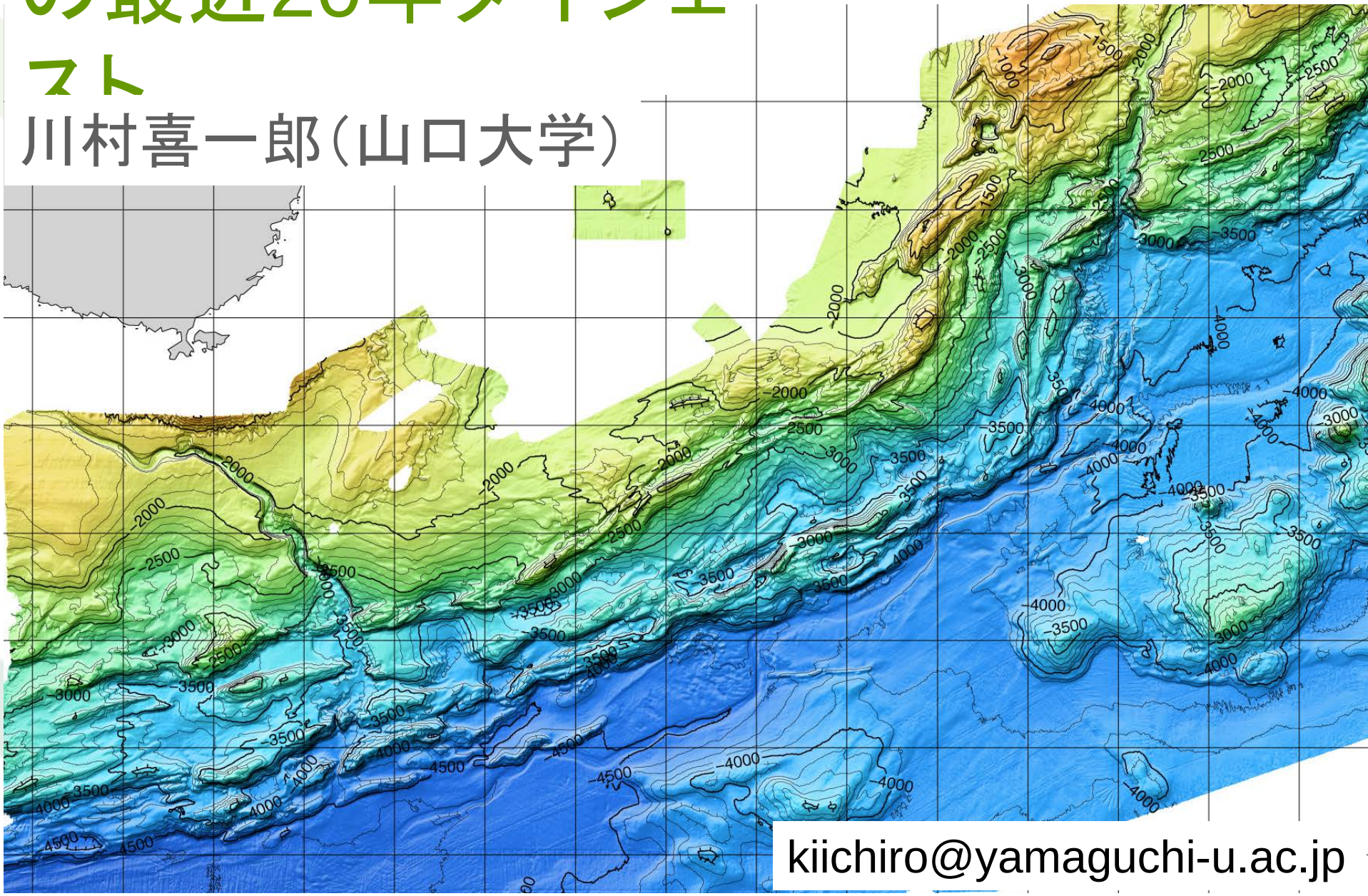
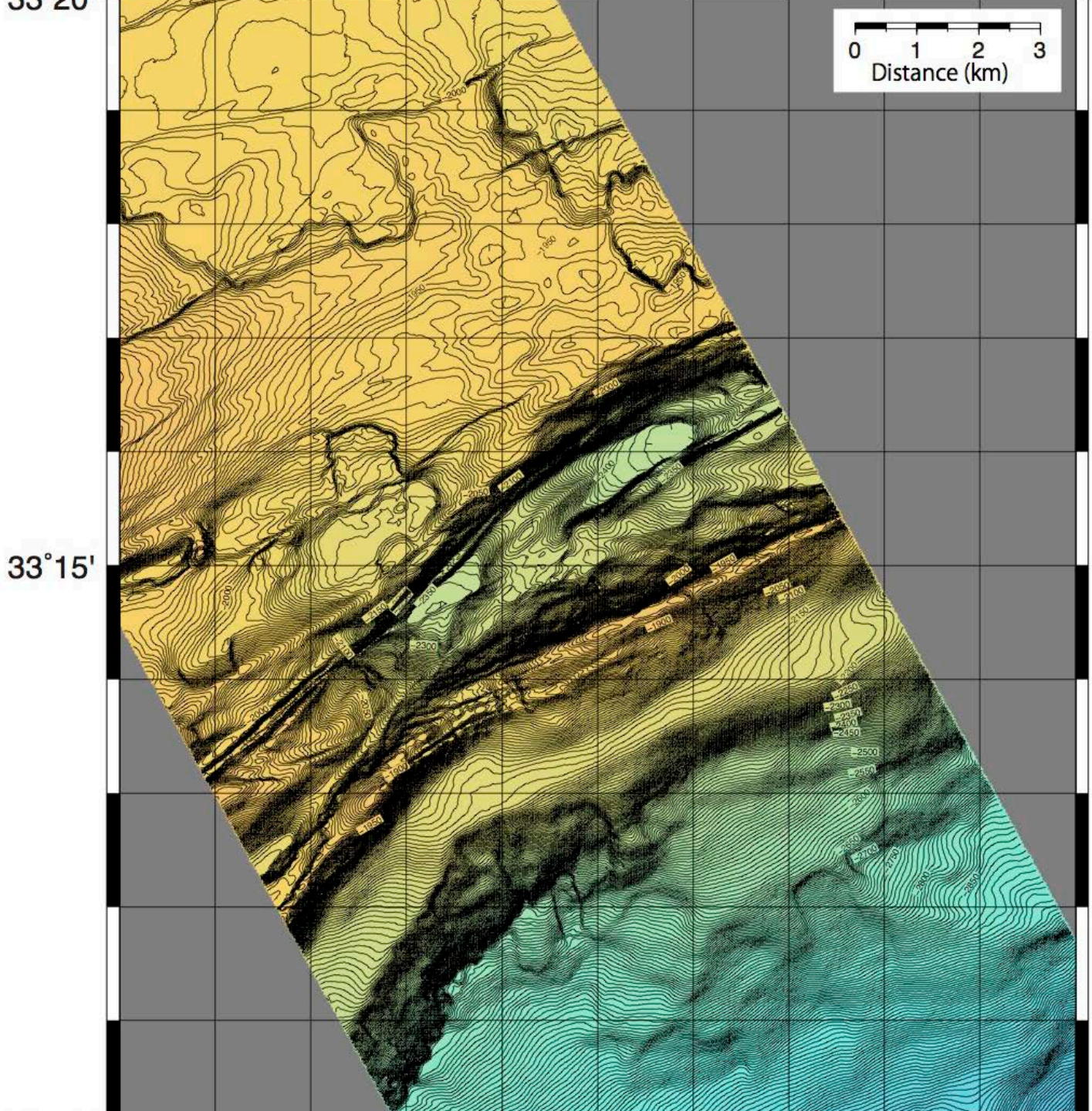
海底地すべり研究の最近20年ダイジェスト

YAMAGUCHI UNIVERSITY

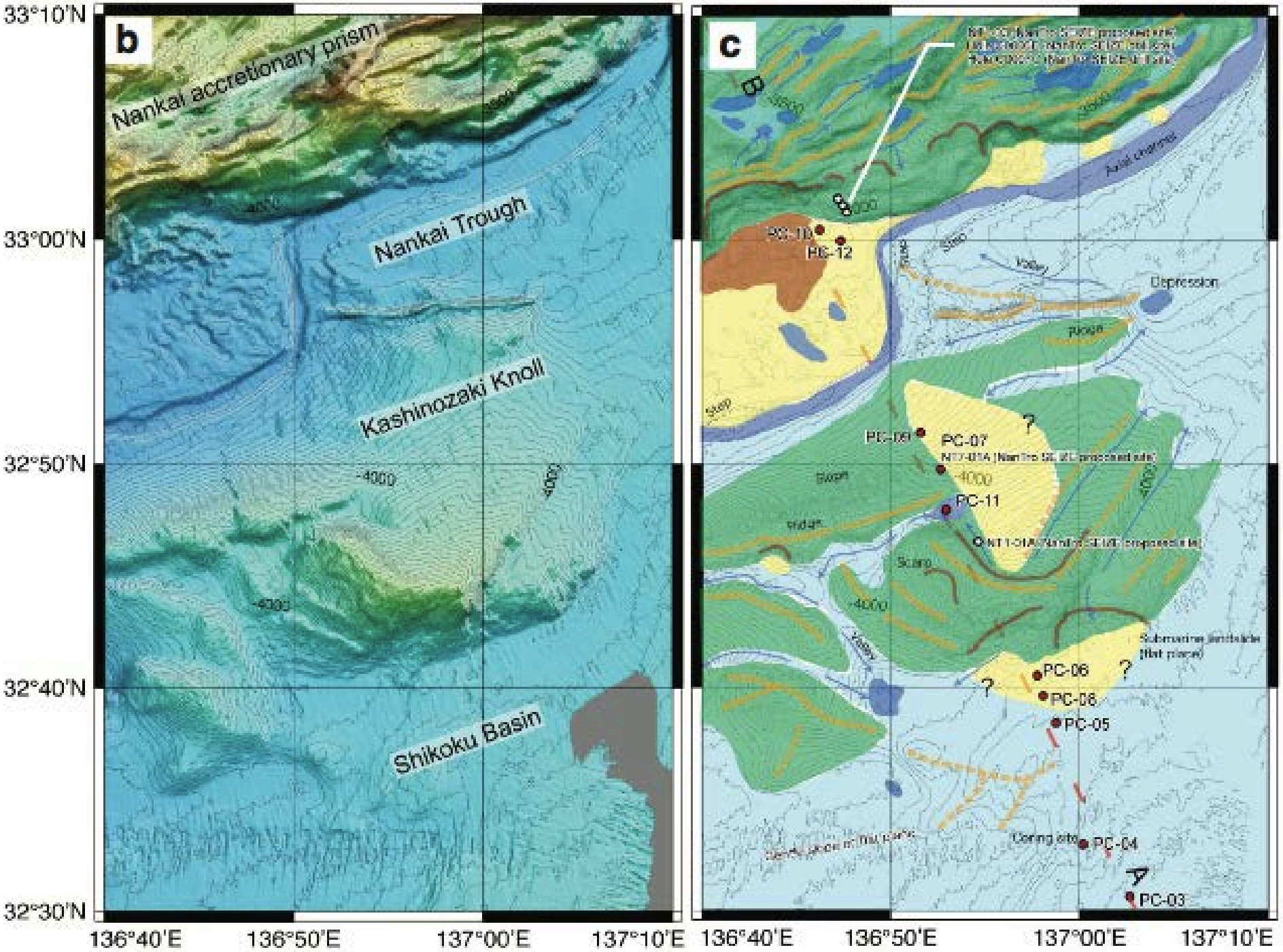
川村喜一郎（山口大学）



kiichiro@yamaguchi-u.ac.jp

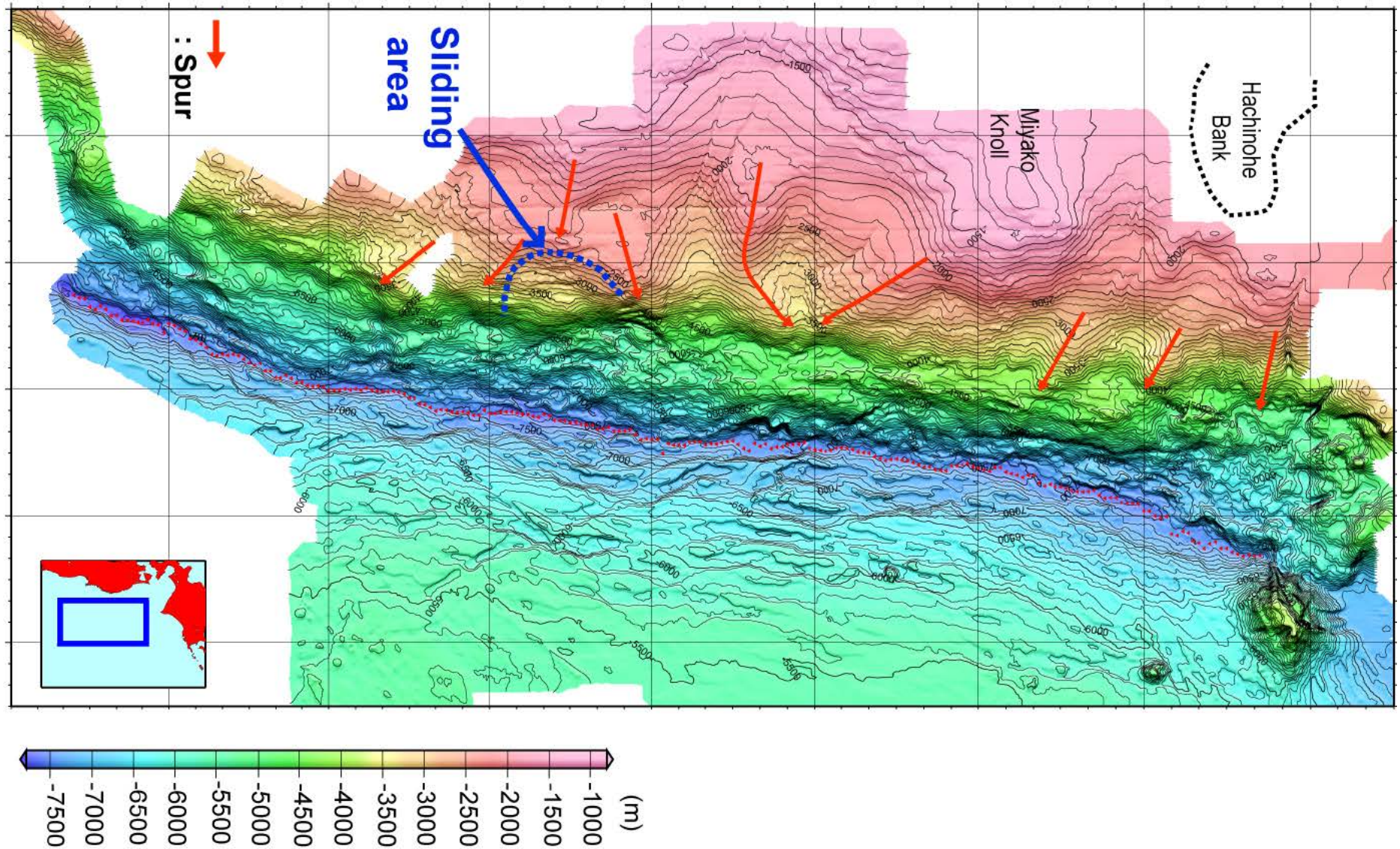


RSITY

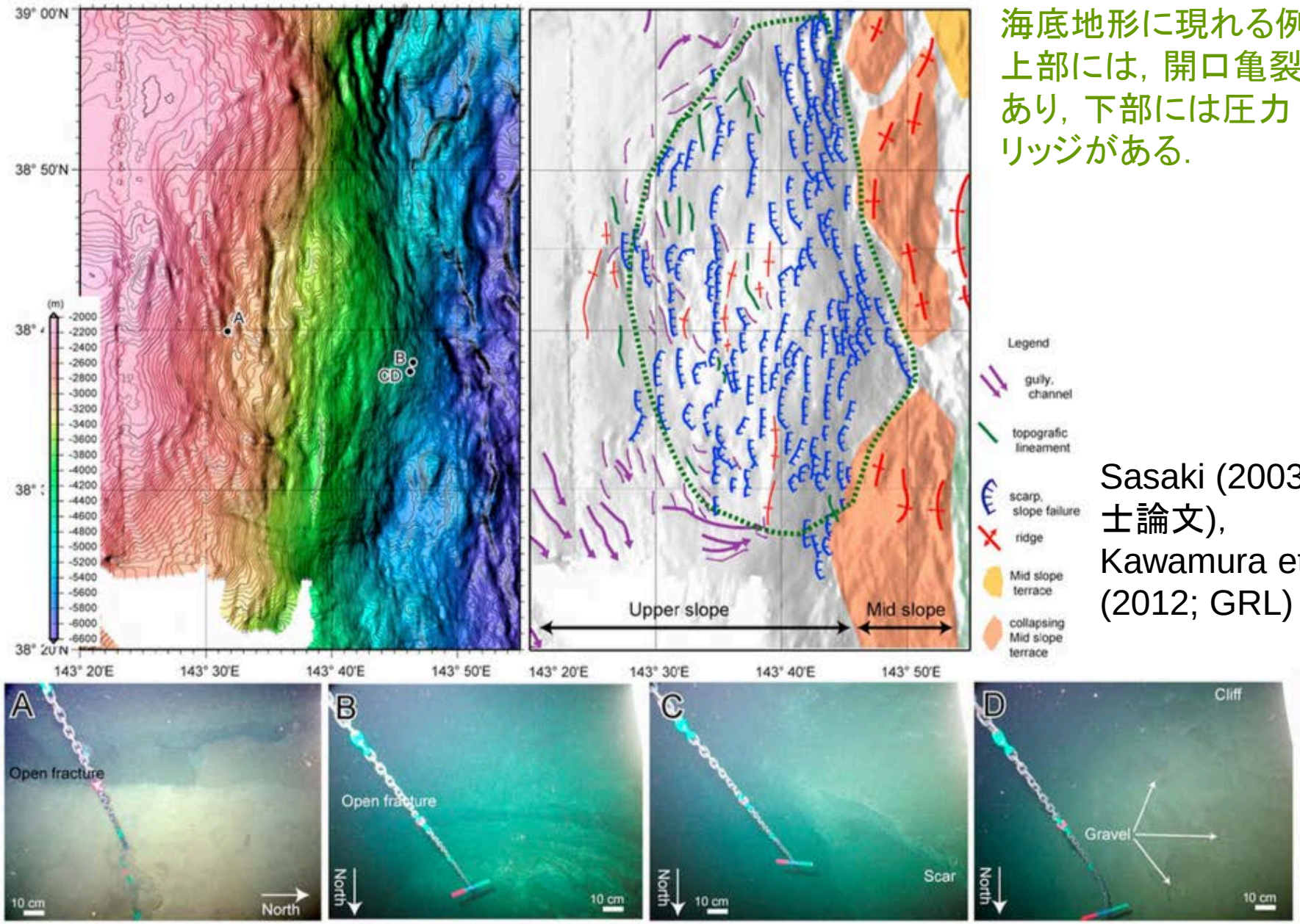

b
Nankai accretionary prism
Nankai Trough
Kashinozaki Knoll
Shikoku Basin
-4000
-4000
-4000
c
PC-10
PC-12
Depression
Ridge
Slope
Valley
PC-09
PC-07
PC-11
Scarp
-4000
Submarine landslide
(flat place)
PC-06
PC-08
PC-05
Coring site
PC-04
PC-03
33°10'N
33°00'N
32°50'N
32°40'N
32°30'N
136°40'E
136°50'E
137°00'E
137°10'E
136°40'E
136°50'E
137°00'E
137°10'E

日本海溝

Sasaki (2003 ; 博士論文)



海底地形に現れる例：上部には，開口亀裂があり，下部には圧力リッジがある．



Sasaki (2003；博士論文), Kawamura et al. (2012; GRL)

Figure 2. (left) Arcuate topography and (right) structural map. The bathymetric contour interval is 20 m. Filled circles A–D indicates YKDT Dive points. The green dotted line shows an area of sliding between spurs. Scarps and slope failures and channels have developed on the lowermost part of the upper slope. Photographs of the seafloor: (a) YKDT Dive 94; (b–d) YKDT Dive 97.

2011年東北地方太平洋沖地震

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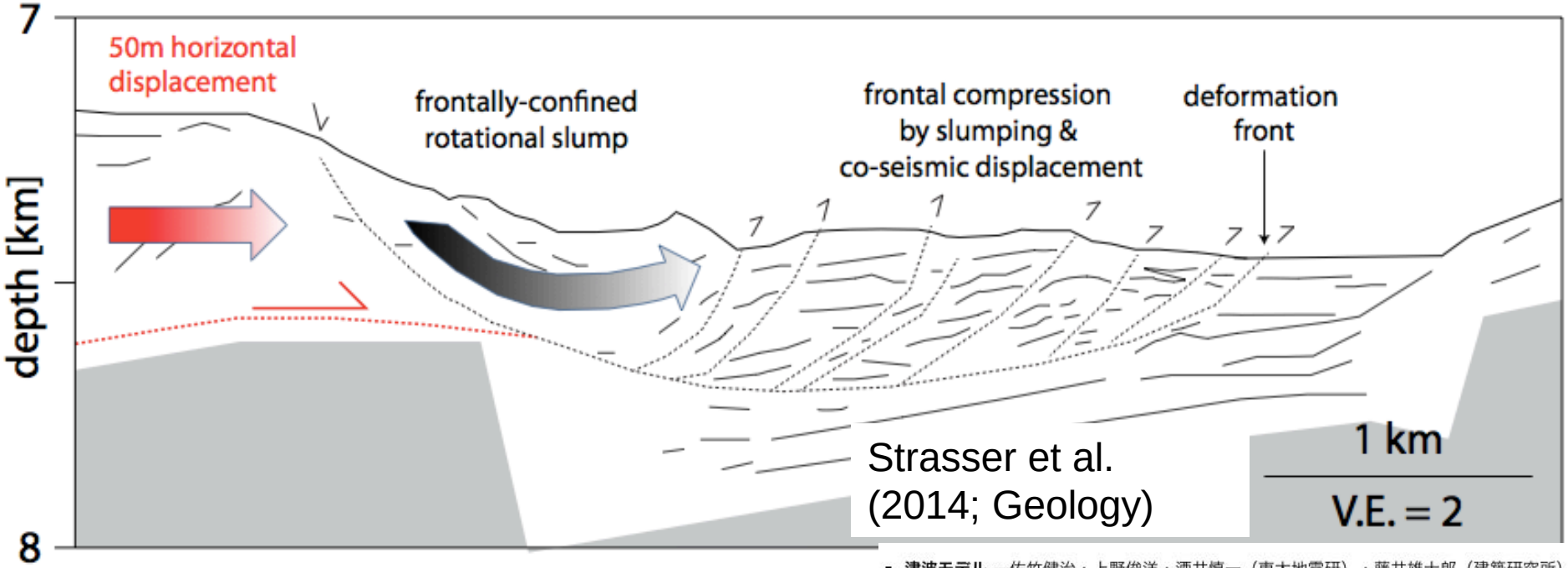
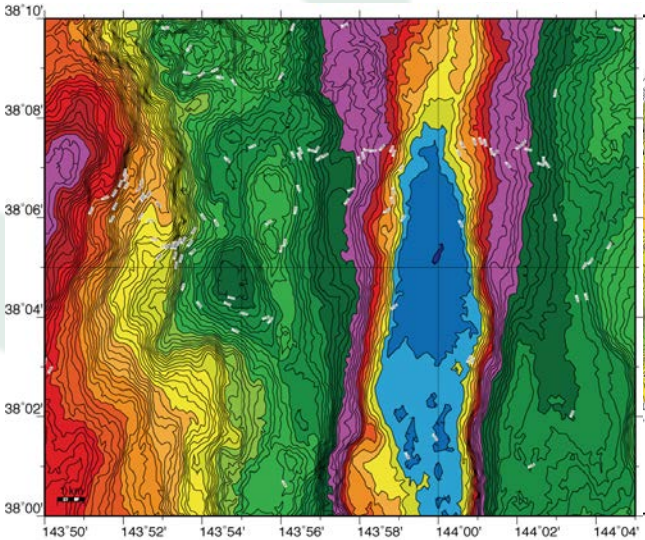
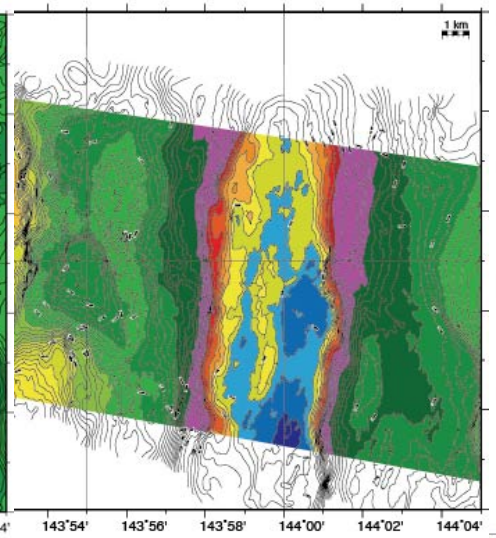


Strasser et al. (2014; Geology)

地震前後の地形変化

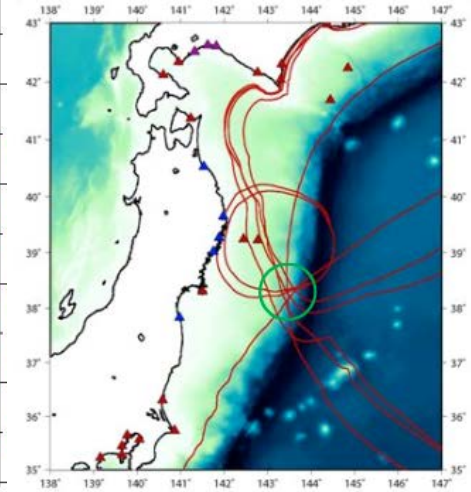
Kawamura et al. (2014; Mar. Geol.)





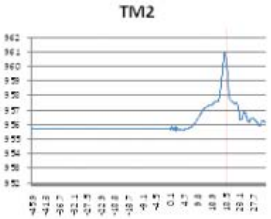
地震研究所ウェブサイト

海底水圧計からの逆伝播図



最大波から描いた逆伝播図

宮城沖に集中



■ 津波モデル ―佐竹健治・上野俊洋・酒井慎一（東大地震研）・藤井雄士郎（建築研究所）

坂口（2017；地盤工学会）

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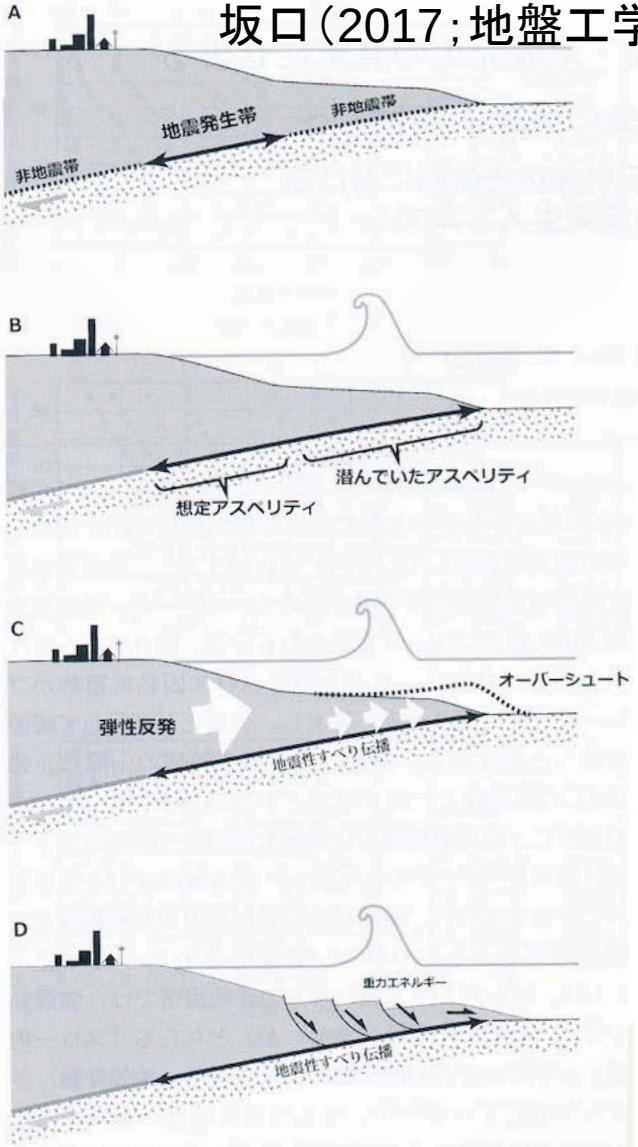
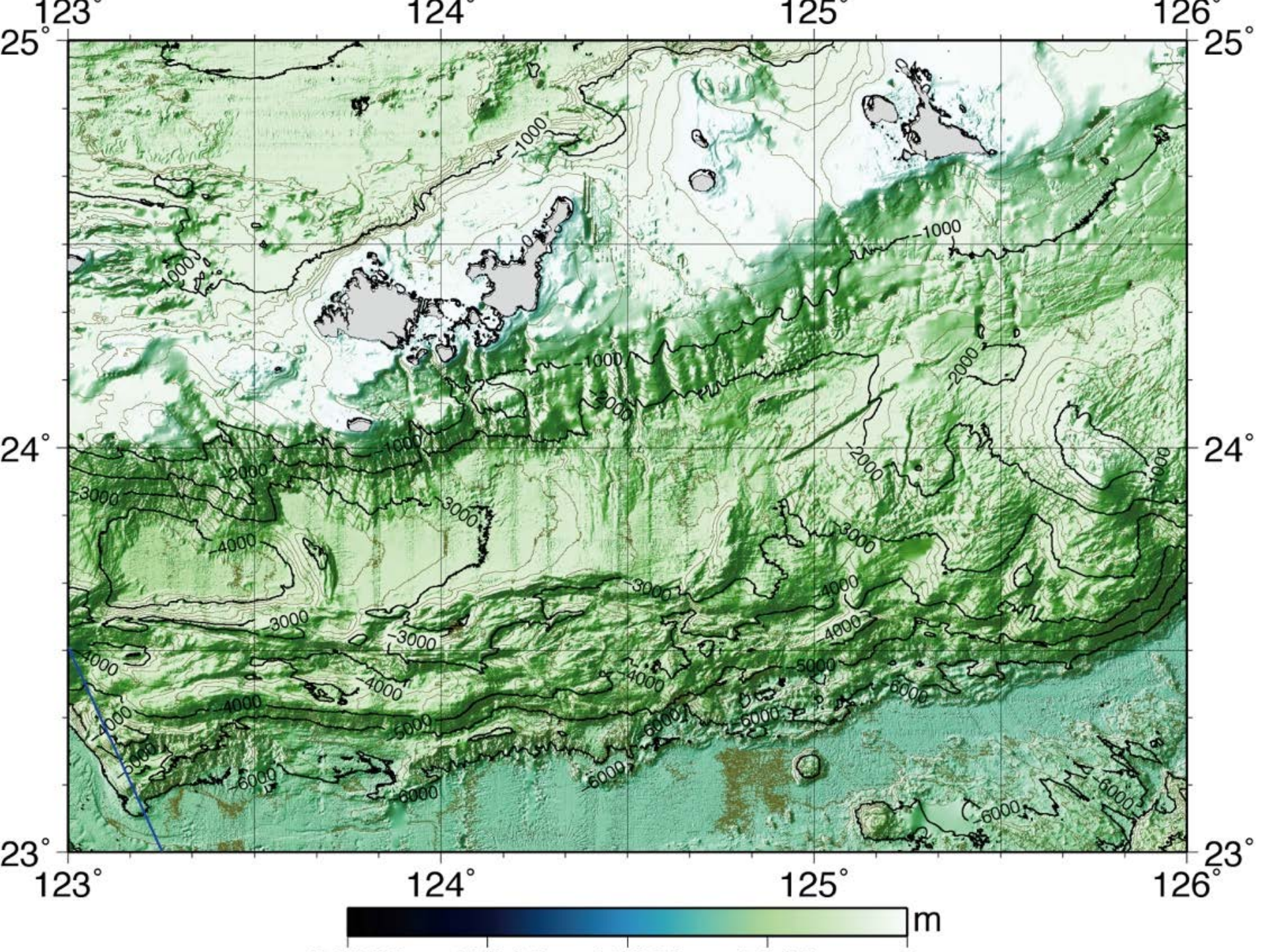
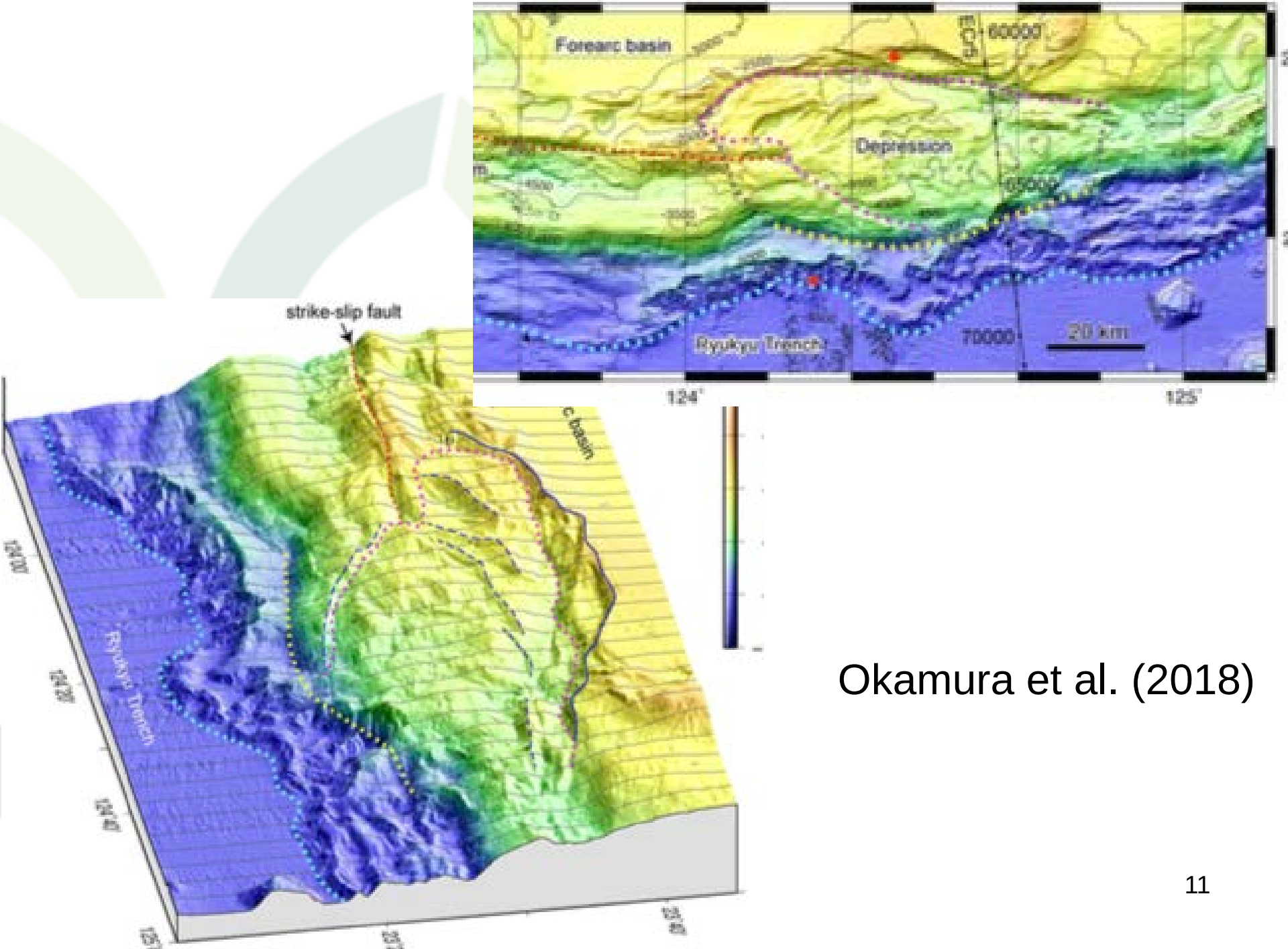


図―3.1　地震発生帯のモデル。（(B)～(C)海溝付近の巨大変位が生じたモデル。）としつつ，(A)従来のモデル。浅すぎず深すぎない深度で巨大地震は発生する。(B)海溝付近にアスペリティが潜んでいたというもの。(C)地殻の弾性反発によって先端部が過剰に押し出されたもの。(D)重力エネルギーによる先端部の形状変化が海溝付近の巨大変位を引き起こしたもの

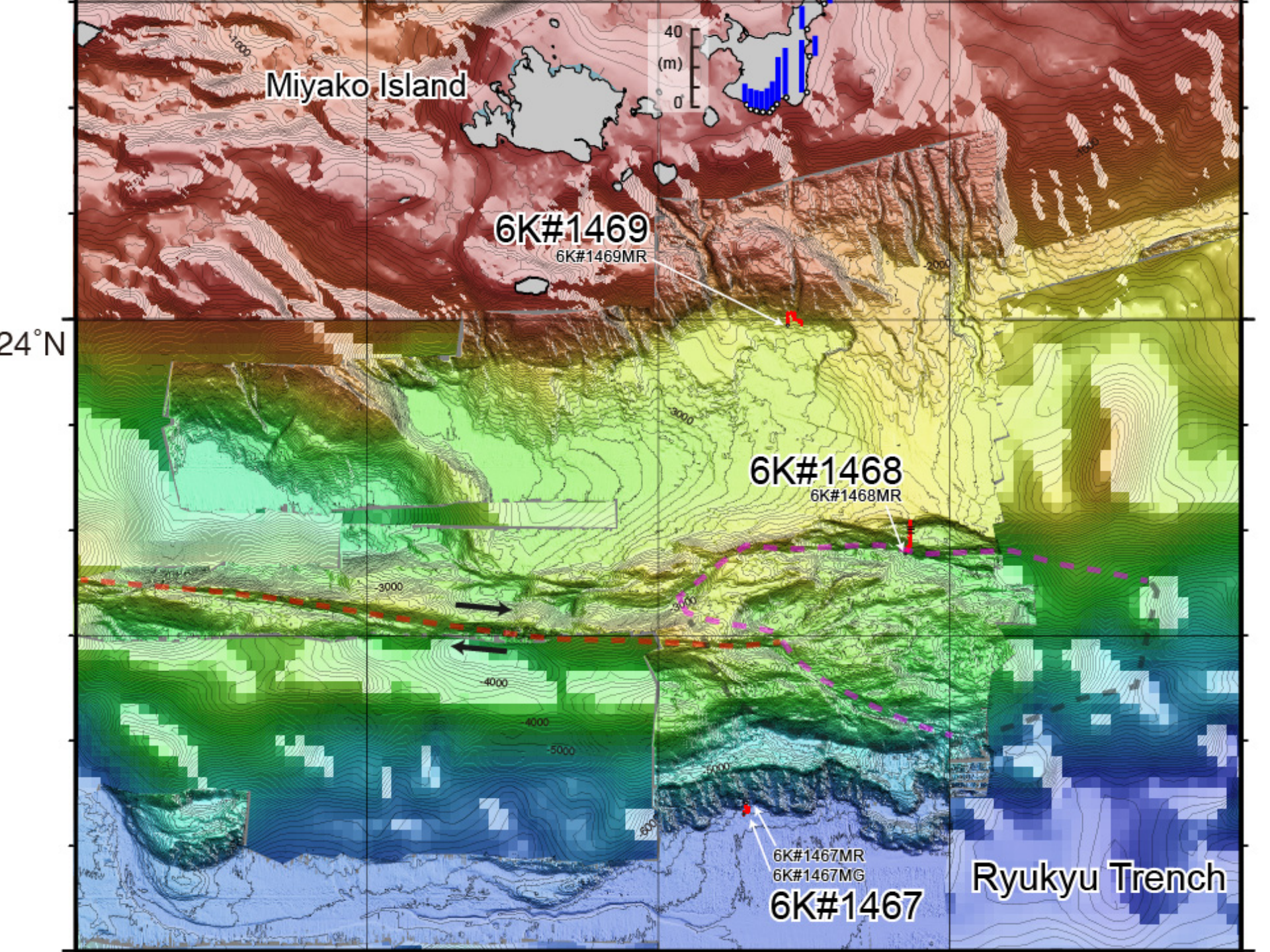
さまざまな仮説が提唱されるが海底地すべり説は消えない．

ただし，先端部分での海底地すべりは受け入れられている（これが津波に貢献したとは考えられていないが）．ただし，海底地すべりによる津波増幅（additional tsunami generation）は十分にありうるだろう．


123°
124°
125°
126°
25°
24°
23°
-1000
-2000
-3000
-4000
-5000
-6000
m



Okamura et al. (2018)


Miyako Island
40
(m)
0
6K#1469
6K#1469MR
24°N
6K#1468
6K#1468MR
6K#1467MR
6K#1467MG
6K#1467
Ryukyu Trench
-1000
-2000
-3000
-4000
-5000

1771年明和津波

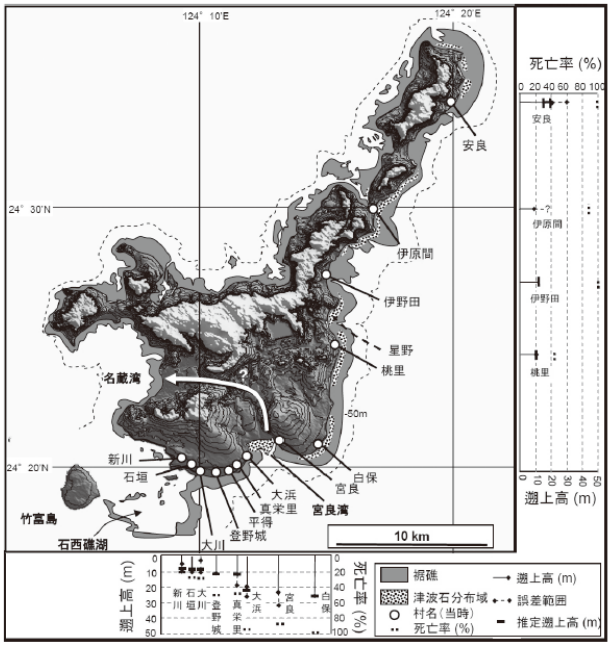


図3—石垣島における各村での死亡率と遡上高の関係
津波石分布域も示す。Goto et al.(2010)[8]を改変。矢印は、宮良湾から名蔵湾に津波が抜けたという流路を示すが、古文書記録にもとづくと否定できる。

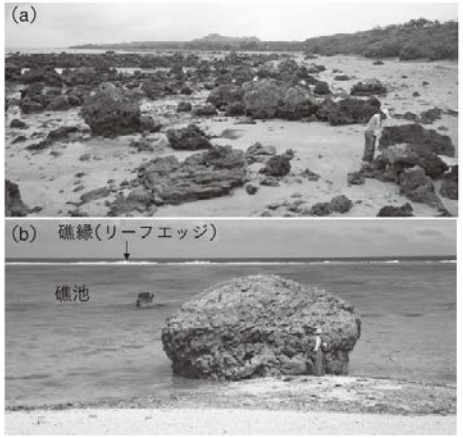


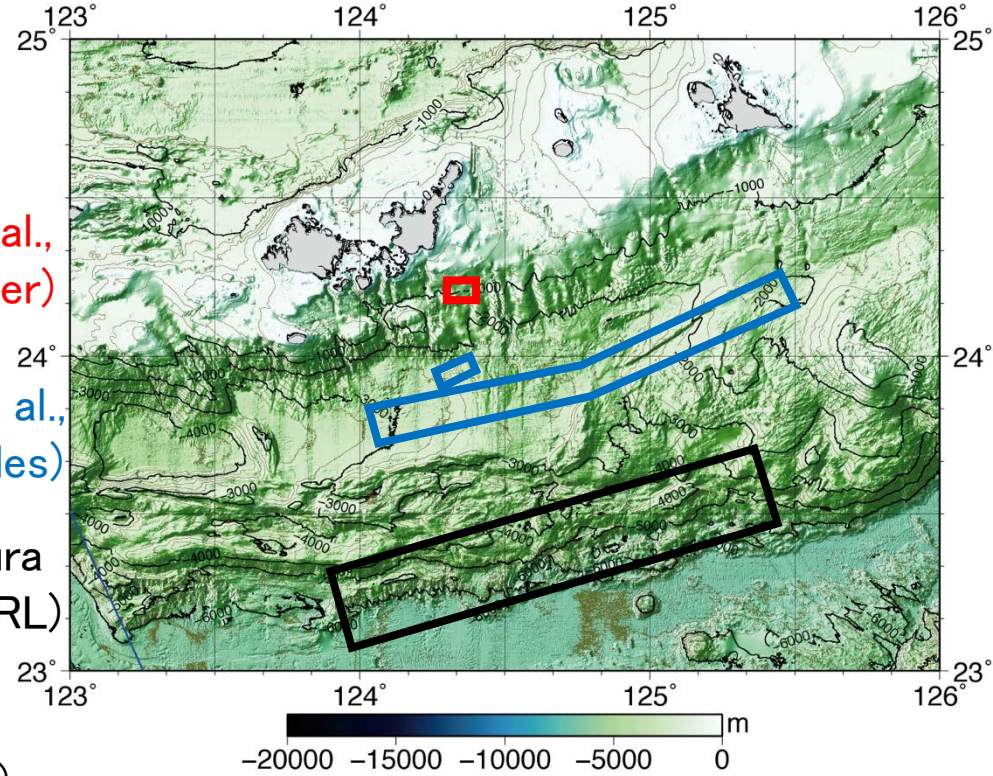
図4—(a)石垣島星野の海岸の風景
膨大な数の岩塊が異様な光景を呈している
(b)石垣島伊原間の海岸に堆積している津波石(巨大ハマサンゴ岩塊)

