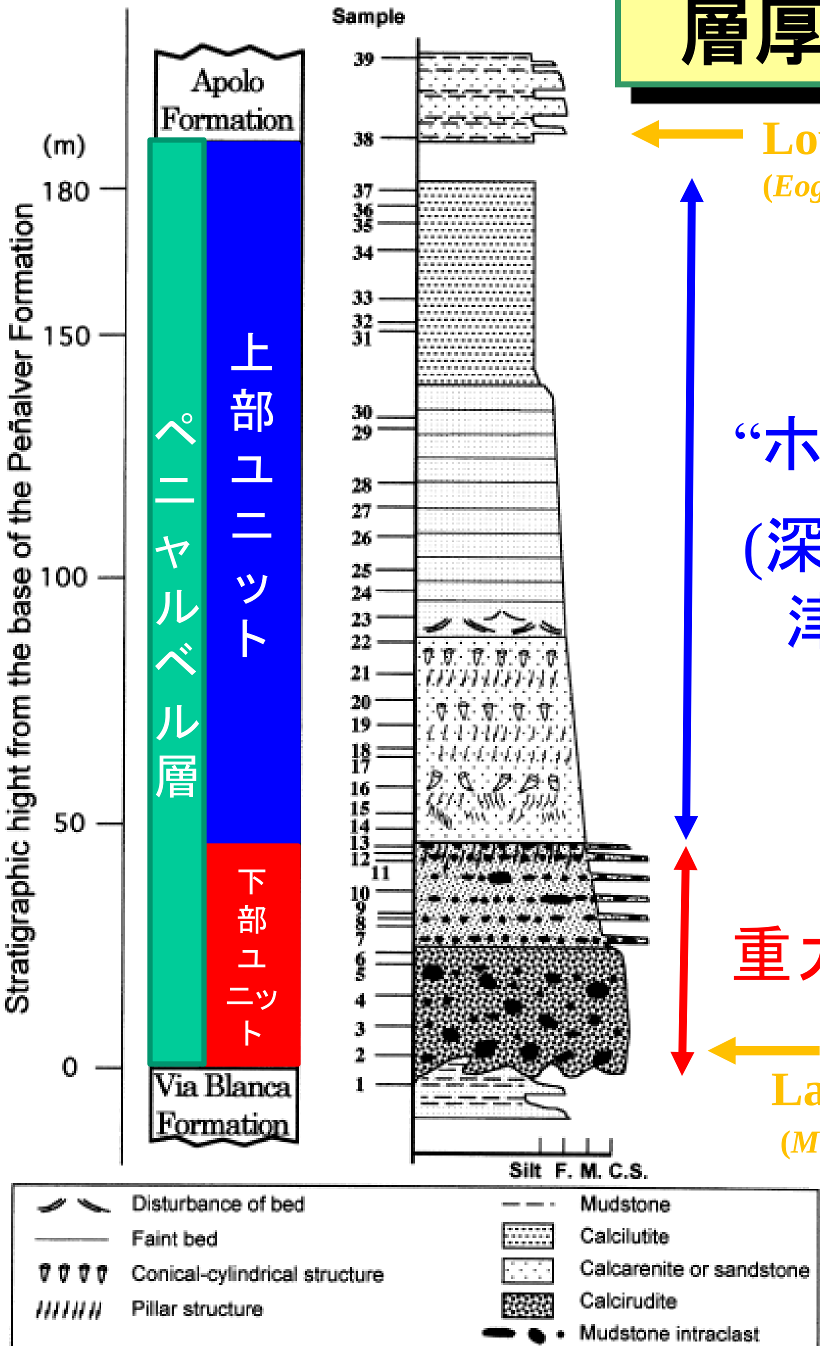
Penelver Formation, Habana

深海性津波堆積物

Tsunamis affected toward the deep-sea bottom (~2,000 m)

[*Takayama et al.*, 2000; *Tada et al.*, 2003; *Goto et al.*, 2008]

層厚200メートルのK/T境界堆積物



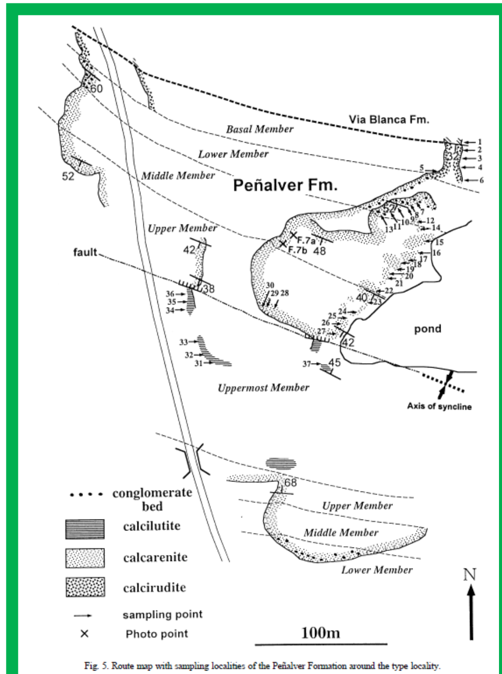
Lower Danian
(*Eoglobigerina fringa, Globoconusa daubjerjensis*)

“ホモジェナイト”
(深海性
津波堆積物)