■ 1771年4月24日石垣島に遡上高30m以上の津波が地震とともに発生した．海底地すべりモデルが提唱されている(Miyazawa et al., (2012; Springer)．ただし，断層モデルもあり，どれが正しいか不明である．

Miyazawa et al., (2012; Springer)

Hisamatsu et al., (2014; Episodes)

Nakamaura (2009; GRL)



後藤・島袋(2012;科学)

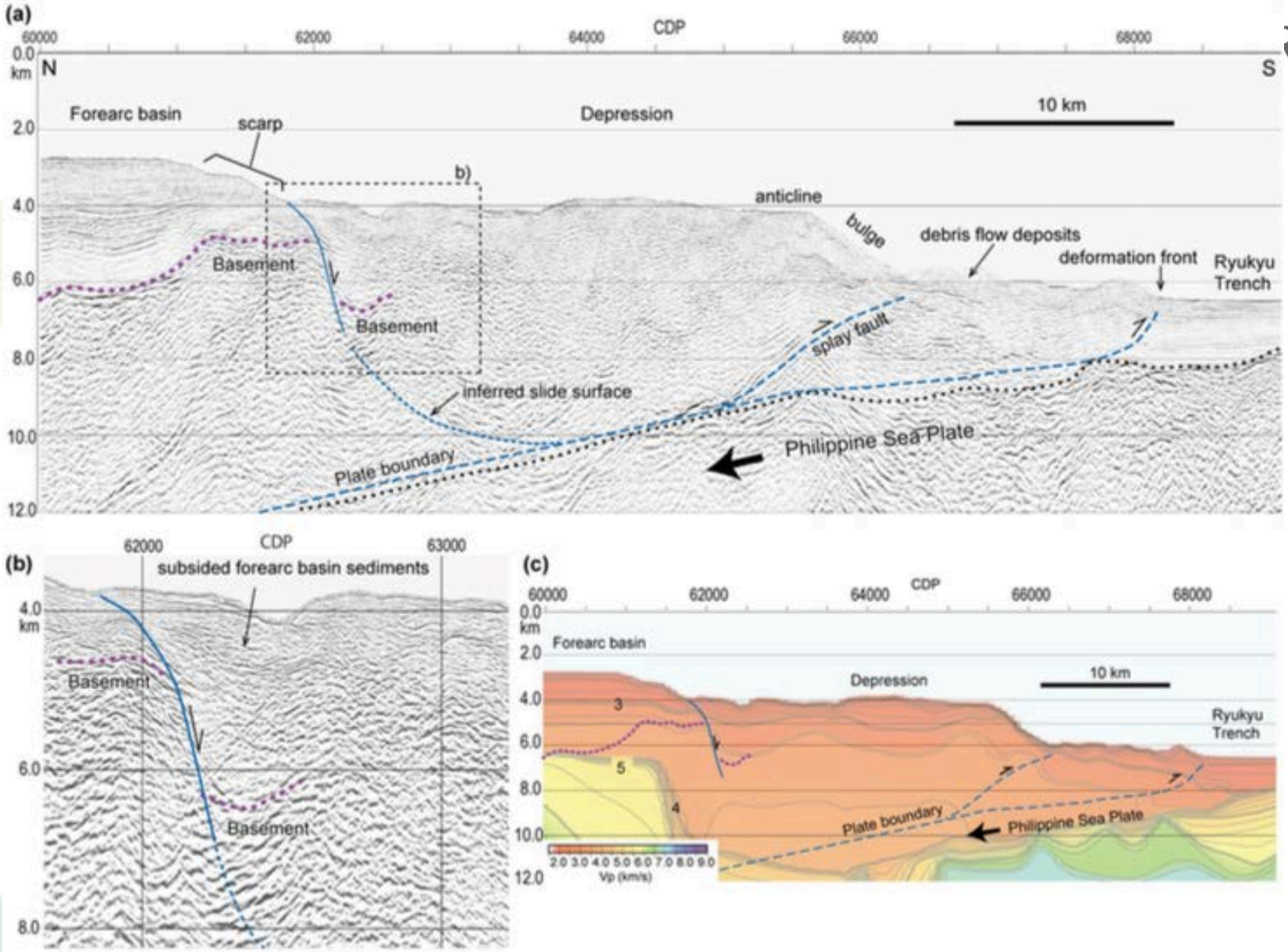
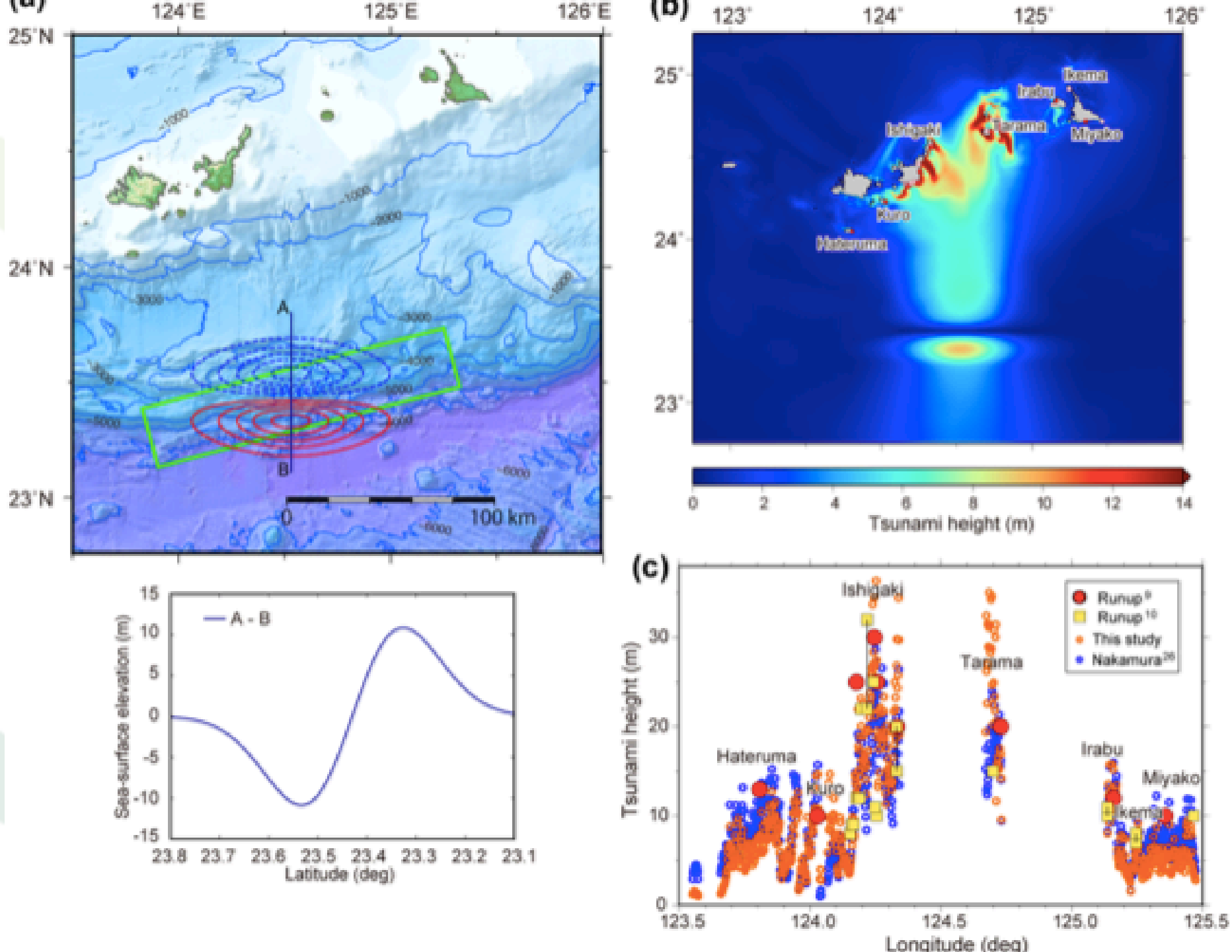
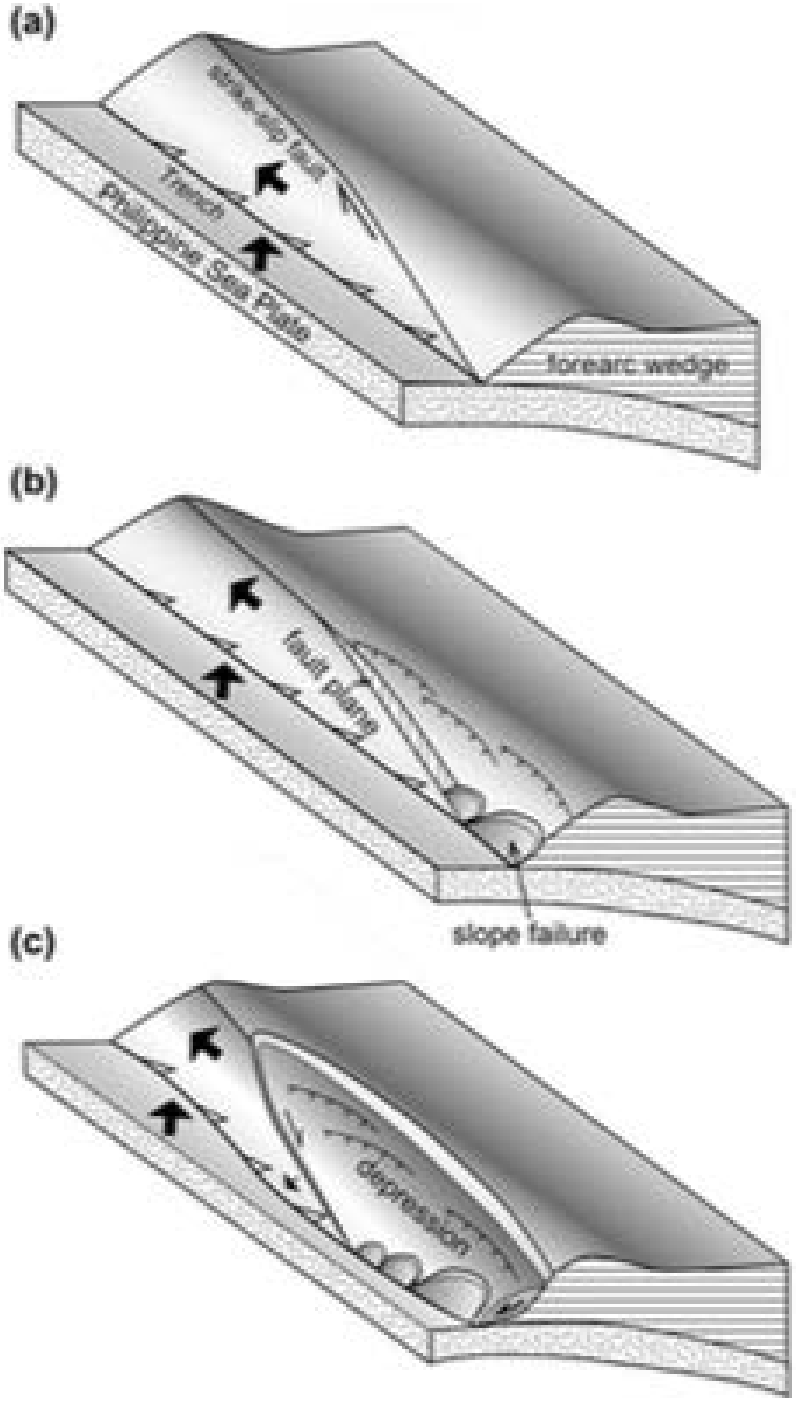
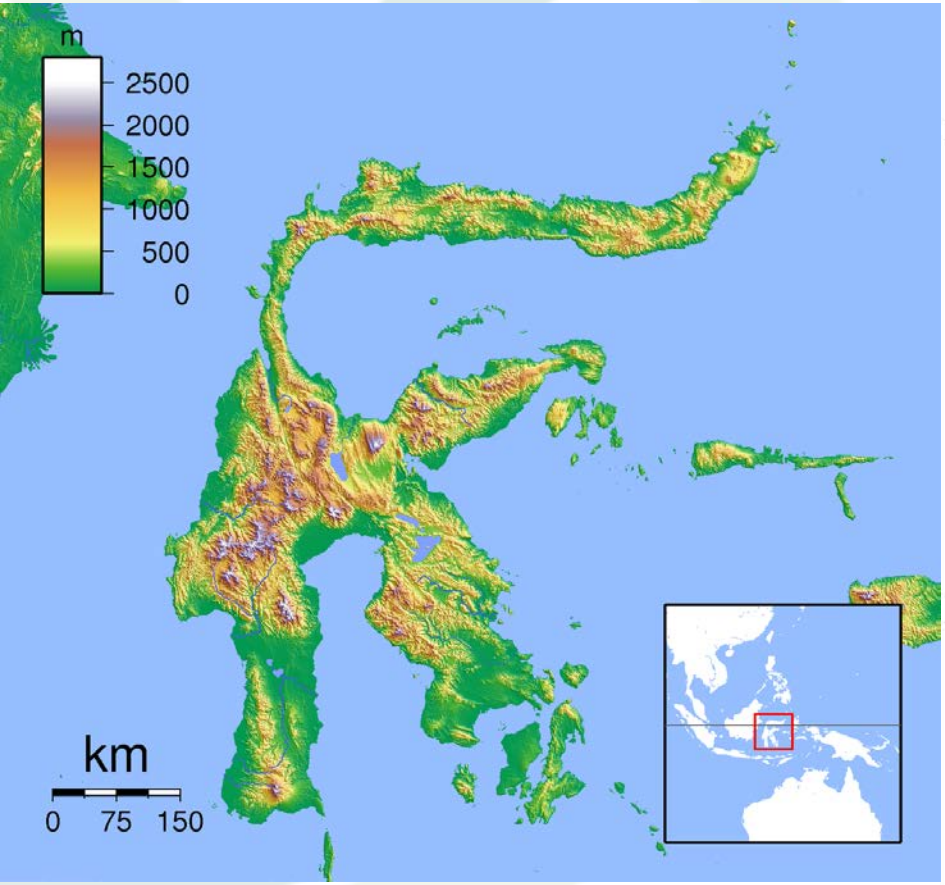


Figure 5. (**a**) Seismic cross section of the accretionary wedge along survey line ECr5. (**b**) Close up structure of the landward depression margin. (**c**) Velocity section of survey line ECr5, which is the same area as section a. Purple dotted lines are basement reflections. The plate boundary is based on the reflection profile. The images were generated with SPW 2.2 [http://www.parallelgeo.com/], GMT 4.5[46] and Adobe Illustrator CS6.

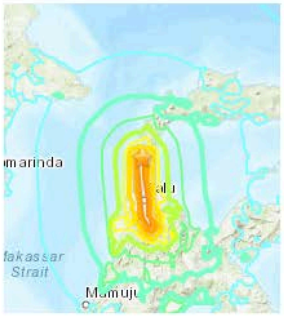

(a)
124°E
125°E
126°E
25°N
24°N
23°N
A
B
0
100 km
(b)
123°
124°
125°
126°
25°
24°
23°
Iheya
Irabu
Ishigaki
Tarama
Miyako
Kuro
Hateruma
0
2
4
6
8
10
12
14
Tsunami height (m)
A - B
Sea-surface elevation (m)
Latitude (deg)
(c)
Ishigaki
Tarama
Hateruma
Kuro
Irabu
Miyako
Runup [9]
Runup [10]
This study
Nakamura [26]
Tsunami height (m)
Longitude (deg)


(a)
Trench
Philippine Sea Plate
forearc wedge
(b)
fault plane
slope failure
(c)
depression

地震の概要



Interactive Map



Contributed by US [1]

Regional Information

Contributed by US [1]

Felt Report - Tell Us!

0 0 0 0 1 8

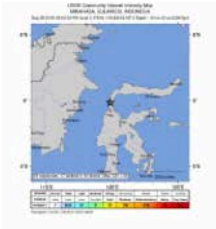
Responses

Contribute to citizen science. Please tell us about your experience.

Citizen Scientist Contributions

Did You Feel It?

VIII



Community Internet Intensity Map

Contributed by US [1]

ShakeMap

Estimated Intensity

IX mmi

Perceived Shaking

Violent

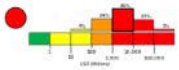
Potential Damage

Heavy

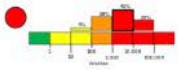
Contributed by US [1]

PAGER

RED



Estimated Economic Losses



Estimated Fatalities

Contributed by US [1]

Ground Failure

Landslides

Significant area affected

Significant population exposed

Liquefaction

Significant area affected

Extensive population exposed

Contributed by US [1]

Origin

Review Status

REVIEWED

Magnitude

7.5 mww

Depth

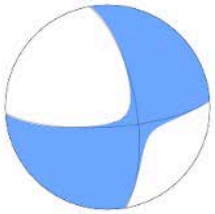
10.0 km

Time

2018-09-28 10:02:43 UTC

Contributed by US [1]

Moment Tensor

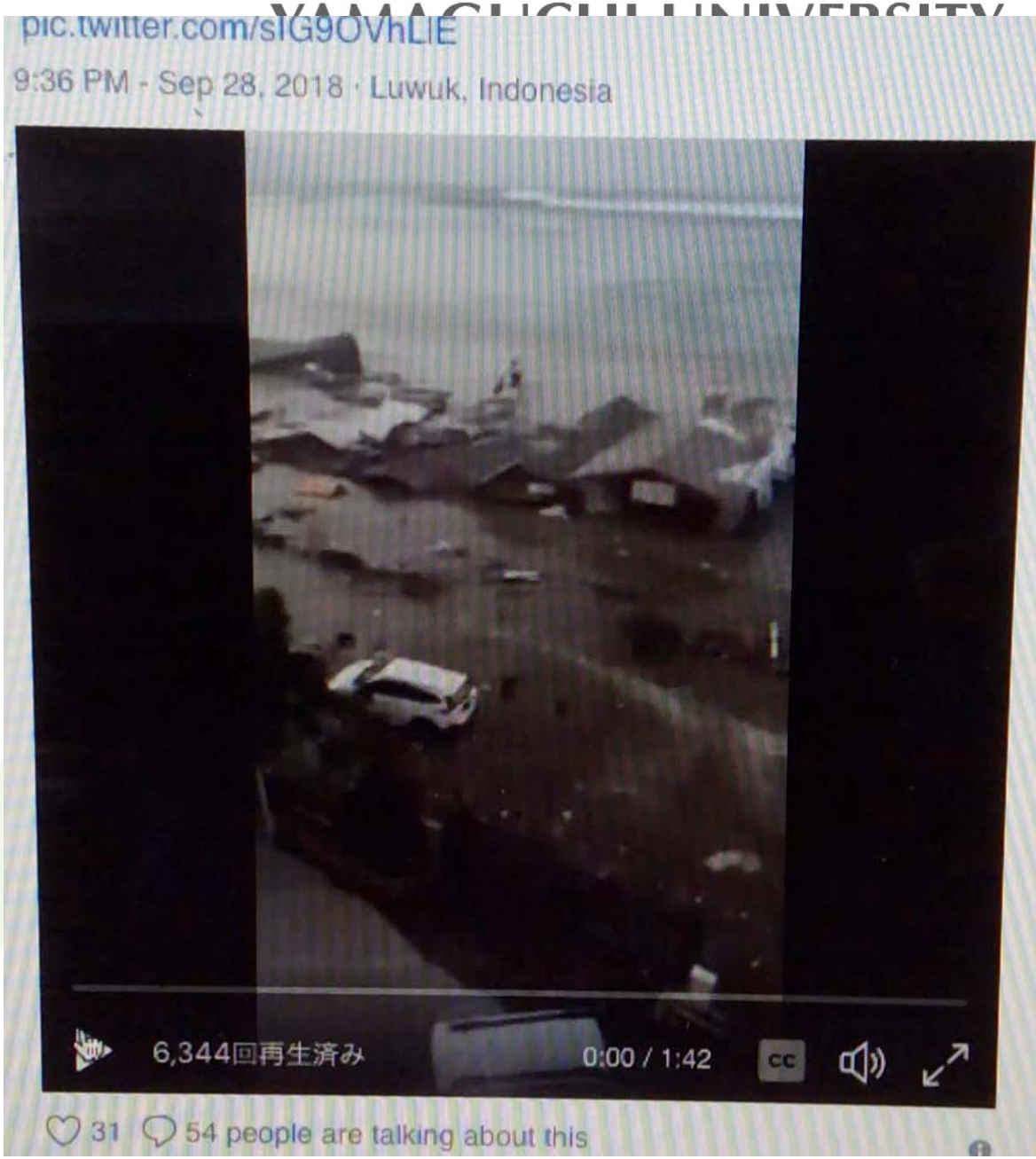


Fault Plane Solution

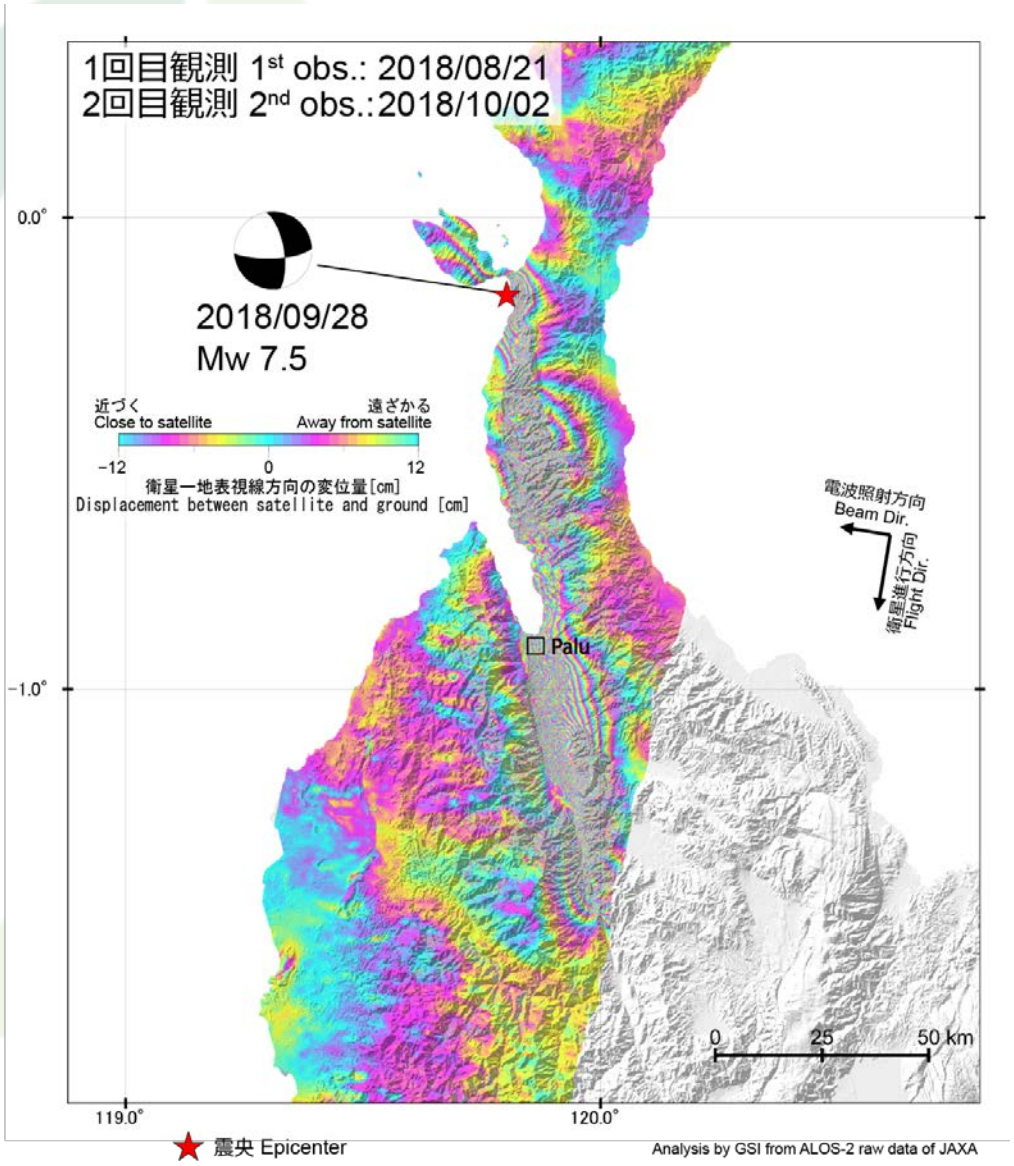
Contributed by US [1]

津波の概要

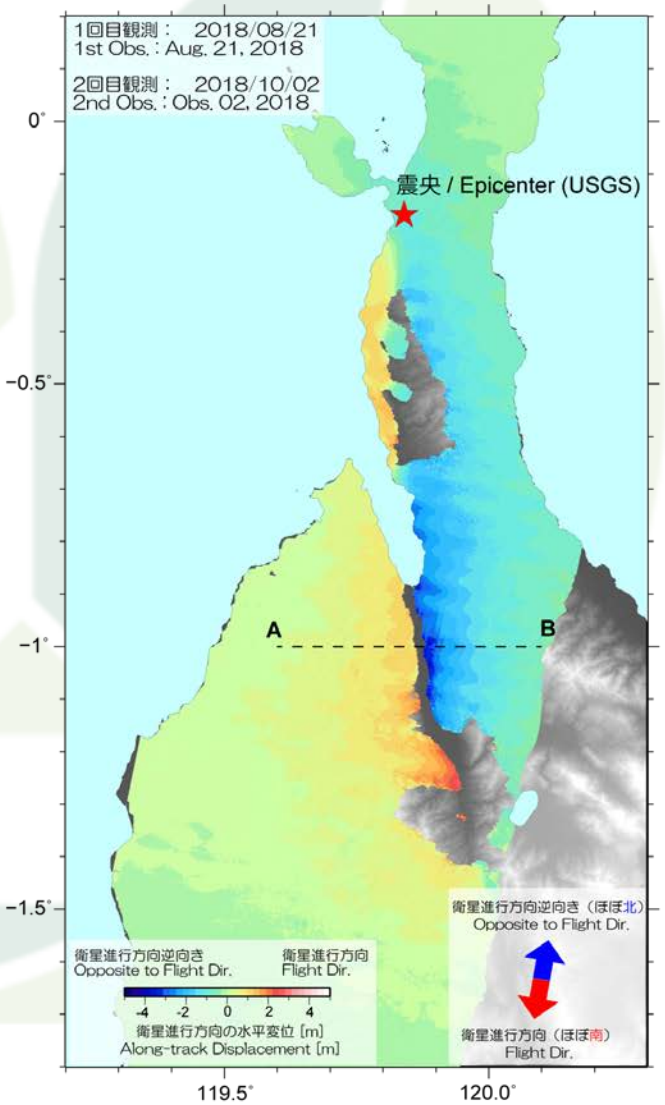
Balaesang
2.16
2.29
Sirenja
Ampibabo
DONGGALA
3.85
6.77
PARIGI MOUTONG
7.08
5.1
8.68
4.02
Towaeli
7.31
5.51
5.87
8.336
Banawa
9.58
11.51
7.09
3.75
10.91
Palu Barat
Kota PALU
Sigibi Romaru


pic.twitter.com/sIG9OVhLIE
9:36 PM - Sep 28, 2018 · Luwuk, Indonesia
6,344回再生済み
0:00 / 1:42
CC
31
54 people are talking about this

津波を生じさせた地盤変動

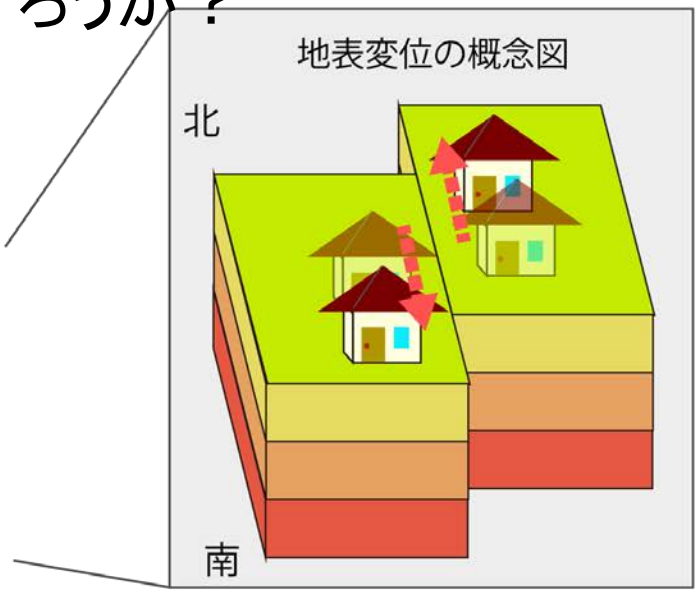


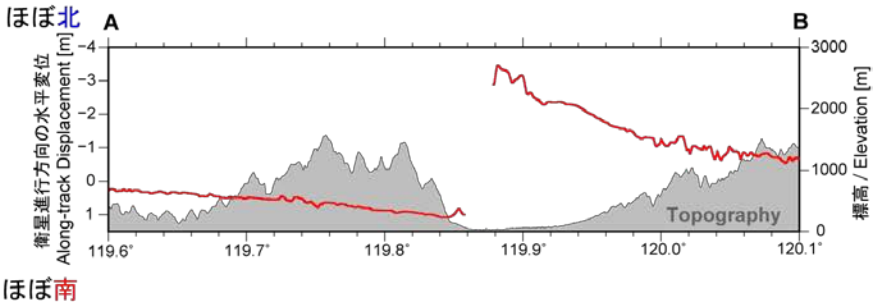
津波を生じさせた地盤変動



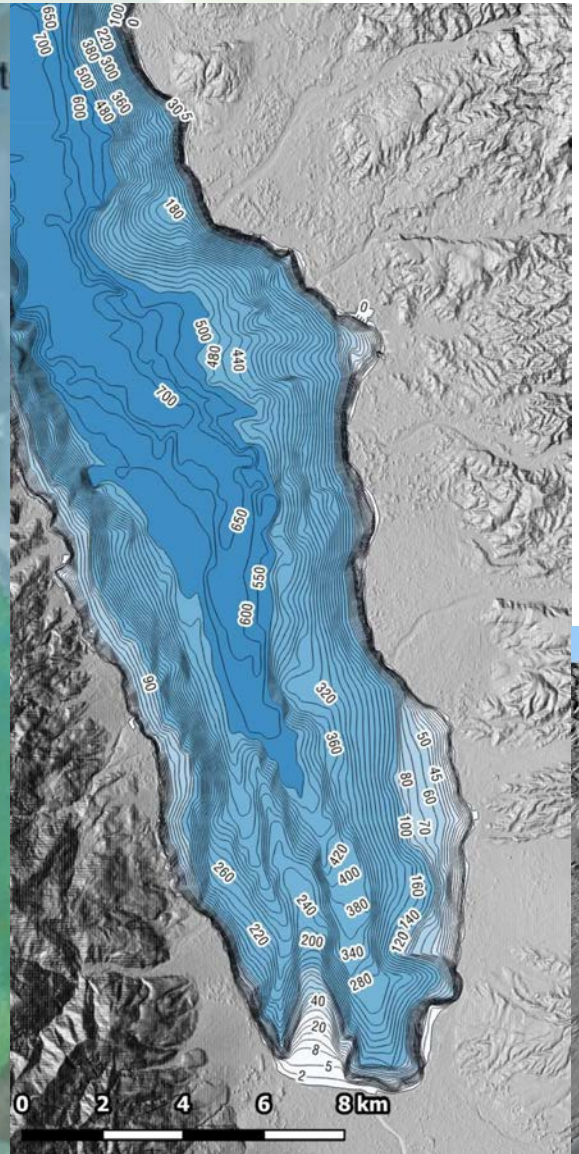
Analysis by GSI from ALOS-2 raw data of JAXA

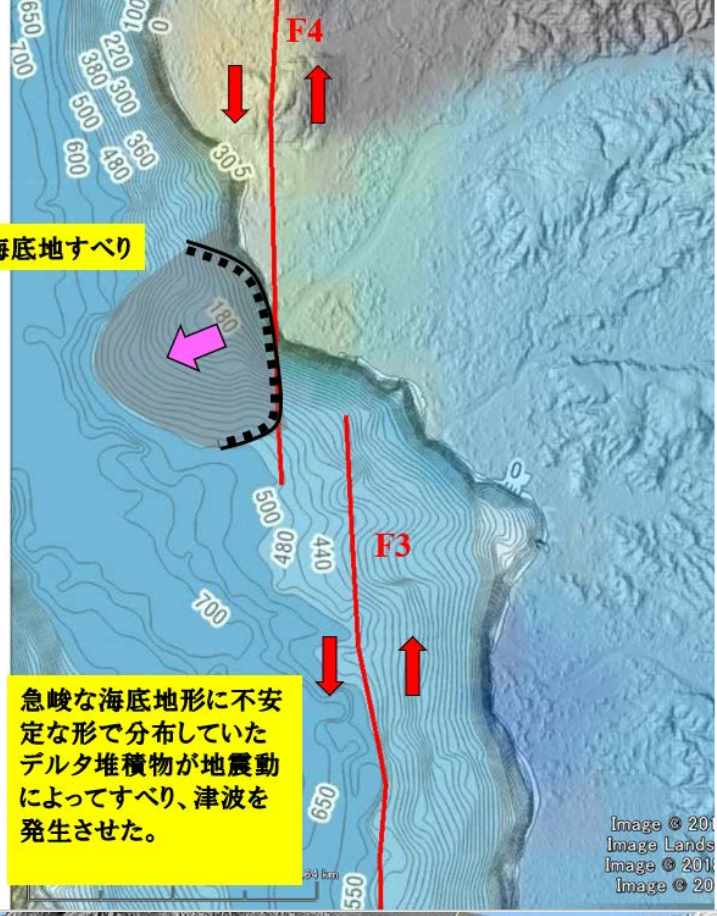
横ずれは地表を縦にずらすのだろうか？

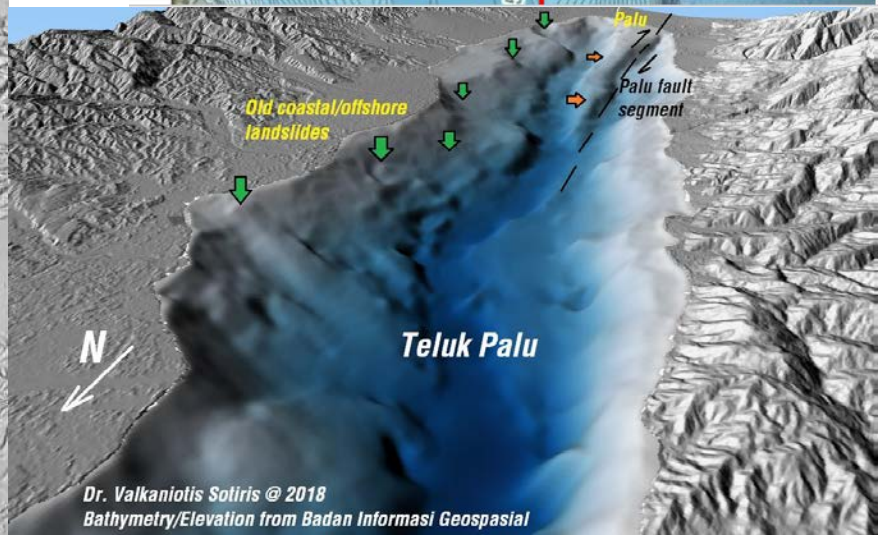




海底地すべりで津波発生







本日の話す内容

■はじめに：どういった地層が残るのか

■海底地すべり研究の最近20年ダイジェスト：

1）トリガー問題：気候変動が悪いのか

2）地質地形問題：過去の記録を読み取るにはどうすればよいか

3）災害問題：津波と海底ケーブル

■さいごに：未来に向けてどうすればよいか

はじめに

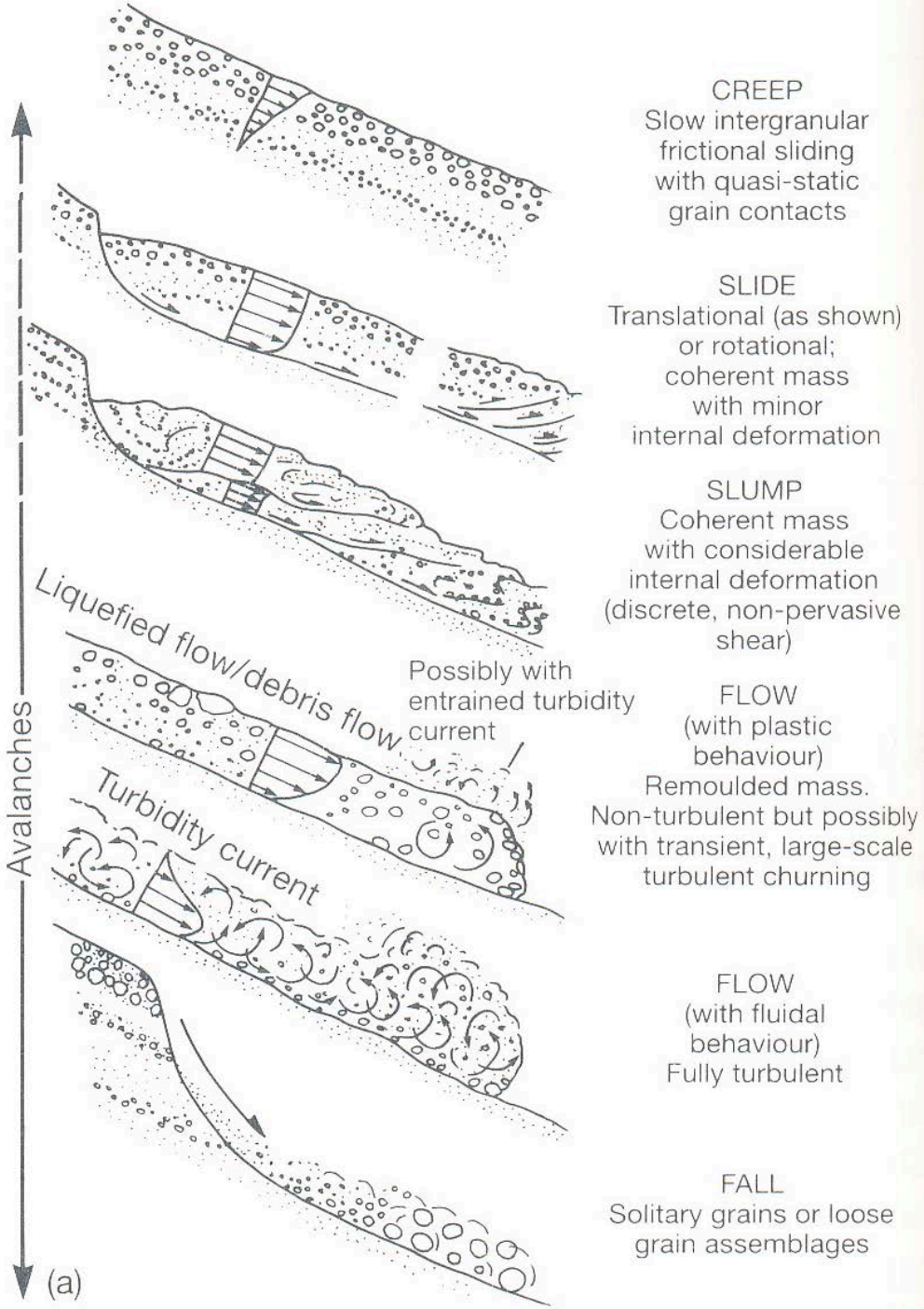
海底地すべりとは？

（用語で混乱しないように）

クリープ性から崩壊性まである．狭義でSlideというと，崩壊物が原型をほぼ保ったまま斜面を滑落する現象である．

海底地すべりは，スランプもフローも含めて議論していることが多い．

Maltman (1993; Chapman&Hall))



メタンハイドレート層分解→海底地すべり→混濁流→メガタービダイト？

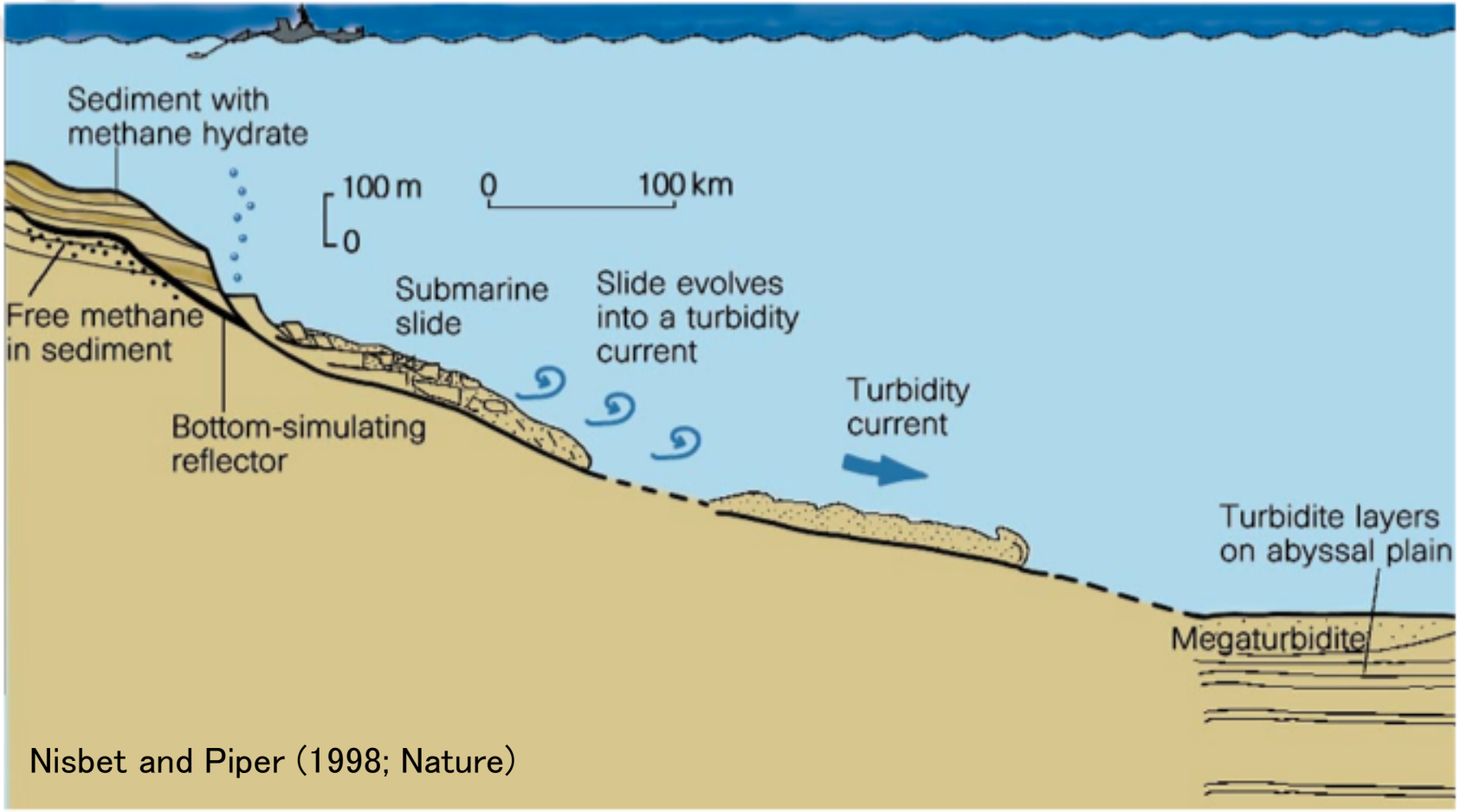
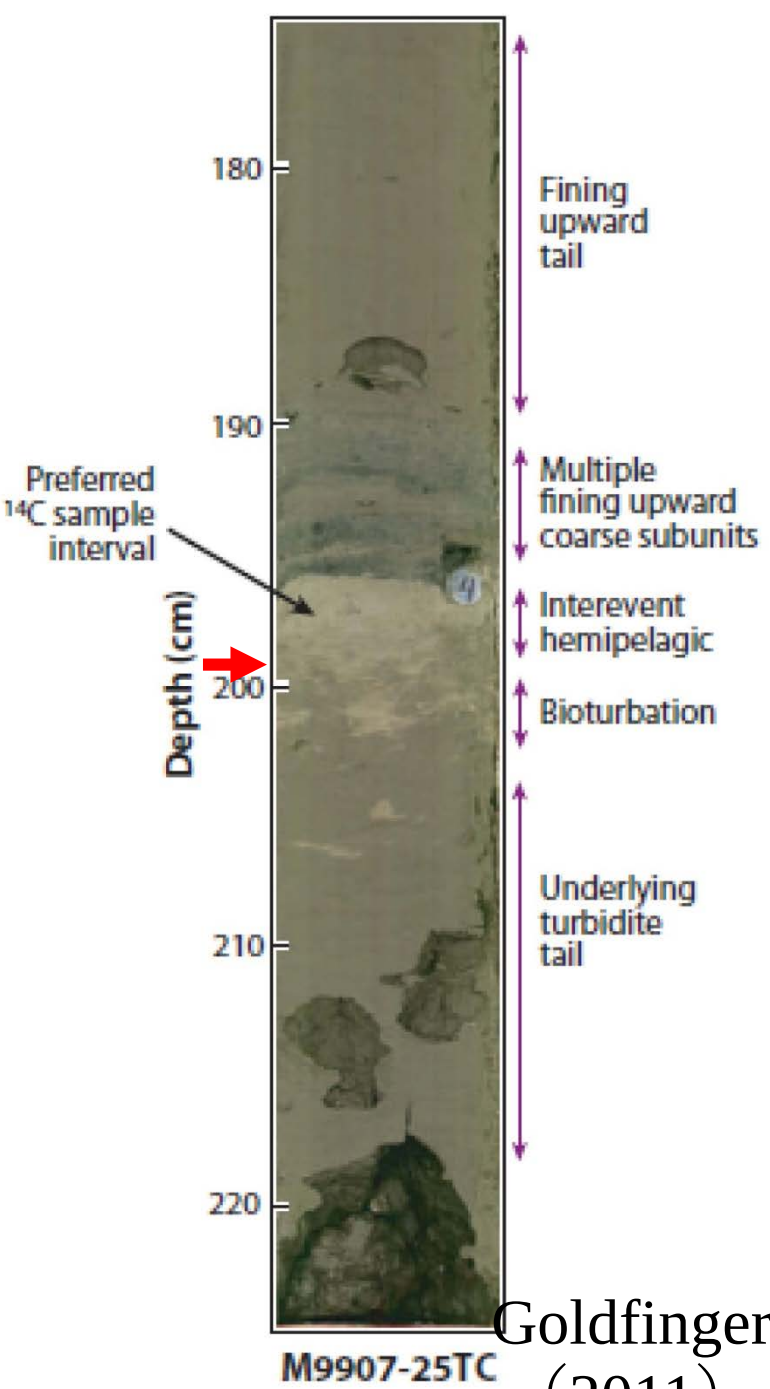