重力流堆積物

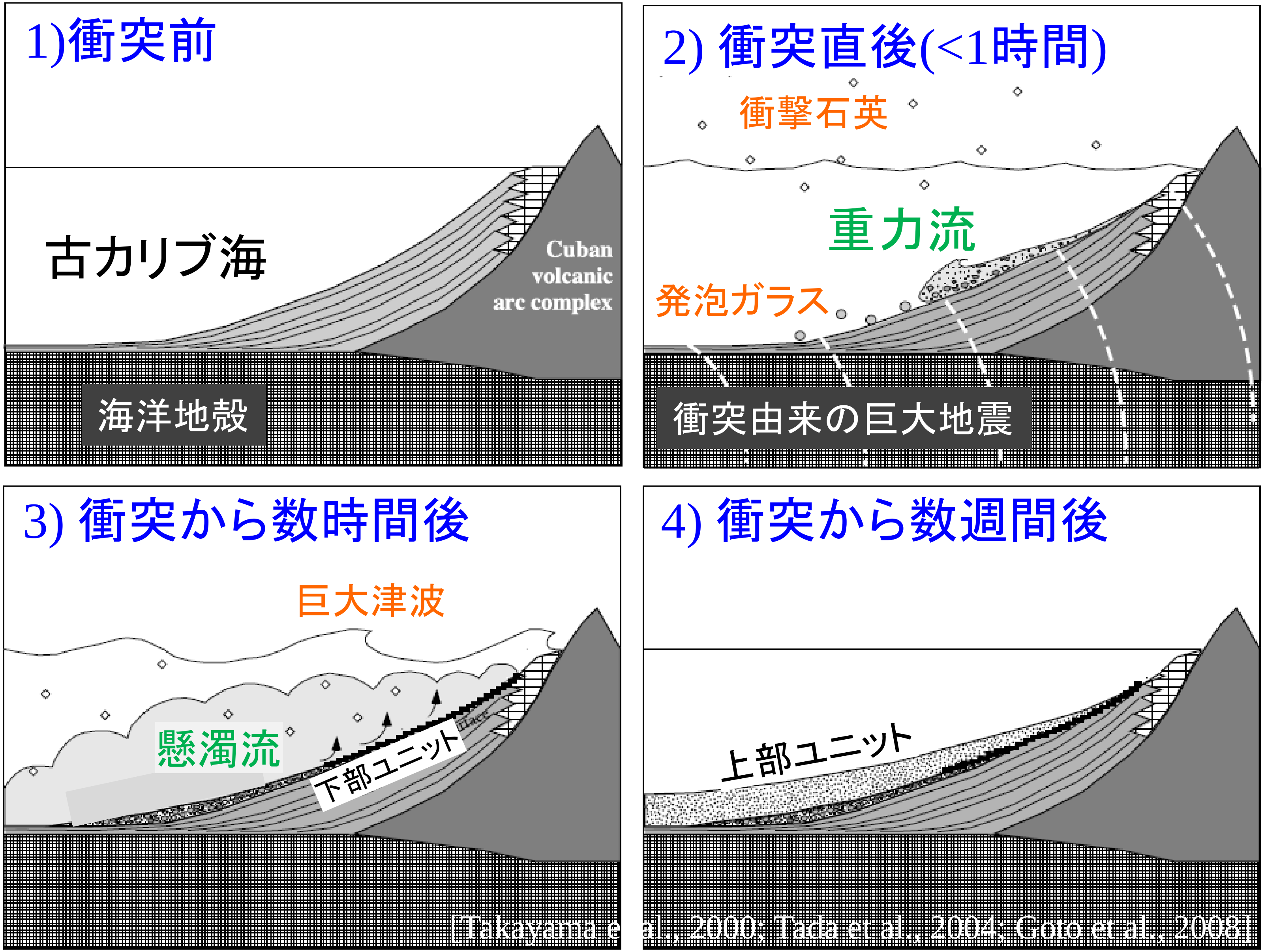
Latest Maastrichtian
(*Micura prinsii*: 65.4~65.0 Ma))

- 厚く均質な堆積物
- 上方細粒化
- 侵食面や流れの作用を示す堆積構造を持たない
- 生物擾乱が見られない
- 広範囲に分布

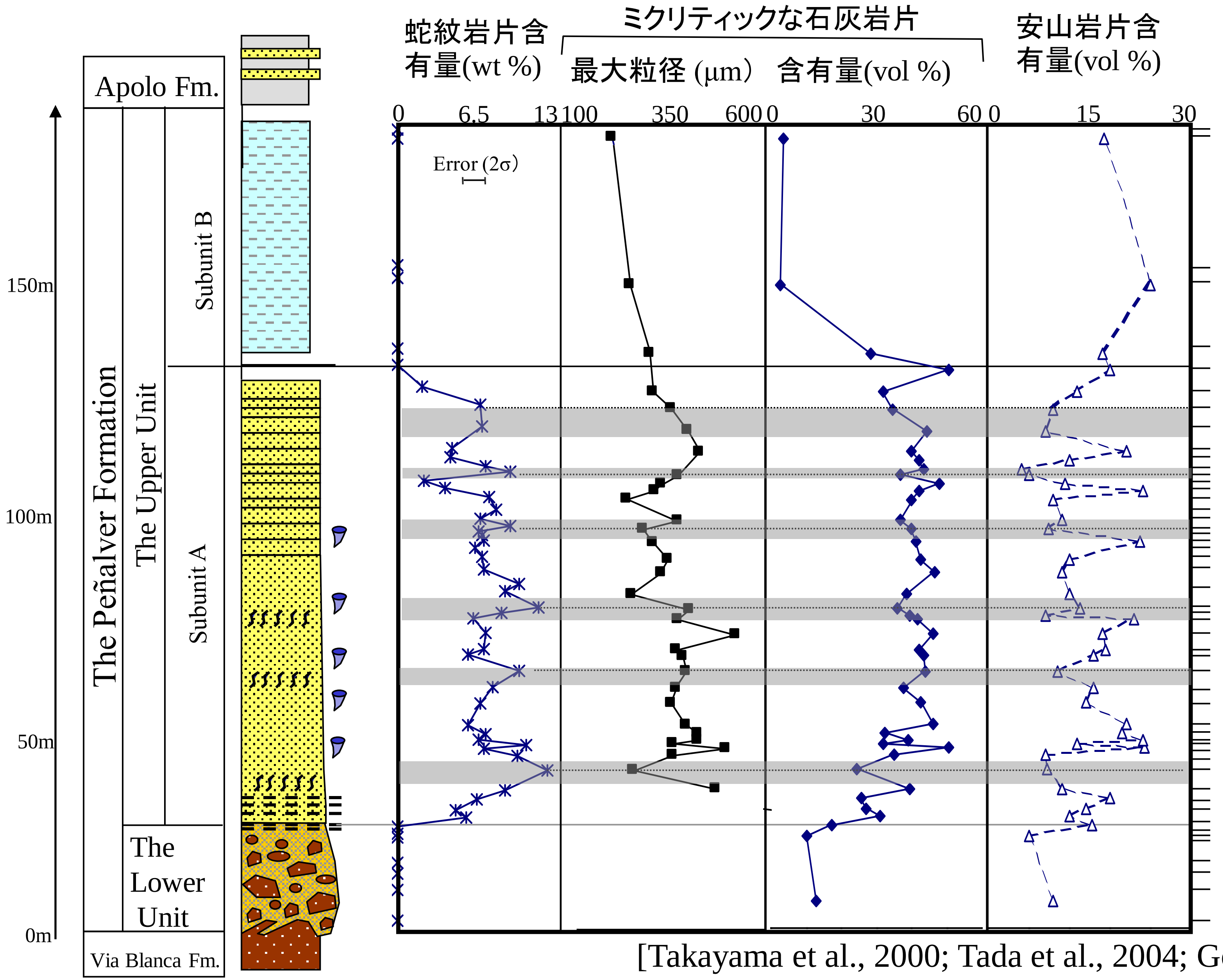


[Takayama et al., 2000; Tada et al., 2004; Goto et al., 2008]