Figure 1 **The likely mode of formation of a megaturbidite deposit, such as that described by Rothwell *et al.*[4]. Unstable sediment accumulations collapse when perturbed, maybe with associated release of methane, resulting in a submarine landslide and flow of dense currents of sediment (turbidity currents) down a continental slope. The end result is turbidite sequences on the abyssal plain.**

タービダイト層上限が明瞭な例

- 混濁流の供給源での地質と堆積域での地質とが大きく異なり，タービダイトの上限の決定が容易なことがある．
- 右図は，カスカディアのタービダイトである．赤矢印の部分を境に色が変化し，明るい色が半遠洋性泥層，より下位がタービダイトであり，タービダイトの上限が明瞭になっている．
- しかし，日本周辺では，供給源と堆積域との地質が大きく異ならない，すなわち構成粒子が類似している場合があり，このとき，タービダイト泥の上限とその上位に堆積する泥質堆積物層との区別がつきにくくなる．



Goldfinger（2011）

近年言われている泥質堆積物の年代問題(Urlaub et al., 2013)

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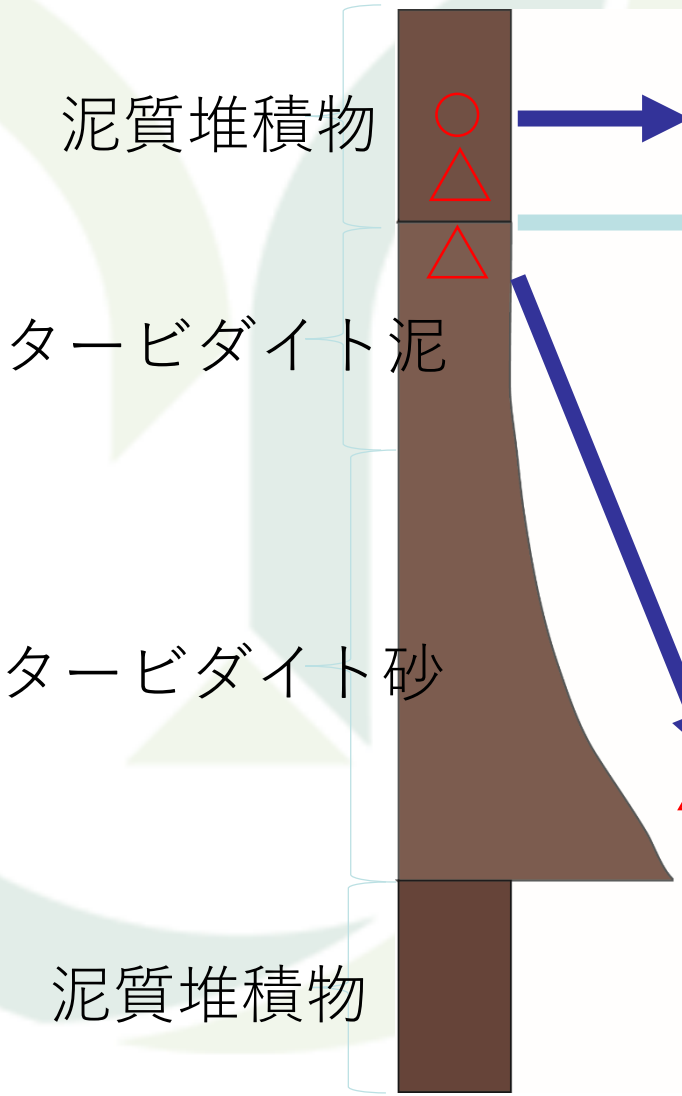


○ 例えば，タービダイト上限より十分上位の泥質堆積物は年代測定に適している．

しかし，タービダイト上限は生物擾乱で不明瞭になることがある

△ そのため，上限付近は、年代が古い可能性がある

Urlaub et al. (2013)

Ulraub et al. (2013)が指摘している年代問題

報告される最小年代値　報告される最大年代値　報告された年代

Event		Age [ka]			
		Min	Max	Best	Published
Agadir basin	A3	35.00	45.00	40.00	
	A5	54.00	64.00	59.00	
	A7	75.00	85.00	80.00	
	A10	95.00	115.00	105.00	
	A11	105.00	125.00	115.00	
	A12	120.00	130.00	125.00	
	A13	120.00	140.00	130.00	
Amazon	Shallow W	12.35	21.38		
	Deep E	35.00	37.00	36.00	
	Deep W	41.00	45.00	43.50	
Balearic abyssal plain		20.32	23.58	21.95	
BIG95*		11.60	15.57	12.39	>11.00
Black Shell			18.65		
Cape Blanc		135.00	175.00		
Cape Fear*		11.12	31.10	11.29	11.00–31.10
Flemish Pass (Ca)	1	128.50	143.80	136.00	
	2	81.70	118.10	102.00	
	3	78.50	115.10	99.00	
	4	59.10	116.80	83.70	
	5	56.10	117.00	74.00	

海底地すべりに関する疑問

- ■長期的な要因はあるのか
- ■最終的なトリガーはなにか
- ■規模を決めるのはなにか
- ■地層記録として残るのか
- ■どんなことが起こるのか
- ■どうやったら減災できるのか

ということで，まずは，長期的な要因と最終的なトリガーについて解説したい.

本日の話す内容

■はじめに：どういった地層が残るのか

■海底地すべり研究の最近20年ダイジェスト：

1）トリガー問題：気候変動が悪いのか

2）地質地形問題：過去の記録を読み取るにはどうすればよいか

3）災害問題：津波と海底ケーブル

■さいごに：未来に向けてどうすればよいか

1）気候変動と海底地すべり

- **海水準の低下**→水圧減少→メタンハイドレート分解→海底地すべり（これは**高緯度**において否定される，地すべり年代約8000年）
- **底層流の温度上昇**は，5度？．これにより，一部のメタンハイドレートが分解し，崩壊が連鎖した．
- クラスレートガン仮説に示されるように，歴史から言ってもメタンハイドレートと海底地すべりは関連している．
- 海底地すべりの崩壊域の水深が1000m程度でそろっている．

大西洋の海底地すべりの分布図（西側）

滑落崖のヘッドの水深はおおよそ1000–1300 mでそろっている.
→メタンハイドレートとの関連性が指摘される.

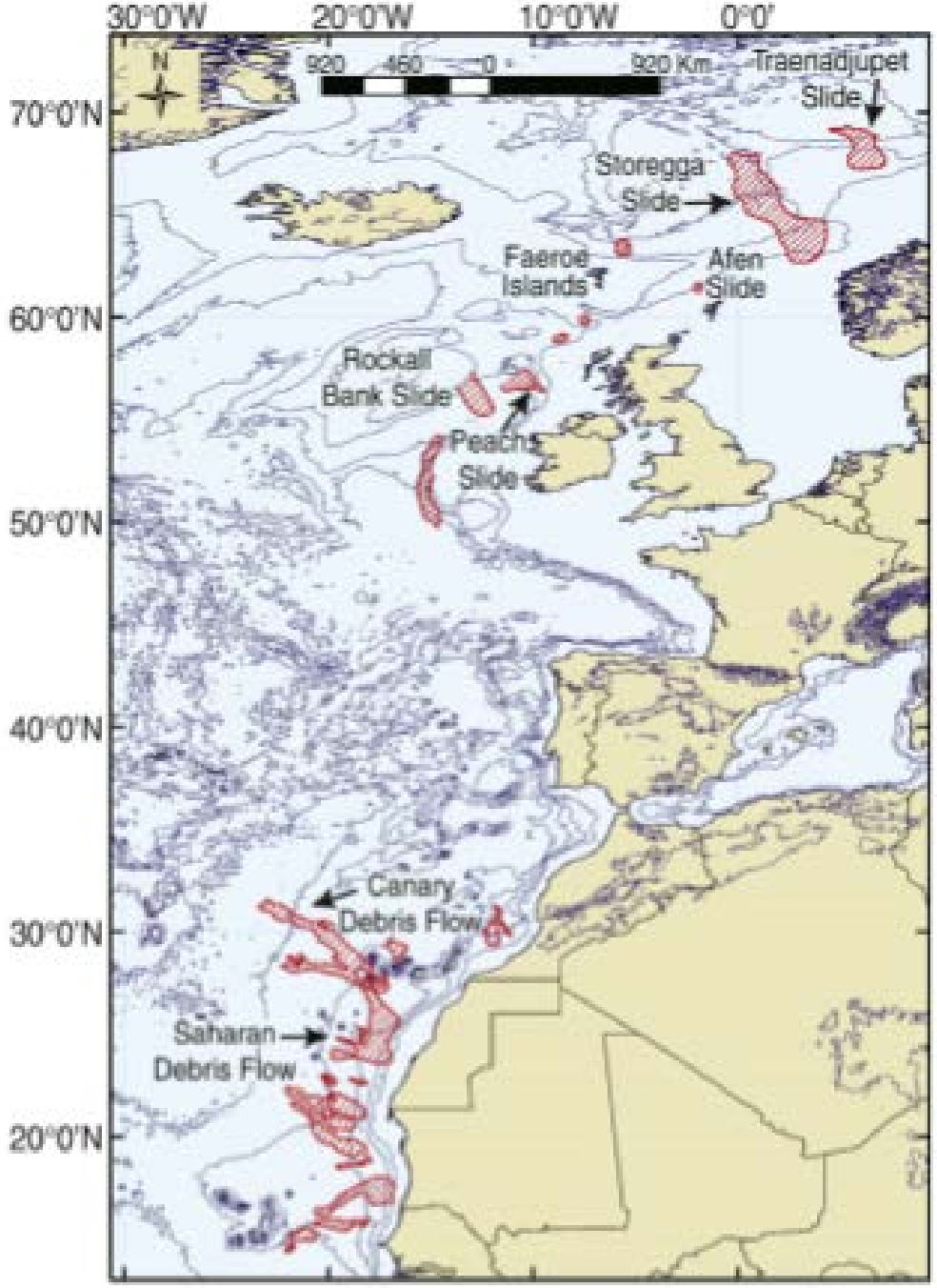
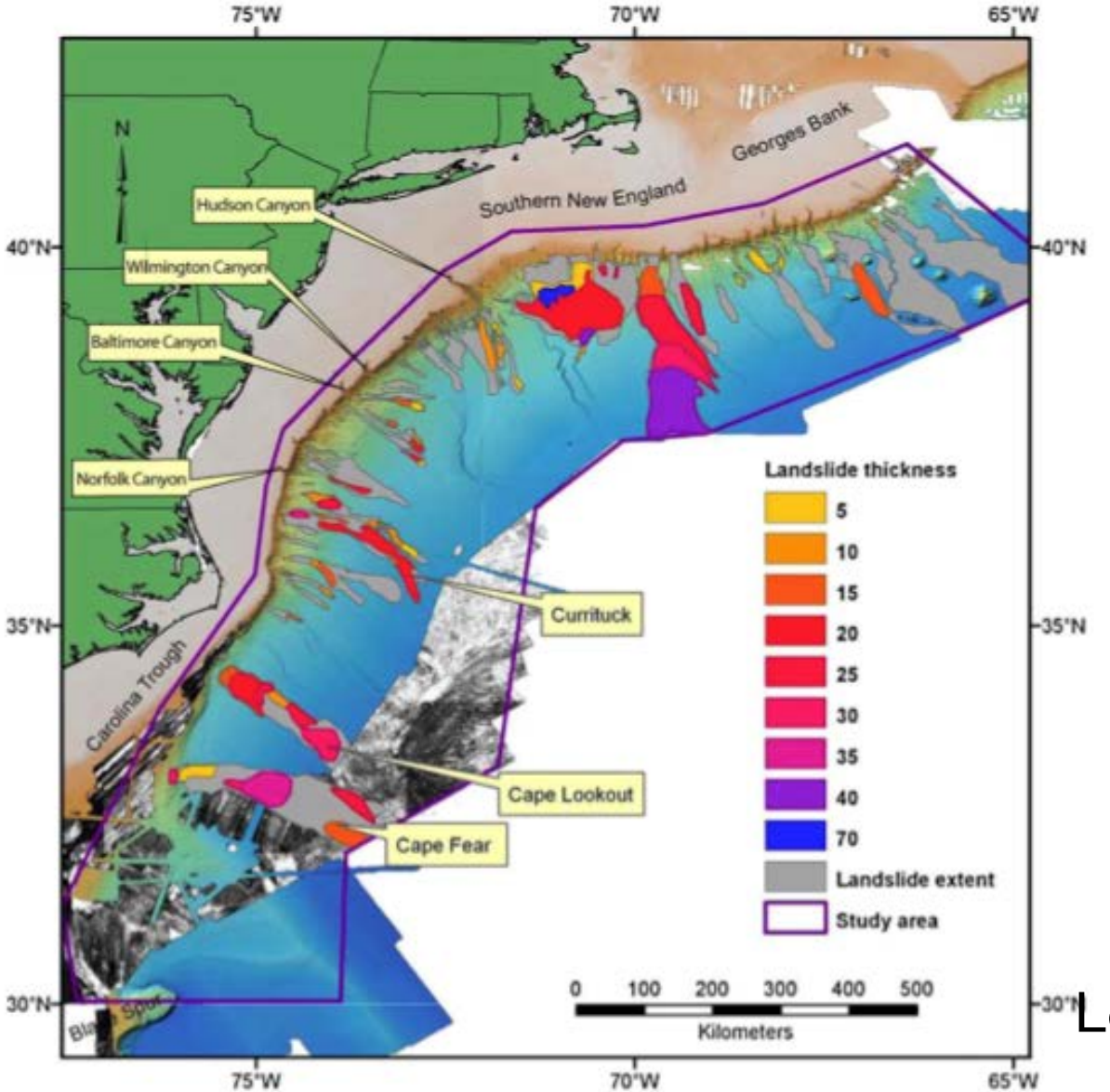


Fig. 4. Locations of submarine landslides discussed in the text off Europe and North Africa.

Lee (2009; Mar. Geol.)

大西洋の海底地すべりの分布図（東側）



大西洋の海底地すべりの分布図（東側）
やはりヘッドの水深がそろっている.

Lee (2009; Mar. Geol.)

Fig. 3. Locations of east coast submarine landslides discussed in the text (after Twichell et al., 2008-this issue). Deposit thicknesses shown for several of the large landslides.

Clathrate Gun hypothesis

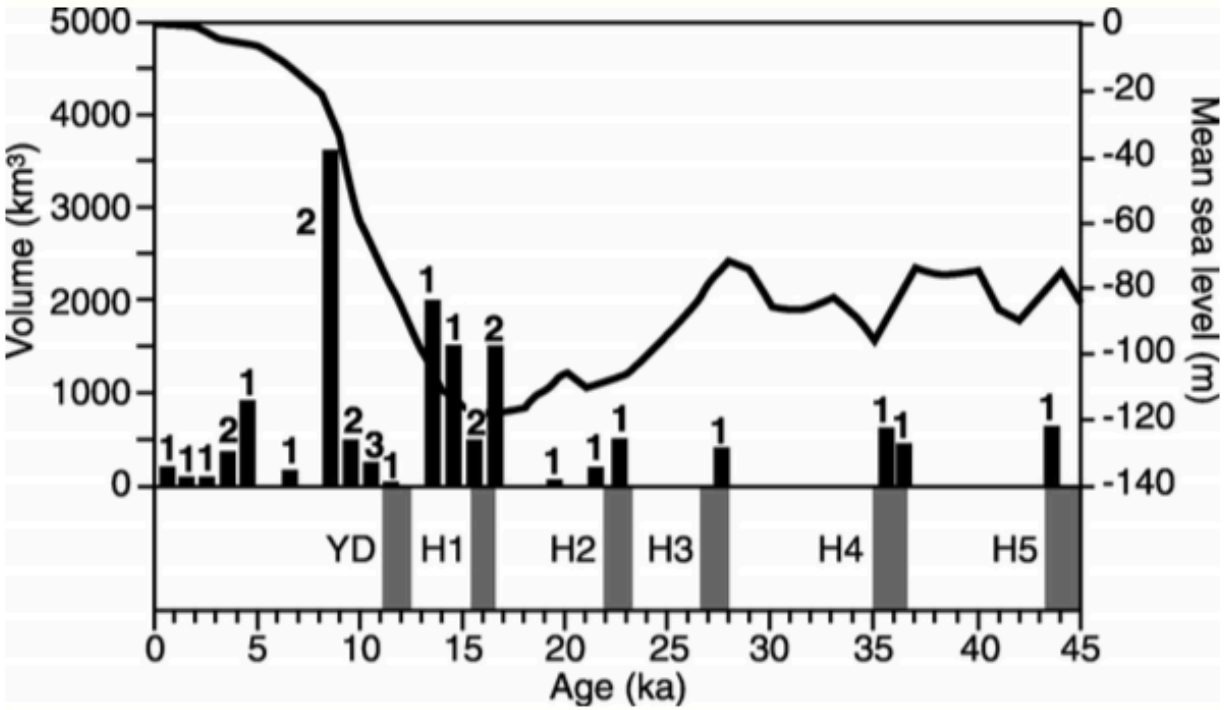


Figure 2. Total volume of mass transport or slide deposits (black bars) and number of failures (small numbers next to bars) compared with mean relative sea level (curve) for past 45 k.y. (McGuire et al., 1997). Heinrich events (H1–H5) and Younger Dryas (YD) are shown for comparison.

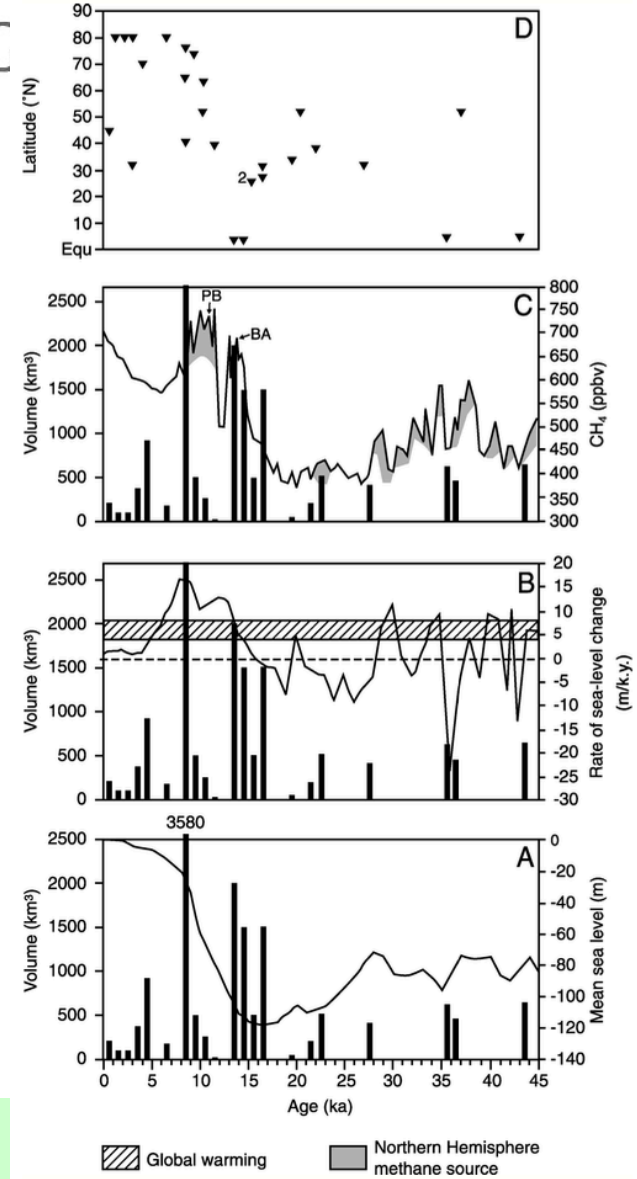


Figure 3. Total volumes of mass transport or slide deposits are compared with (A) mean sea level (McGuire et al., 1997), (B) rate of sea-level change (McGuire et al., 1997), and (C) atmospheric methane (Brook et al., 1999). Note that in B, current predicted sea-level rise over next century due to global warming has been plotted for comparison. Note that in C, shaded region indicates distinct Northern Hemisphere methane source (Dällenbach et al., 2000). Plot of latitude of each slide deposit (D) shows marked change from predominantly low-latitude occurrences prior to ca. 14 ka to high-latitude occurrences after 11 ka. BA—Bølling-Allerød; PB—Preboreal.

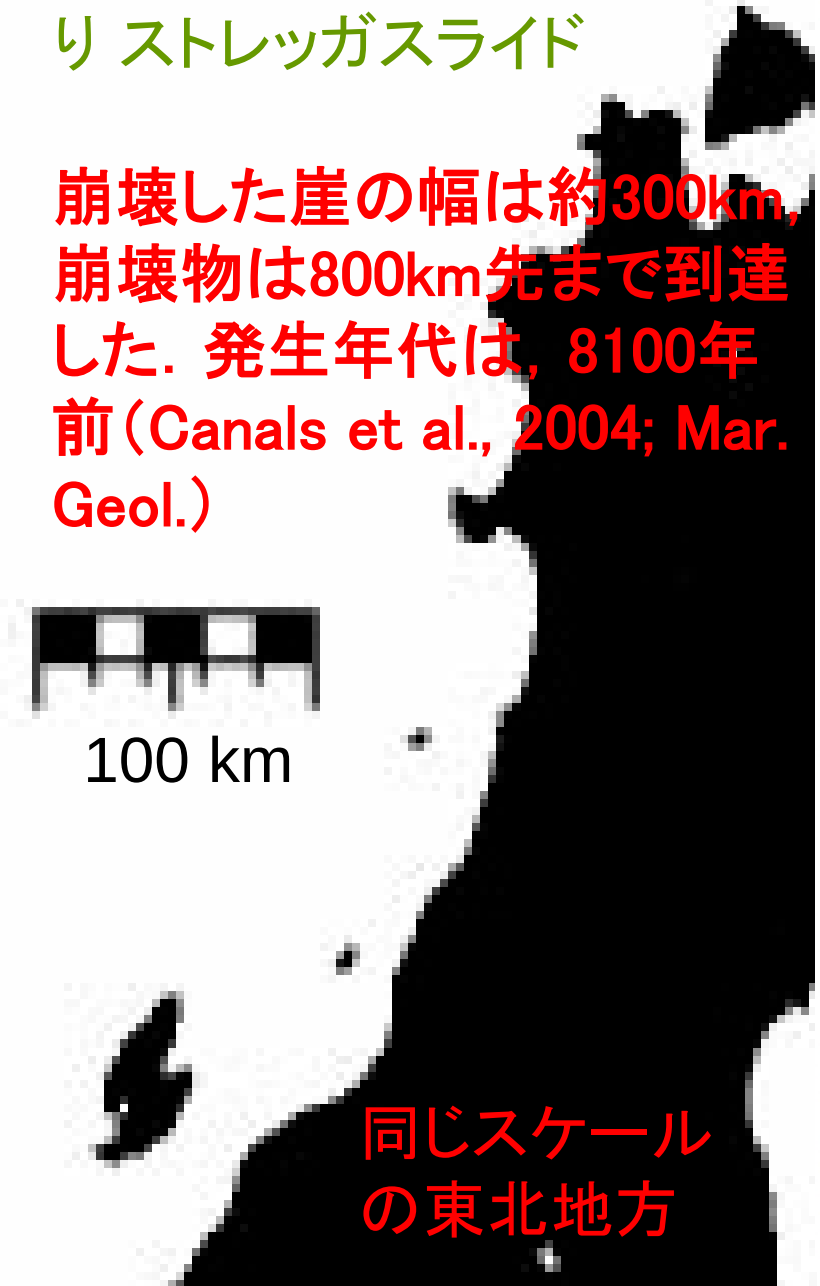
MH崩壊によって大気中にメタンが放出される．それは氷期の海水準の低い時期．すなわち，氷期→海水準低下→減圧→MH崩壊→海底地すべりとなる．

Maslin et al. (2004; Geol.)

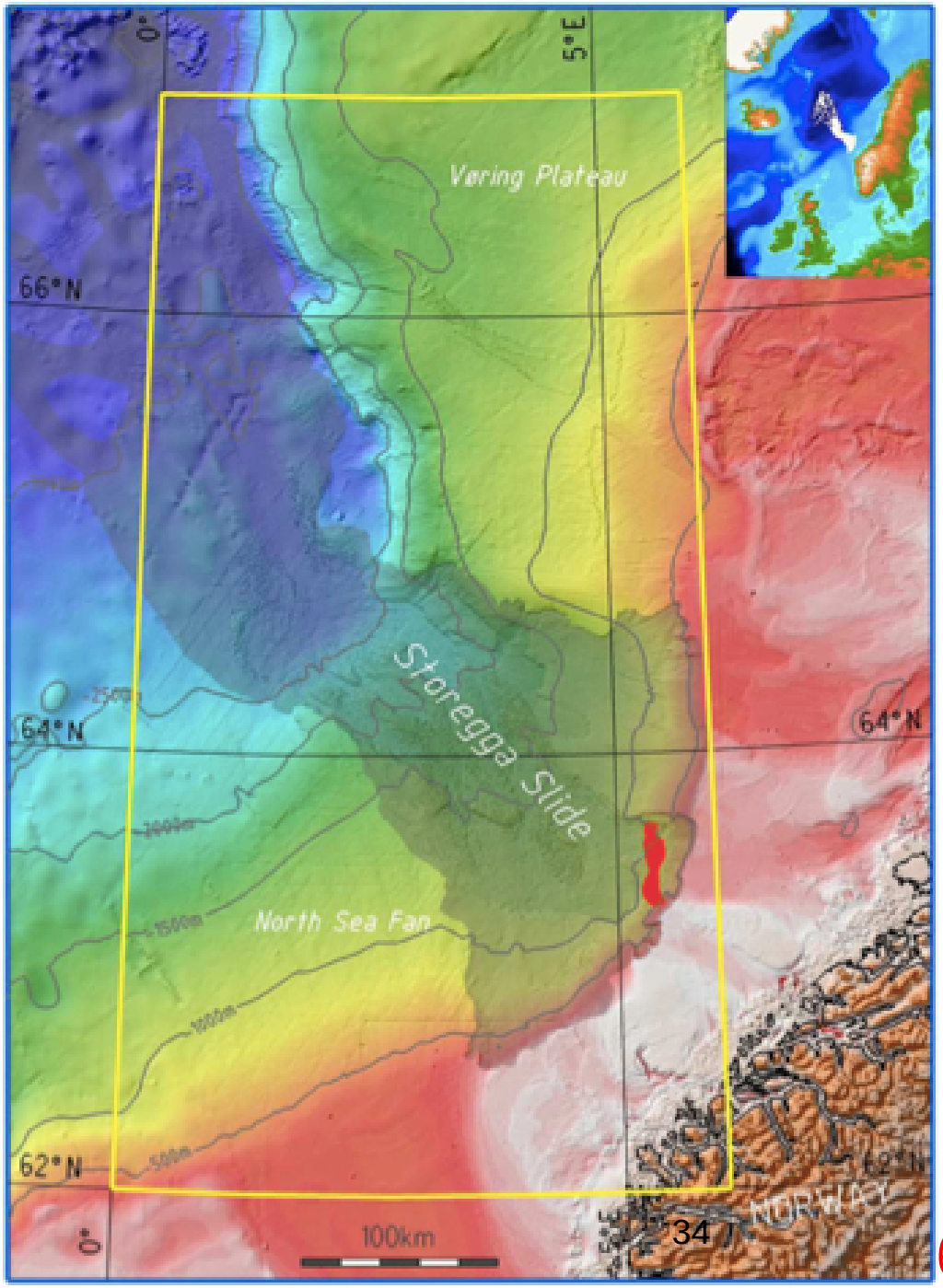
Solheim et al. (2005; MPG)

ノルウェー海の海底地すべり ストレッガスライド

崩壊した崖の幅は約300km，崩壊物は800km先まで到達した．発生年代は，8100年前（Canals et al., 2004; Mar. Geol.）



同じスケールの東北地方



海面低下と海水温上昇によって，ある程度のメタンハイドレート崩壊はありうる．現在のBSRは切れ切れ．これは過去に何度も変動したからか？

Mienert et al. (2005; MPG)

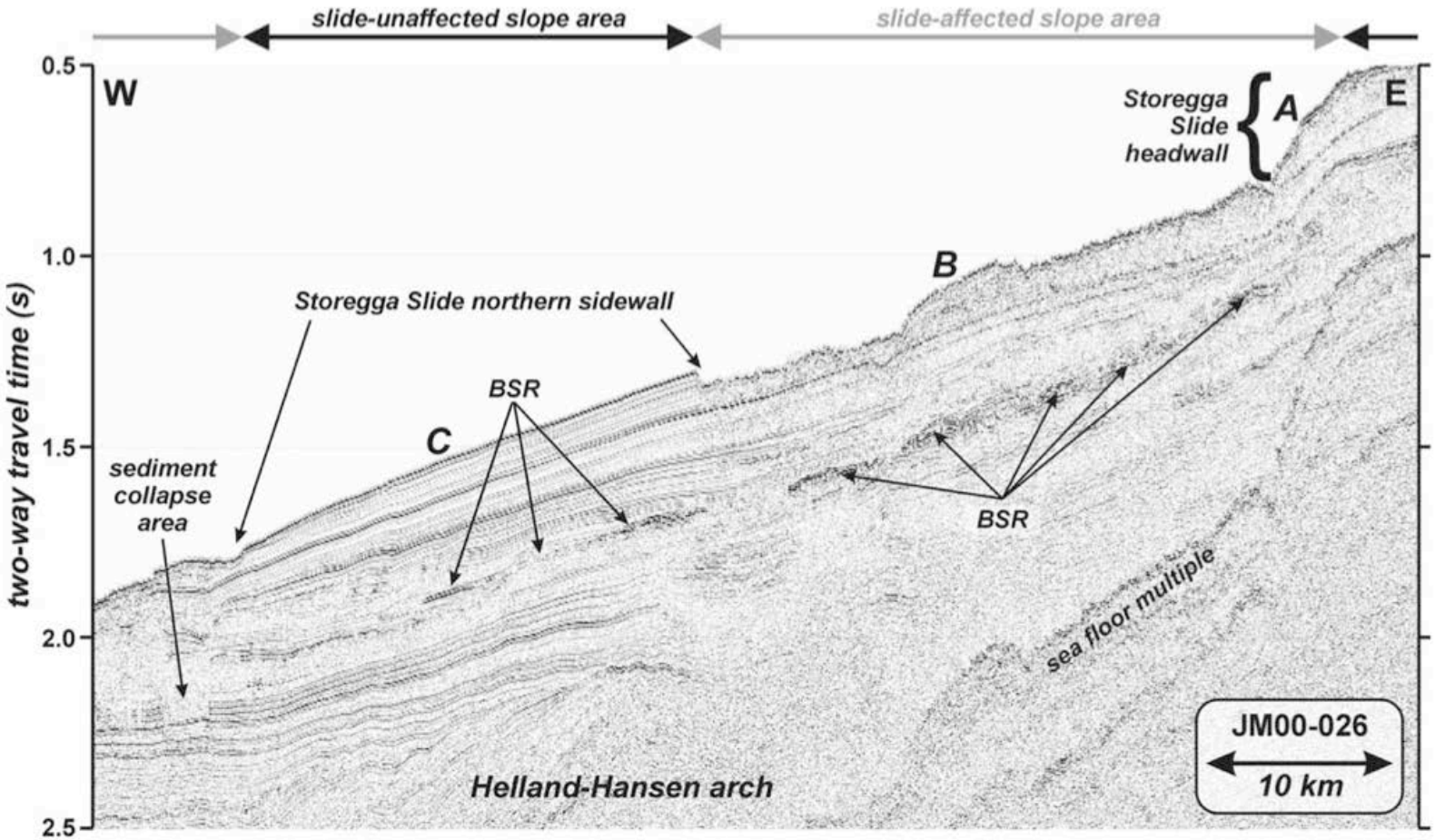
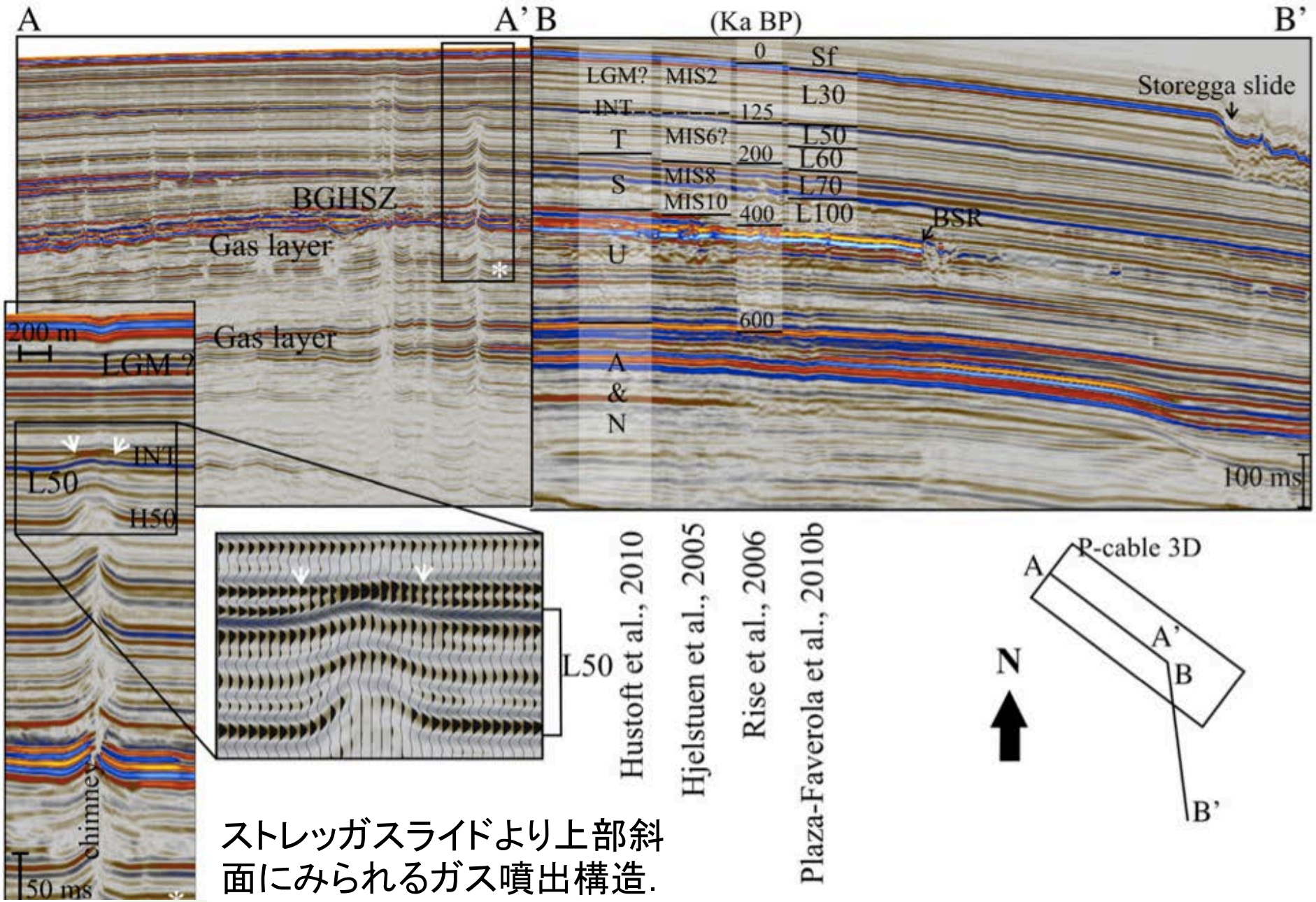


Fig. 4. 70.8 km long high-resolution seismic reflection profile JM00-026 crossing both the Storegga Slide headwall and its northern side wall. For location, see Fig. 1. The discontinuous and irregular BSR feature lies at approximately 320 ms TWT or close to 270 m sub-bottom depth, both within and outside the slide-affected area. The 'collapse area' denotes the area of inferred landslide-induced hydrate dissociation discussed in Berndt et al. (2005). (A)–(C) refer to the comparison with the modelling, presented in Fig. 6.



ストレッガスライドより上部斜面にみられるガス噴出構造.

Plaza-Faverola et al. (2011; EPSL)

オルメンランゲ・ガス田

YAMAGUCHI U

北海・ノルウェー海の
天然ガスや石油は，
海底パイプラインに
よって輸送されている．

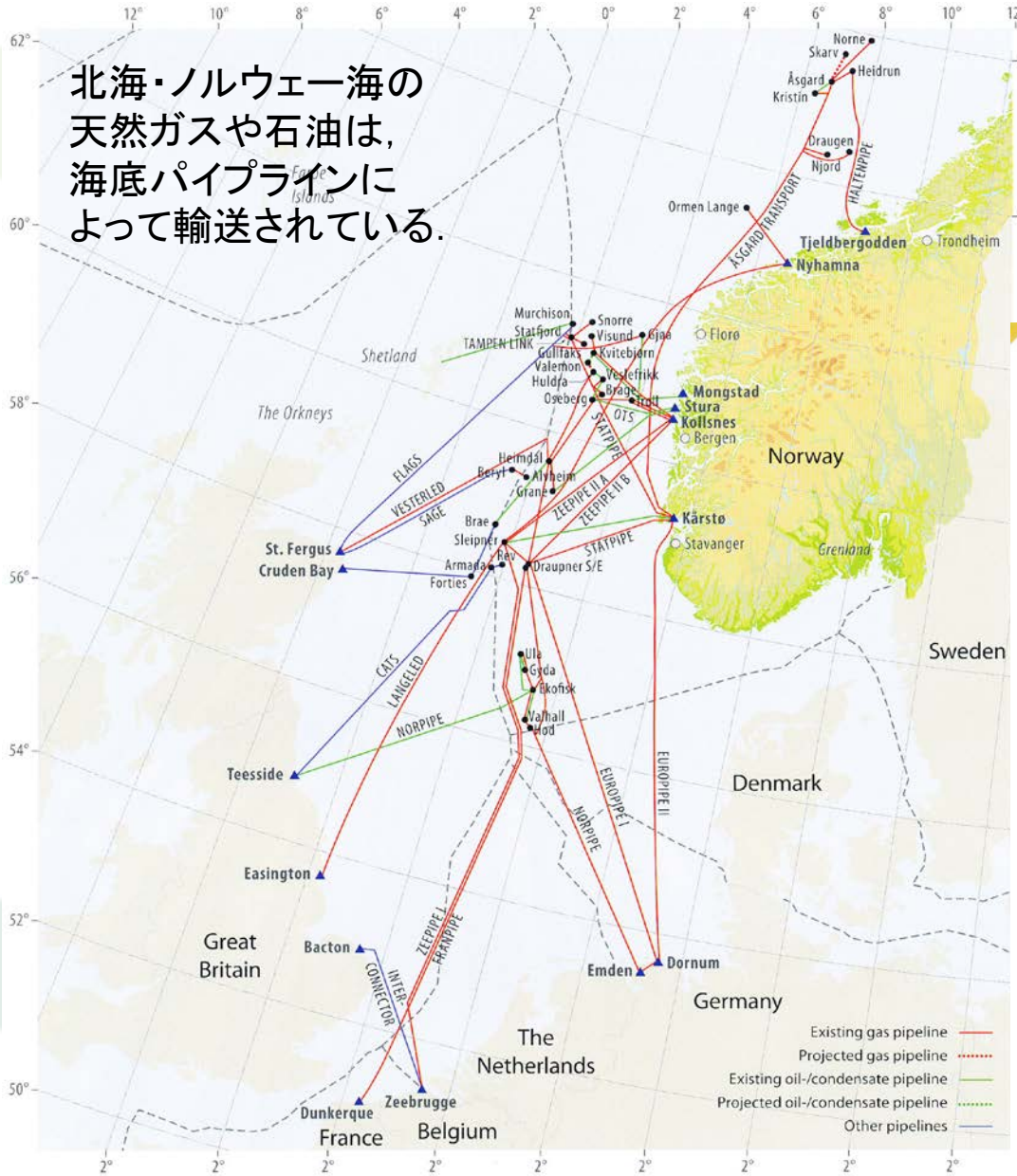


Figure 14.1 Existing and projected pipelines *(Source: The Norwegian Petroleum Directorate)*

1997年に発見され，2007年から採取している．回収可能スタンダードガス（20℃換算），約3000億立米．これがストレッガスライドの直下にある．

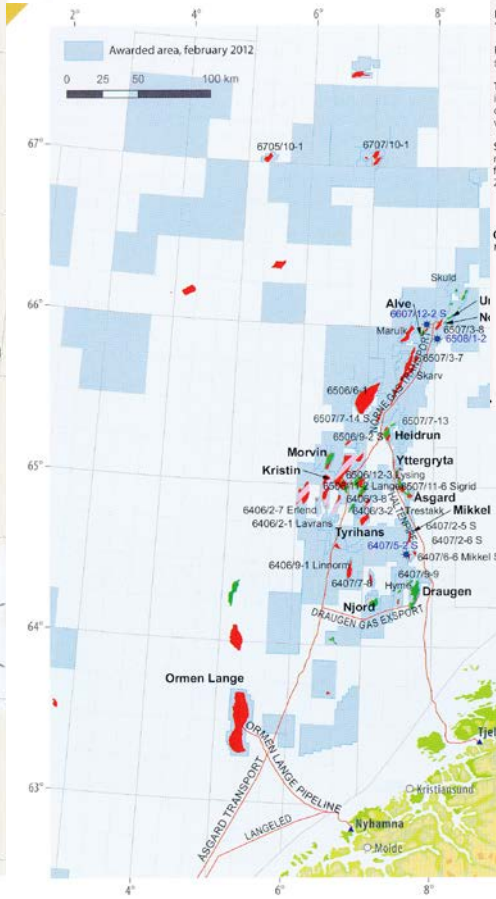
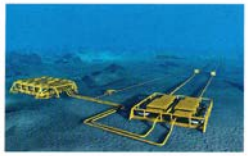


Figure 10.6 Fields and discoveries in the Norwegian Sea *(Source: Norwegian Petroleum Directorate)*

Ormen Lange

Blocks and production licences	Block 6305/4 - production licence 209, awarded 1996. Block 6305/5 - production licence 209, awarded 1996. Block 6305/7 - production licence 208, awarded 1996. Block 6305/8 - production licence 250, awarded 1999.		
Development approval	02.04.2004 by the Storting	Discovered 1997	
On stream	13.09.2007		
Operator	A/S Norske Shell		
Licensees	A/S Norske Shell		17.04 %
	DONG E&P Norge AS		10.34 %
	ExxonMobil Exploration & Production Norway AS		7.23 %
	Petoro AS		36.48 %
	Statoil Petroleum AS		28.92 %
Recoverable reserves	Original	Remaining as of 31.12.2011	
	297.0 billion Sm^3 gas	220.5 billion Sm^3 gas	
	16.2 million Sm^3 condensate	10.2 million Sm^3 condensate	
Estimated production in 2012	Gas: 21.23 billion Sm^3, Condensate: 1.69 million Sm^3		
Expected investment from 2011	30.6 billion 2011 values		
Total investment as of 31.12.2010	31.1 billion nominal values		
Main supply base	Kristiansund		

Development: Ormen Lange is a gas field located in the More Basin in the southern part of the Norwegian Sea. The water depth in the area varies from 800 to in excess of 1 100 metres. The deep water and the seabed conditions have made the development very challenging and have triggered development of new technology.



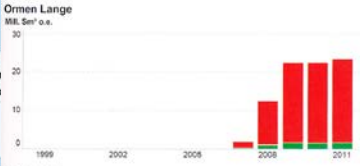
The field is being developed in several phases. The plans for development of Ormen Lange call for 24 deepwater wells. In 2007 two subsea templates were located in the central area of the field. In 2009 the third template was installed in the southern part of the field. The fourth template was installed in the northern part of the field in 2011.

Reservoir: The main reservoir consists of sandstones of Paleocene age in the "Egga" Formation, about 2 700 - 2 900 metres below sea level.

Recovery strategy: The field is recovered by pressure depletion and, at a later stage, gas compression.

Transport: The wellstream, which contains gas and condensate, is transported in two multi-phase pipelines to the onshore facility at Nyhamna, where gas is dried and compressed before it is sent in the gas export pipeline, Langeled, via Sleipner R, to the UK.

Status: The field is producing at plateau with 15 wells. Reserve estimates were reduced considerably in 2011. During 2011, the licence changed its base case for future gas compression to a combination of onshore compression from 2016 together with an infield compression solution from 2021.



NPS（2012）

底層流と海底地すべり

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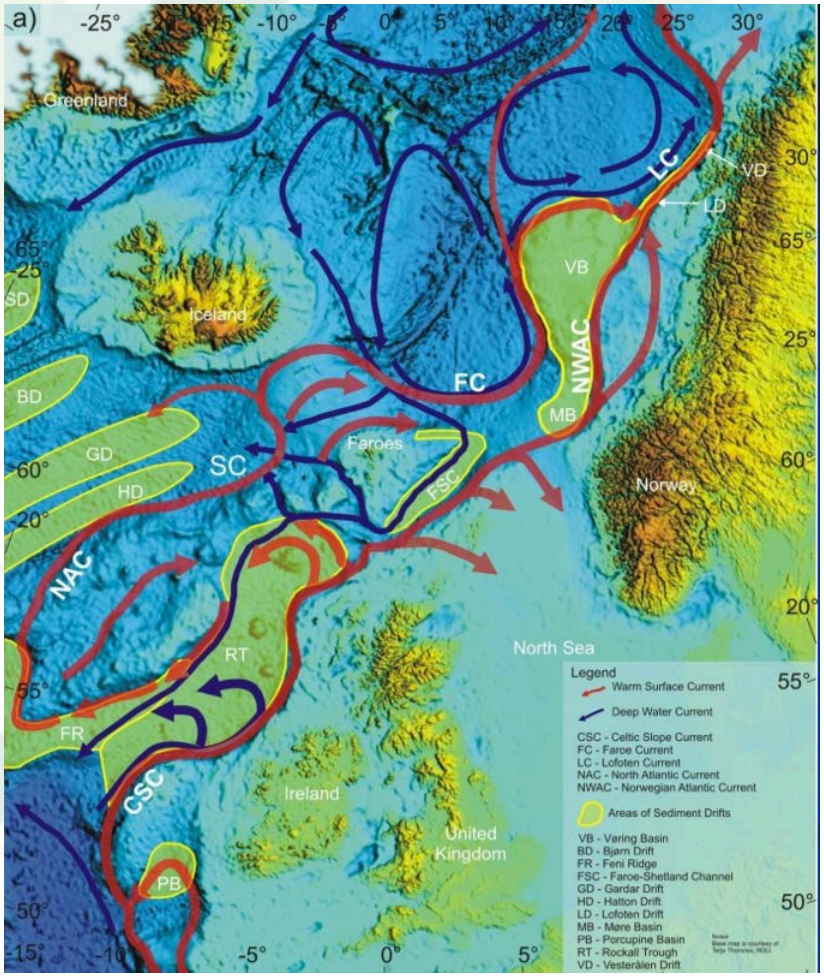
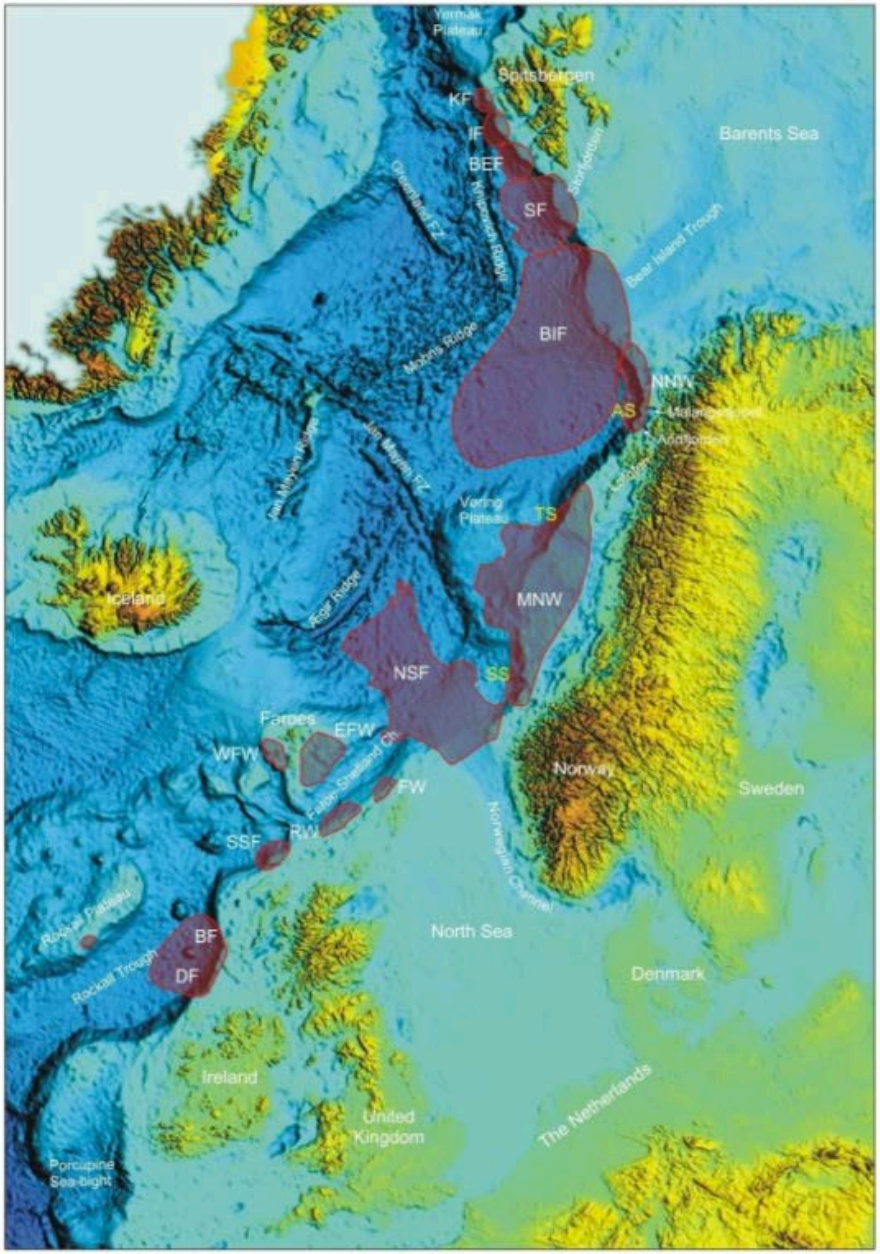
Laberg et al. (2005; MPG)

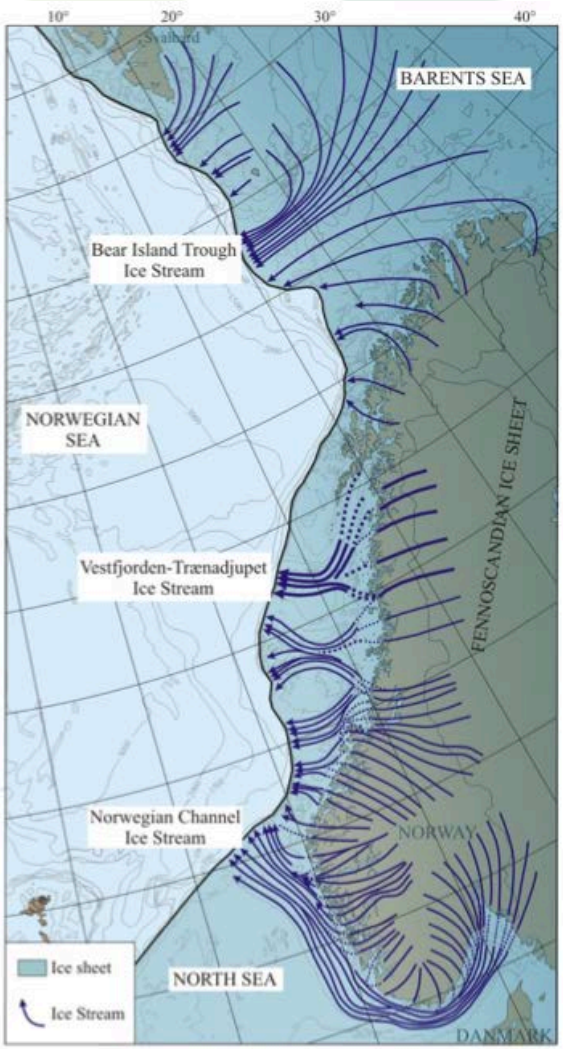
- 粘土仮説：氷期にダイアミクトン，間氷期にコンターライト．コンターライトで滑る

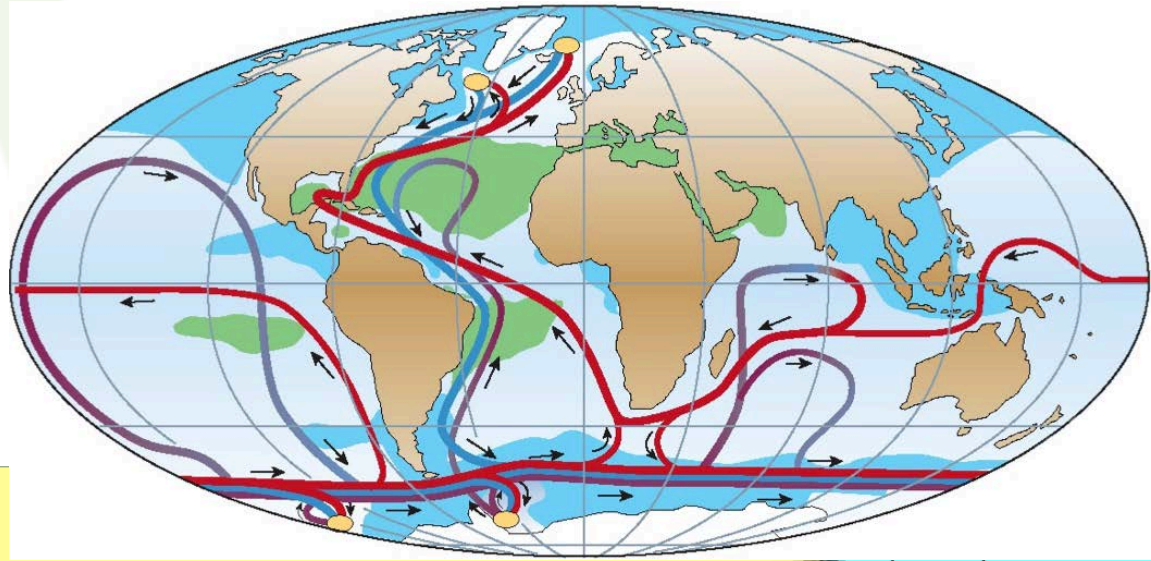


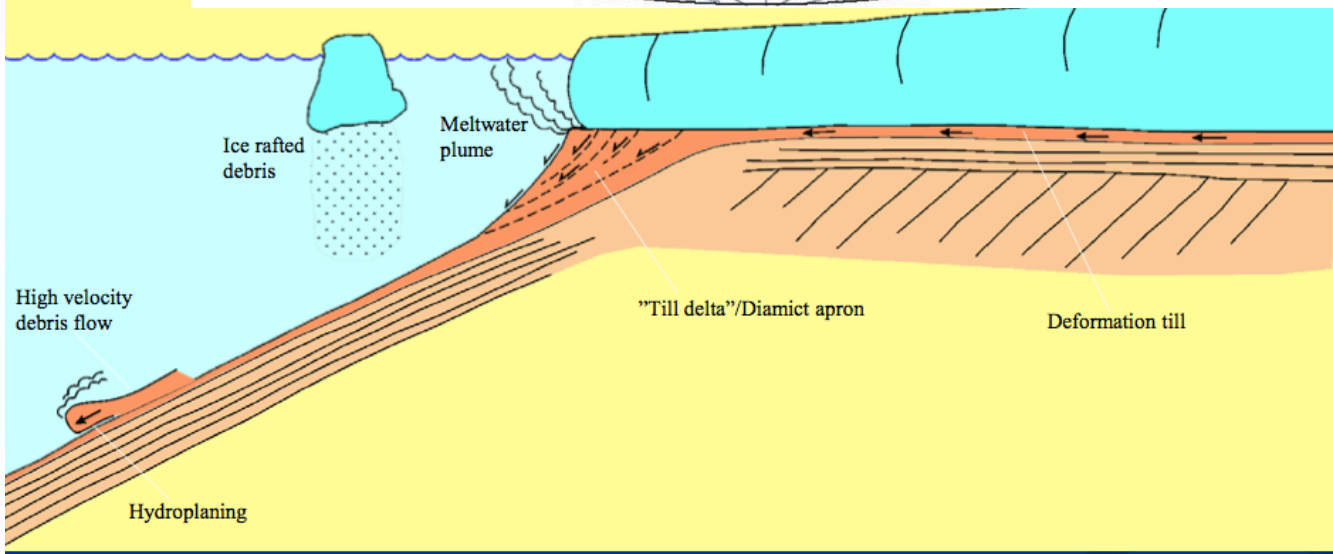


底層流と海底地すべり

■粘土仮説：氷期にダイアミクトン，間氷期にコンターライト．
コンターライトで滑る







滑り面は粘土？

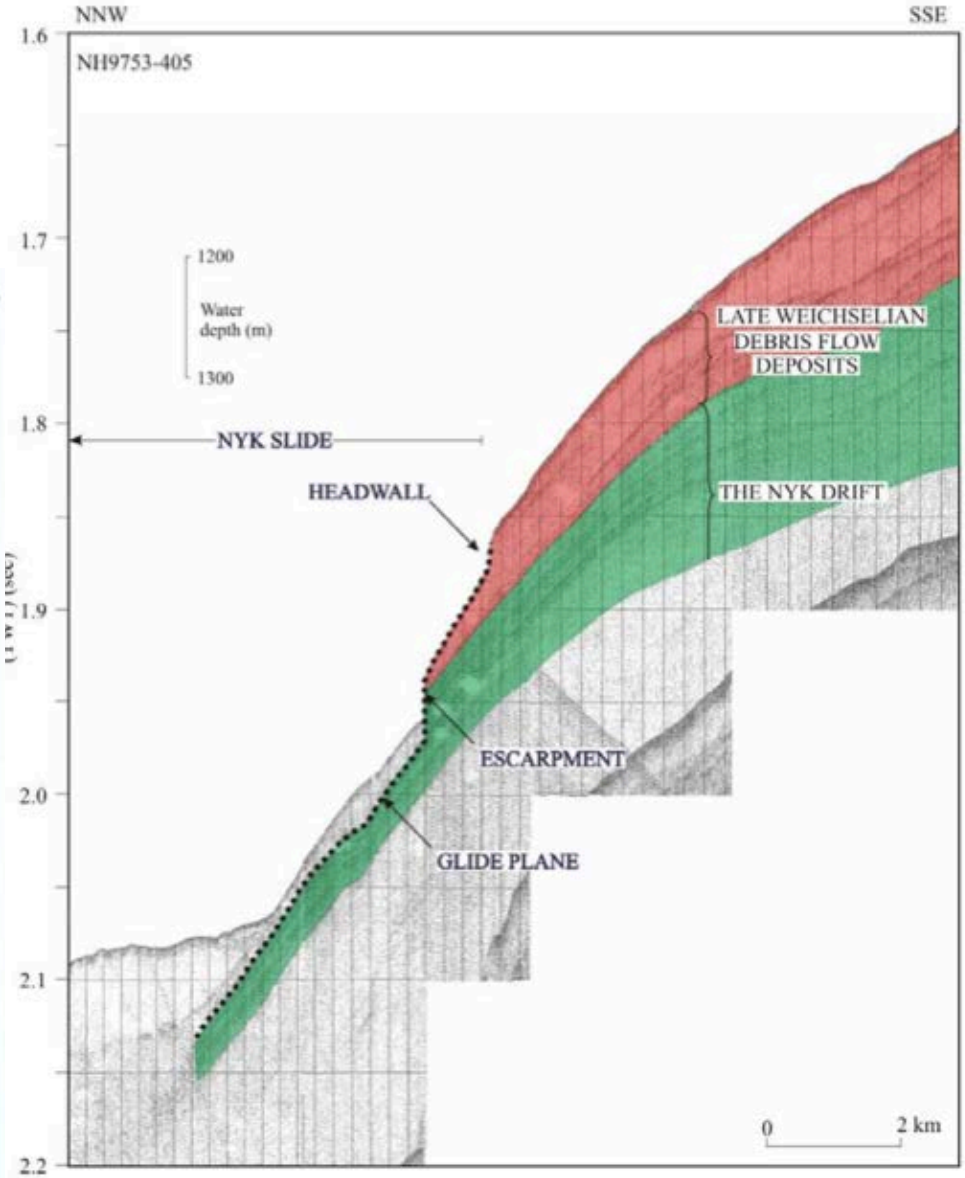
Evans et al. (2005; MPG)

- 粘土仮説：氷期にダイアミクトン，間氷期にコンターライト
  コンターライトで滑る

ダイアミクトン

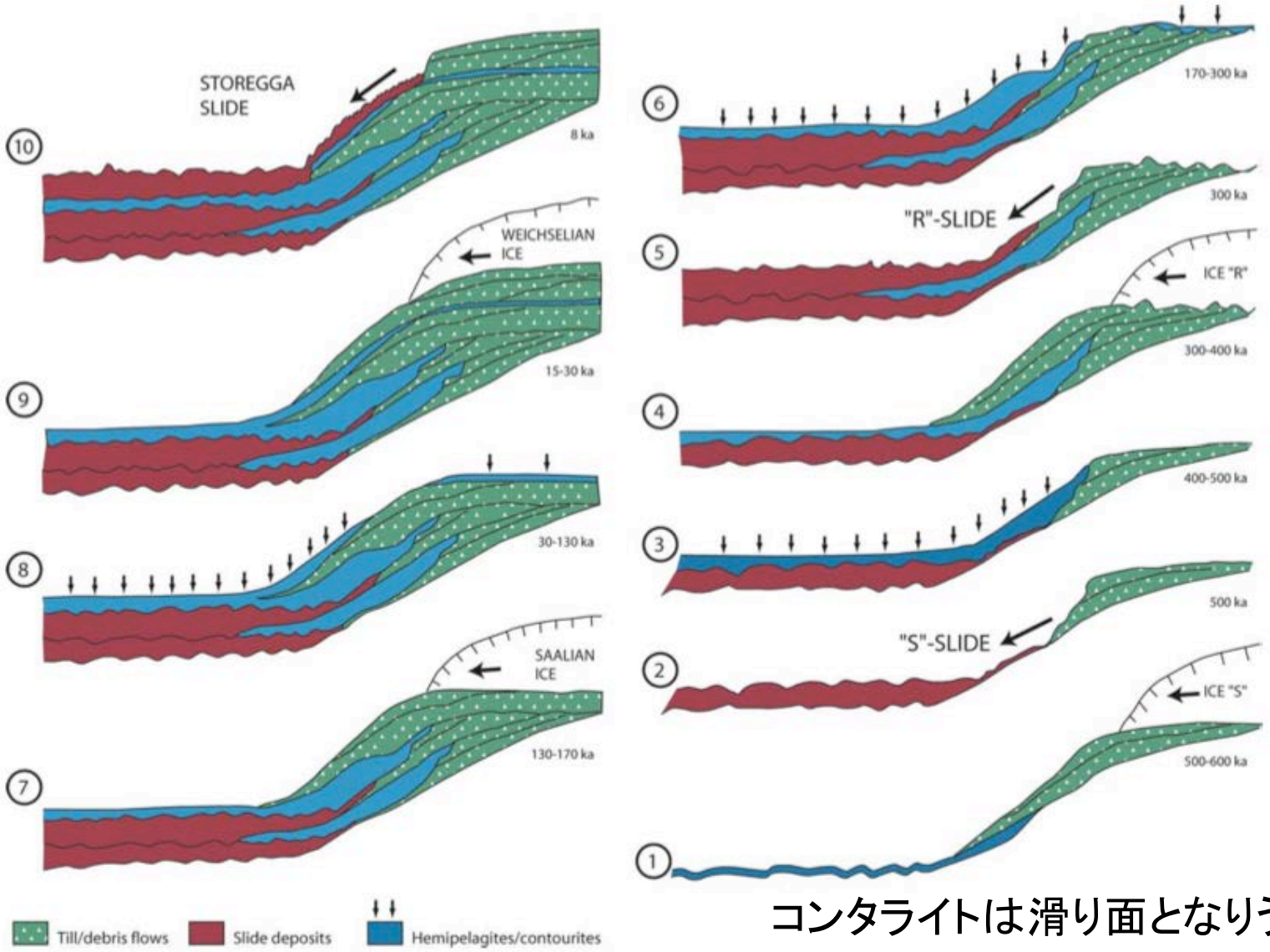
10 cm

コンターライト



底層流と海底地すべり．底層流堆積物（コンターライト）とダイアミクトンとの互層．

（Rise et al., 2005; Mar. Geol.）

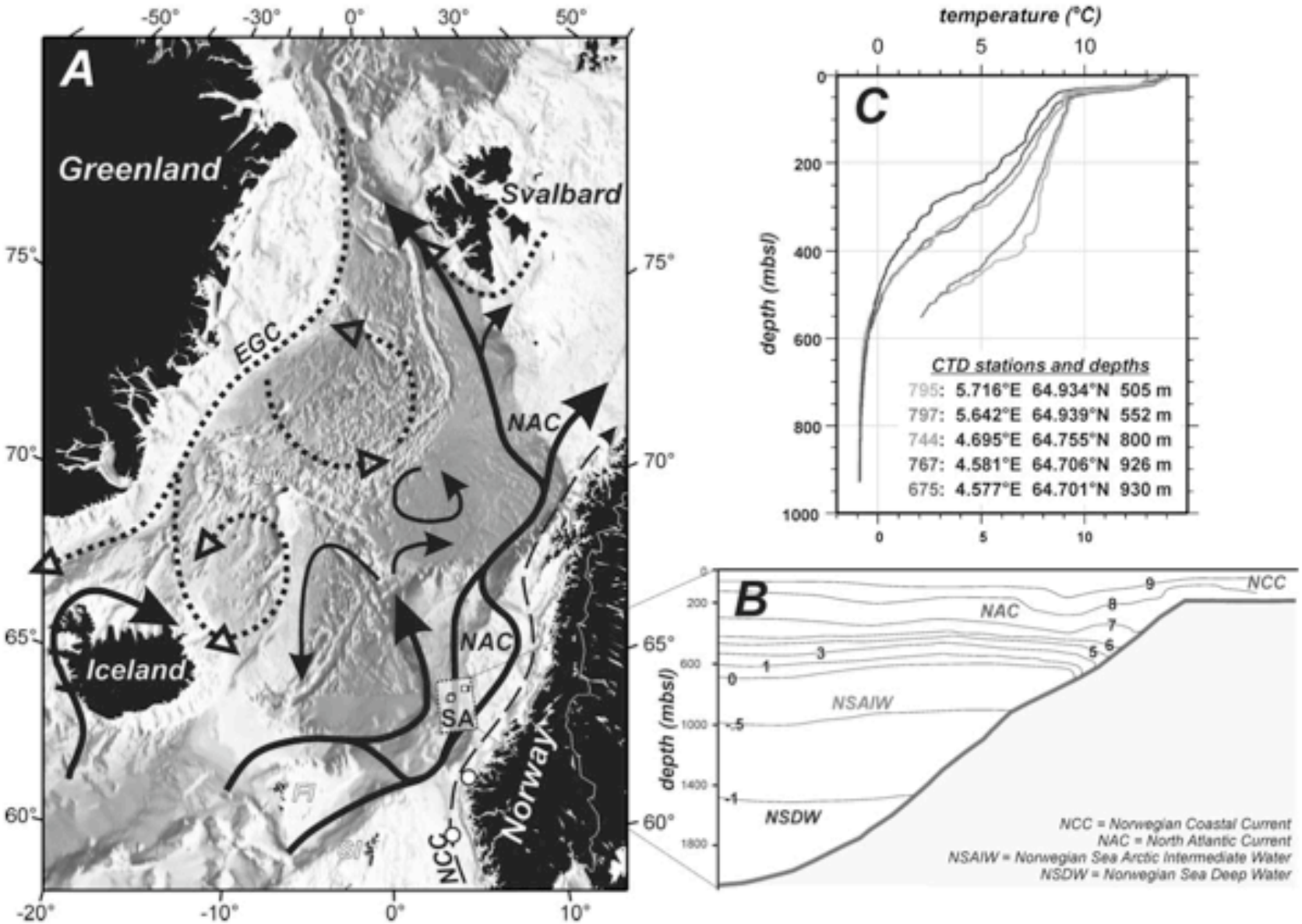


コンタライトは滑り面となりうるか？

Fig. 9. Conceptual model illustrating the development of the Møre margin during the last c. 0.5 My. The last three gigantic slides seem to be cyclic events occurring after extensive glaciations. Note that weak layers in the fine-grained sediments infilling the slide scars acted as glide planes for younger slides.

ストレッガスライド付近での底層流

(Mienert et al., 2005; MPG)



ストレッガスライド周辺の堆積物の底生有孔虫化石による同位体分析

(Mienert et al., 2005; MPG)

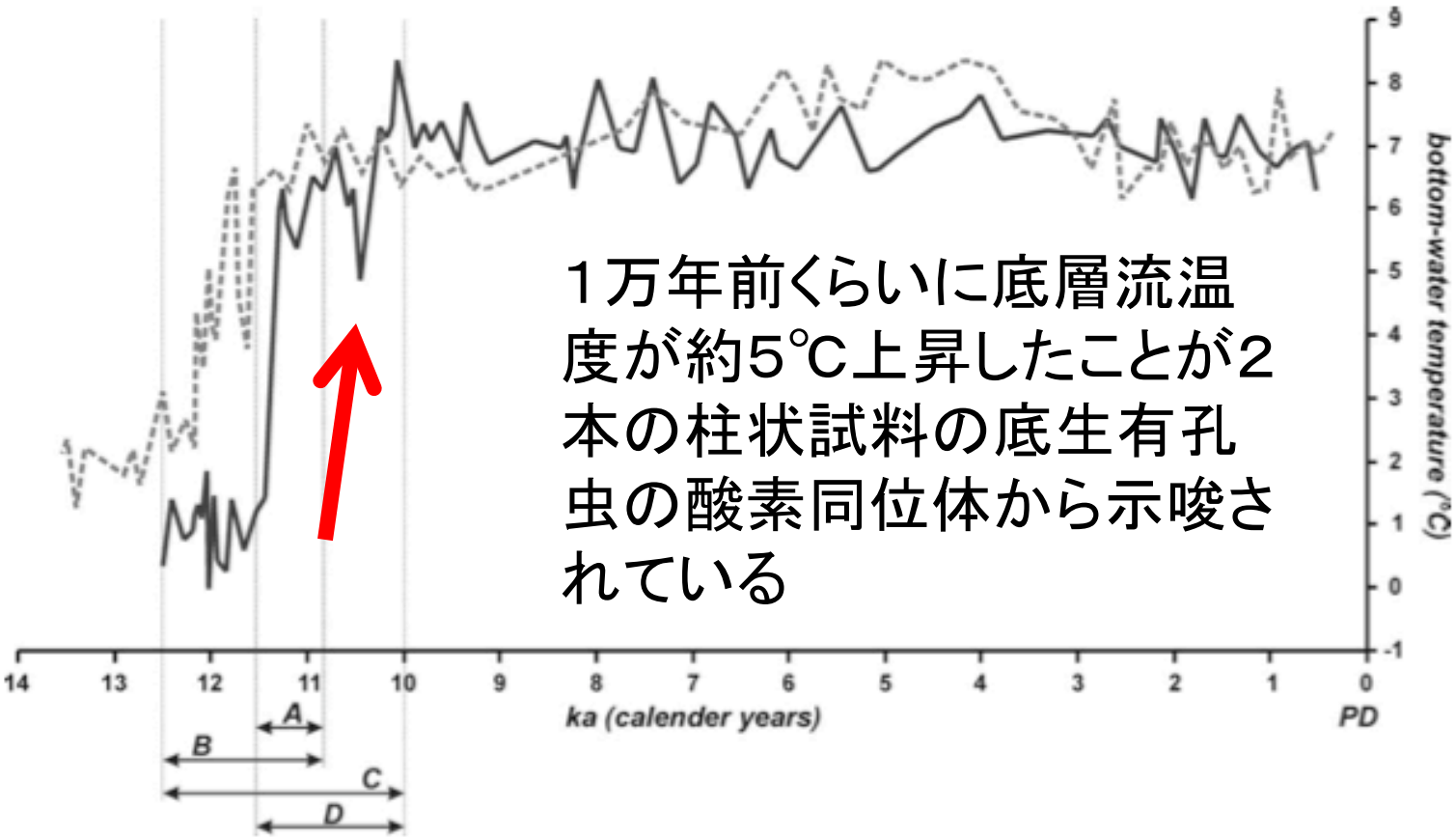


Fig. 3. Paleo-BWT records over the last 14 000 calendar years, estimated from benthic foraminifera on the Voldafjord core (dashed) and Troll8903 core (solid) (Sejrup et al., 2004; Klitgaard et al., 2003; Haflidason et al., 2002) (see Fig. 1 for location), illustrate that warmer water inflow started after the Younger Dryas. Over the last ~10 ka, only minor fluctuations are observed. The arrows and letters (A)–(D) delimit the time intervals over which the temperature change takes place, used in the hydrate stability modelling (Fig. 7). PD stands for present-day.

(Mienert et al., 2005; MPG)

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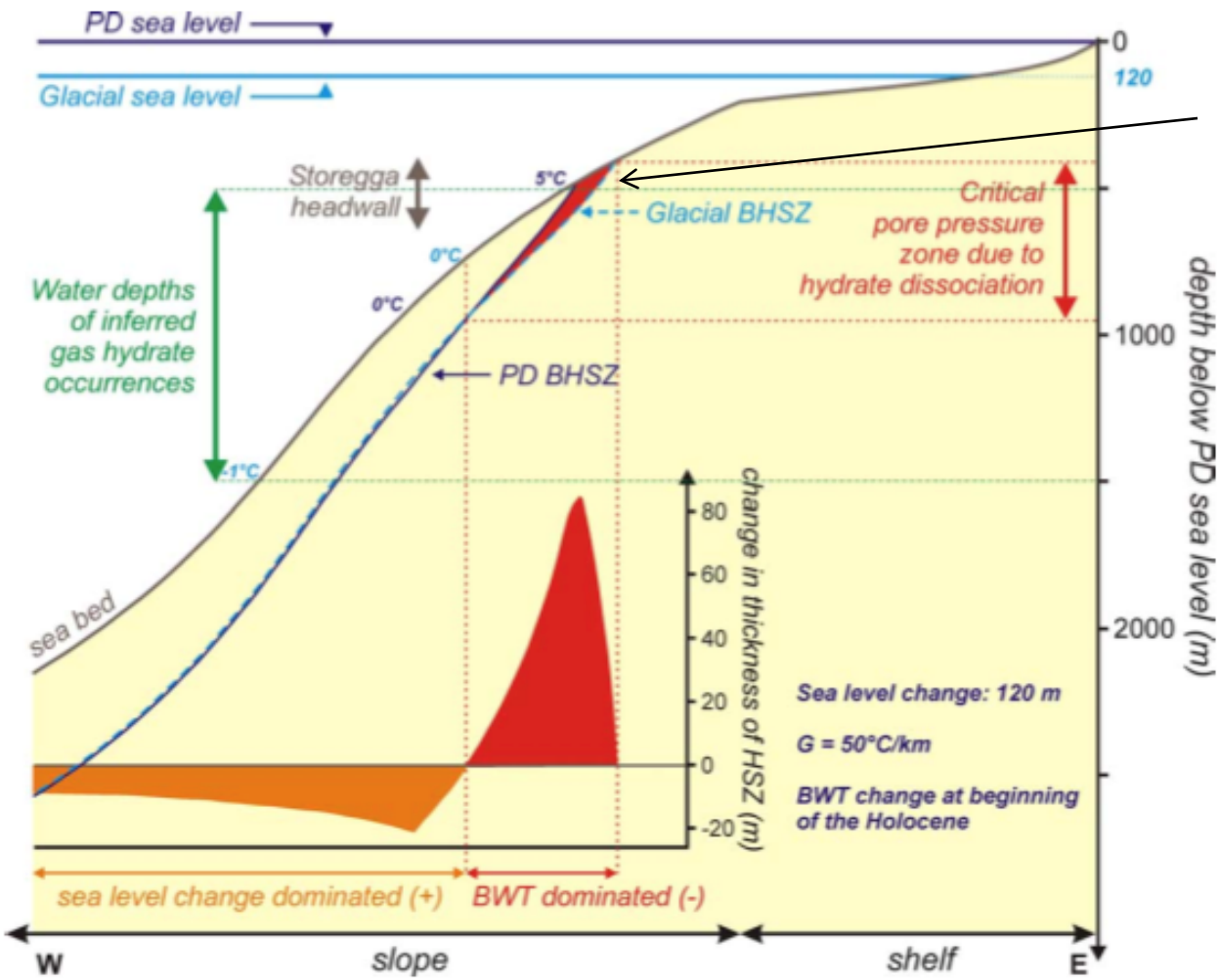
ストレッガスライドでのメタンハイドレート安定領域



メタンハイドレート安定領域は，海底水温の上昇に伴い氷期に比べて750-800m深くなった．これにより，水深の浅い領域のメタンハイドレートは，分解されたのだろう．ストレッガの滑落崖は約500m．分解領域にあたる．

Fig. 5. Sketch of the evolution of methane hydrate stability along the mid-Norwegian margin from the last glacial maximum (LGM) (dashed light blue curves) to the present (dark blue), as a result of the combined effects of eustatic sea level rise since (PD, present day) the LGM and bottom water temperature (BWT) warming initiated at the termination of the Younger Dryas event. The inset shows the difference in thickness of the sub-surface hydrate stability zone. The outcome is an asymmetric situation of reduced hydrate stability conditions in the upper slope area (red shading) in contrast to more stable hydrate conditions in the lower slope area (orange shading). The inversion takes places at 750–800 m water depth.

（Bungum et al., 2005; Mar. Geol.）

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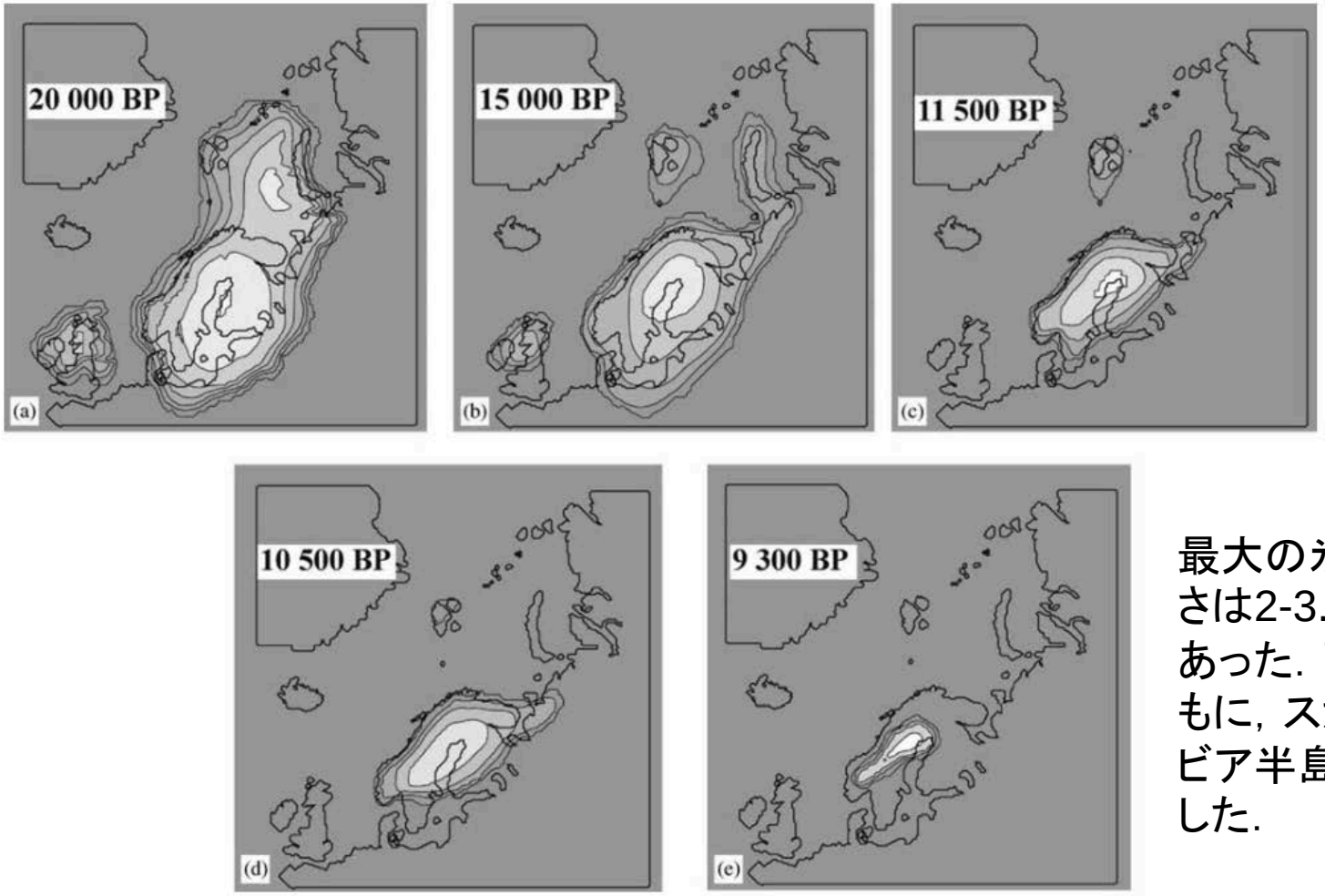
一方で温暖化に伴い大陸氷床が融解してきた歴史がある



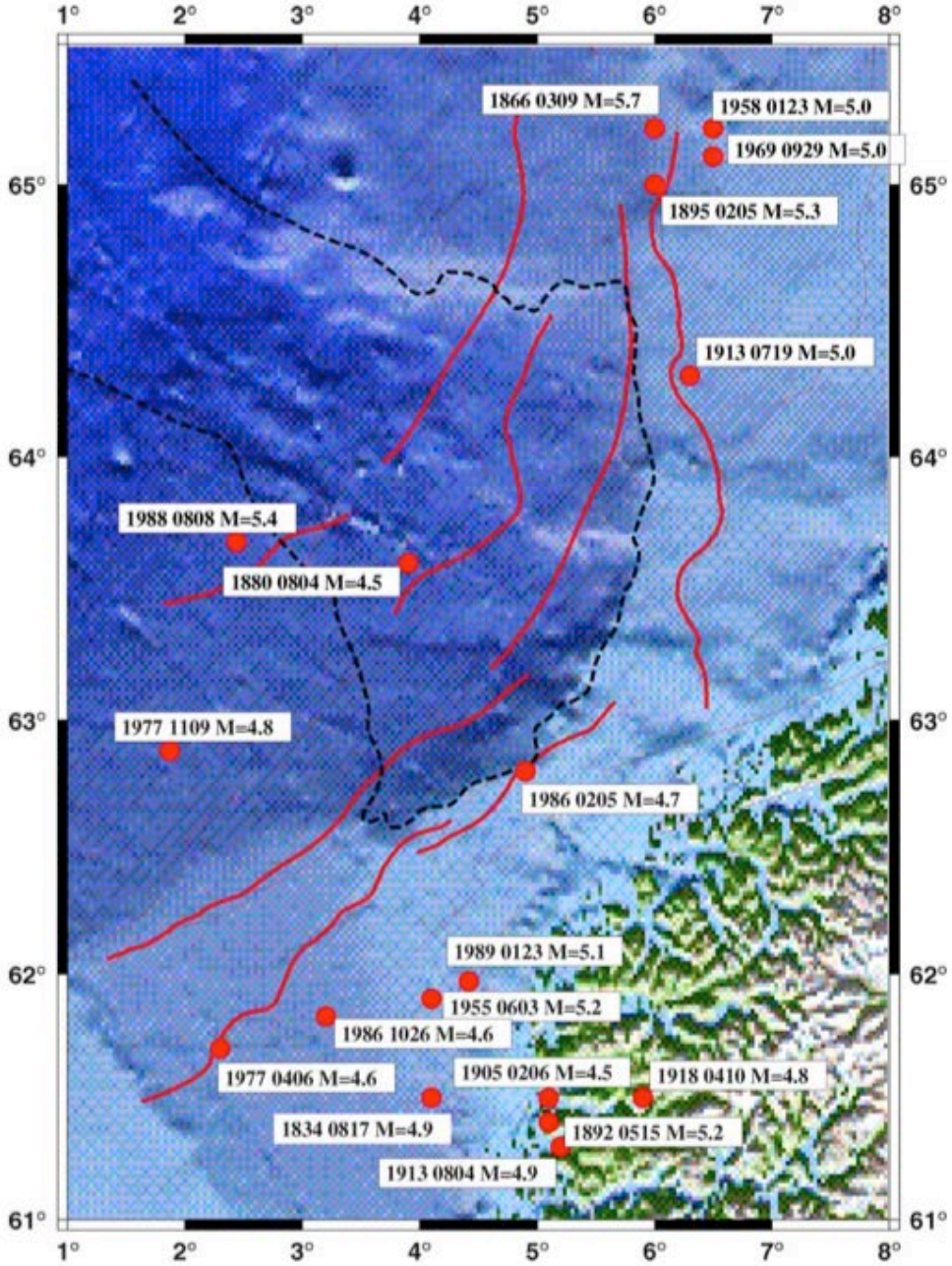
最大の氷床の厚さは2-3.5 kmであった．融解とともに，スカンジナビア半島は隆起した．

Fig. 6. Extent and thickness of the ice sheet during the deglaciation in Northern Europe partly based on Denton and Hughes (1981), for five time periods between (a) 20,000 and (e) 9300 ybp. Contour interval is 500 m, except for (e), where the contour interval is 200 m. From Fjeldskaar et al. (2000).

M4-5の近年発生している地震

M5程度の地震は，この地域でも存在する．これらがトリガーとなる可能性は十分にある．

（Bungum et al., 2005; Mar. Geol.）



orical seismicity record with earthquakes greater than or equal to 4.5 in mid-Norway. The thick red lines represent major geologic structures mapped by J.I. Faleide during a special study for the Ormen Lange field, and the dashed black line represents an outline of the disrupted area during the ~8100 ybp Storegga slide. The uncertainties in the locations for the historical earthquakes on this map may be considerable (Lindholm and Bungum, 2000). Redrawn from Bungum et al. (2002).

確かに断層崖がスカンジナビア半島にある.

もしかしたら，アイソスタシーによるリバウンドでの隆起に伴う地震が海底地すべりを誘発させたのかもしれない.

（Bungum et al., 2005; Mar. Geol.）

Fig. 1. Aerial photograph of the Stuoragurra (Masi) fault (e.g. Olesen, 1988), which is part of the Mierujavr'i–Sværholt fault zone (see also Table 2).

Table 2
Postglacial faults in Lapland (northern Fennoscandia)

Fault	Fault length (km)	Displacement (m)	Aspect ratio	Seismic moment (Nm)	Moment magnitude
Pärve	165	13	0.8×10^{-4}	1.4×10^{21}	8.1
Stuoragurra (Masi)	80	7	0.9×10^{-4}	3.7×10^{20}	7.7
Laino-Suijavaara	55	30	5.5×10^{-4}	1.0×10^{21}	8.0
Suasselka	48	5	1.0×10^{-4}	1.3×10^{20}	7.4
Lansjärv	50	22	4.4×10^{-4}	6.1×10^{20}	7.9

Fault lengths and displacements are from Muir Wood (1993), and seismic moments and moment magnitudes are estimated under the assumption that the faults are created by single events (see main text for details). From Bungum and Dahle (1993) and Bungum and Lindholm (1997).