堆積メカニズム

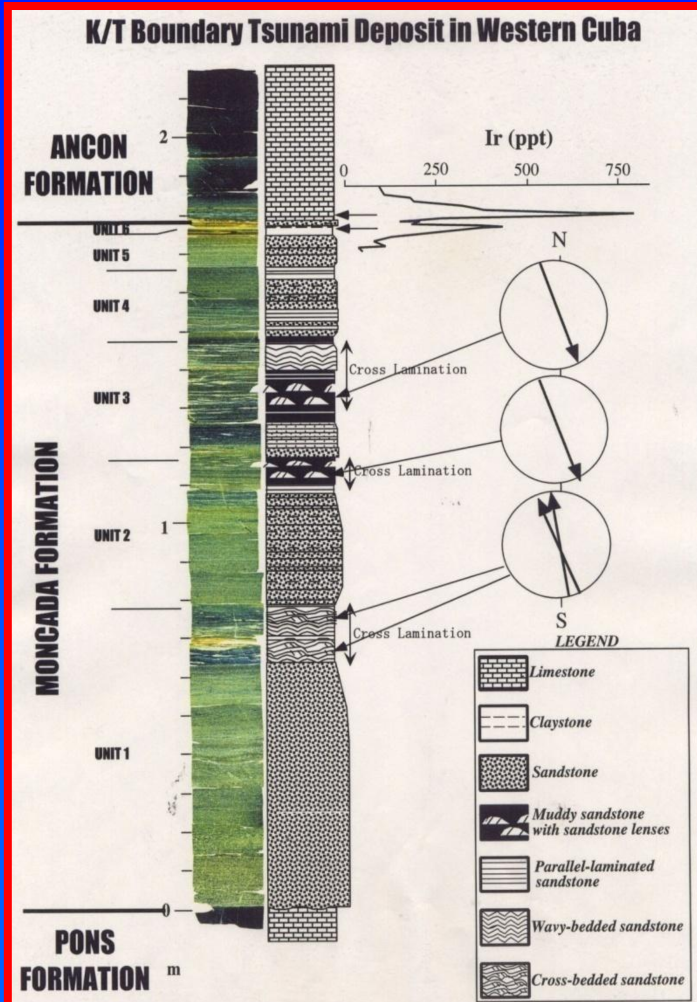

1)衝突前
古カリブ海
Cuban
volcanic
arc complex
海洋地殻
2) 衝突直後(<1時間)
衝撃石英
重力流
発泡ガラス
衝突由来の巨大地震
3) 衝突から数時間後
巨大津波
懸濁流
下部ユニット
4) 衝突から数週間後
上部ユニット
[Takayama et al., 2000; Tada et al., 2004; Goto et al., 2008]

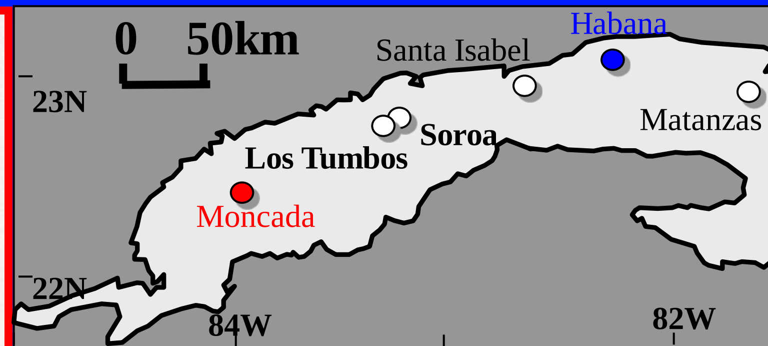
組成と粒径の変動の繰り返し

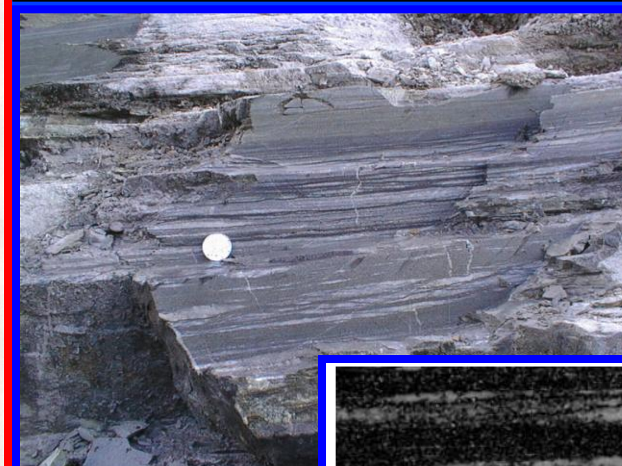


[Takayama et al., 2000; Tada et al., 2004; Goto et al., 2008]