北海周辺の海底地すべりは，断層帯周辺にあるように見える→大西洋であっても，変動域で海底地すべりが生じているのだろうか？

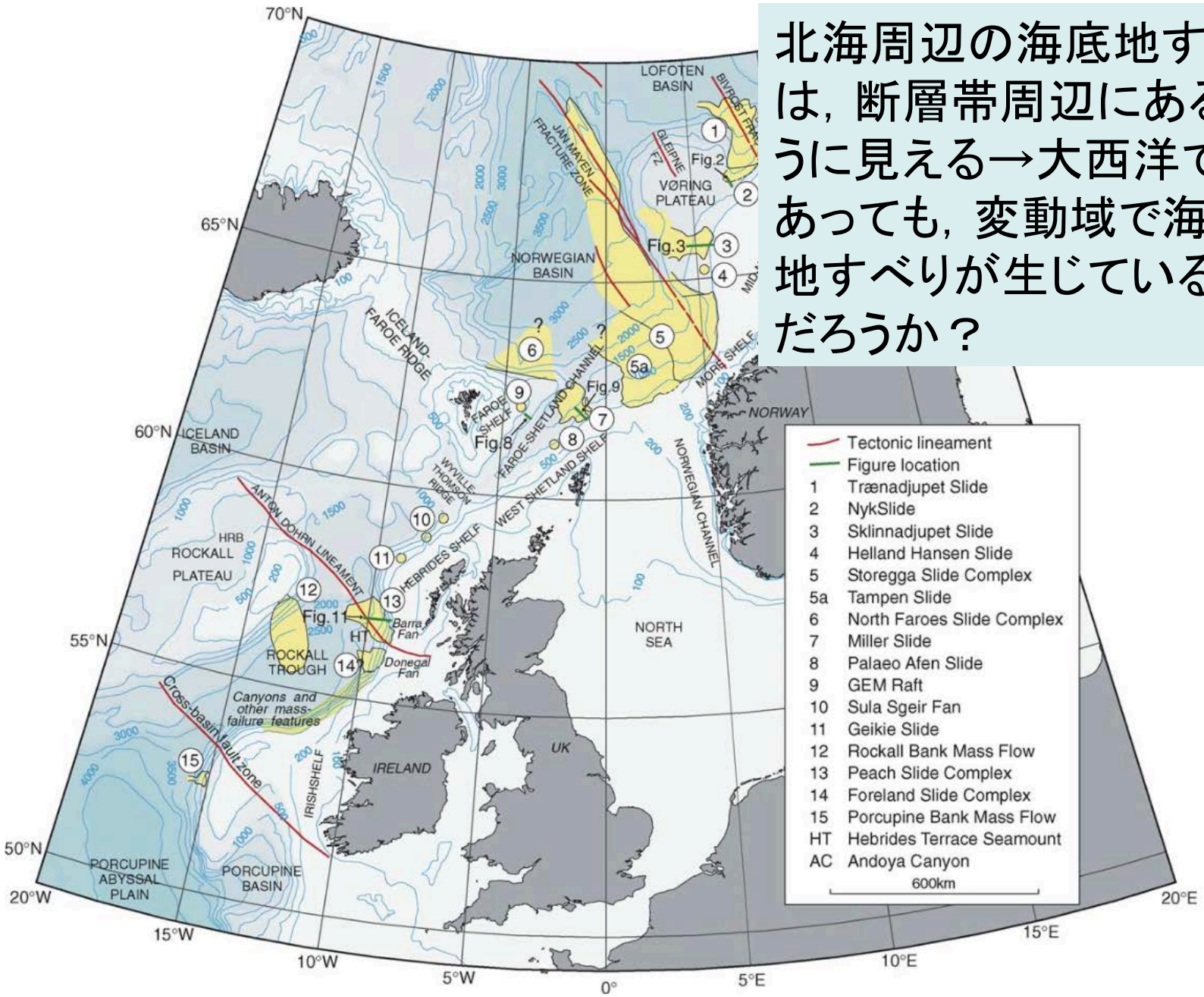


Fig. 1. The latitudinal extent of the study area together with the locations of the slides and palaeo
in the text. Bathymetry after GEBCO.

Evans et al. (2005; MPG)

少なくとも，海面低下→減圧→MH崩壊→海底地すべり，というクラスレートガンのような単純な構図ではないように思える．

Lee (2009; Mar, Geol.)

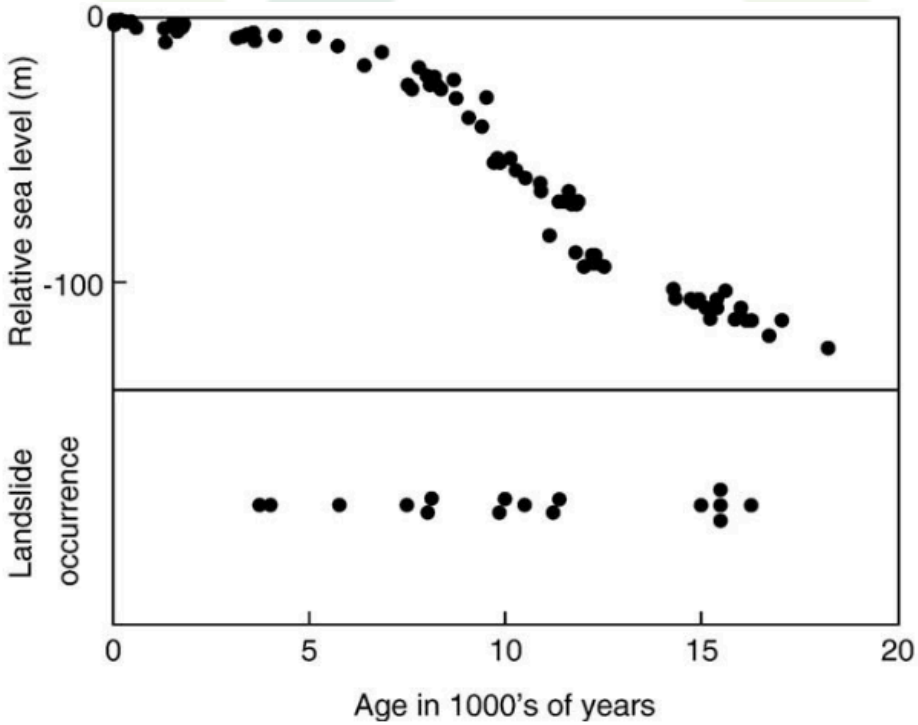


Fig. 5. Plot showing the distribution of ages of landslides younger than 20 ky and listed in Table 1. For comparison with glacial cycles, sea level versus time (according to corrected ^{14}C dating of samples from Barbados and elsewhere; Fairbanks, 1992) are also plotted. The figures shows a reduced occurrence of landslides during the last 5 ky, an interglacial time with elevated sea level.

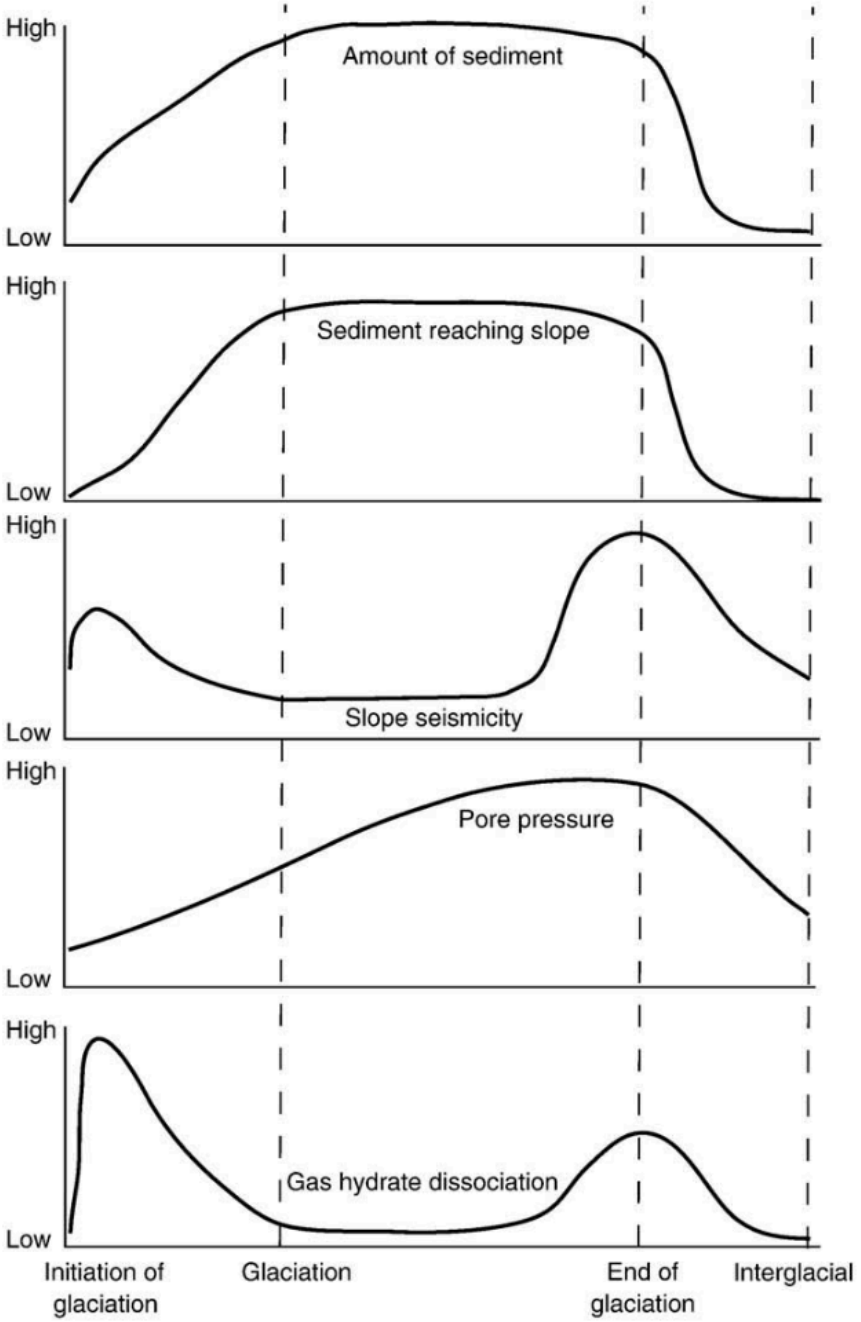


Fig. 1. Approximate impact of time on several factors that influence the stability of submarine slopes.

ビンゴはここまで．みなさんビンゴできましたか？
できたひとは，かえるときにおしえてね！

本日の話す内容

■はじめに：どういった地層が残るのか

■海底地すべり研究の最近20年ダイジェスト：

1）トリガー問題：気候変動が悪いのか

2）地質地形問題：過去の記録を読み取るにはどうすればよいか

3）災害問題：津波と海底ケーブル

■さいごに：未来に向けてどうすればよいか

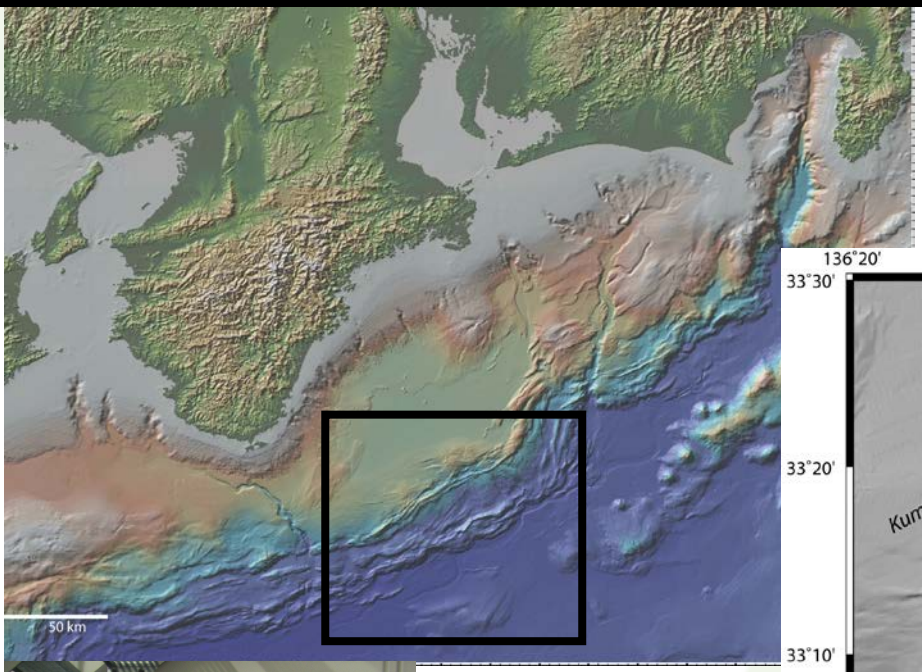
2）地質地形問題：過去の記録を読み取るにはどうすればよいか

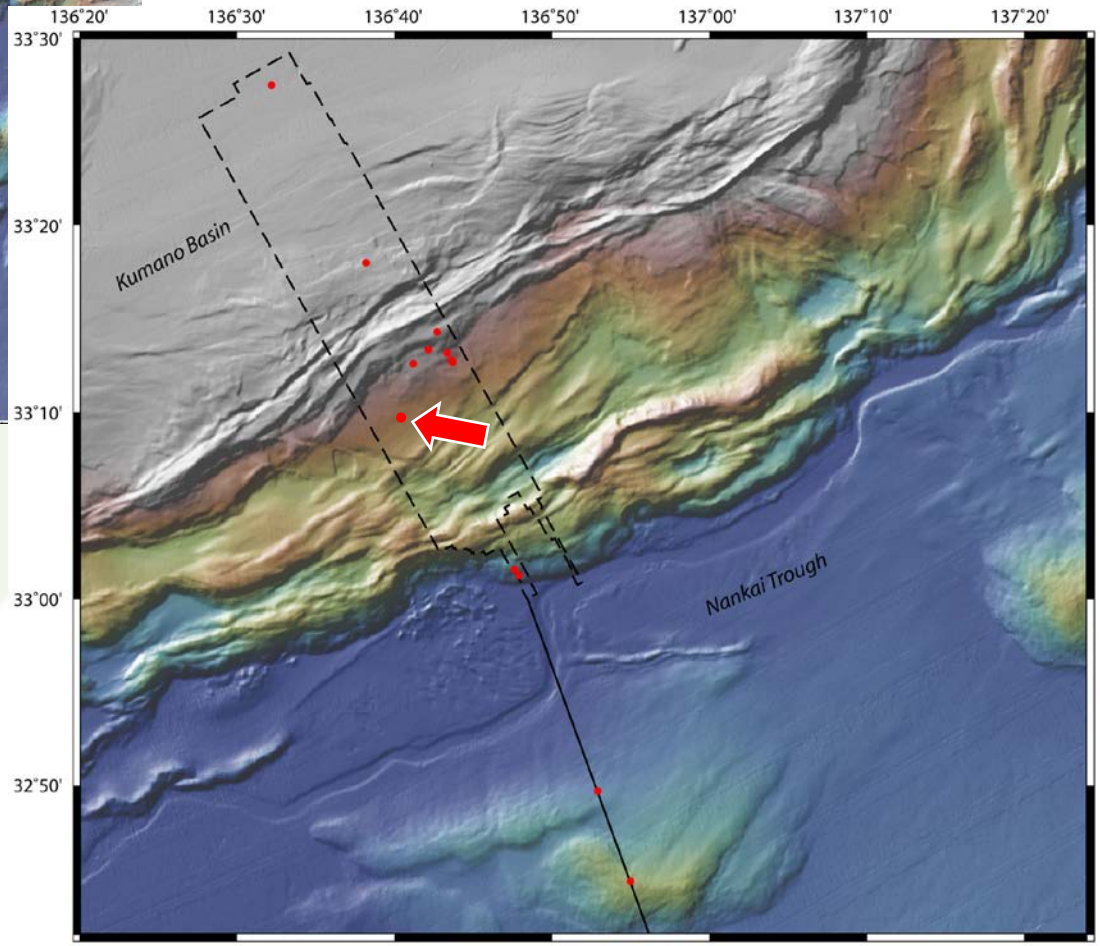
（海底地すべりに関する素朴な疑問）

- ■長期的な要因はあるのか
- **■最終的なトリガーはなにか**
- ■規模を決めるのはなにか
- ■地層記録として残るのか
- ■どんな恐ろしいことが起こるのか
- ■どうやったら減災できるのか

厚さは規模を反映するのか．ということで，海底地すべりを100万年間分，掘ってみた．

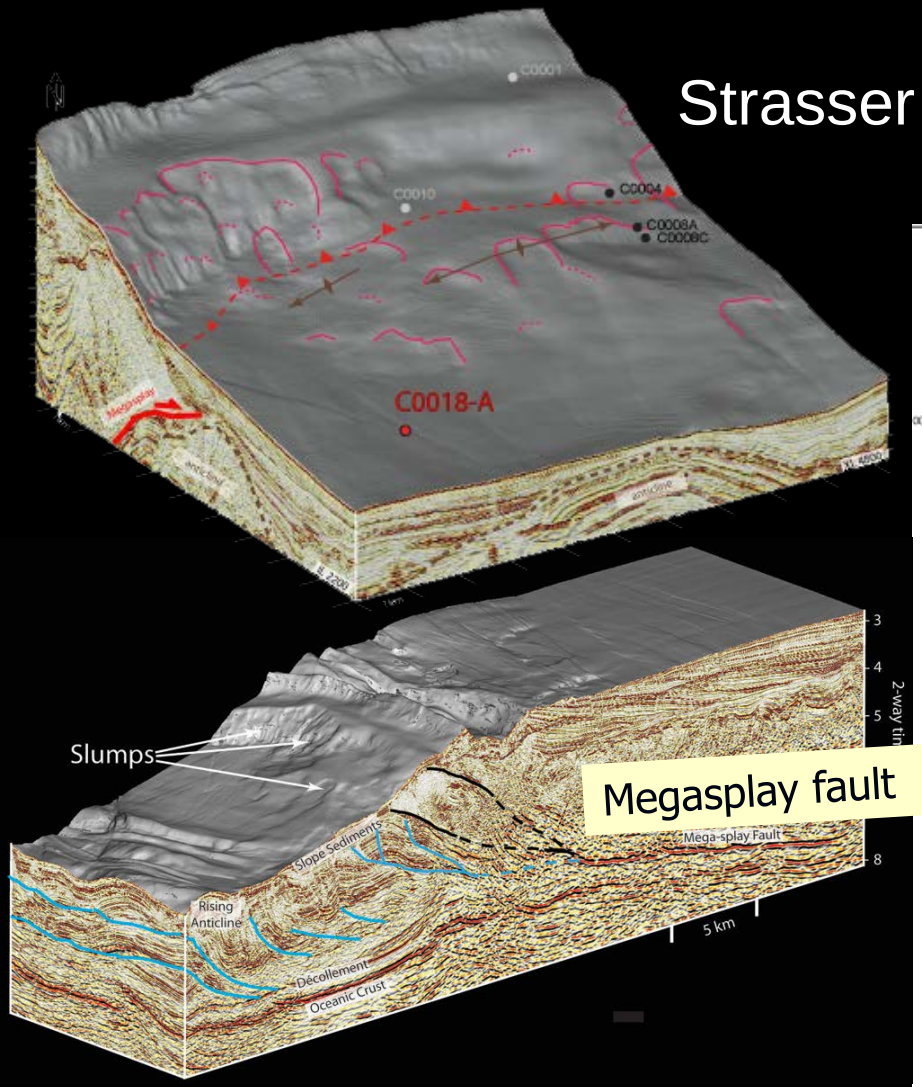
Nankai **Tro**ugh Submarine Land**SLIDE** History
NanTroSLIDE

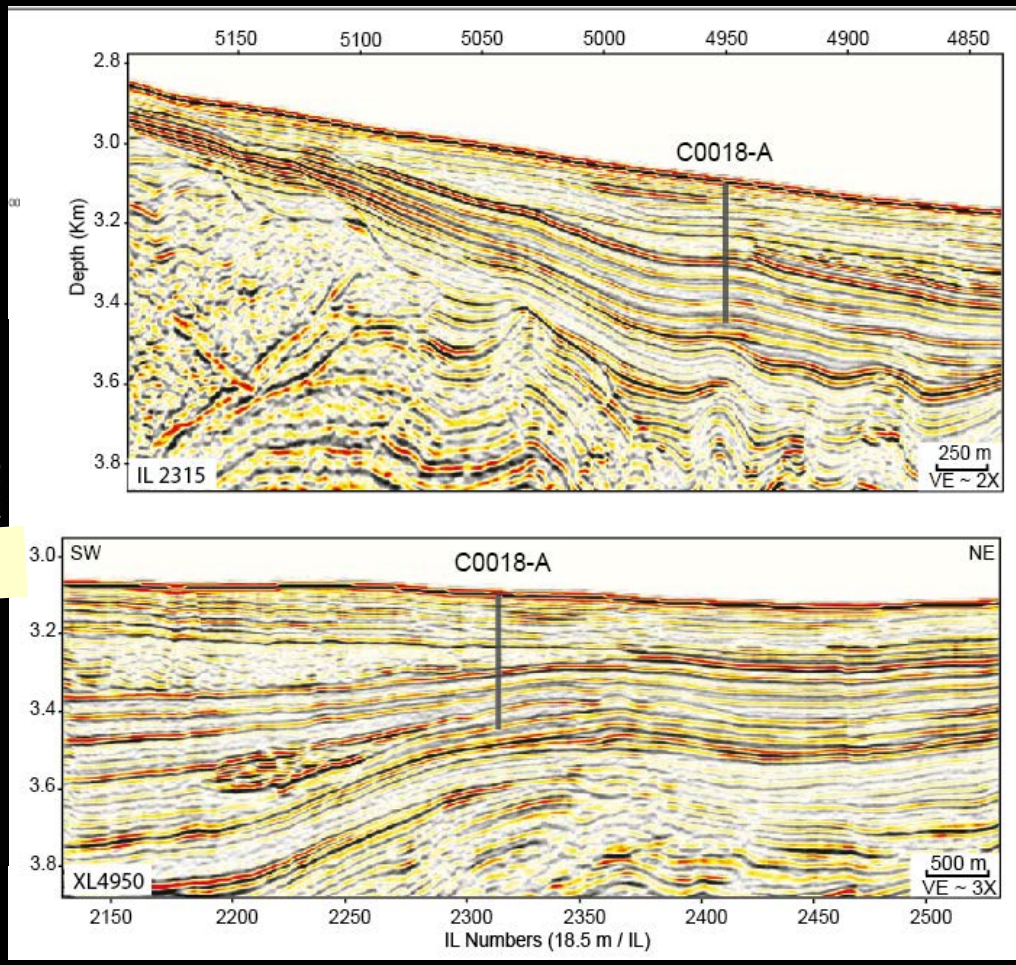




Nankai **Tro**ugh Submarine Land**SLIDE** History

Strasser et al. (2012; Springer)





Moore et al. (2007; Science)

Results from IODP Exp 333

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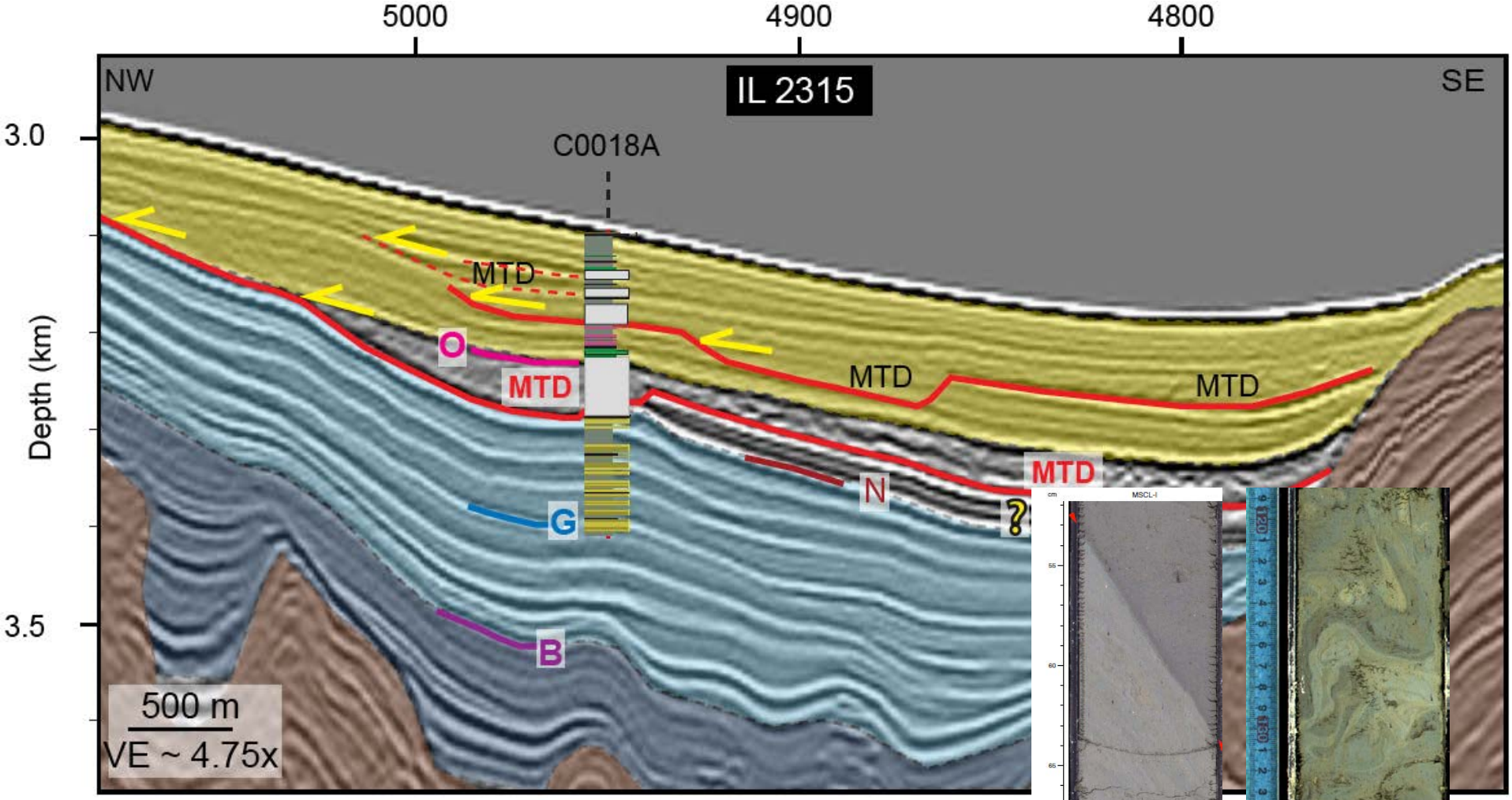
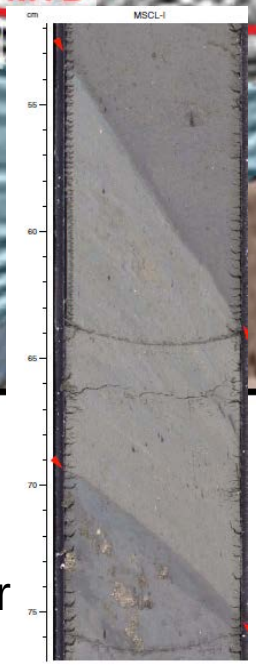




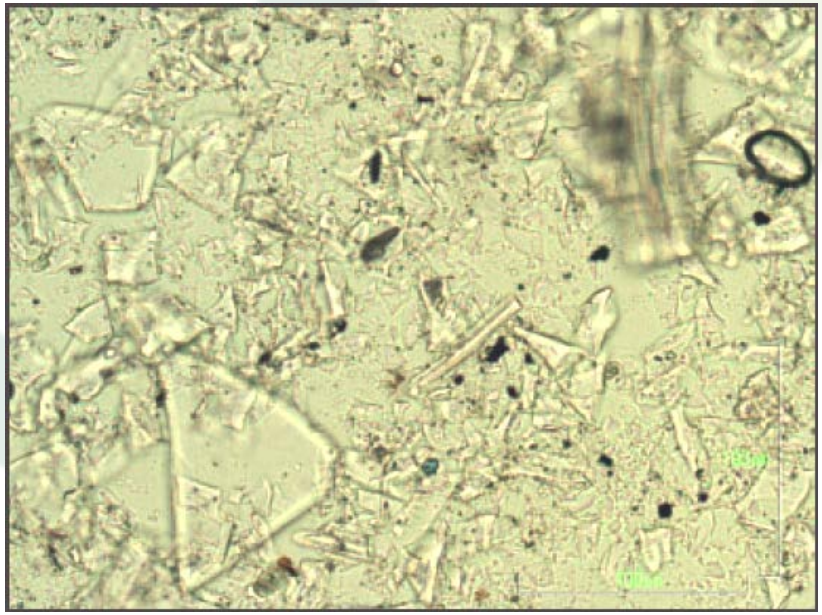
Strasser et al. (2012; Springer)

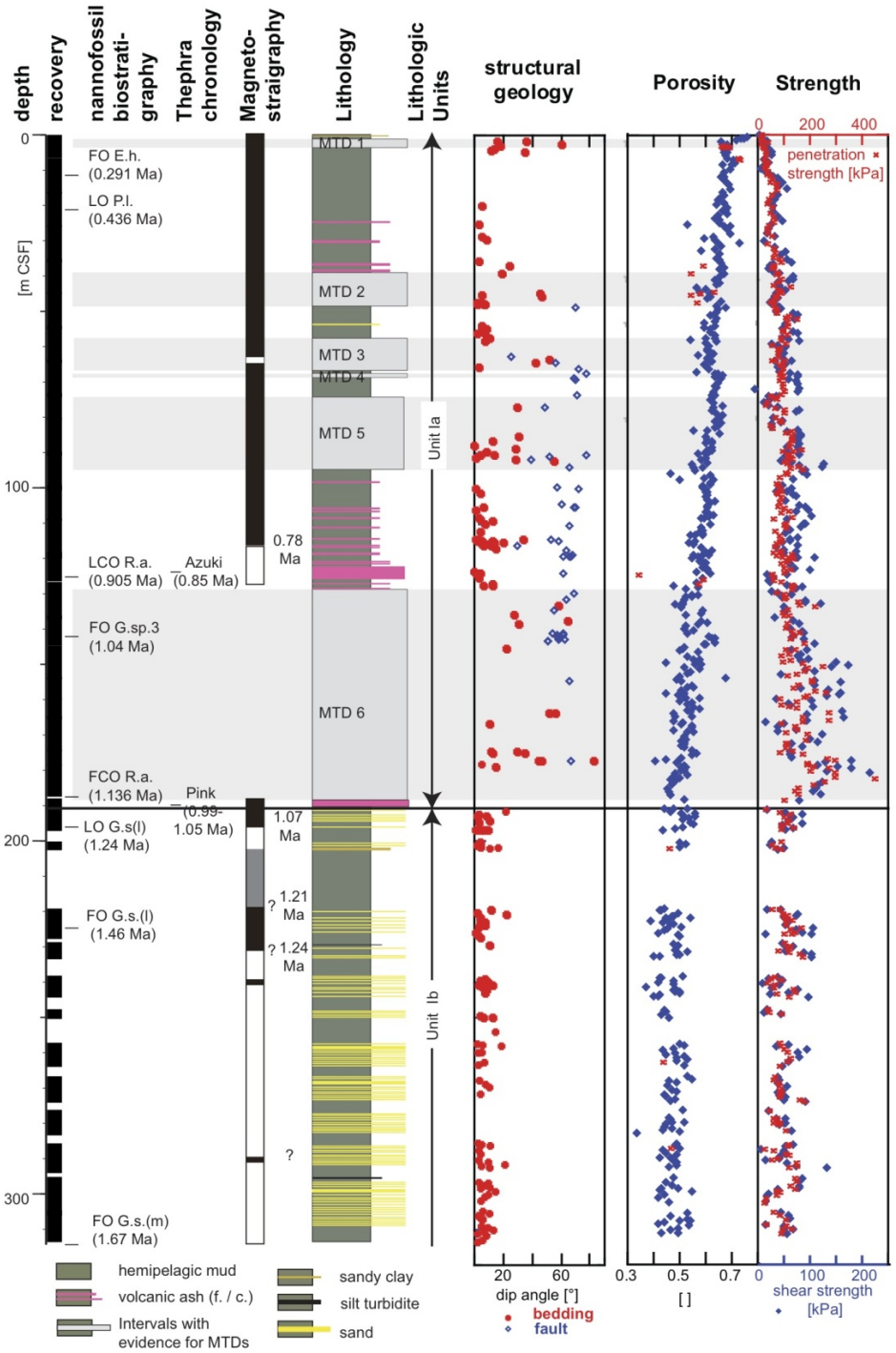
Internal, dipping shear zones

Chaotic bedding

Base of large MTD

- “Pink” <u>ash bed</u>: 0.90-1.05 Ma, at the base of thick MTD
- <u>Liquefaction</u> and <u>accelerated motion</u> in coarse ash (Sassa et al., 2014; Landslides)





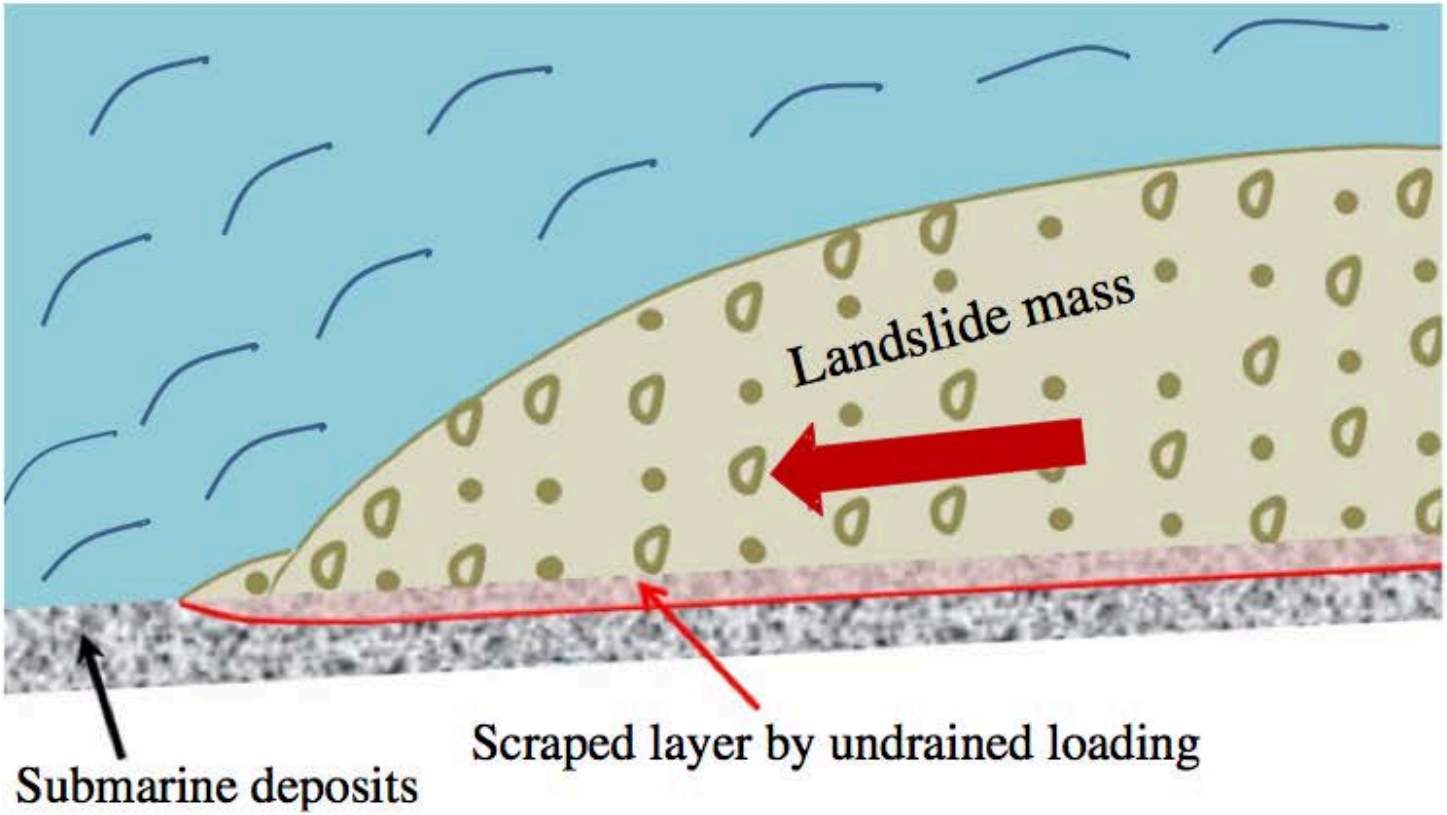


Fig. 16 Illustration of moving landslide mass along the Suruga trough

Sassa et al. 2012

海底地すべりの発生間隔は温暖化と関係する？

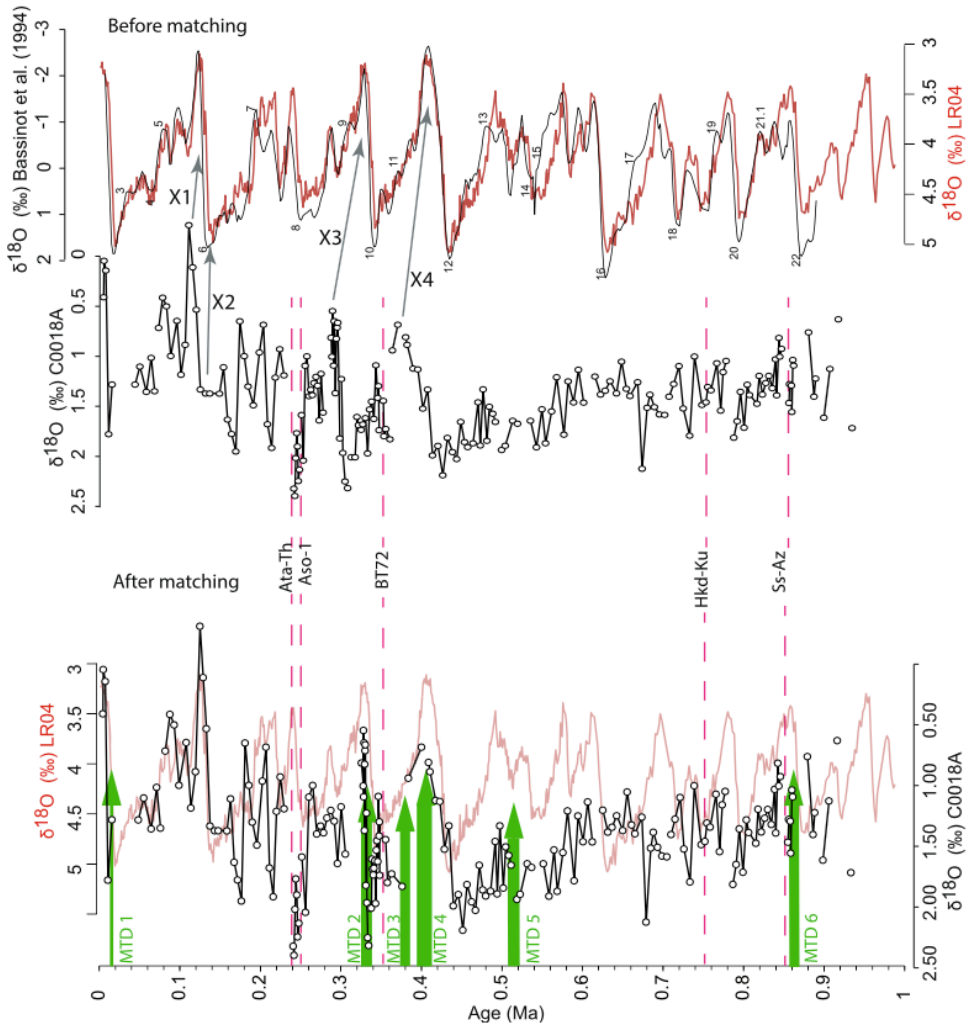


Fig. 7 Core C0018 $\delta^{18}O$ profile as a function of age based on tephrochronology and the LR04 stack (Lisiecki and Raymo 2005) before and after matching. The dataset from Bassinot et al. (1994) is shown in *black*. The *gray arrows* between the two curves indicate the timing of the matching points (X1–X4). The *pink dotted lines* indicate the dated tephras used as time markers for the correlation. *Green arrows* indicate MTDs. MIS stages are from Bassinot et al. (1994)

海底地すべりは，10万年以上の発生間隔があり，一定ではない．知られている南海地震の発生間隔は約100年なので，これとも大幅に異なる．ただ，MTDは地球温暖化で発生しているようにも見える．気候変動とテクトニクスとの関係性が関係しているのかもしれない．

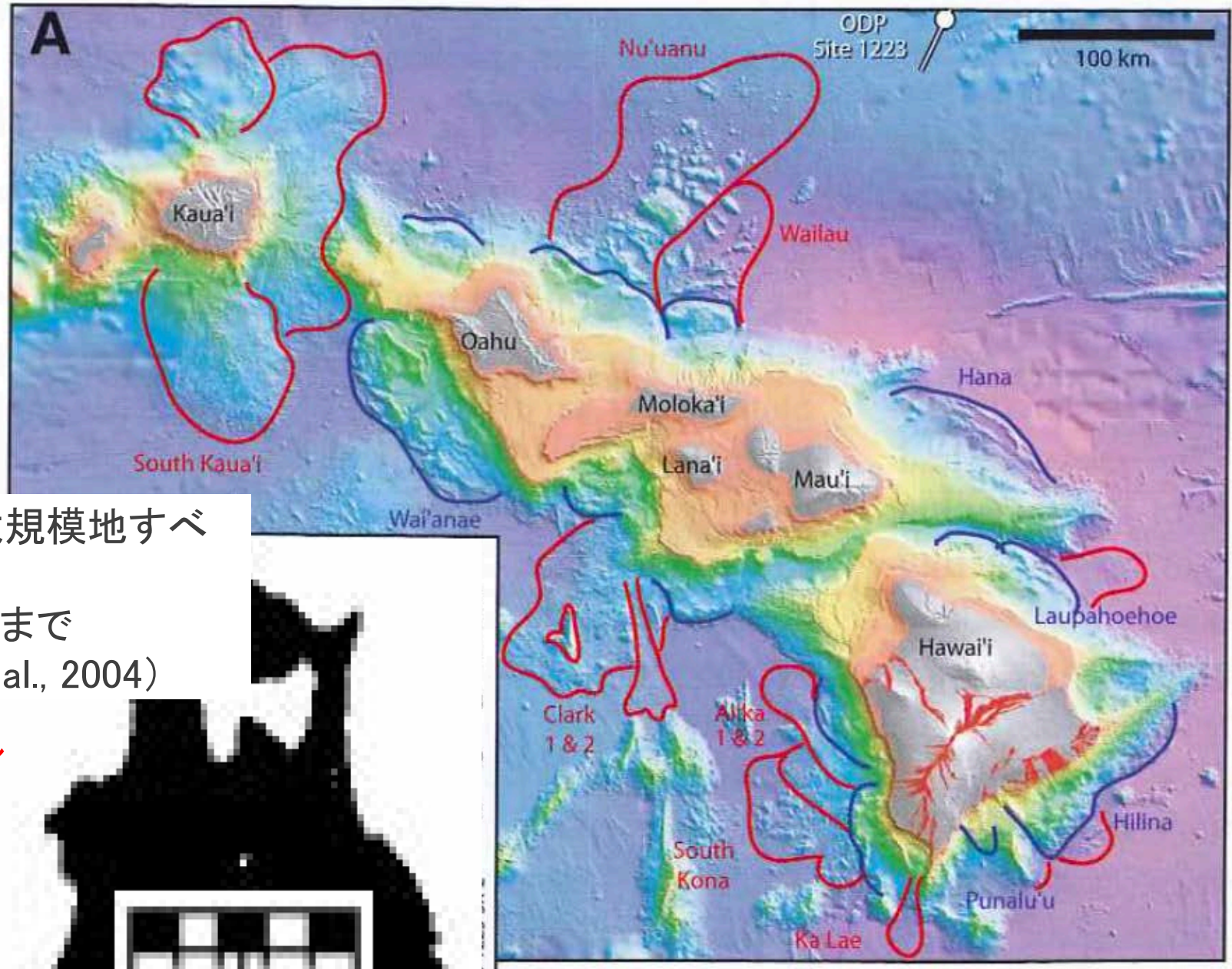
Kremer et al. (2017; PEPS)

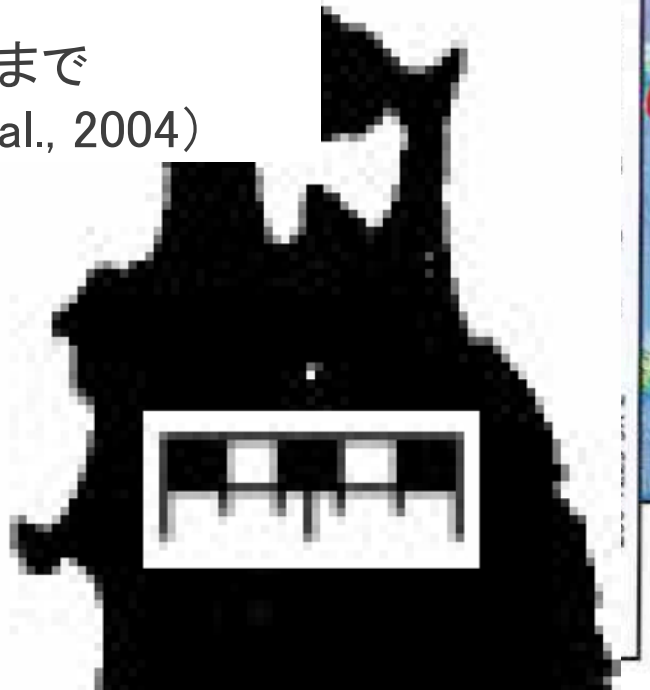
地形・地層記録としての海底地すべり

- 日本周辺だったとしても海底地すべりは気候変動と関わっているのだろうか？堆積層の厚さはイベントの大小を反映するか？未だ不明.
- ハワイでは，2Maの巨大海底地すべりが海底地形に現れている．しかし，それは一回で滑ったものなのだろうか？巨大な馬てい形の陥没地形だけではその発生規模はわからない.
- 海底地すべり下部は，付加体のような地質構造である．房総半島の陸上に露出するデュープレックスは海底地すべり起源であると議論された論文がある．地層記録で海底地すべりを研究したい場合，付加体か地すべり下部か，どうやって判定すれば良いのだろう

ハワイでの大規模地すべりの痕跡
2Maから現在まで
（McMurty et al., 2004）

同じスケールの東北地方





Morgan et al. (2007; Sci. Drill.)