正逆方向の斜交葉理　津波の繰り返し







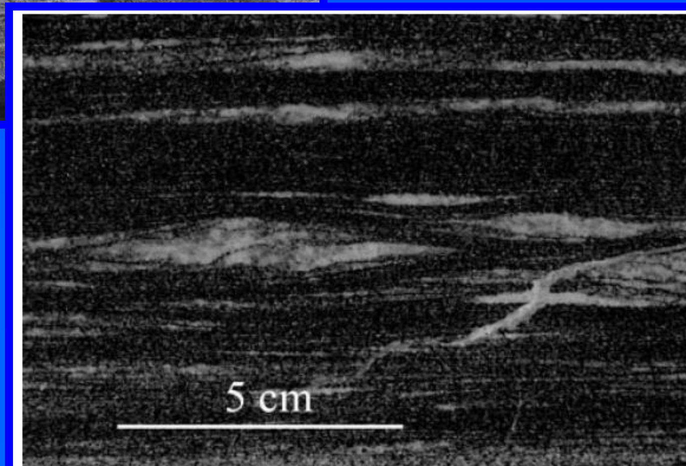
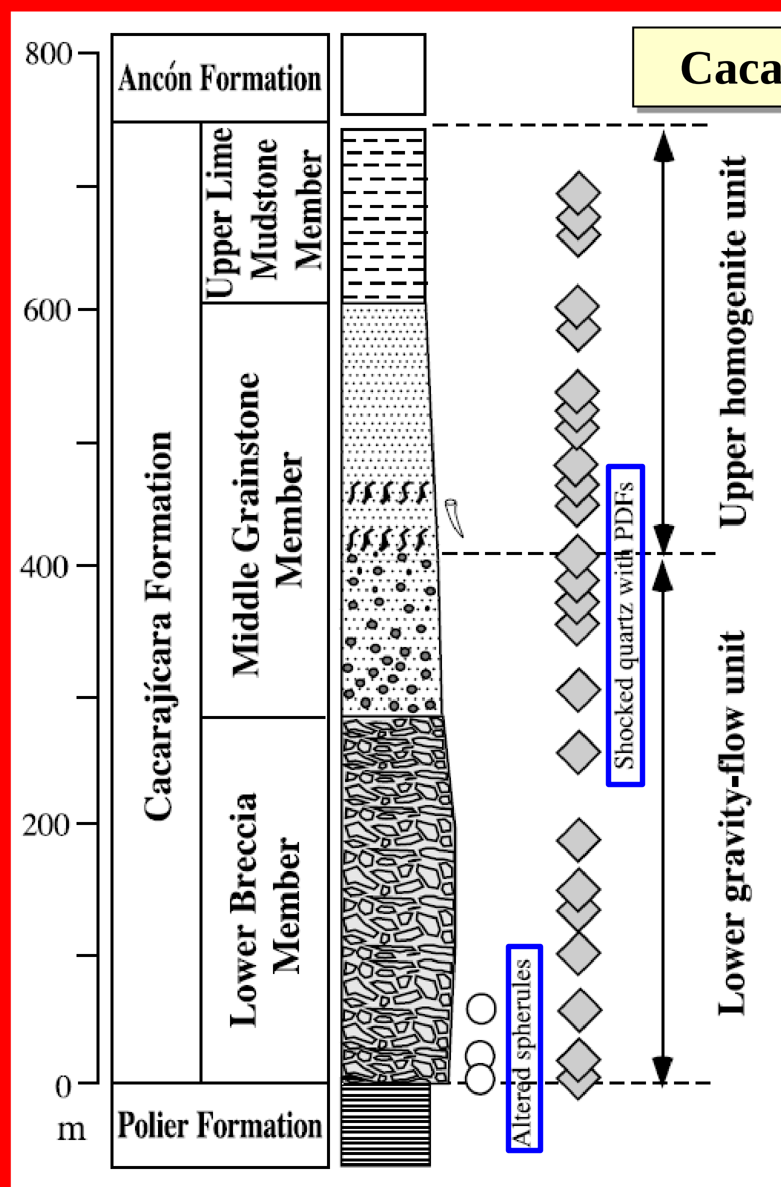


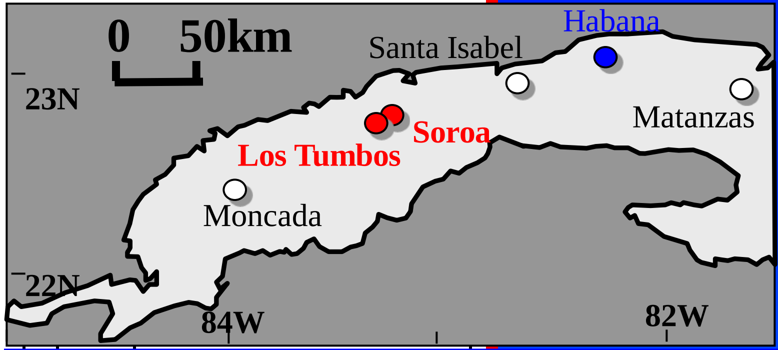
Figure 11. Ripple cross-laminated calcarenite with mud drapes in the upper part of unit 1 in the Moncada Formation.

Moncada Formation

[Tada et al., 2002]