ヒリナスライド

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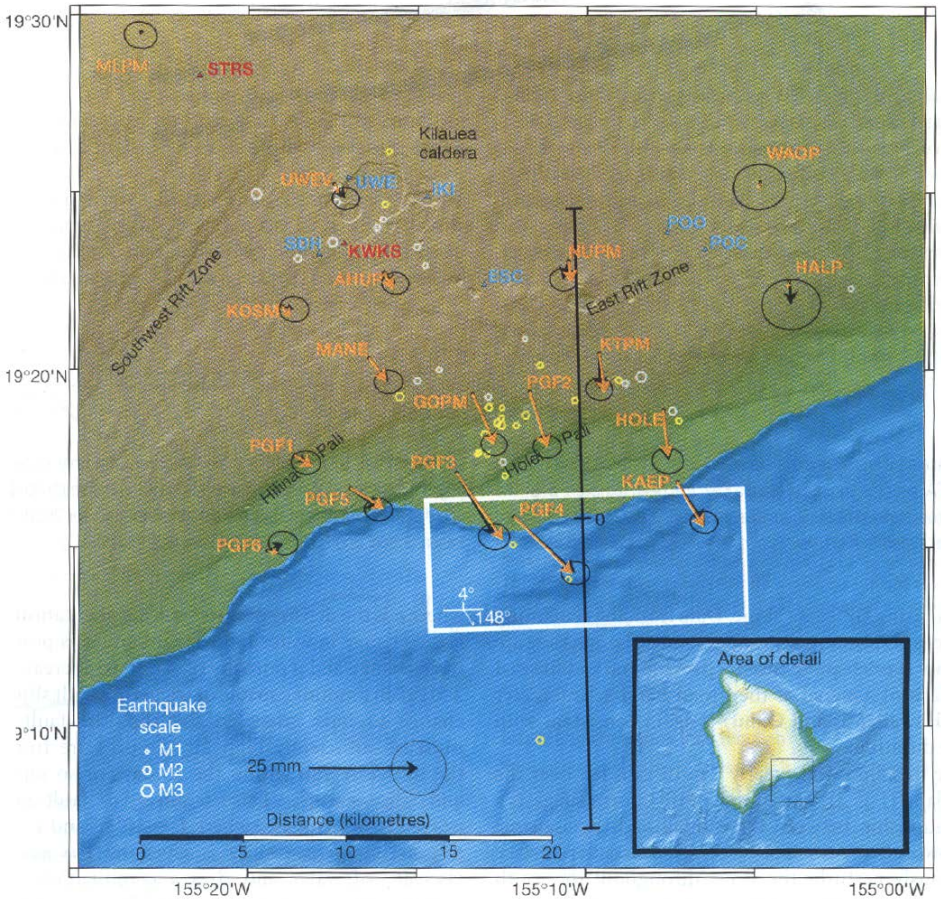
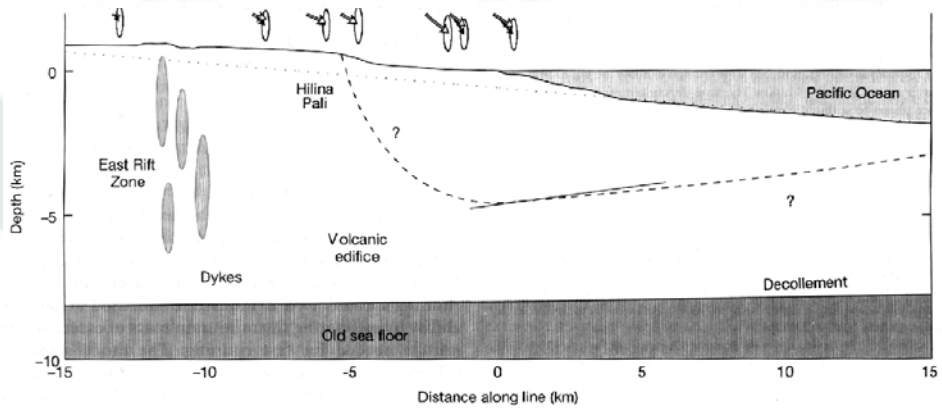
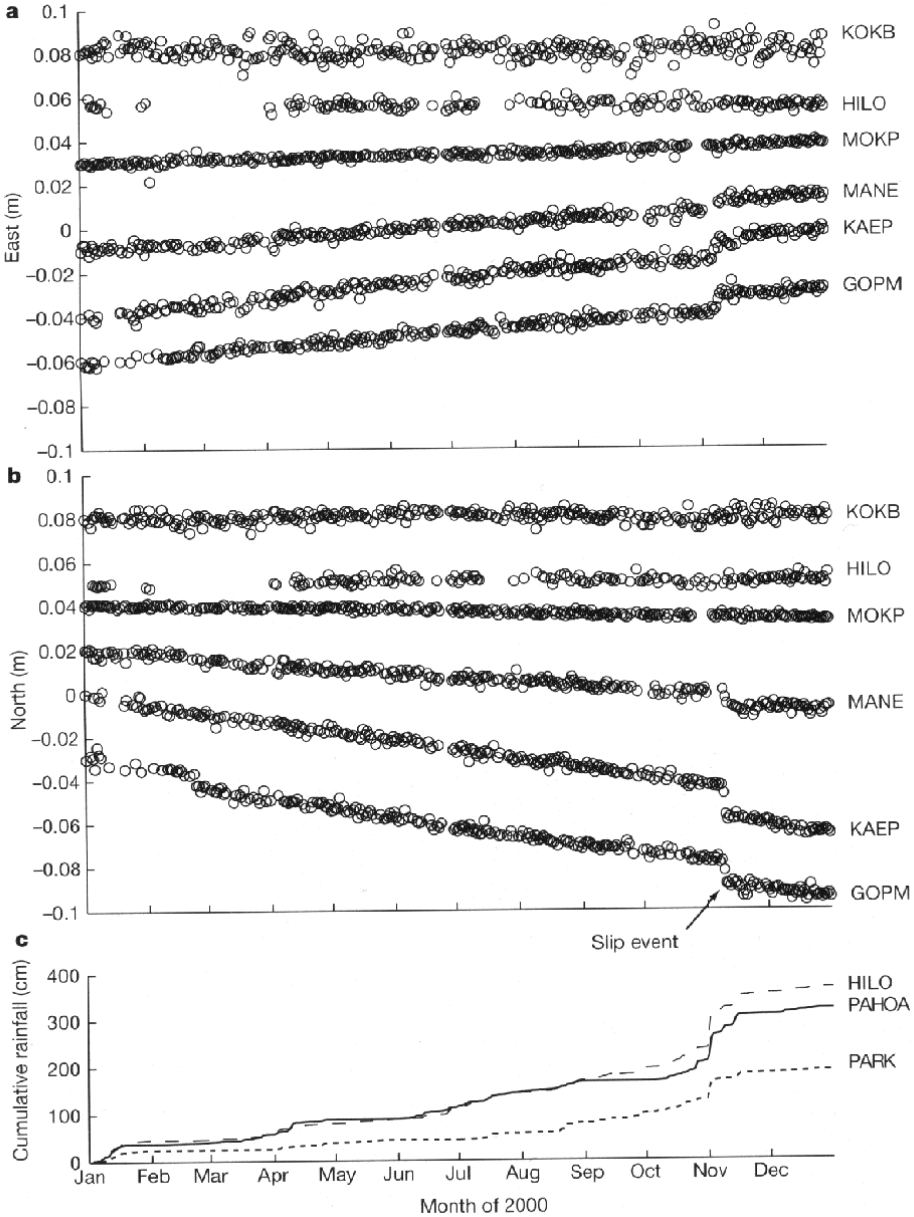
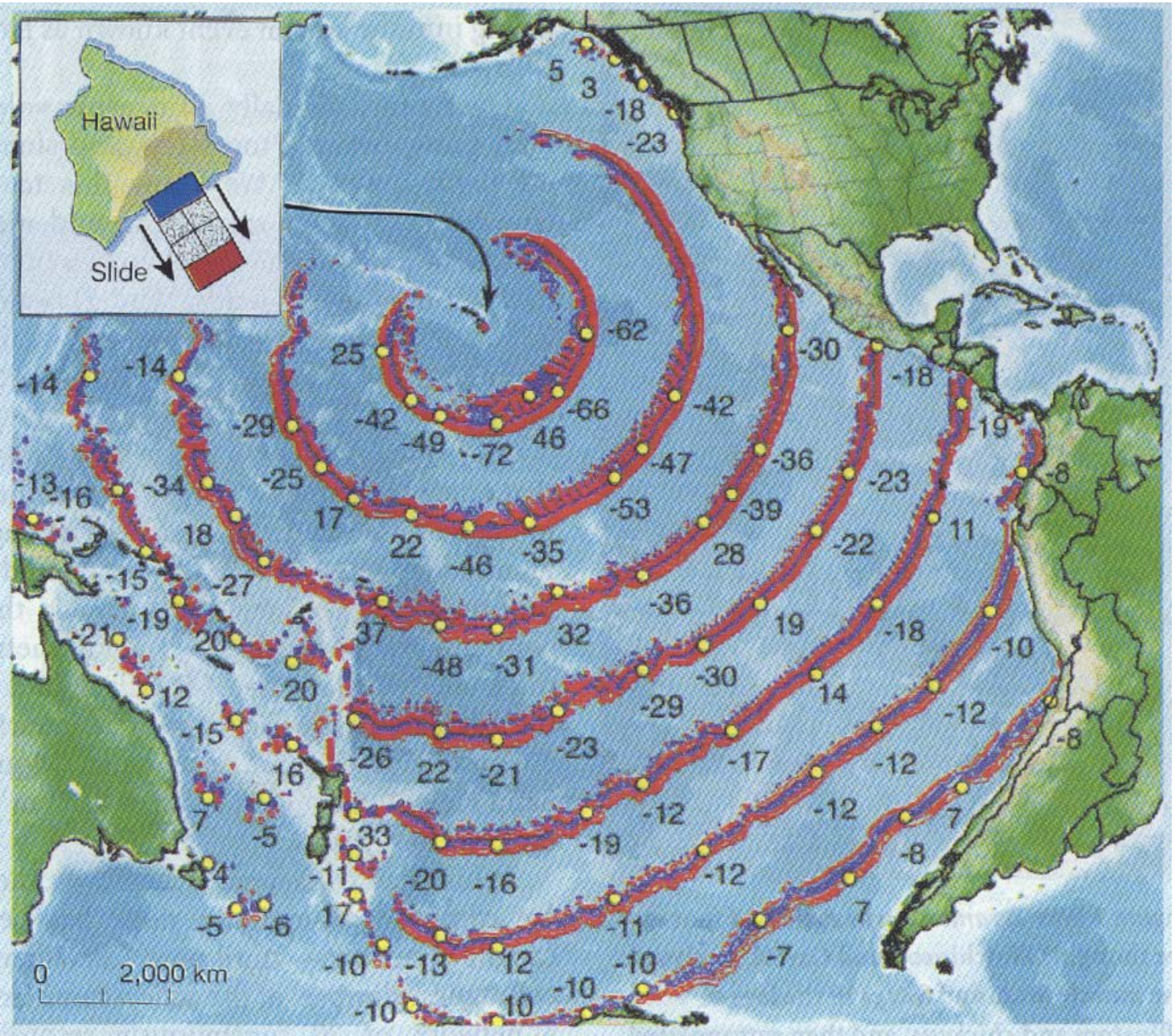






Corvelli (2002; Nature)

もし地すべりが発生すると．．

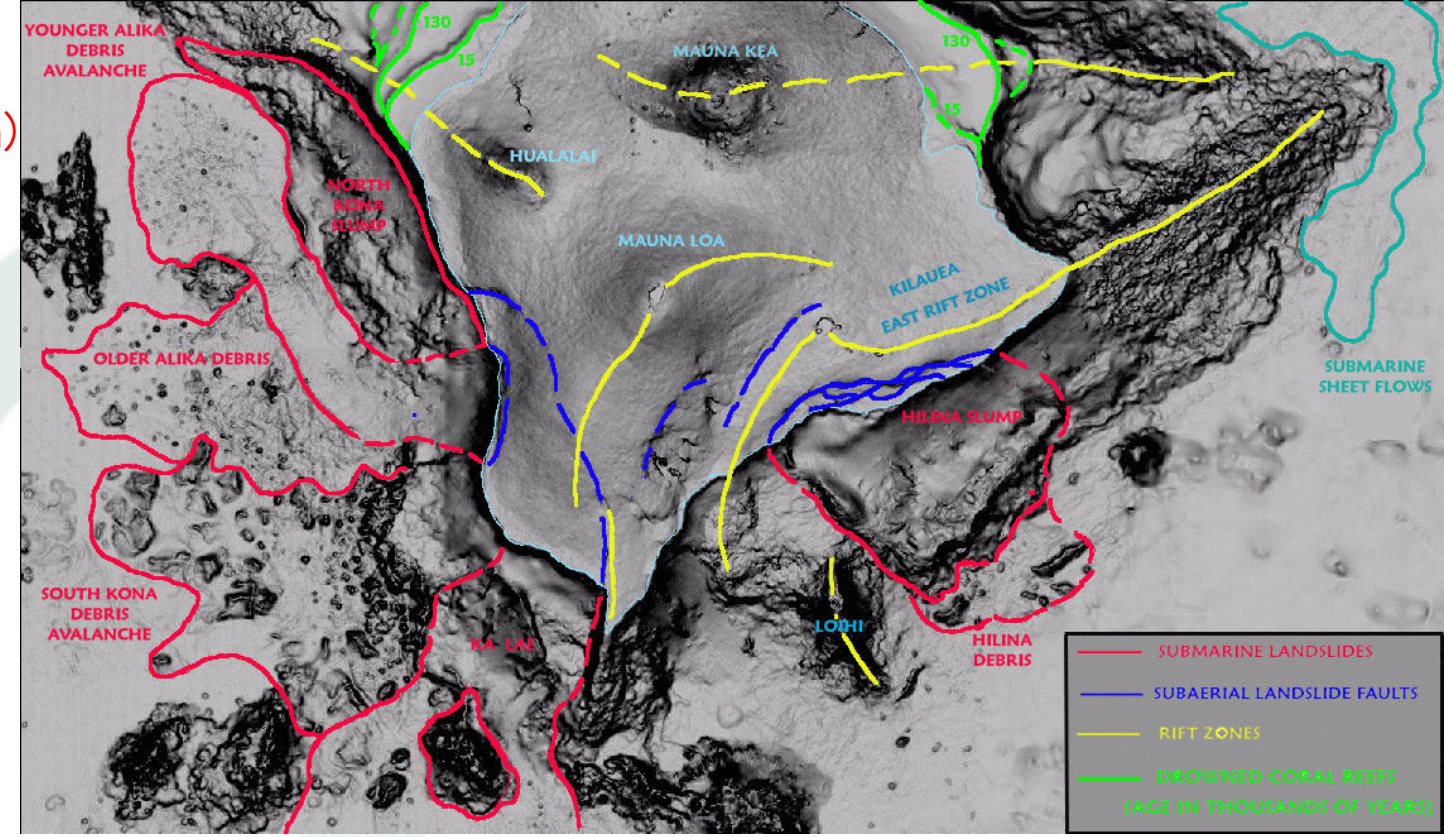


カリフォルニアには，30mを超える津波が押し寄せる．日本にも10m程度の津波が押し寄せるだろう．本当だとしたら恐ろしい．

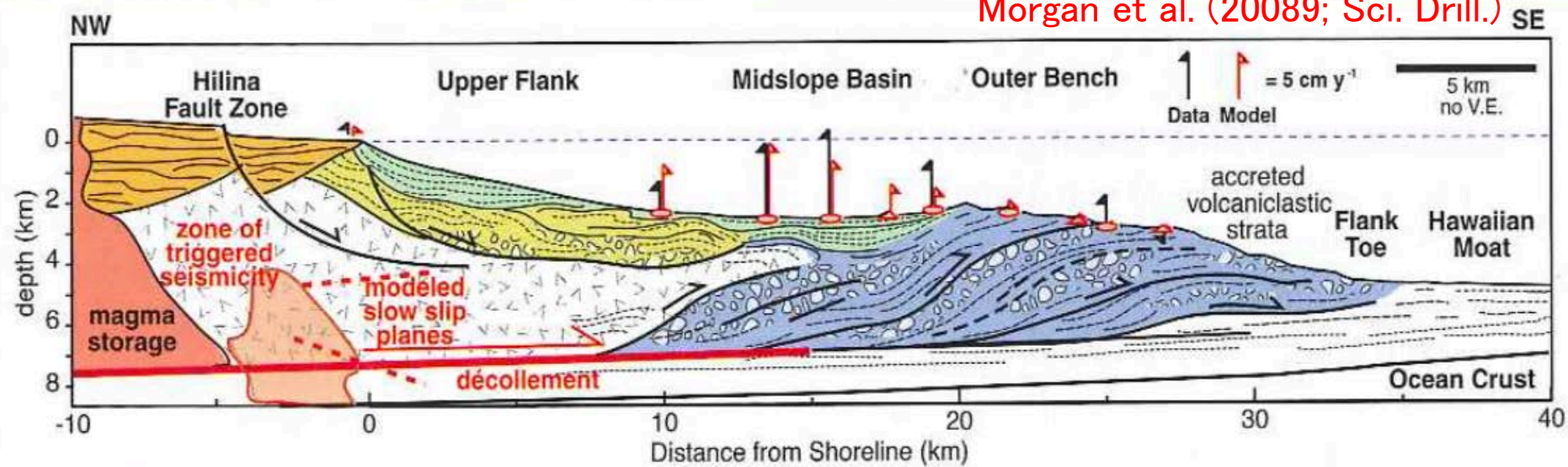
Ward (2002; Nature)

Moore and Chadwick (1995; AGU Monograph)

ヒリナスライド
現在でも活動している．ただし，これが一回で滑り落ちる確証はない．



Morgan et al. (20089; Sci. Drill.)



RSITY

Facts on the stability of Kilauea's south flank, past and present.

May 14, 2018

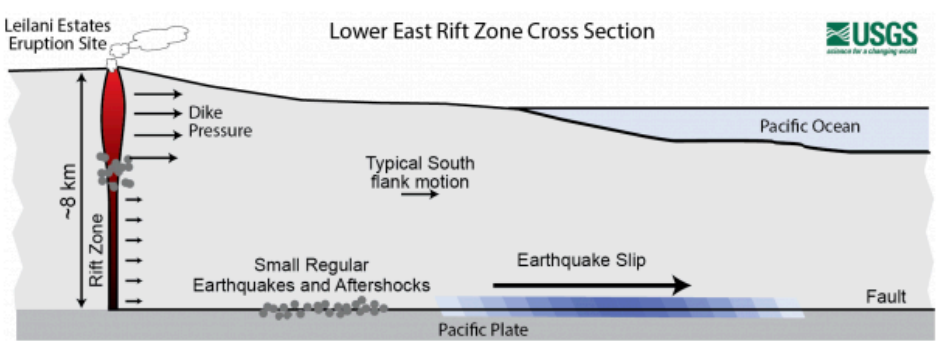
There have been several recent highly speculative stories, rumors and blogs about the stability of the south flank of Kilauea and the potential for a catastrophic collapse that could generate a Pacific-wide tsunami. We wish to put these speculations in their proper context by presenting observations of the current situation and an assessment of past evidence of landslides from Kilauea.

There is no geologic evidence for past catastrophic collapses of Kilauea Volcano that would lead to a major Pacific tsunami, and such an event is extremely unlikely in the future based on monitoring of surface deformation. Kilauea tends to "slump", which is a slower type of movement that is not associated with tsunamis, although localized tsunamis only affecting the island have been generated by strong earthquakes in the past.

The May 4 M6.9 earthquake resulted in seaward motion of approximately 0.5 m (1.5 ft) along portions of Kilauea's south flank as measured by GPS stations across the volcano. A preliminary model suggests that the motion was caused by up to 2.5 meters (8 feet) of slip along the fault that underlies the volcano's south flank, at the interface between the volcano and the ocean floor, about 7-9 km (4-6 mi) beneath the surface. This motion is within the expected range for a large earthquake on this fault. The earthquake was probably caused by pressure exerted by the magmatic intrusion on the south flank fault, following the pattern of past earthquake activity that has been observed during Kilauea East Rift Zone intrusions. A small, very localized tsunami did occur as a result of the fault slip. Similar local tsunamis were generated by past large earthquakes, including the 1975 M7.7 and 1868 ~M8 events, both of which resulted in multiple deaths along the south coast of the Island of Hawaii.

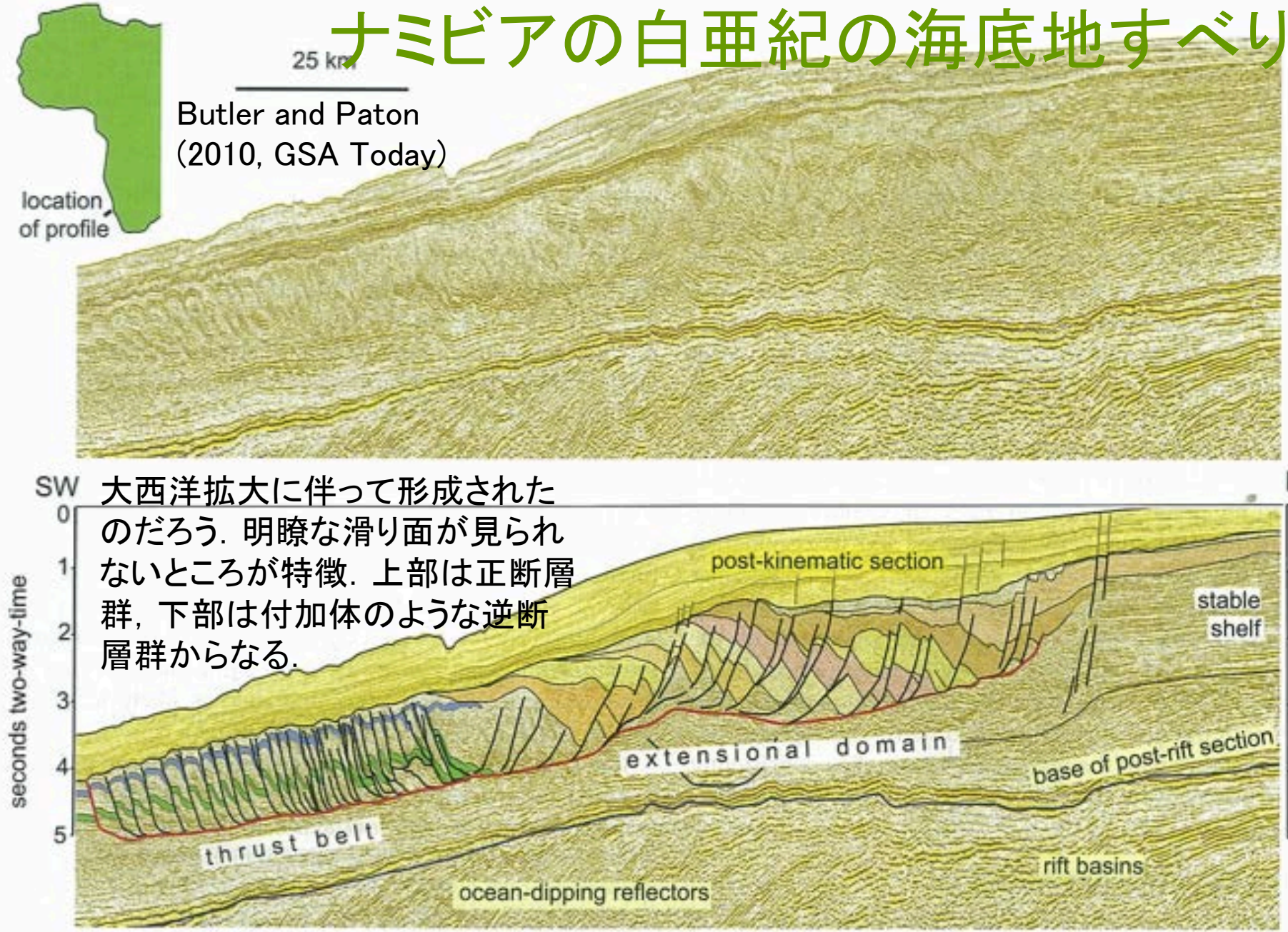
Adjustments on the south flank caused another ~9 cm (3.5 inches) of motion at the surface in the day after the earthquake, followed by another 2-3 cm (~1 inch) since May 5. This is higher than the normal rate of south flank motion (~8 cm (3 inches) per year) but is expected as the volcano adjusts after a combination of a magmatic intrusion along the East Rift Zone and a large south flank earthquake. We did observe minor ground ruptures on the south flank, but this is expected given the strength of the May 4 earthquake, and deformation data show that the south flank continues to move as an intact slump block.

Geologic history combined with models of south flank motion suggest that the likelihood of a catastrophic failure event is incredibly remote. There are certainly signs on the ocean floor for landslides from other volcanoes on the Island of Hawaii and from other islands, but none are associated with Kilauea. In addition, Kilauea has experienced much larger earthquakes and magmatic intrusions in the recent past. The large earthquakes of 1975 and 1868 were not associated with significant south flank landsliding, nor were major East Rift Zone intrusions in 1840 and 1924.



Cross-section through the lower East Rift Zone of Kīlauea Volcano. Magma intruded into the rift zone and exerted pressure on the south flank of Kīlauea, likely encouraging the M6.9 earthquake that occurred on a fault located at the interface between the volcano and the preexisting ocean floor.

ナミビアの白亜紀の海底地すべり



Butler and Paton
(2010, GSA Today)

大西洋拡大に伴って形成されたのだろう．明瞭な滑り面が見られないところが特徴．上部は正断層群，下部は付加体のような逆断層群からなる．

Figure 3. Regional seismic reflection profile across the continental margin offshore Namibia (see inset) shown in clean and interpreted form. Assu mean seismic velocity of 2.7 km/s, the vertical exaggeration is ~7:1. Original image courtesy of CGGVeritas and the Virtual Seismic Atlas.

デュープレックスは地すべりの証拠か？

付加体でのデュープレックスは前進して形成されるが，地すべりでは後退しながら作られるのではないか？

Shanmugam (2016; Jour. Paleogeogr.)

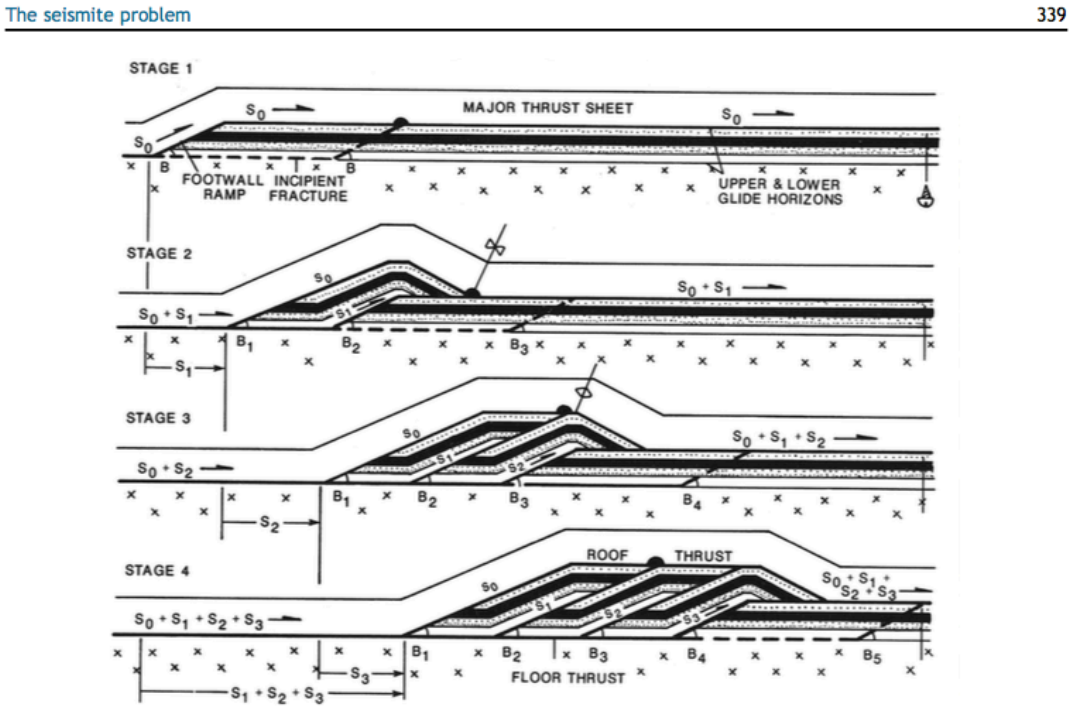


Fig. 19 Theoretical stages of development of duplex-like structures in thrust tectonics. Simplified after Boyer and Elliott (1982). Diagram from Shanmugam *et al.* (1988), with permission from Geological Society of America (GSA).

本日の話す内容

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■海底地すべり研究の最近20年ダイジェスト：

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2）地質地形問題：過去の記録を読み取るにはどうすればよいか

3）災害問題：津波と海底ケーブル

■さいごに：未来に向けてどうすればよいか

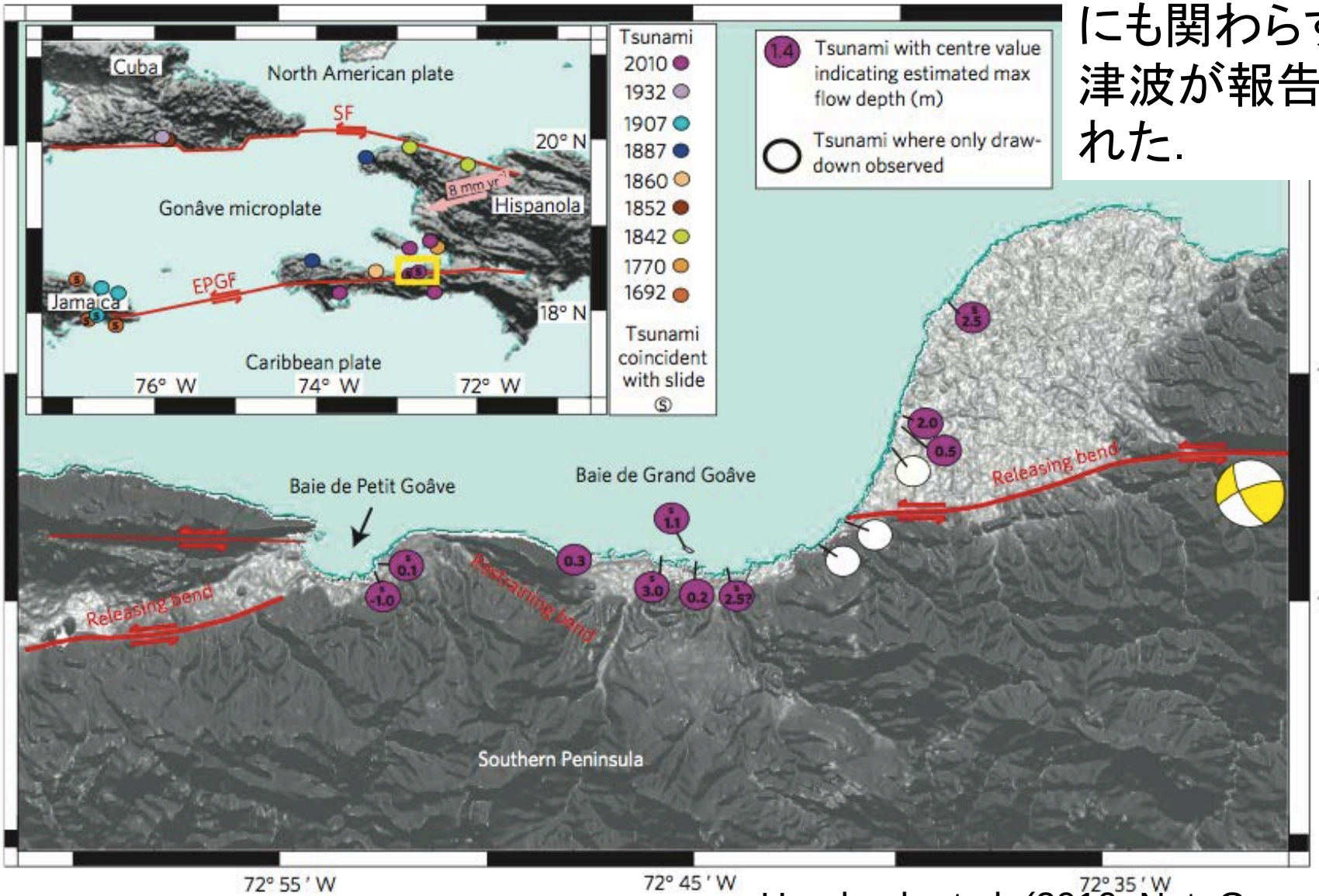
3）災害問題：津波と海底ケーブル

- 海底地すべりによる津波は，アラスカ，ハイチで地震による沿岸デルタで，ニューファンドランド沖グランドバンクスで地震による大陸斜面で，南フランスニースで沿岸工事に伴い斜面で生じている．
- 海底ケーブル切断は，グランドバンクス，台湾，東京湾，茨城沖で生じている．
- 懐疑的な巨大津波としては，パプアニューギニア・シッサノ，アラスカ沖，八重山諸島，富山湾，駿河湾，日本海溝で生じている．

2010年ハイチ地震

YAMAGUCH

横ずれ断層にも関わらず津波が報告された.



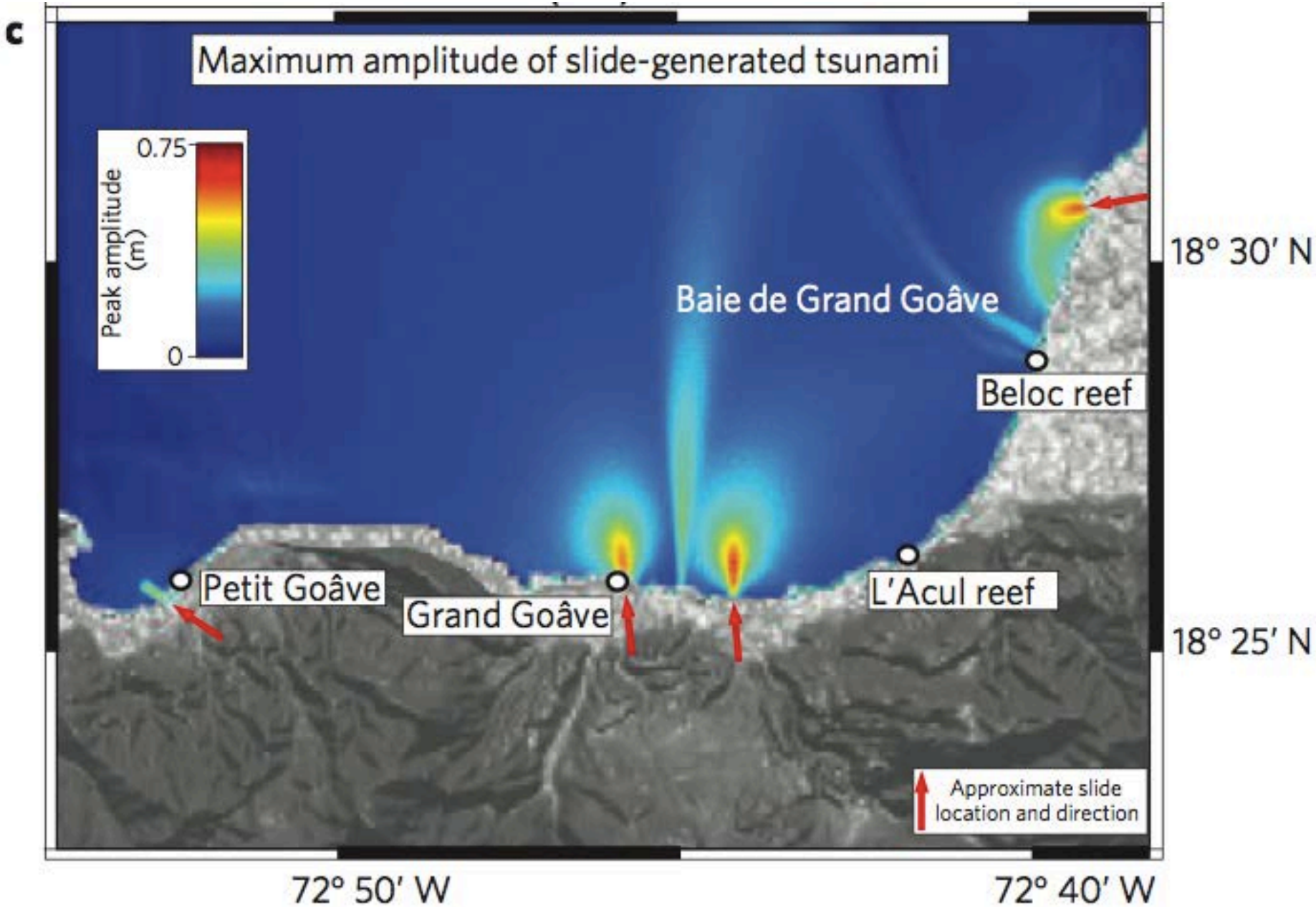
Hornbach et al. (2010; Nat. Geosci.)

Figure 1 | Tsunami reports across Haiti and Gonâve microplate. The 12 January epicentre is denoted by the yellow US Geological Survey moment tenso solution. Circles indicate locations of reported tsunami. Inset: The location of the Gonâve microplate with respect to the North American and Caribbean

2010年ハイチ地震

YAMAGUCHI UNIVERSITY

Hornbach et al. (2010; Nat. Geosci.)



1964年アラスカ地震

YAMA

海底地すべりによって
破壊された港湾施設

Plafker and Mayo (1965; USGS Rep.)

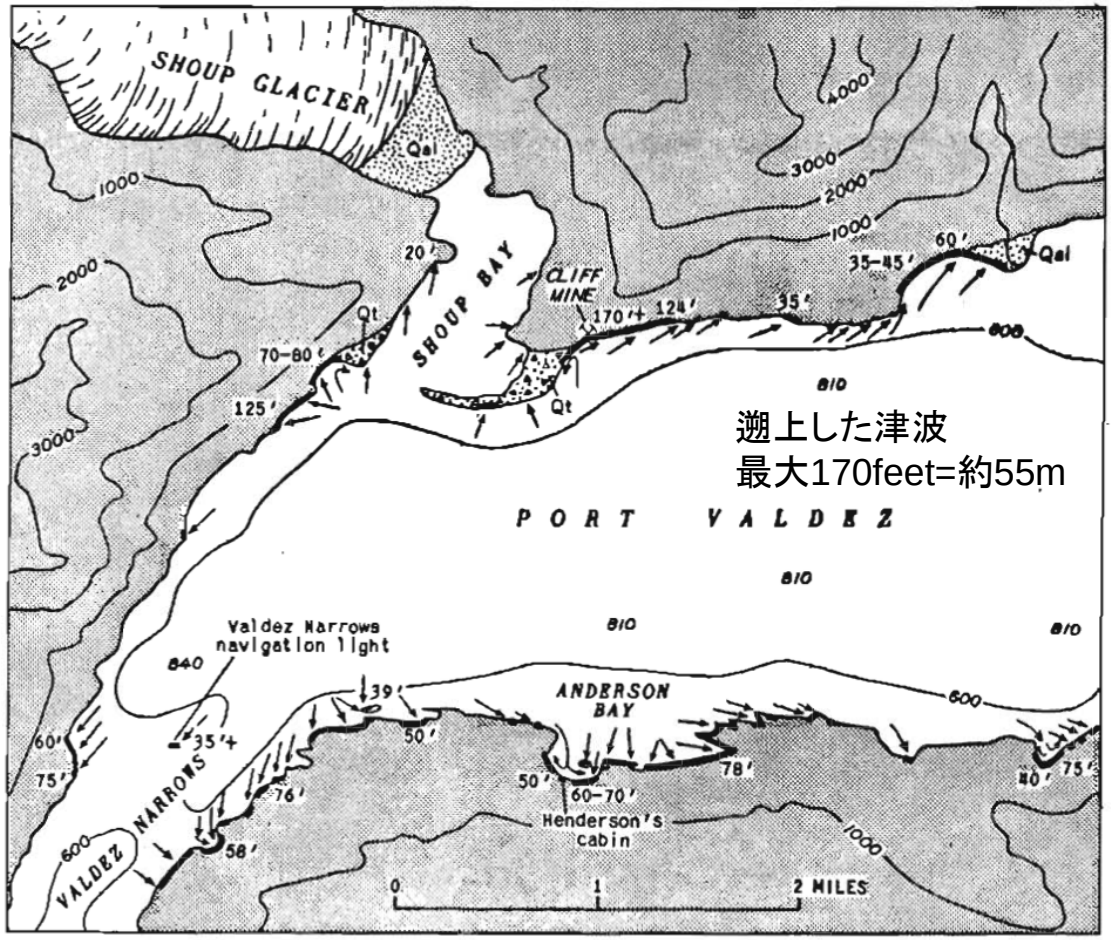


Figure 16. Heights and inferred directions of local waves in the western part of Port Valdez, Prince William Sound. Heavy line along shore indicates distribution of damage; numeral is measured maximum run-up. Shaded pattern, bedrock; dotted pattern, alluvium and intertidal mud; triangular pattern, terminal moraine of the Shoup Glacier. Contour interval on land is 1,000 feet; submarine contour interval is 600 feet.

遡上した津波の証拠（これで約25-33mの遡上高）

Figure 15. Slide scarp in terminal moraine-outwash-delta complex at the head of Passage Canal. The submarine slide carried away a portion of the railroad spur in the right foreground and partially undermined the abandoned house shown at the left. Water depth beneath the stern of the boat is 63 feet, indicating a submarine

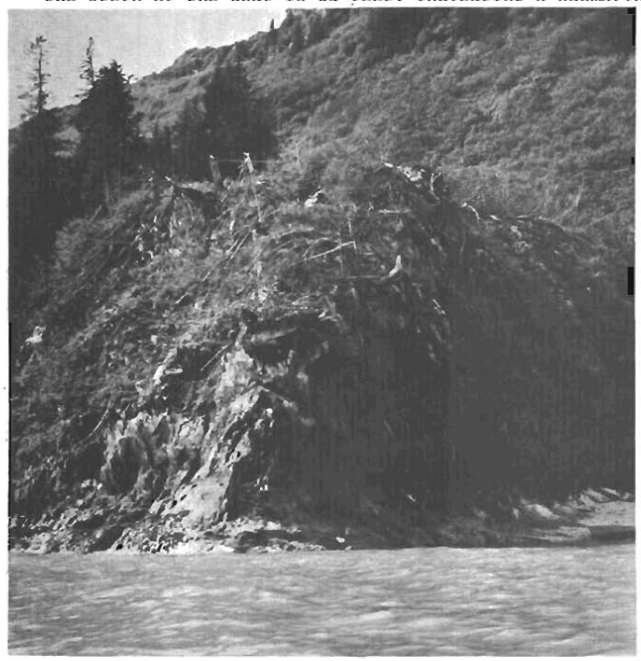


Figure 17. Spur west of Shoup Bay that was overtopped by a local wave travelling from right to left. Trees and branches are broken to an elevation of more than 100 feet above lower low water.

Masson et al. (2010; Springer)

デルタで発生する海底地すべり

■間隙水圧の上昇

1）速い堆積速度

→比較的短時間の水圧上昇→浅部で発生→デルタ上部で海底地すべり→上部斜面の欠落と除荷→徐々に前進して地すべり巨大化

2）圧密

→時間をかけて水圧上昇→深部で発生→デルタ先端部で海底地すべり→滑落崖の不安定化→徐々に後退して地すべり巨大化

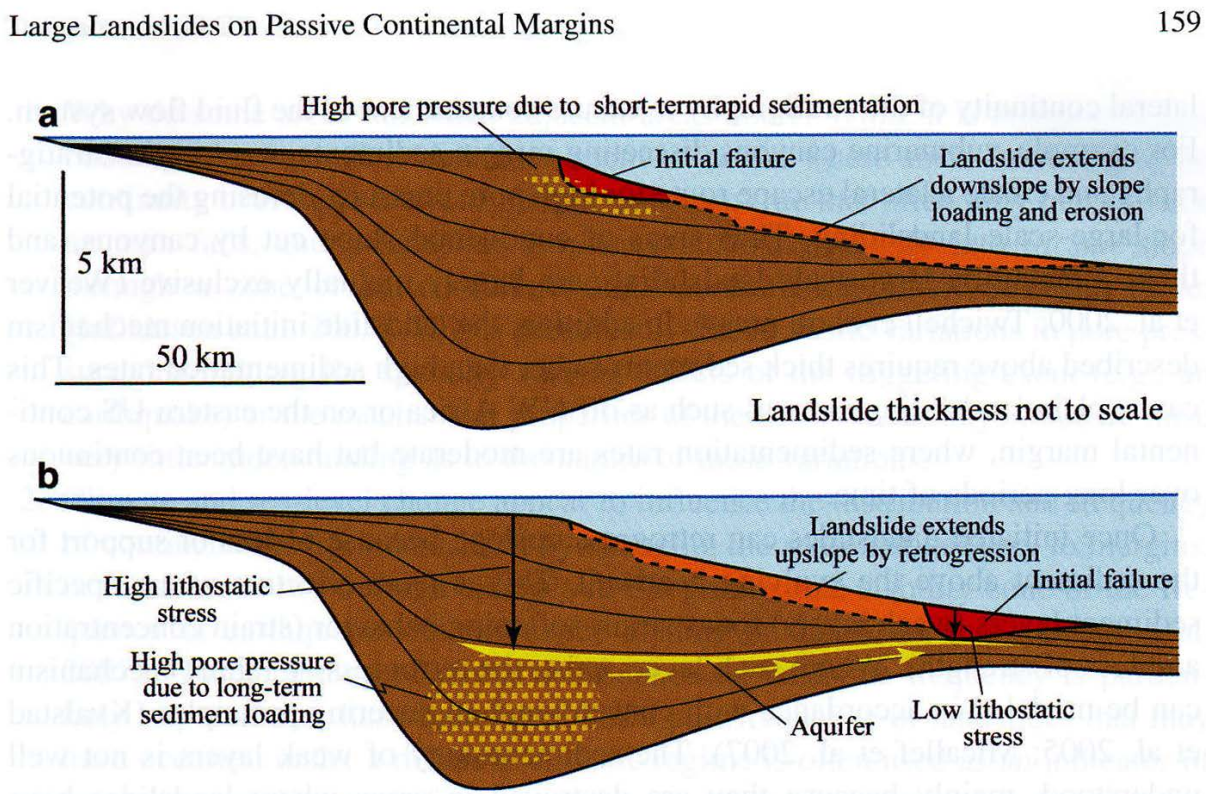
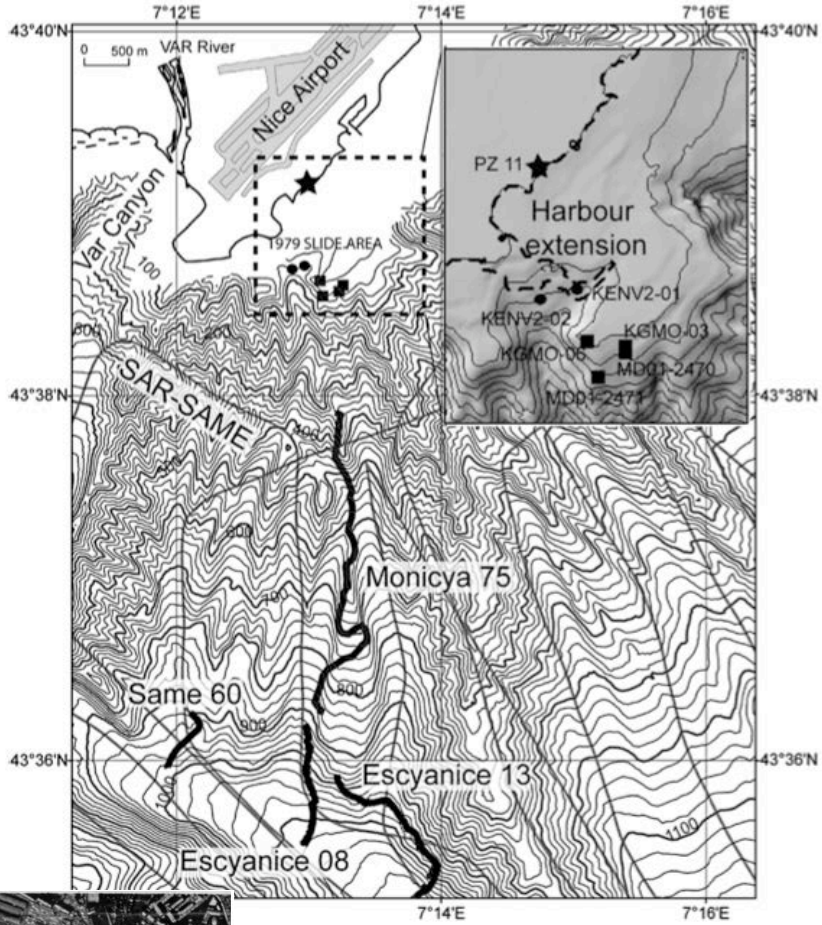


Fig. 4 Schematic illustration of a continental margin illustrating contrasting 'end member' initiation mechanisms for giant landslides. Landslide thickness is exaggerated to improve presentation. (**a**) Landslide initiated on the upper slope due to rapid sedimentation. (**b**) Landslide initiated on the lower slope due to lateral advection of high pore pressure from thicker sediment accumulation beneath the upper slope. In both (**a**) and (**b**), development of the landslide beyond the initial failure is controlled by weak layers within the parallel bedded slope sediment sequence

南フランス，ニース空港の拡張工事での津波

- 1979年10月16日，空港に接続する商業港を建設しているときに，突然崩壊し，遡上高3-5 mの津波が発生した.



a: side-scan sonar data (Same, 1986) and submersible dives: Escyanice 08 et 13 (Esc
, 1989) (Mercator, WGS 1984).

（Dan et al., 2007; Mar. Geol.）

http://www.lamouettelaurentine.net/st_laurent_du_var/port/tsunami.htm

想定される海底地すべり地域

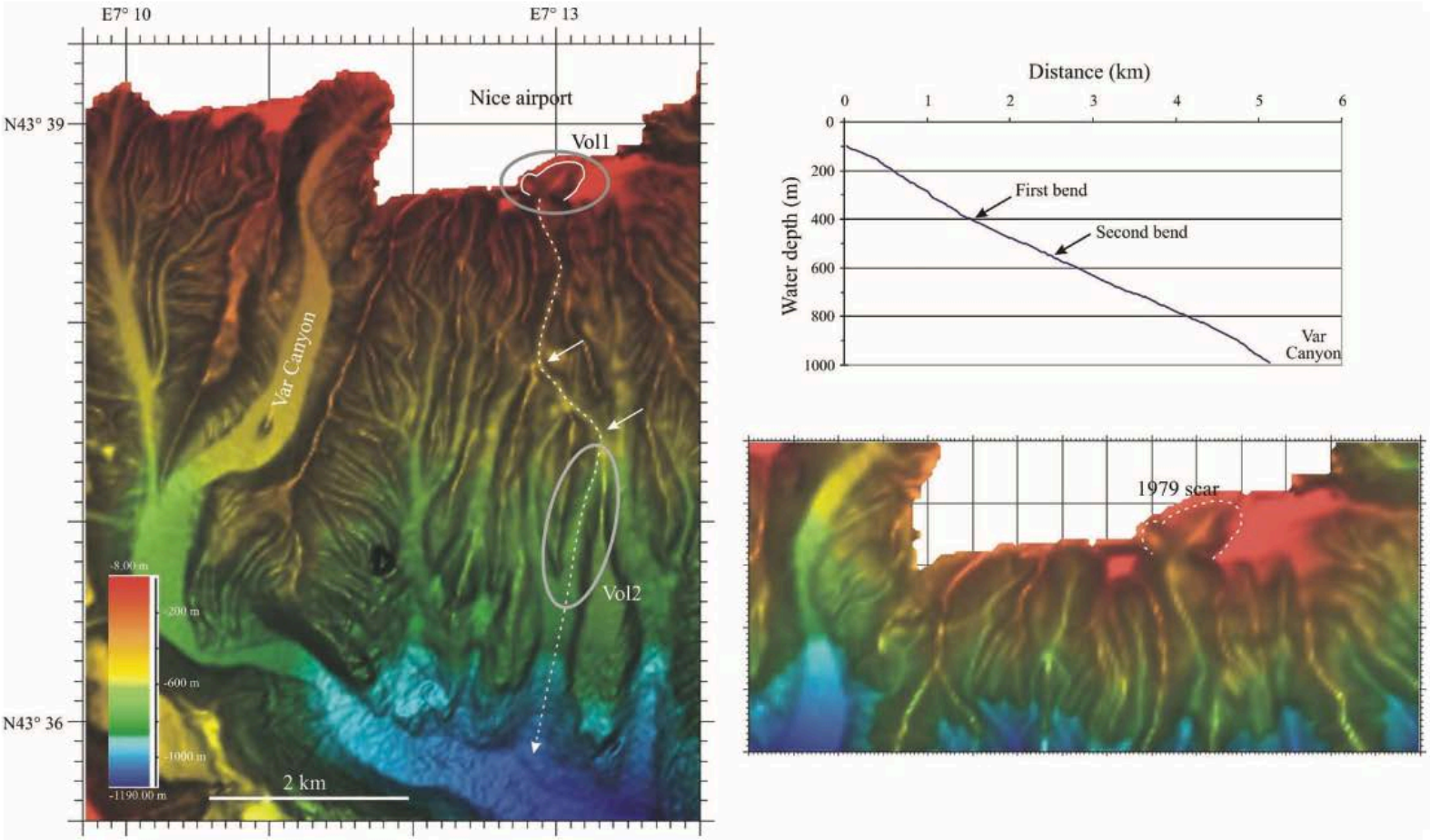


Figure 3. Bathymetric maps showing the morphology of the continental slope offshore the Nice airport, the location of the scar of the 1979 event and the pathway of the reworked deposits on the slope (white dashed line). The location of Vol1 and Vol2 discussed in the text are also represented. The bathymetric profile is taken along the pathway of the 1979 event, from the base of the scar to the Var Canyon. The two arrows locate the two bends observed along the pathway of the 1979 event.

Iualalen et al. (2010; GJI)

津波シミュレーション（馬てい形に抜け落ちるところと移動体が移動したところ）

Iualalen et al. (2010; GJI)

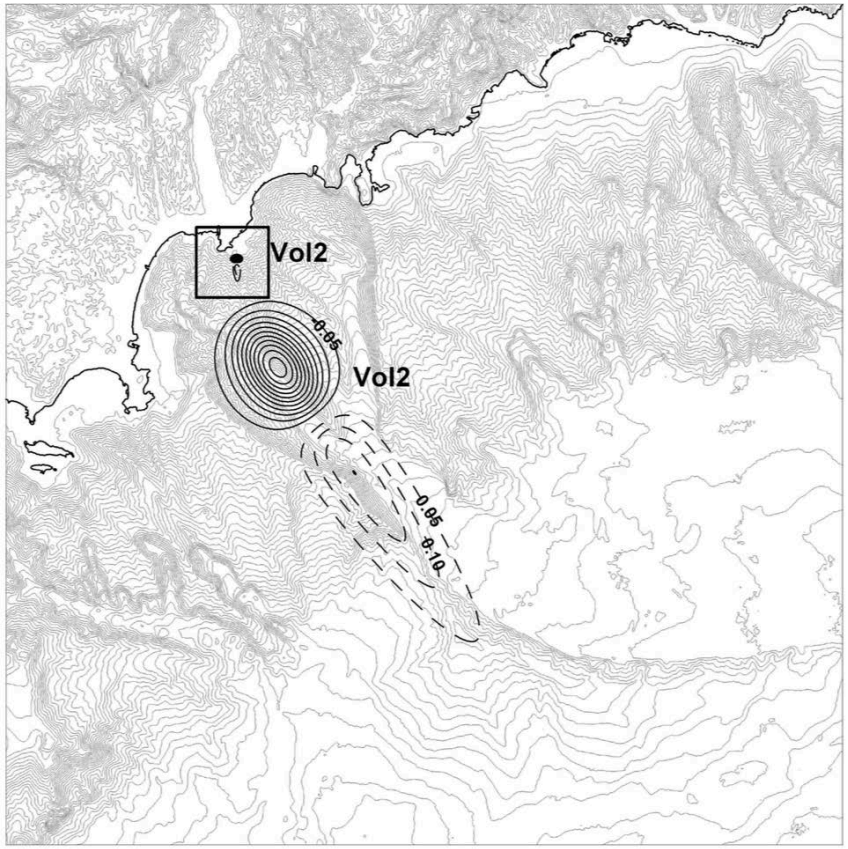


Figure 5. Initial surface elevation generated by TOPICS for SMFs Vol1 and Vol2. Dashed lines correspond to seafloor uplift (tsunami crest) and solid lines to subsidence (tsunami trough) (0.5 m iso-contours for Vol1 and 0.05 m iso-contours for Vol2). The bathymetry is plotted in the background (20 m iso-contours).

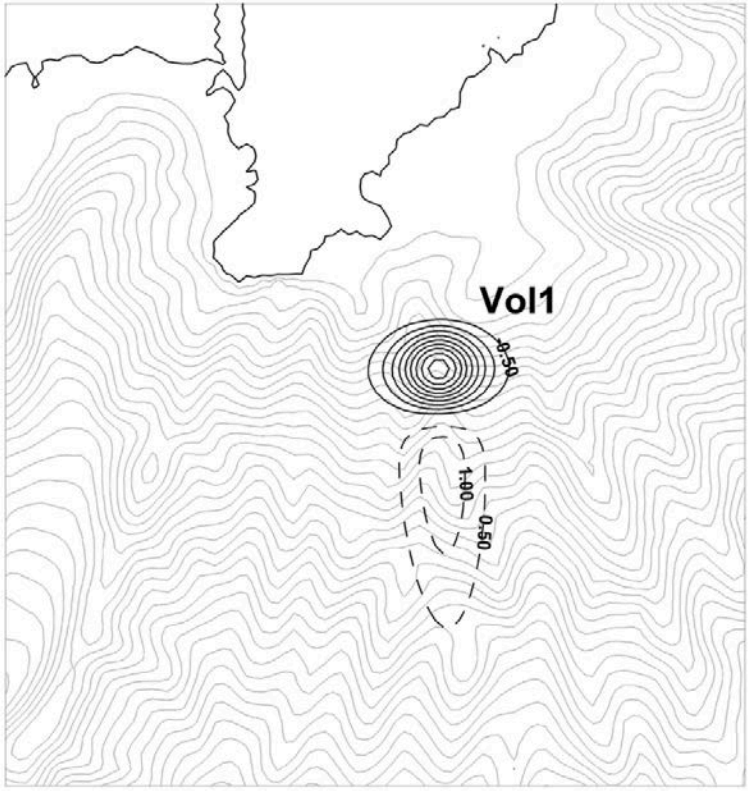
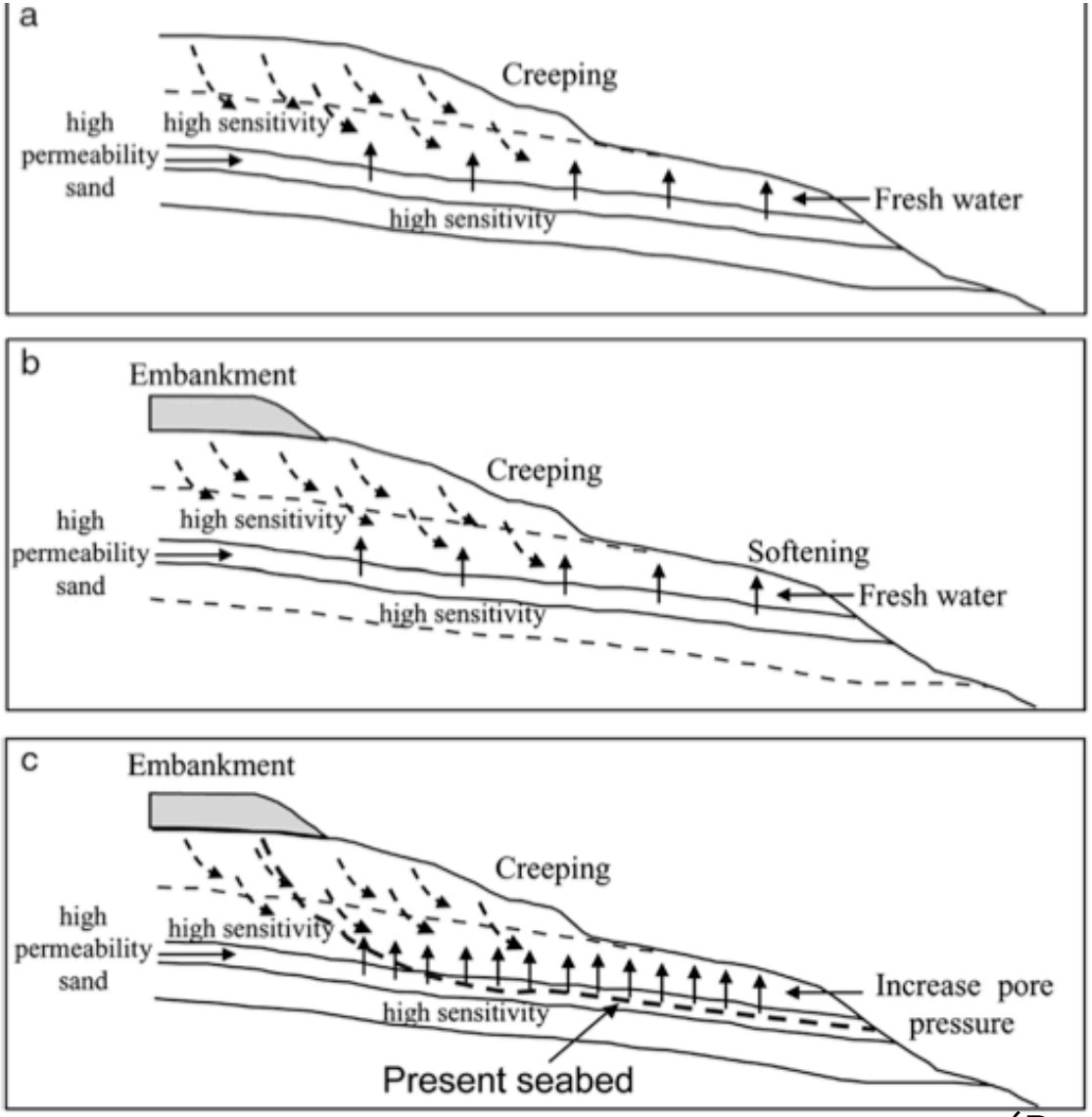


Figure 6. Enlargement of the area contained in the rectangle drawn in Fig. 5 (10 m bathymetry iso-contours).

フランス・ニース沿岸での事例：鋭敏粘土が原因



（Dan et al., 2007; Mar. Geol.）

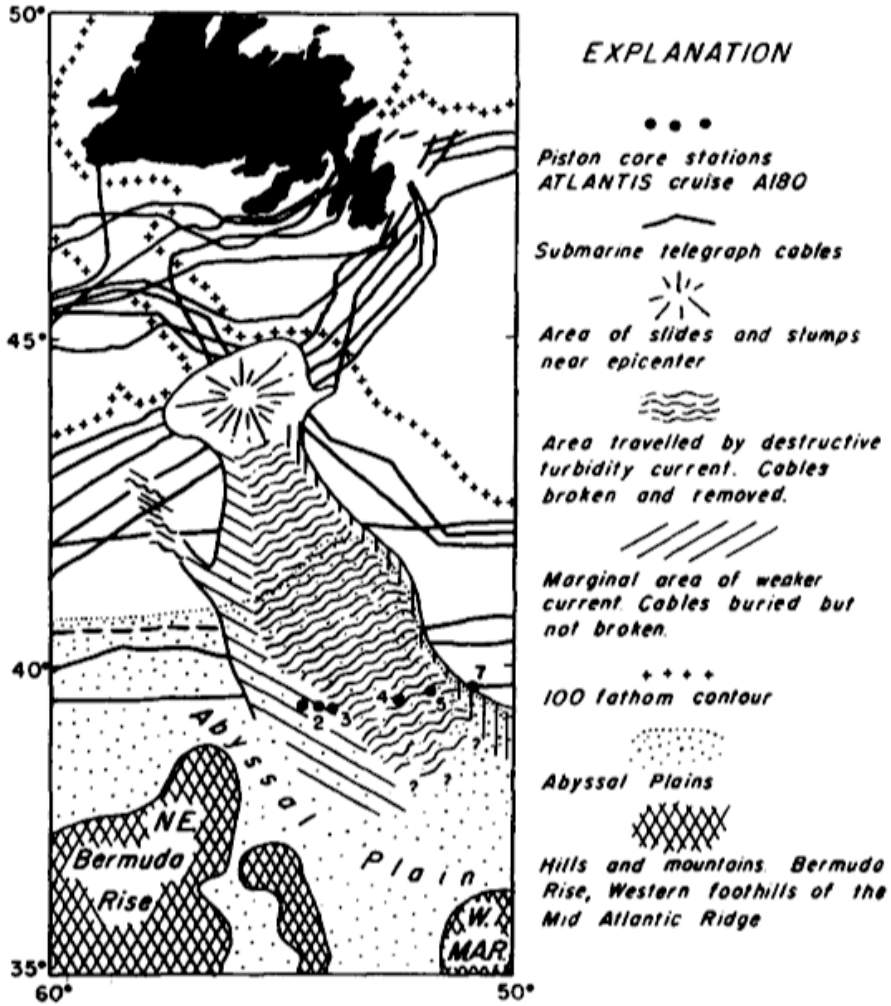
Fig. 20. Sketch illustrating the probable scenario of the 1979 Nice slope failure: (a) The high permeability sand layer represents a fresh water conduit inducing the increase of the sensitivity of the surrounding clay by leaching. (b) The embankment generates the softening of the mechanical properties of the sensitive clay layer and an increase in creeping. (c) After a period of rainfall, the pore pressure possibly increases and induces the decrease of the effective stress which conducts to failure.

3）災害問題：津波と海底ケーブル

- 海底地すべりによる津波は，アラスカ，ハイチで地震による沿岸デルタで，ニューファンドランド沖グランドバンクスで地震による大陸斜面で，南フランスニースで沿岸工事に伴い斜面で生じている．
- **海底ケーブル切断は，グランドバンクス，台湾，東京湾，茨城沖で生じている．**
- 懐疑的な巨大津波としては，パプアニューギニア・シッサノ，アラスカ沖，八重山諸島，富山湾，駿河湾，日本海溝で生じている．

グランドバンクス地震と津波

Heezen et al. (1954; Deep-Sea Res.)



THE 1929 GRAND BANKS TURBIDITY CURRENT

Showing relative position of sediment cores and turbidity current

Chart of current showing areas of cable breakage and cable burial in relation t

1929年11月18日M7.2地震によって海底地すべりが生じ，　海底地すべりとそれに伴う混濁流が生じた．12本のケーブルを切断し，その切断間隔から，混濁流のスピードは55knot（約100km/h）から始まり，最後のケーブル切断は12knot（約20km/h）であった．

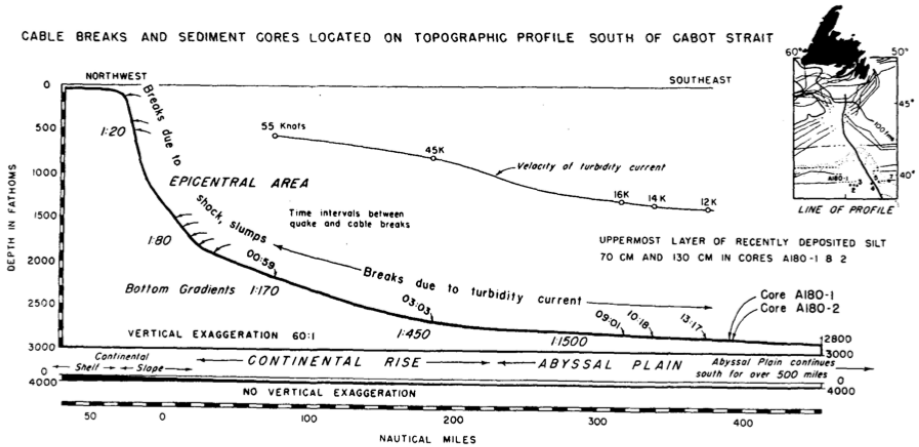


Fig. 1. Cable breaks and sediment cores located on a topographic profile south of Cabot strait with superimposed graph of velocity of the turbidity current.

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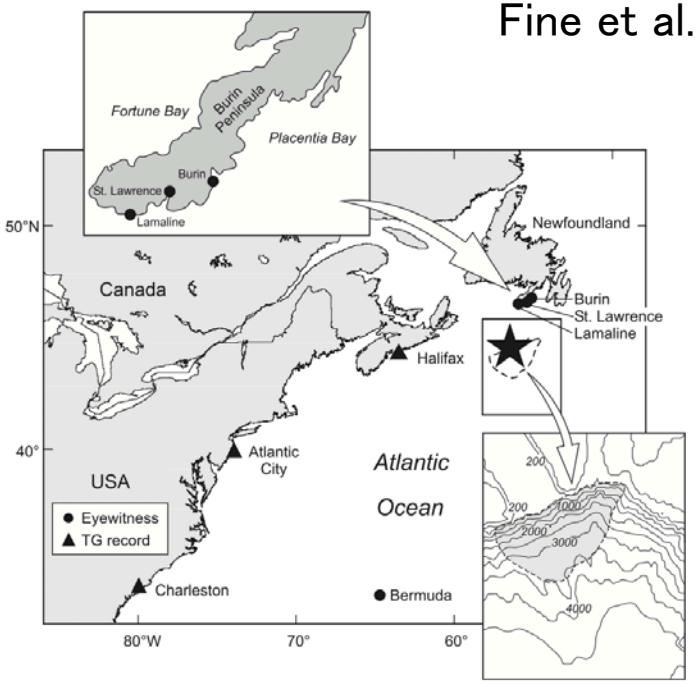
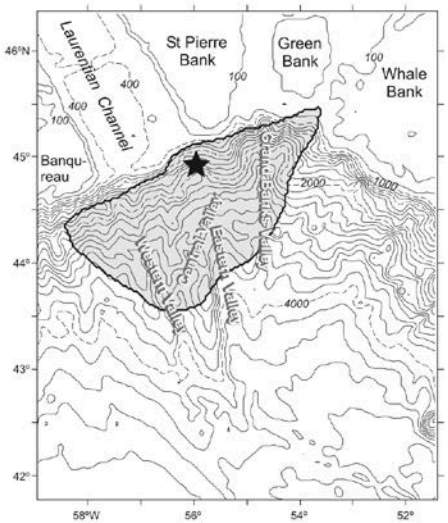
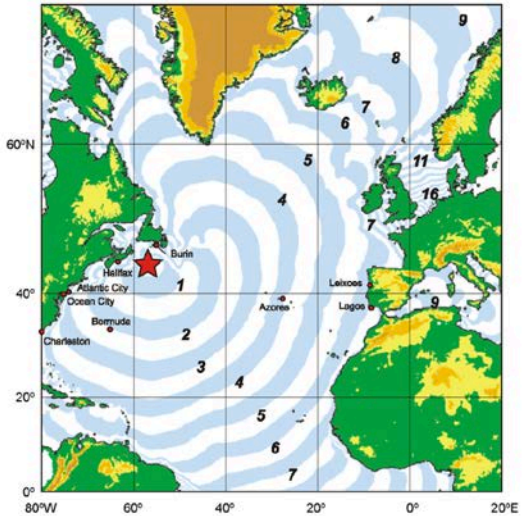
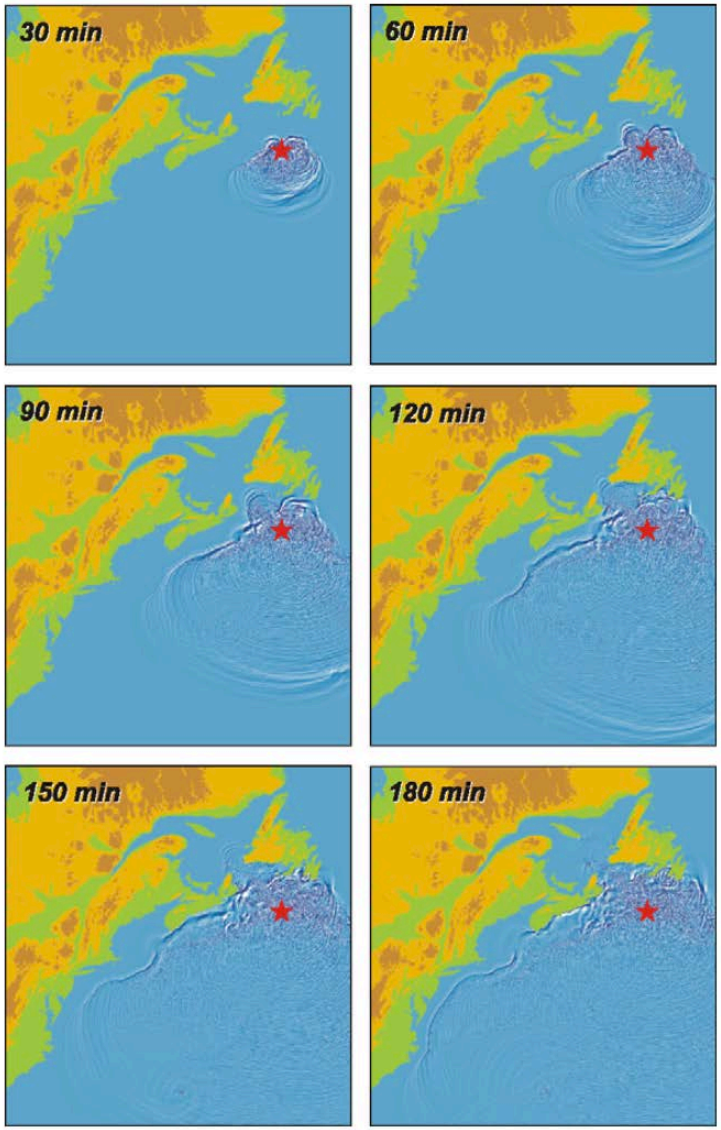
グランドバンクスの海底地すべりと津波（波高3−8m，遡上高13m）．海底地すべりは，60−100km/h程度であったと算出されている．

Fine et al. (2005; Mar. Geol.)









he Laurentian Fan with the location of the 1929 Grand Banks earthquake (marked by a

Fig. 8. Map of the estimated tsunami travel times (in hours) in the North Atlantic Ocean for waves generated by the l failure. Red circles indicate the observation sites (see Table 1).

Fig. 5. Snapshots of simulated tsunami waves for 30, 60, 90, 120, 150, and 180 min after the 1929 Grand Banks slide failure. The star indicates the epicenter of the earthquake.

台湾での事例

YAM インターネットが遮断されると，政治，経済など社会に関わる通信が一切できなくなる

2006年12月26日，少なくとも6本。インターネットが数日に渡り，不通となった．

768 Hsu et al.

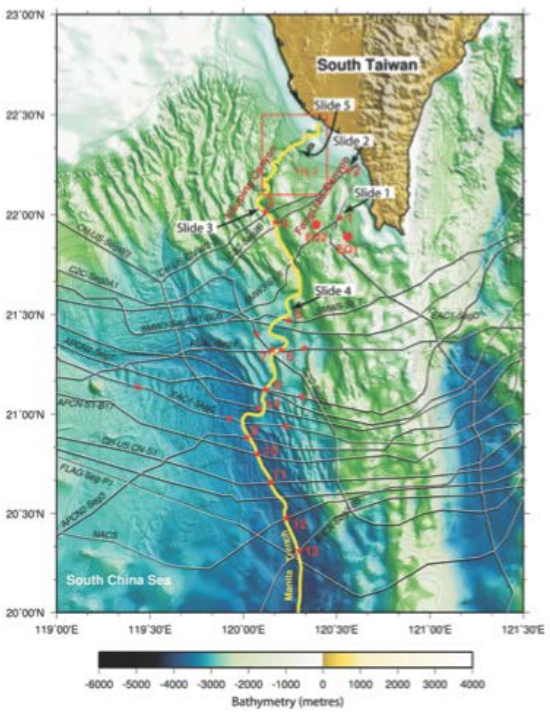


Fig. 1. Location of submarine telecommunication cables and cable breaks offshore SW Taiwan. EQ1 and EQ2 are the two major Pingtung earthquakes of magnitude 7.0. The yellow continuous line underlines the channel of the Kaoping canyon and Manila trench. Red stars correspond to the locations of cable breaks. Numbered stars are used in Fig. 3. Five submarine landslides are identified. Cable break times and locations are given in Table 1.

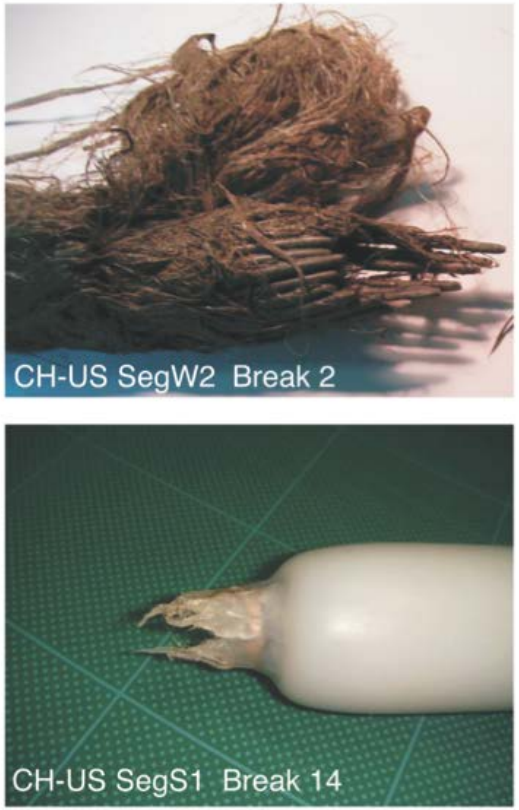
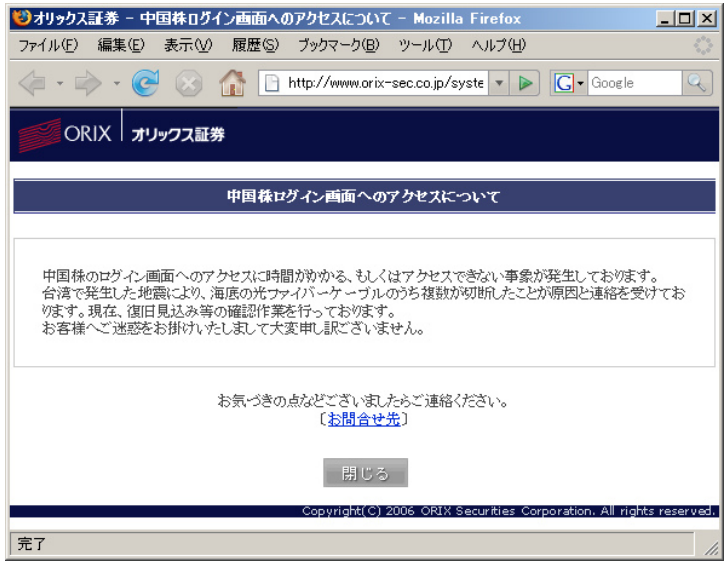


Fig. 2. Broken cables recovered during cable repair operations. Upper piture: break of an armoured type cable recovered during break 2 repair (located in Fig. 1). Lower picture: break of a lightweight type cable recovered during break 14 repair (located in Fig. 1).

Hsu et al.（2008; TAO）



AFP（2007; http://www.afpbb.com/articles/-/2165775?pid=

大正関東地震での海底ケーブル切断の事例

海底ケーブル障害は対岸の火事ではない．日本でも事例が報告されている1923年9月1日の関東大震災（M7.9）では，合計6箇所で切断された．

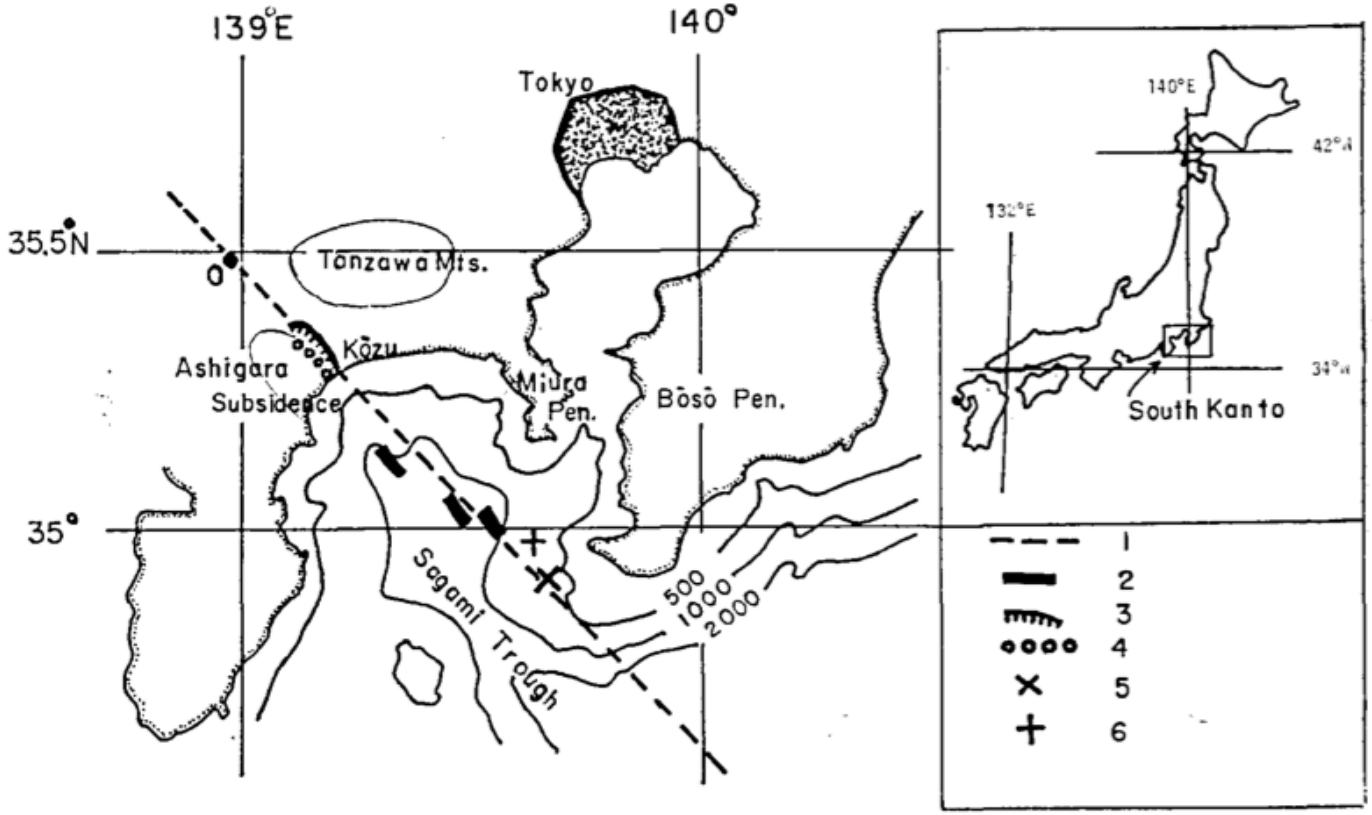


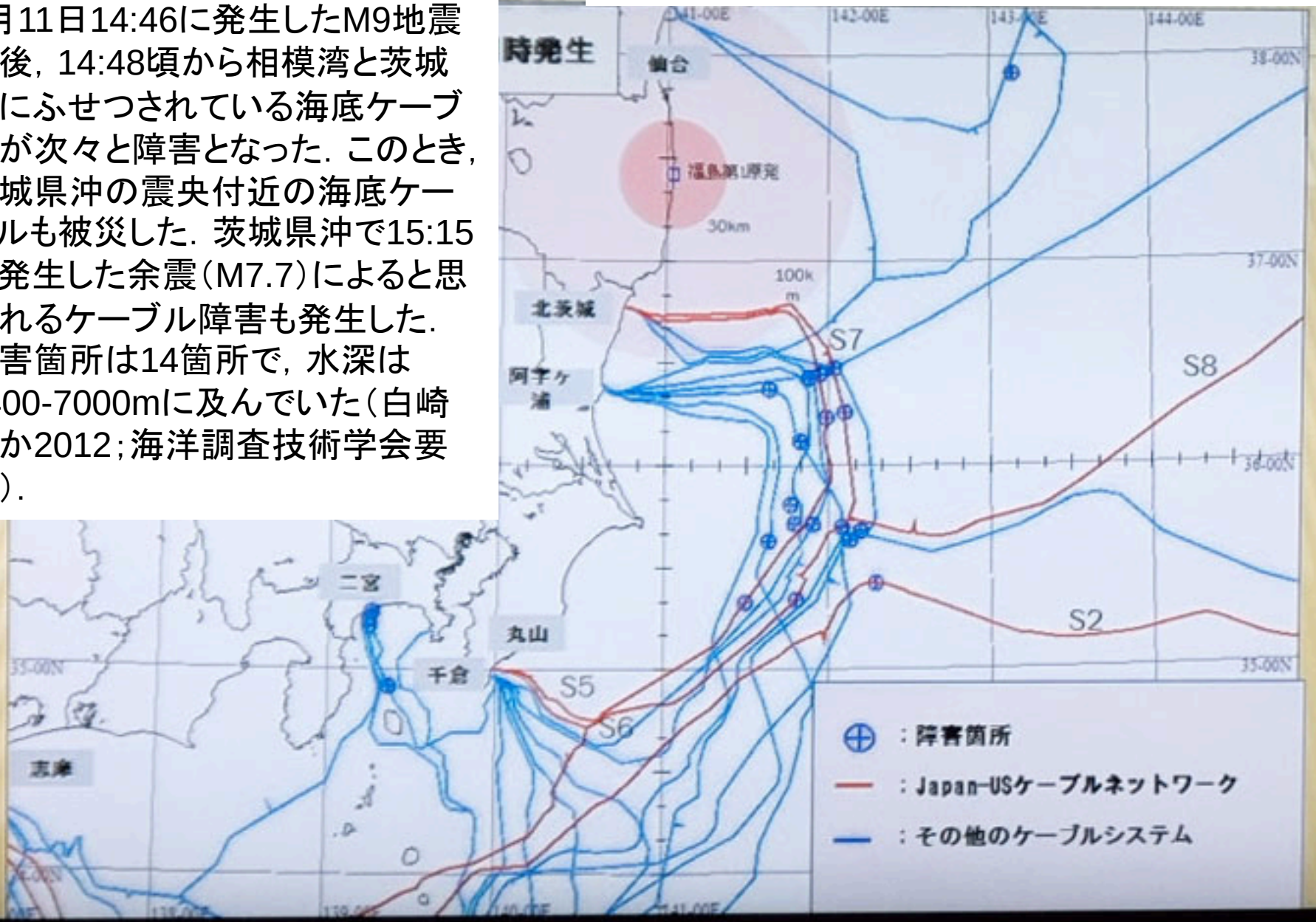
Fig. 1. Sketch map of the south Kanto district (right), assumed fault trace and supporting evidence of it. 1, assumed fault trace; 2, submarine faults after Kimura et al. (1971), 3, Kozu-Matsuda fault; 4, fracture trace of the great Kanto earthquake after Kaneko (1969); 5, location of submarine cables cut; 6, location dead fishes.