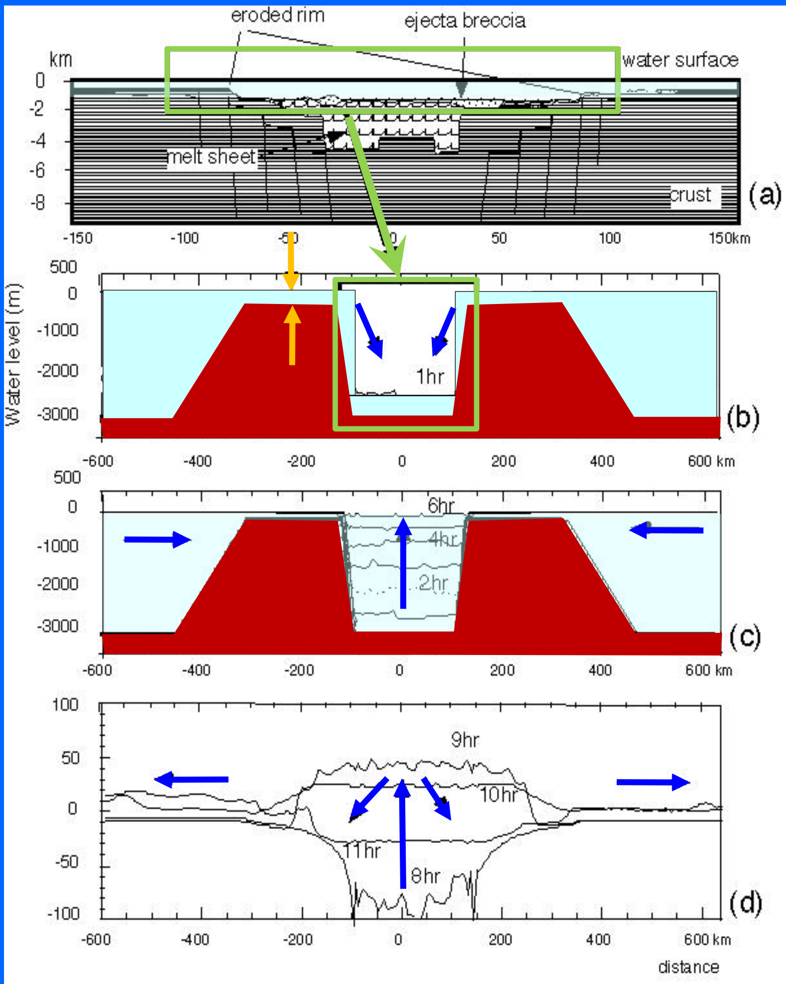
層厚800メートルのK/T境界堆積物も存在！



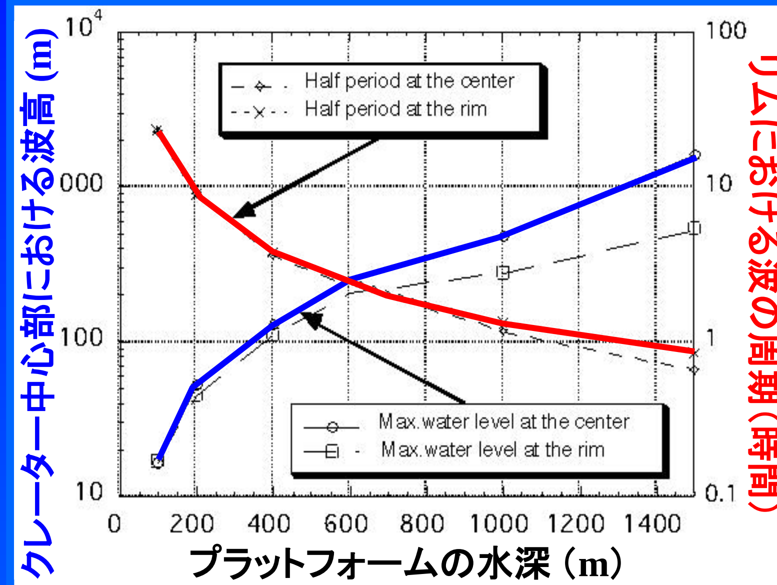


[Kiyokawa et al., 2002; Tada et al., 2004; Goto et al., 2008]

衝突による津波発生メカニズム

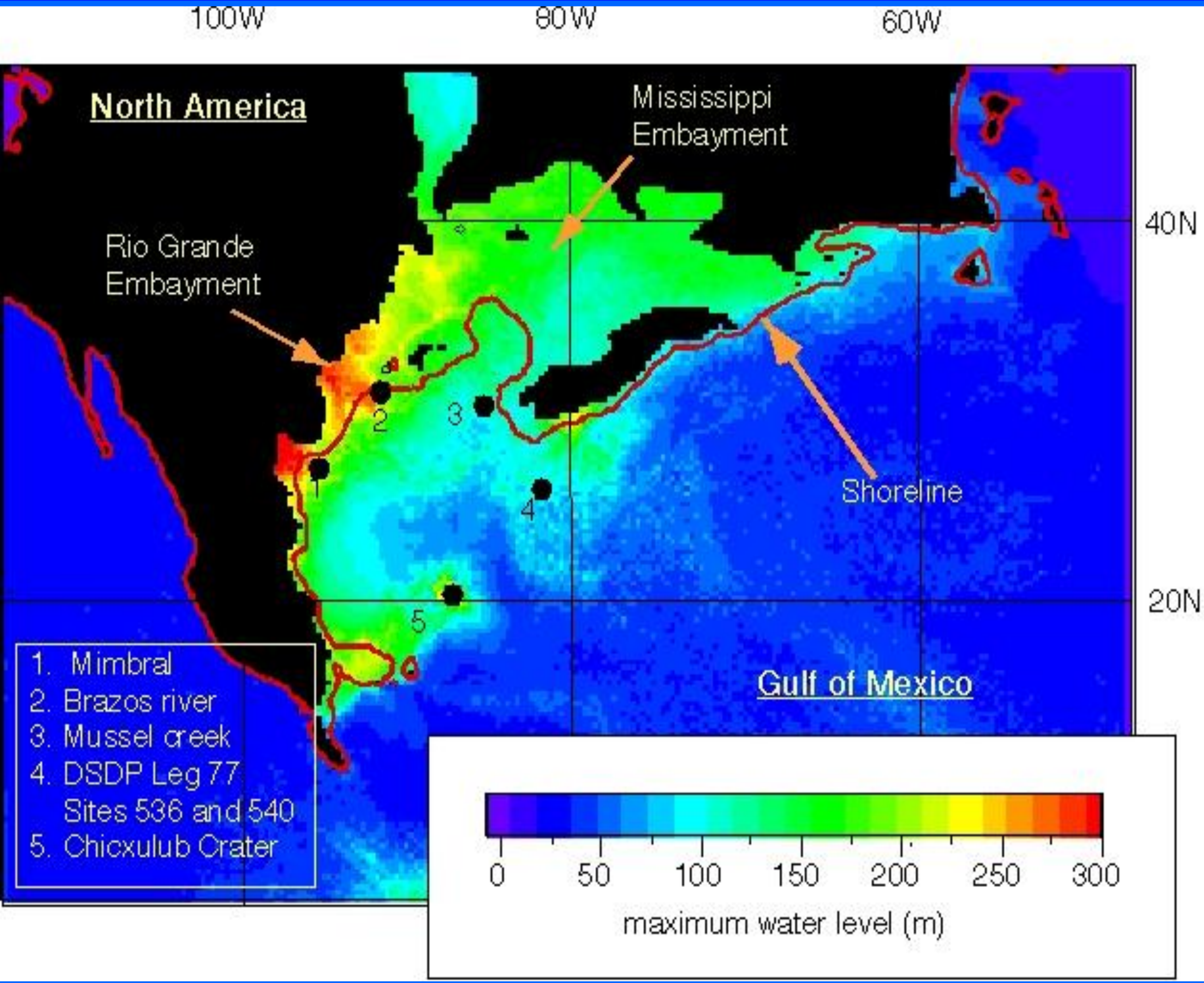


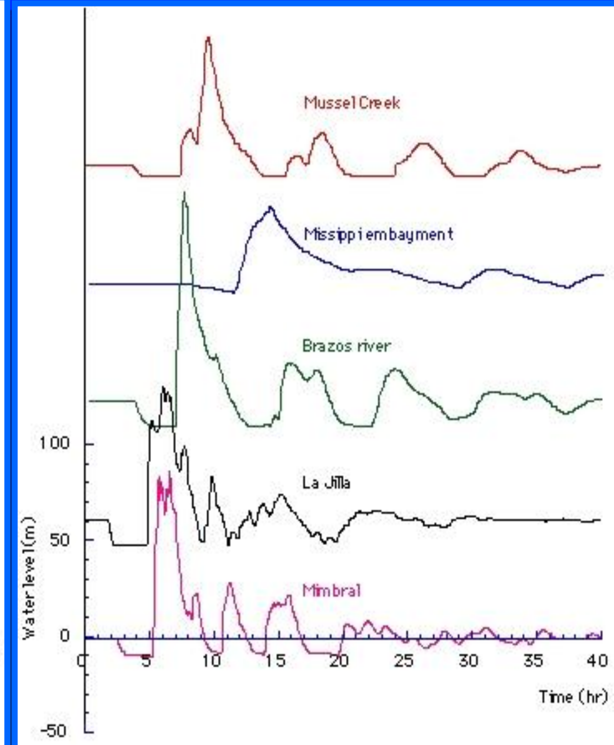
津波の繰り返しメカニズム



[Matsui et al., 2002]

衝突による津波の伝搬





[Matsui et al., 2002]

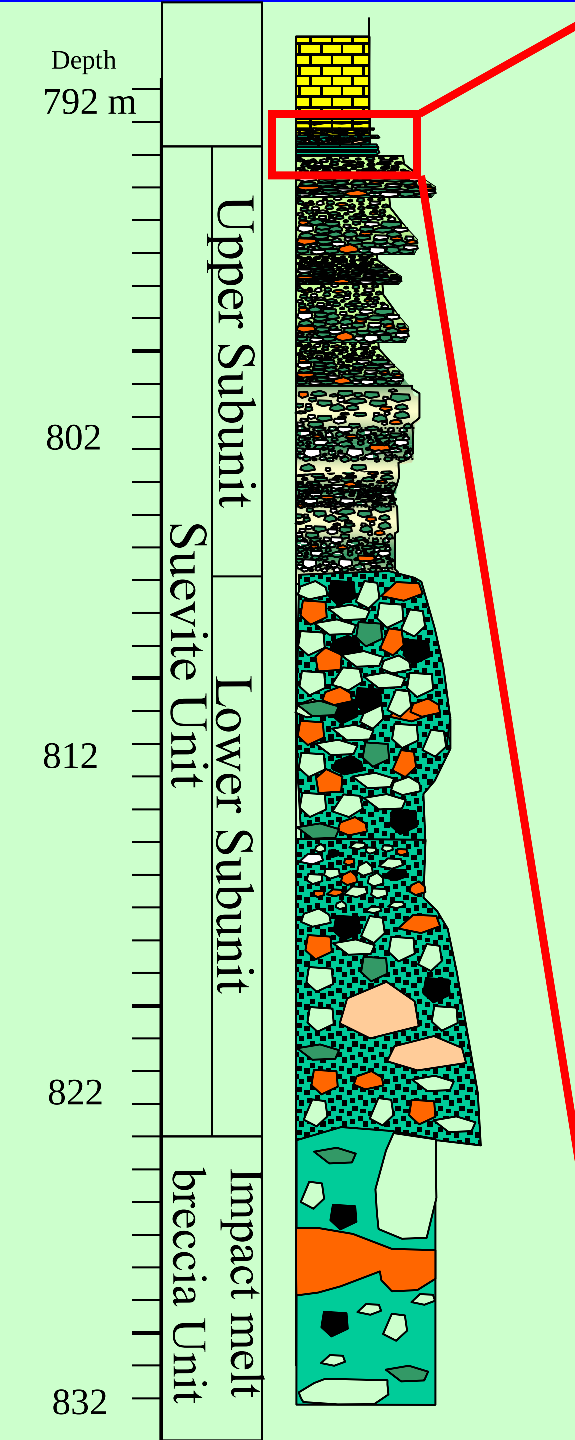


Photo: UNAM

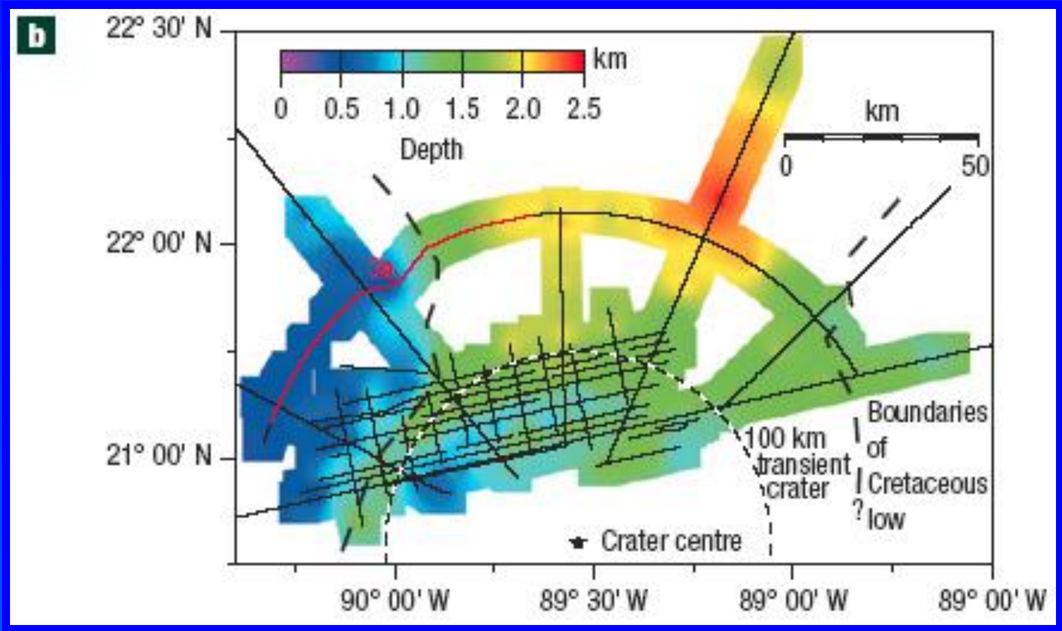
クレーター内部への海水流入の証拠 (1)

衝突直後の堆積物に斜交葉理が発達していることを発見！

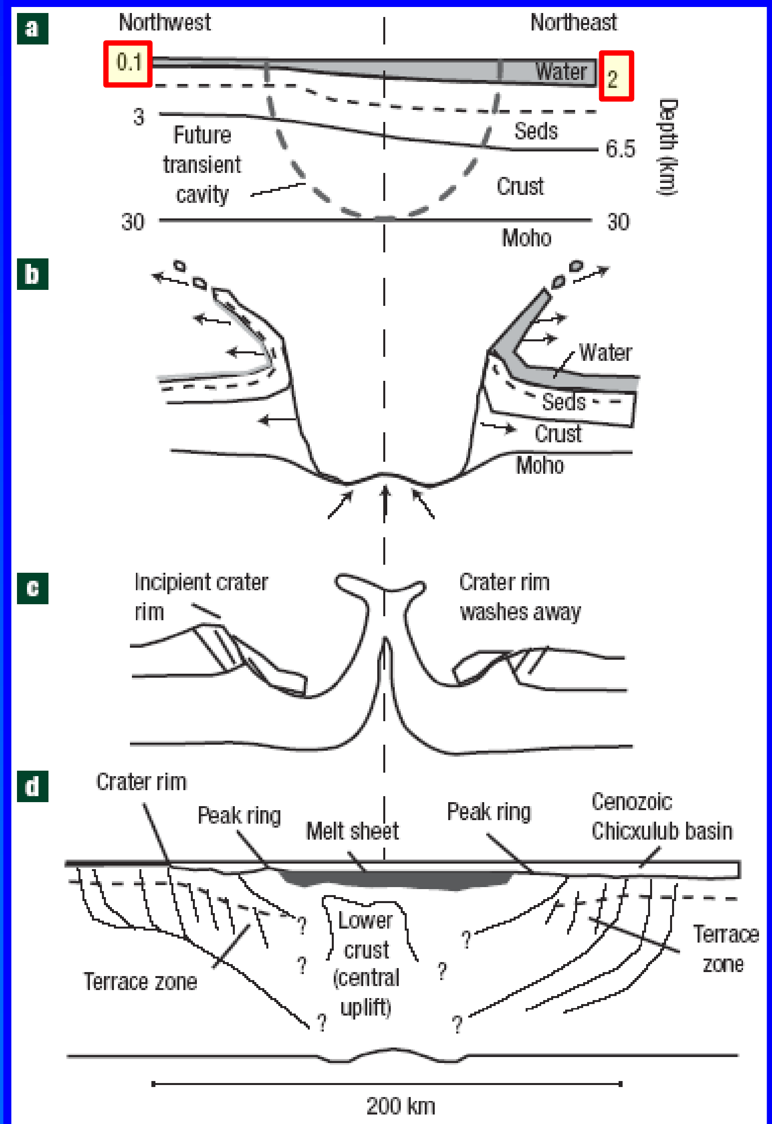
衝突直後に海水流入が起きていた決定的な証拠！

リムの崩壊？
ガリーの形成？

衝突地点の非対称性



[Gulick *et al.* (2008) *Nature Geoscience*]



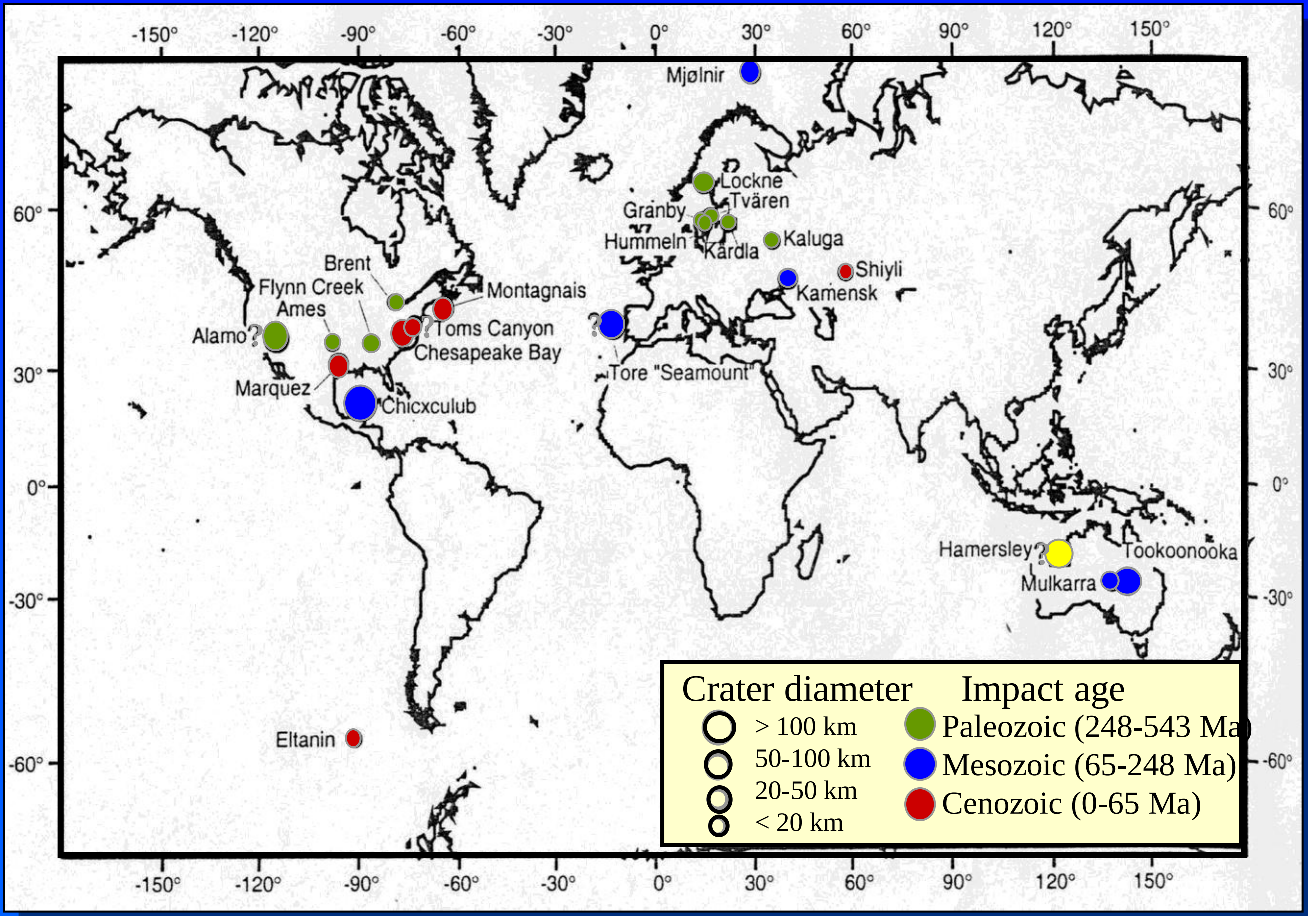
■地震波探査の結果：
衝突地点は北東へ傾いた斜面だった！

- ・西側　の水深～　100 m
- ・北東側の水深～2,000 m

→ リサージによってリムは崩壊

[Collins *et al.* (2008) *EPSL*]

海洋域での衝突



浅海衝突クレーター18個（＋候補1カ所）
深海衝突の証拠1カ所（＋候補3カ所）

[Gersonde and Deutsch, 1999]

海洋衝突による環境への影響

1　**海水の蒸発** [e.g. Ahrens and O’Keefe, 1983]

成層圏への水蒸気＋塩分の供給

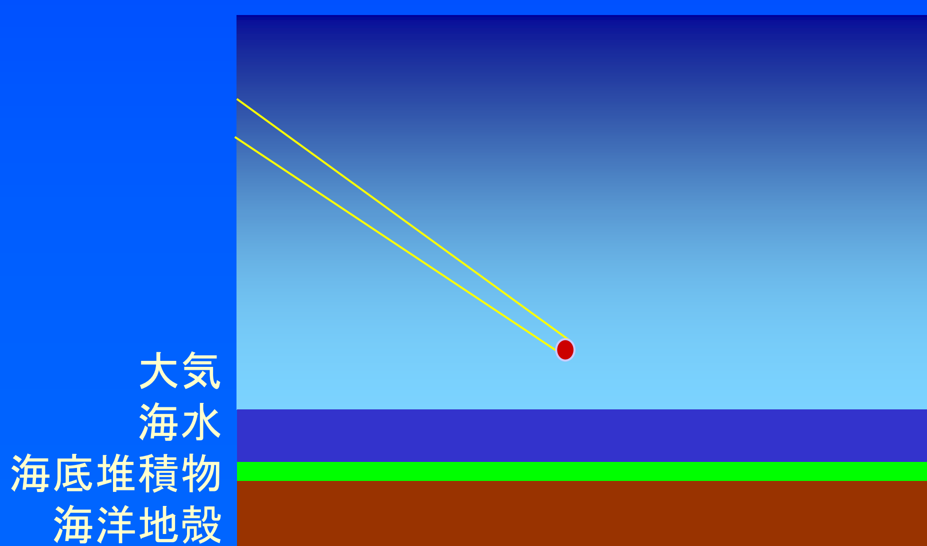
→　オゾン層の激減 [Klumov, 1999]

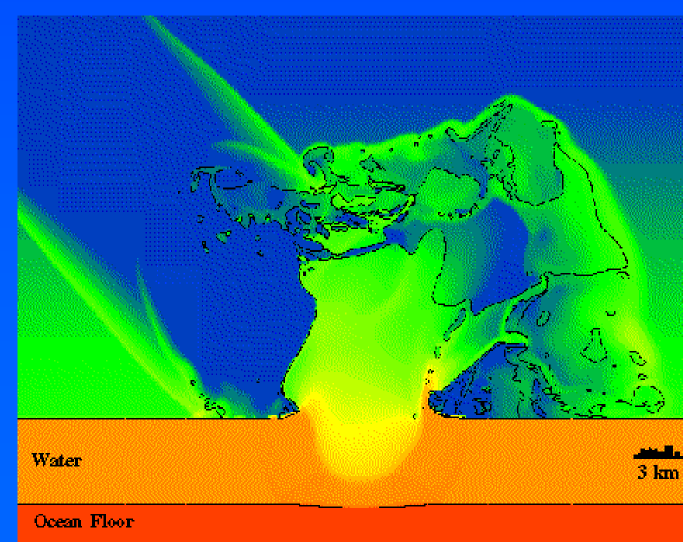
2　**堆積物の蒸発** [e.g. O’Keefe and Ahrens, 1989; Pope et al. 1994, 1997]

炭酸塩岩：　CO_2　→　温暖化

蒸発残留岩：　SO_2　→　日射遮蔽，酸性雨

3　**衝突津波の発生** [e.g. Hills et al., 1994; Ward and Asphaug, 2000]





海洋衝突現象

■ 地球表面の大部分は海洋

約30%: 陸上衝突(Land-target Impact)

約70%: 海洋衝突(Marine-target Impact)
- 約10%: 浅海衝突（陸棚域）
- 約60%: 深海衝突（深海底）

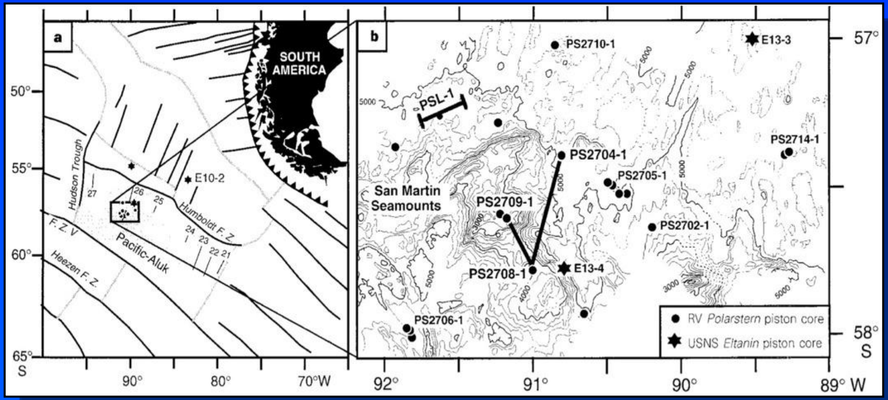
→ ほとんどの衝突は海洋域で生じる

海洋衝突現象とその環境への影響は
これからの重要な研究課題

深海衝突の証拠

The Eltanin Impact

場所: Bellingshausen 海（南大洋の東太平洋セクター）
水深: 約5000 m
年代: 2.15 Ma
衝突天体：メソシデライト d_p=0.5 km [Kyte et al. 1988], 1-4 km [Gersonde et al. 1997]



1960’ USNS *Eltanin* による調査
1981 Ir 異常発見 [Kyte et al. 1981]
1985 Eltanin隕石の発見 [Kyte and Brownlee, 1985]
1995 FS *Polarstern* による調査
1997 ボーリングコアの分析 [Gersonde et al. 1997]
2001 RV *Polarstern* による調査

*発見されている衝突起源物質
- unmelted meteorite fragment
- vesicular impact melt
- spinel-bearing spherule
- Ir anomaly

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