Ando (1971; Bull. ERI)

東北地方太平洋沖地震での海底ケーブル切断の事例

https://internet.watch.impress.co.jp/docs/news/608569.html

3月11日14:46に発生したM9地震の後，14:48頃から相模湾と茨城沖にふせつされている海底ケーブルが次々と障害となった．このとき，宮城県沖の震央付近の海底ケーブルも被災した．茨城県沖で15:15に発生した余震（M7.7）によると思われるケーブル障害も発生した．障害箇所は14箇所で，水深は2400-7000mに及んでいた（白崎ほか2012；海洋調査技術学会要旨）．



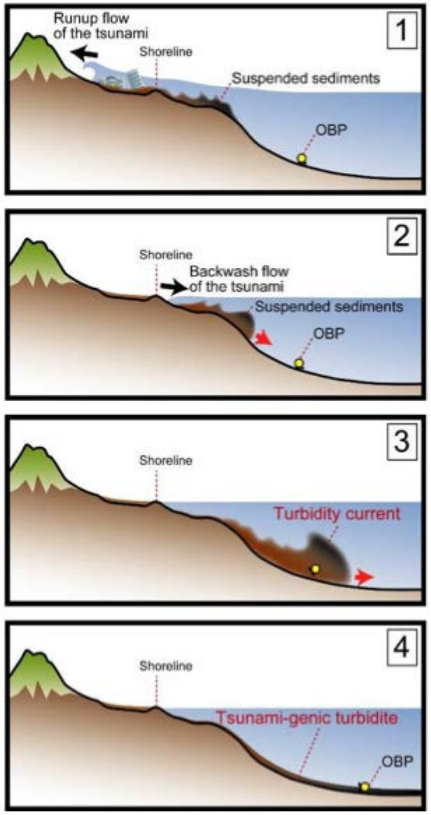
東北地方太平洋沖地震での海底ケーブル切断の事例

海底谷を流下する混濁流が見えてくる．これらはどこから来たのか？

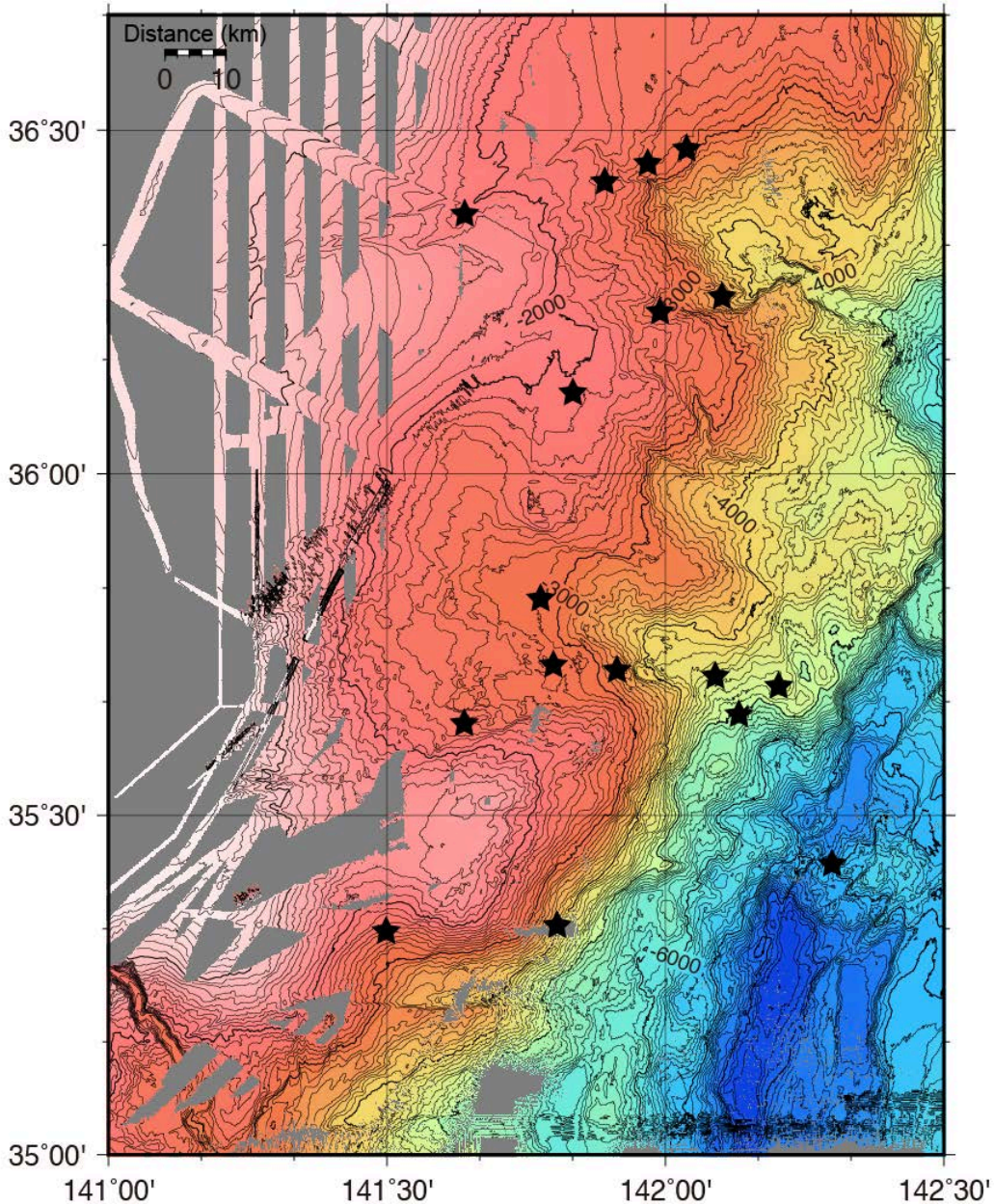
1）海底地すべり，

2）津波による混濁流，

3）表層での流下現象の拡大



Arai et al. (2014; Geology)



3）災害問題：津波と海底ケーブル

- 海底地すべりによる津波は，アラスカ，ハイチで地震による沿岸デルタで，ニューファンドランド沖グランドバンクスで地震による大陸斜面で，南フランスニースで沿岸工事に伴い斜面で生じている．
- 海底ケーブル切断は，グランドバンクス，台湾，東京湾，茨城沖で生じている．
- **懐疑的な巨大津波としては，パプアニューギニア・シッサノ，アラスカ沖，八重山諸島，富山湾，駿河湾，日本海溝で生じている．**

パプアニューギニア・シッサノの事例

The Papua New Guinea tsunami of 17 July 1998: anatomy of a catastrophic event

D. R. Tappin[1], P. Watts[2], and S. T. Grilli[3]

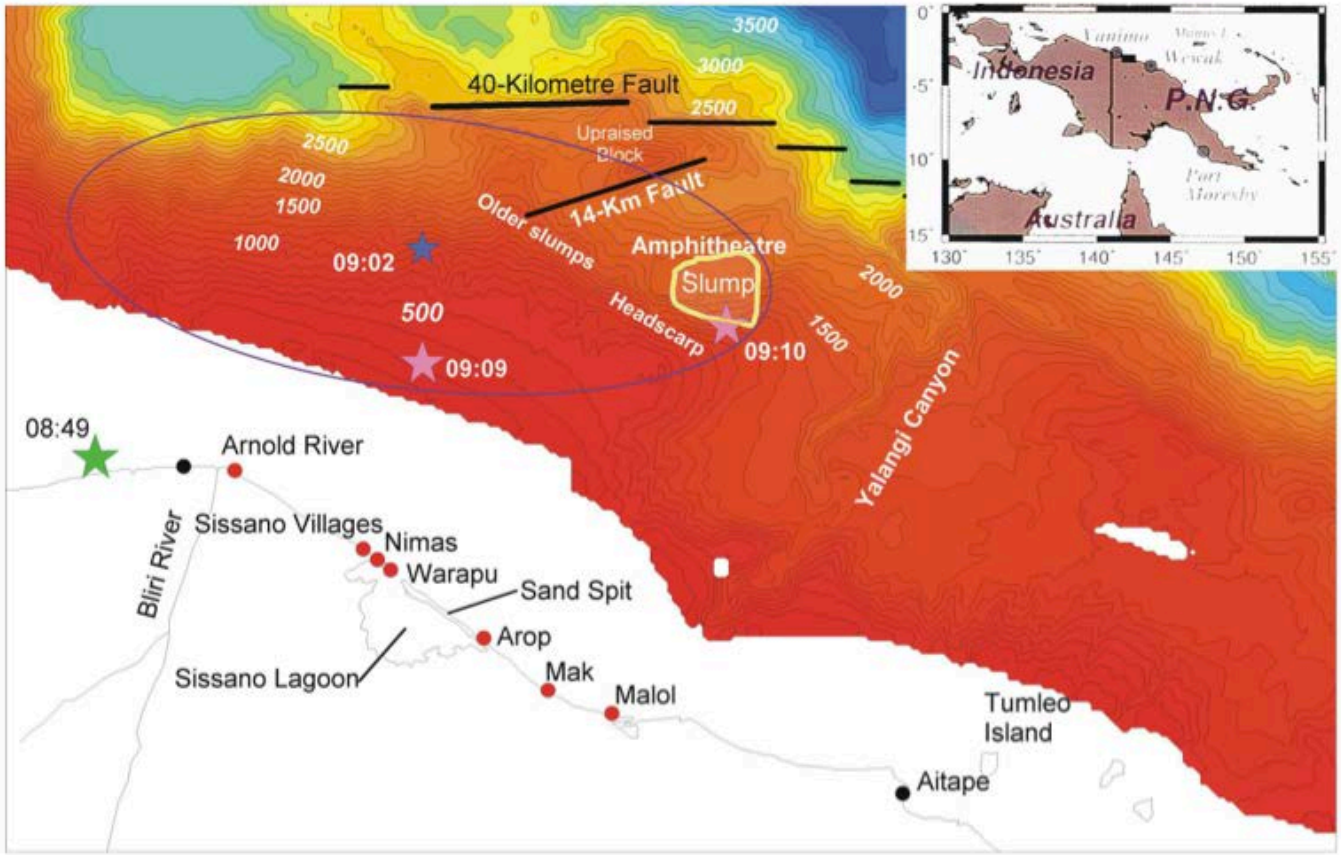
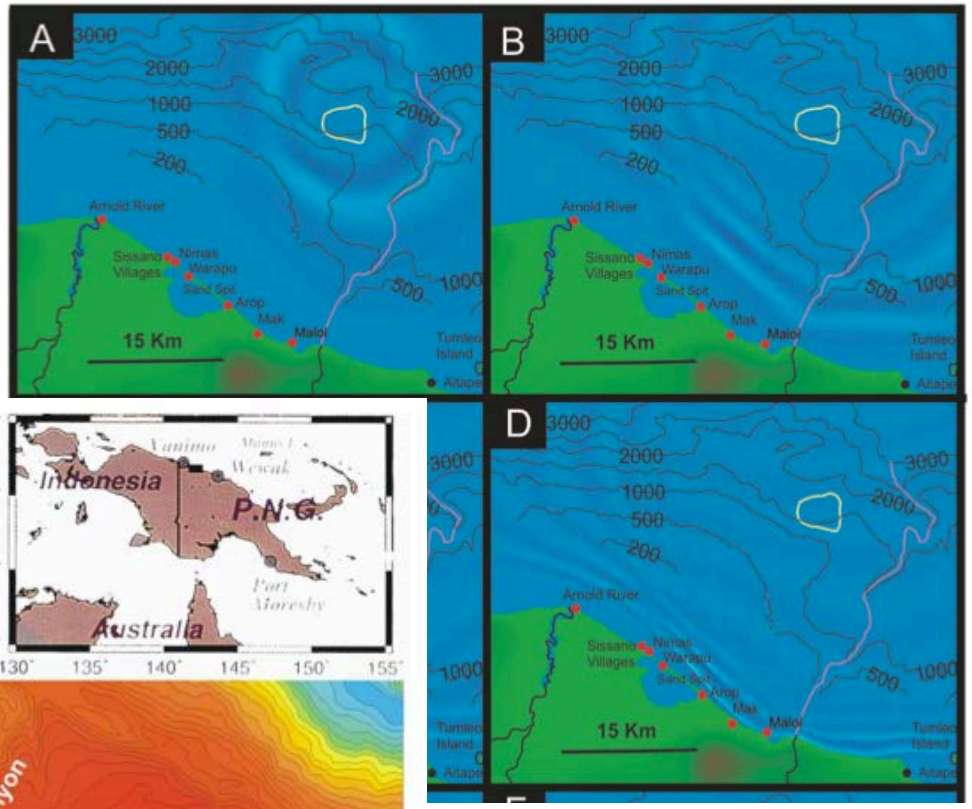


Fig. 1. Location map of the northern PNG coast struck by the tsunami of July, 1998 and bathymetry from the 1999 *Kairei* survey. Also shown is the earthquake epicentre (Green star), the aftershocks of 09:09:30 and 09:10:00 (pink stars), the T-phase slump signal of 09:02 (blue star – with error ellipse in blue from Synolakis et al., 2002), the main villages destroyed (red dots), the slump area, and main seabed features. Water depths are in metres.



1998年7月17日　パプアニューギニア・シッサノ沖でMs7の20分後，波高15mを超える津波が沿岸を襲った．津波シミュレーションから海底地すべりが推測されている．

アラスカ，ユニマック島沖

1946年４月１日にM=7クラスの地震が発生したが，Mt = 9.4の津波が同時に発生した．これにより，ハワイでは津波で160人以上の犠牲者がでた（金森2013；朝日新聞出版）．
これは，Ugamak slideによるものかもしれない．

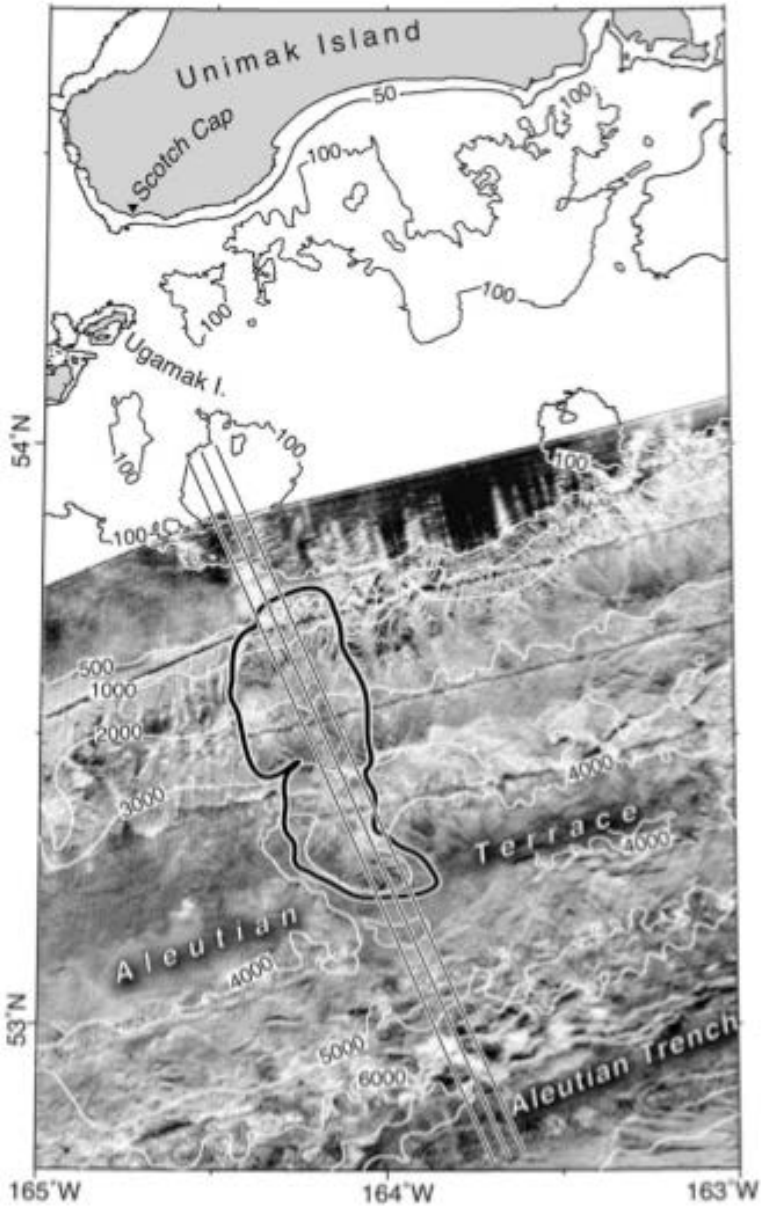


Fig. 5. Setting of the Ugamak Slide. Unit A of the slide is outlined in black. Notice how the slide points upslope directly at Scotch Cap. The three lines from the shelf to the axis of the Aleutian Trench are the locations of the profiles of Fig. 6.

Fryer et al. (2004; Mar. Geol.)

1896年明治三陸地震津波

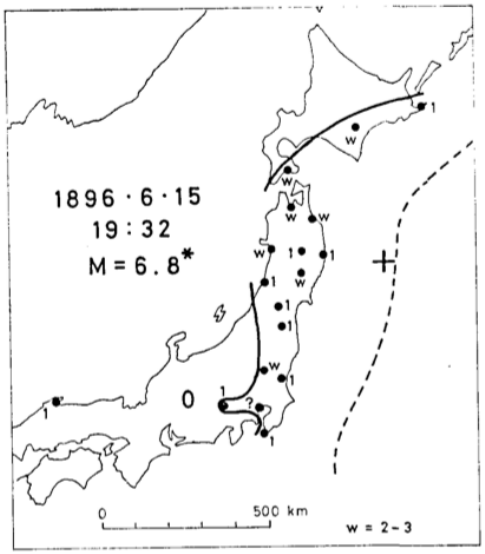
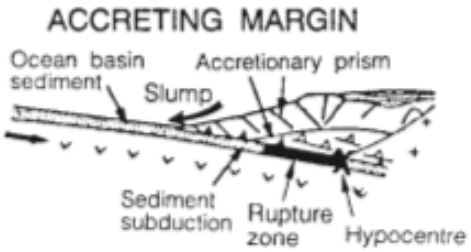


Fig. 20. See the caption of Fig. 5.

1896年6月15日19時32分岩手県沖の地震(三陸沖地震) 震度分布は Fig. 20 に示すとおりで，M 6.8～7.0 程度の地震とみられる．最大振幅による M は宮古 6.5，宇都宮 7.2，東京 6.6，平均 6.8 で，大津波を伴った地震としては余りにも小さく，いわゆる津波地震 (KANAMORI, 1972) の代表的なものである．ABE (1979) は津波の規模に基づく M として 8.6 を得ている．この地震の直後の 16 日 4 時 16 分と 8 時 01 分の地震も日本での観測からは M 6 強程度であるが GUTENBERG (1956) は大きな M を与えている．最大余震は 1897 年 8 月 16 日の M 7.2 のものであろう．この地震は日本での観測からみる限り本震より M が大きいが，津波の報告もなく，地震現象としての規模は本震より遙かに小さい．1898 年 4 月 23 日の M 7.2 の地震は本震の余震域から離れているものと思われる．

宇津(1979;地震研)

Kanamori and Kikuchi (1993; Nature)



（金森2013;朝日新聞出版）

短周期では微動だが，長期ではM8クラスになる

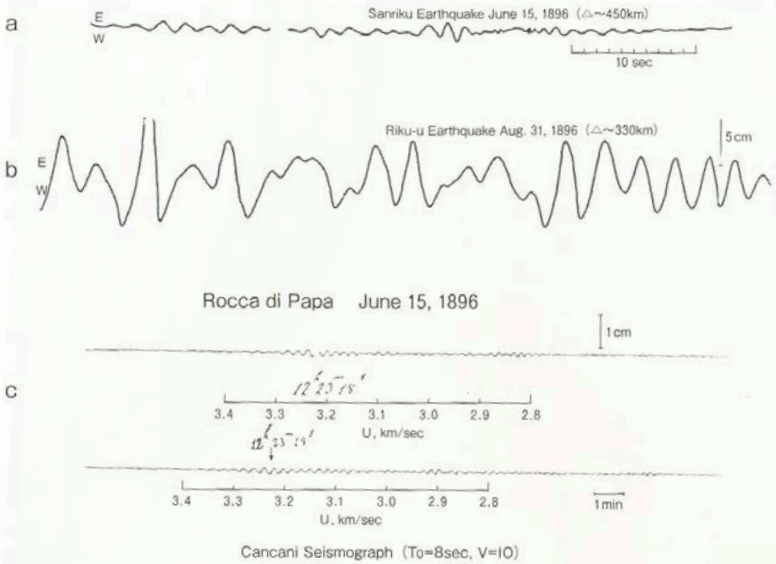


図5-2 震源から離れたところで観測された明治三陸地震
ａｂは宇都宮で記録された明治三陸地震と陸羽地震。短周期（１～３秒）では陸羽地震より三陸地震は揺れが小さい。
ｃはイタリアでの明治三陸地震の観測。イタリアでは長期（約20秒）の波が観測されている。
(Kanamori, 1972)

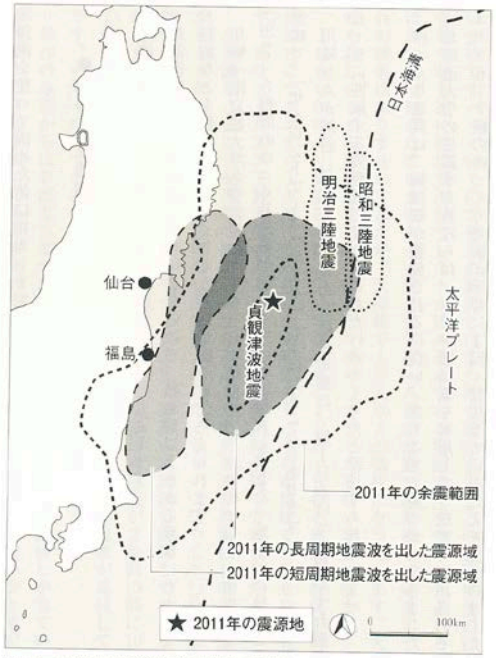


図5-7 東北地方太平洋沖地震の震源域の概略図
過去に周辺海域で起こった地震の震源域も示す。

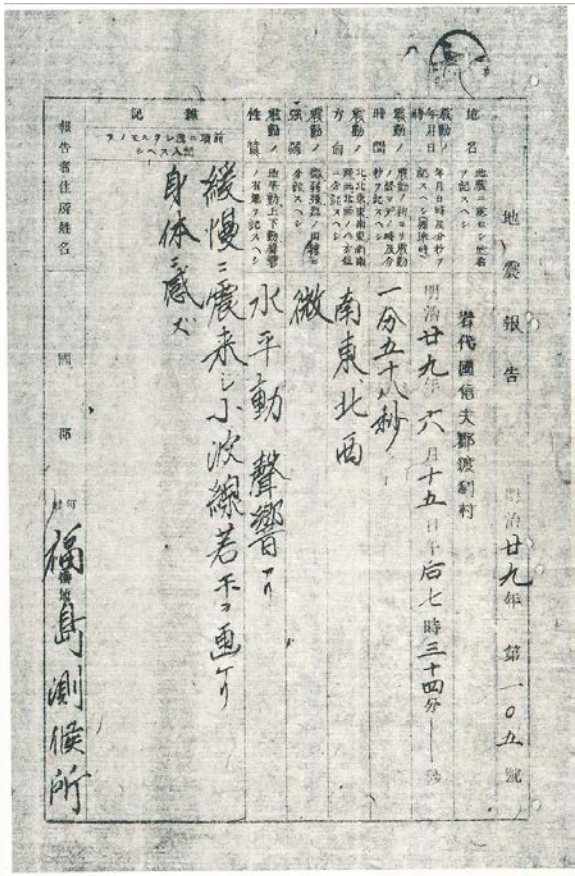


図5-1 「微」と記された明治三陸地震の記録

能登半島地震での海底地すべりと津波

- 2007年3月25日に発生した能登半島地震では，地震の3分後に富山湾のボートが転覆した．これは海底地すべりによる津波と考えられている．

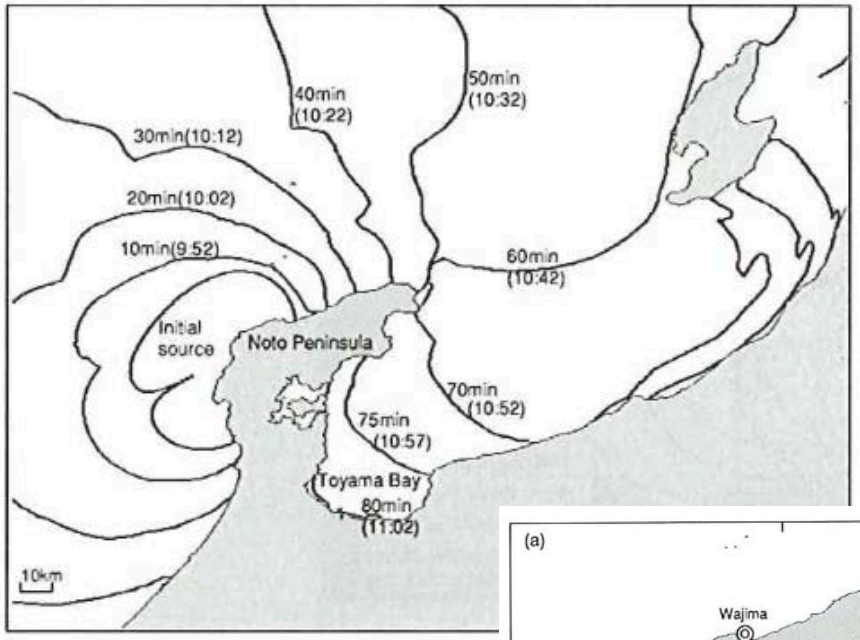
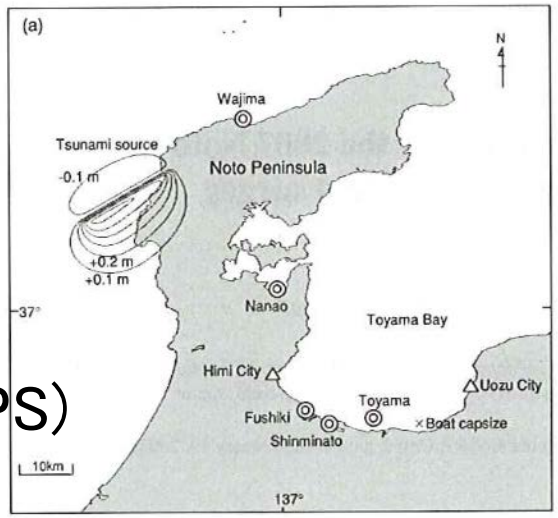
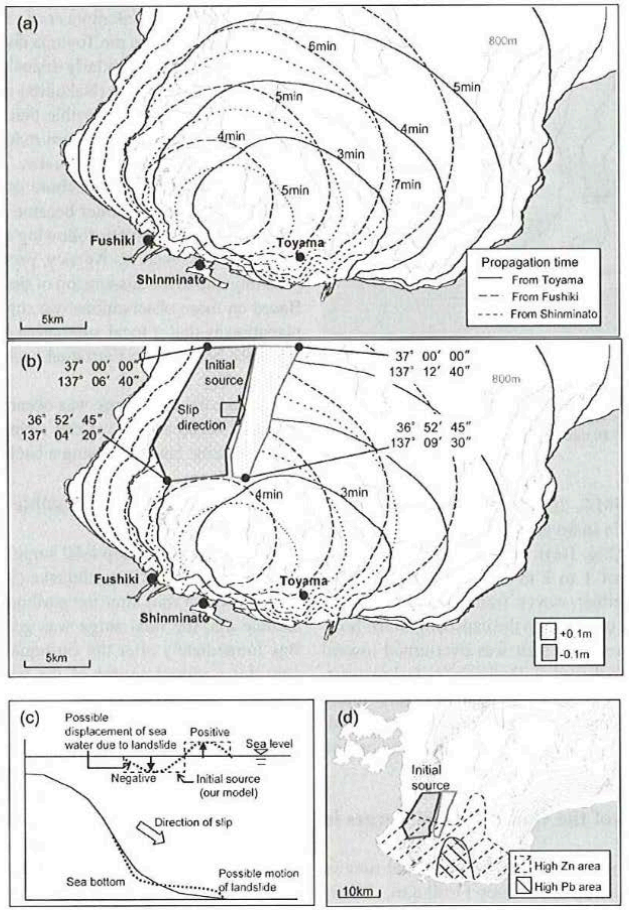


Fig. 3. The map showing wave fronts o
(10-min interval), which suggests that t
arrived at Toyama bay 70–80 min after g

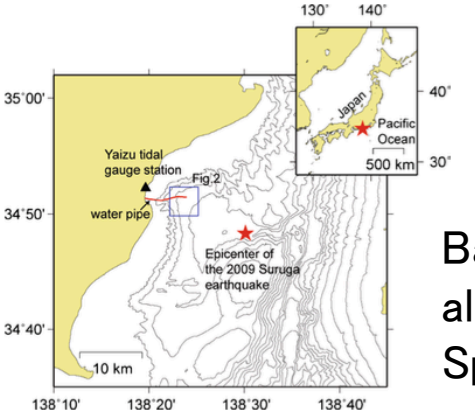




g the loci of the possible origins of the onset and peak of the tidal surges recorded at Toyama, Shinminato and Fushiki re estimated by backward wave propagation analysis. (b) Proposed source area of the tidal surge, flow direction of the displacement. (c) Cross section showing the ideal geometry of the landslide, and the wave it generated, and our model. (d) that metals such as Pb and Zn are exceptionally high (based on Imai *et al.*, 1997).

Abe et al. (2008; EPS)

2009年駿河湾地震での海底地すべり



Baba et al. (2010; Springer)

Fig. 43.1 Regional location and bathymetric map of the study area. Bathymetric contour interval is 200 m. The *red line* indicates the original position of the Suruga deep-sea water plant water pipe that was damaged and moved by the earthquake. Location of the high-resolution bathymetric map

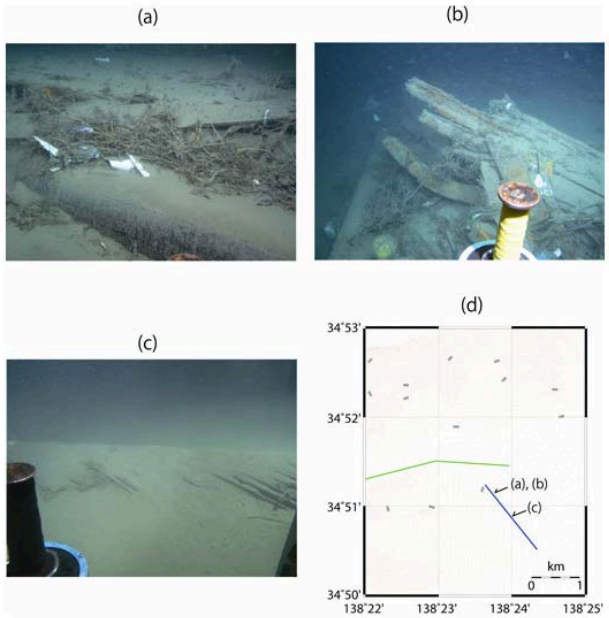


図4：「ハイパードルフィン」によって撮影された取水管（鉄線鎧装硬質ポリエチレン管、外径：270mm）の破損の様子。
（a）：深層水管をはさんで、南西側に多く泥が堆積している。（b）：沈船の残骸が取水管の上に乗り上げている。（c）：取水管の鉄線鎧装がばらけている。（d）：（a）～（c）の撮影場所。赤の等深度線間隔は10m。緑線は取水管本来の位置、青線は地震後の調査で確認された位置。

JAMSTEC (2010; プレス発表資料)

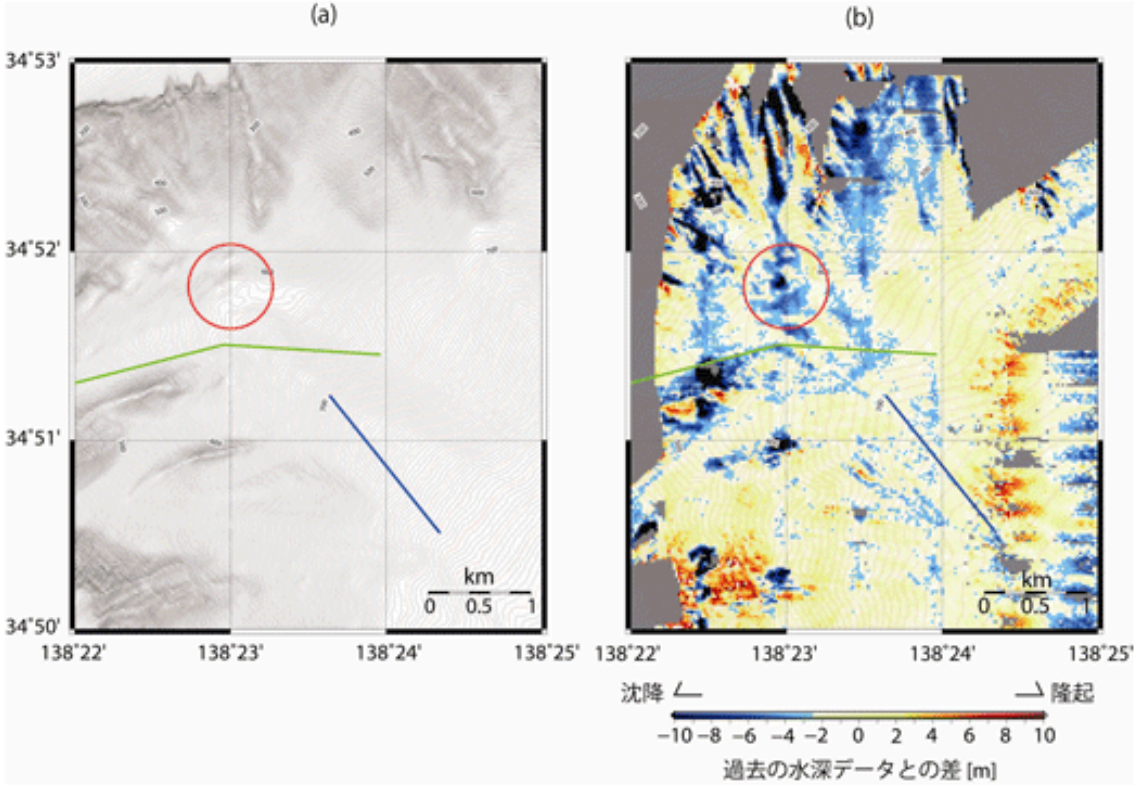


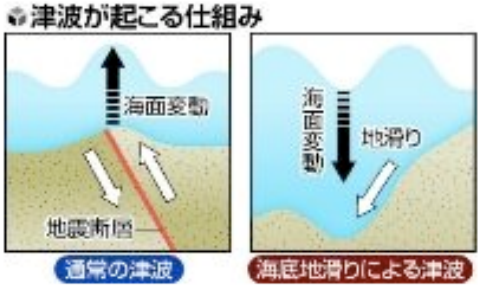
図2：海洋調査船「なつしま」によって得られた海底地形（a）と過去の水深データとの差分（b）。
（a）図1の赤線で囲まれた領域の海底地形。赤の等深度線間隔は10m。黒の等深度線間隔は2mである。（b）過去（平成16年、平成18年）に得られたデータと本調査航海で得られたデータの差。寒色系が沈降、暖色系が隆起を示す。赤線は本調査航海で得られた海底地形。等深度線間隔は10m。急峻な地形と、航跡に平行に走る調査船の動揺に伴うノイズを対象外として、赤丸で囲んだ領域では海底地形の変化が大きい。
緑線は静岡県が所有する687m深層水取水管の本来の位置、青線は地震後に「ハイパードルフィン」によって発見された取水管の位置。

海底地すべりによる津波増幅

海底地滑りが津波増幅…静岡沖地震では６倍に

静岡県の駿河湾を震源とした昨年８月の静岡沖地震で、海底地滑りによって津波が約６倍に増幅され、局所的に高くなったことを、東北大の阿部郁男研究員が突き止めた。

写真の拡大



気象庁の津波予測では現在、地震断層しか考慮されていないが、地滑りが起きやすい地形では想定を超える津波発生の恐れがあるという。２０日に富山市で開かれる日本地質学会で発表する。

この地震では、同県焼津市で６２センチの津波を観測。津波の多くは、断層がずれ、海底が上下に動くのに伴って起きるが、今回の断層運動なら焼津市の津波は１０センチ程度にとどまると推定され、高くなった理由は謎だった。

阿部研究員が津波の観測記録などをもとにコンピューターで計算した結果、震源周辺で長さ３キロほどの海底地滑りが数か所で起きると津波が増幅され、実際に観測された高い津波になることがわかった。

（2010年9月20日03時03分　読売新聞）

本日の話す内容

■はじめに：どういった地層が残るのか

■海底地すべり研究の最近20年ダイジェスト：

1）トリガー問題：気候変動が悪いのか

2）地質地形問題：過去の記録を読み取るにはどうすればよいか

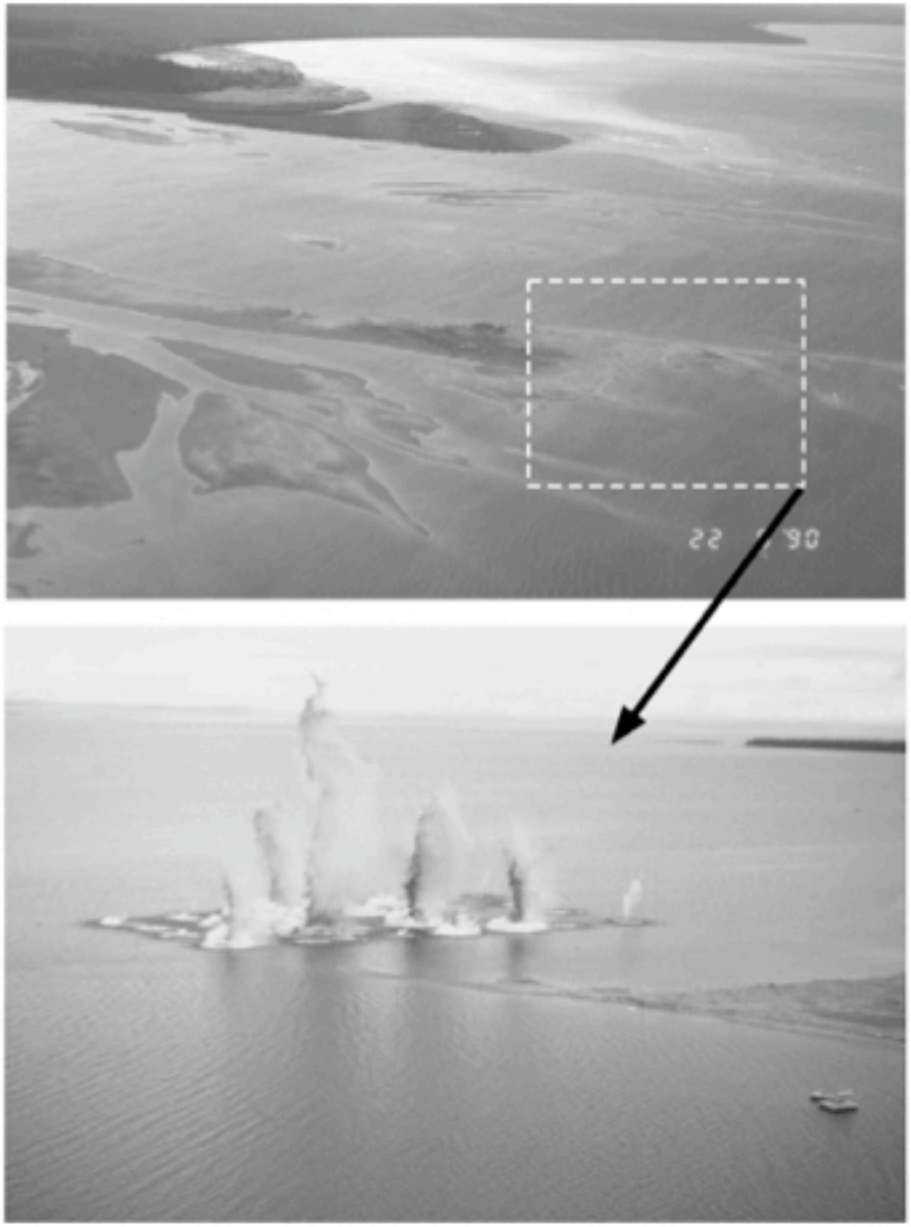
3）災害問題：津波と海底ケーブル

■さいごに：未来に向けてどうすればよいか

むずかしいことはできない．モニタリング，現場実験，安定解析．地形や地質を調べて，その周期性や規模，危険度を評価することはできるだろう．

さいごに：未来に向けてどうすればよいか

最終的には現場実験によって、海底地すべりを再現実験することが必要であろうが、現時点では難しい。

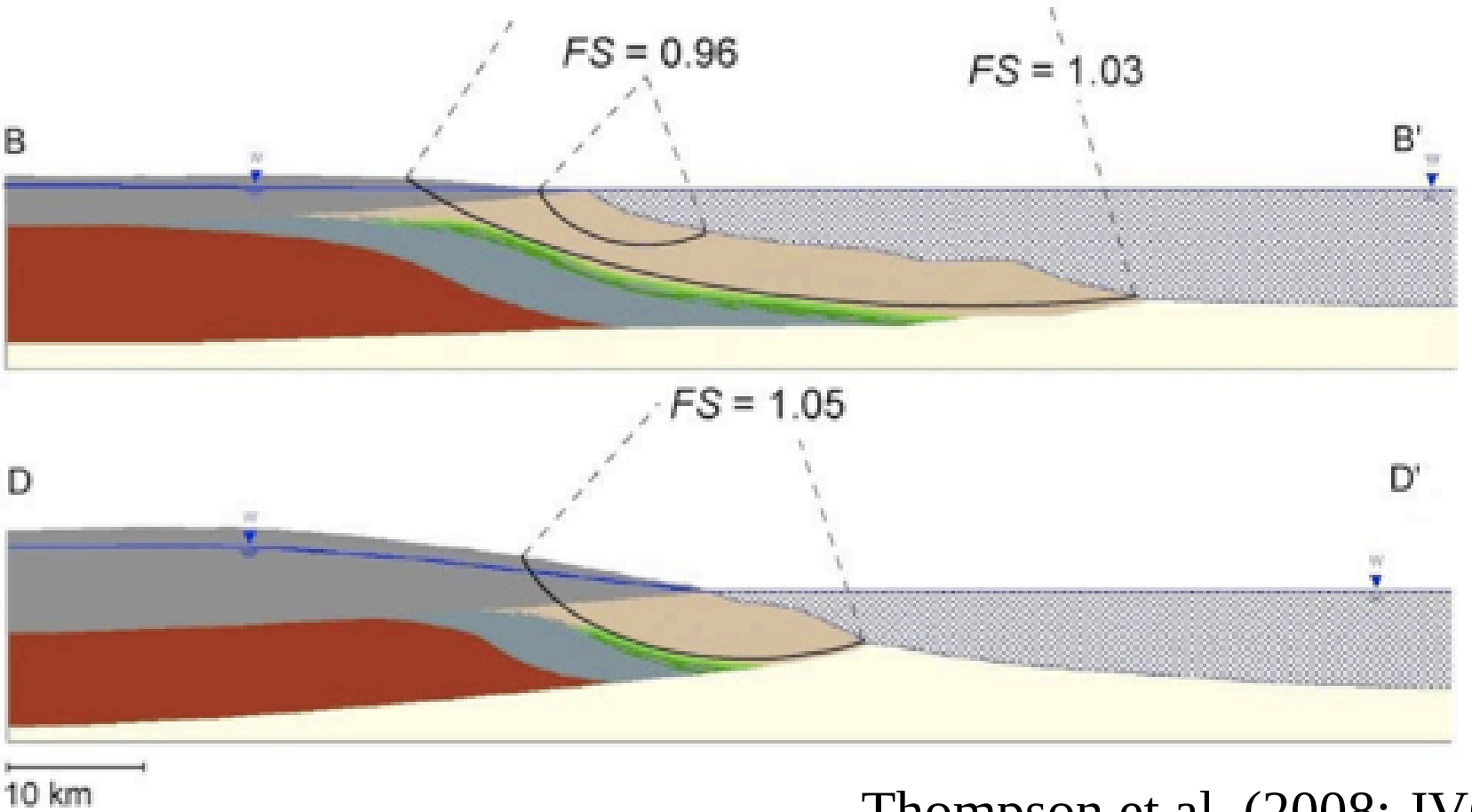


ノルウェー，メルビル湖でのデルタ爆破実験による斜面安定性評価の例（Arctic Delta Failure Experiment (ADFEX), Lacot and Lee, 2002, Can. Geotech. J.）. このプロジェクトでは実際に湖斜面で海底地すべりを発生させた.

斜面安定解析

YAMAGUCHI UNIVERSITY

ハワイ島の例，岩盤の事例は少ない．亀裂をどのように評価すれば良いか．岩盤を相手にするのは難しいだろう．



Thompson et al. (2008; JVGR)

m analysis results given by Slide (2005) for the Kilauea (East) (B–B′) and Alika–Kona (D–D′) cross-sections. The least stable
d by the circular failure and the associated factor of safety. The FS value (1.03) for the least stable slump-type failure geometry is
ss-section. No vertical exaggeration.

斜面安定解析

YAMAGUCHI UNIVERSITY

- 堆積物で行うことは不可能ではなさそうである．いくつか事例がある．
- 滑っていない箇所で堆積物を採取して，もしくは現場で物性・力学特性を測定する．
- 過去の地震記録に基づいて解析する．

スイス・ルツェルン湖での事例
Strasser et al. (2007; Mar. Geol.)

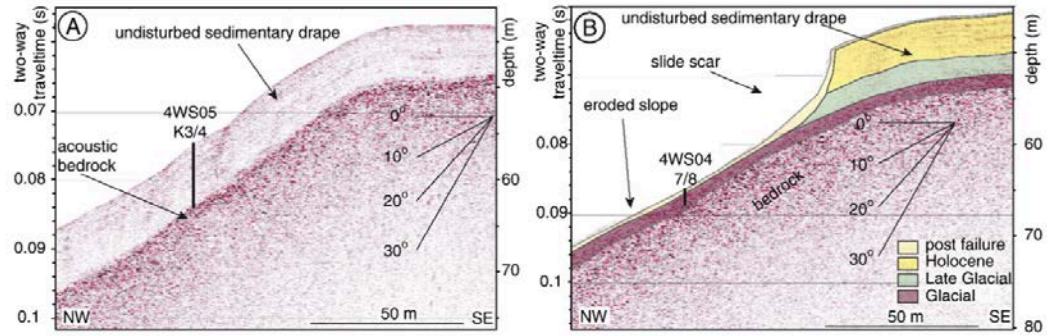


Fig. 4. Two parallel-oriented 3.5 kHz seismic lines across the sub-lacustrine slope in the northeastern edge of Chrüztrichter basin. Distance between the lines is about 80 m. For location see Fig. 2. (A) Profile shows an undisturbed slope characterized by an approximately 6 m-thick continuous sedimentary drape directly overlaying acoustic bedrock and location of cores 4WS05-K3 and K4. (B) Profile displays failure scar of Chrüztrichter Slide with slope model interpretation of lithological units as cored in reference core 4WS05-K4 and short cores 4WS04-7 and 8, which recovered the failure plane of the 1601 A.D. slope failure in core depths of 0.4 m below lake floor. Figure modified after Schnellmann et al. (2005).

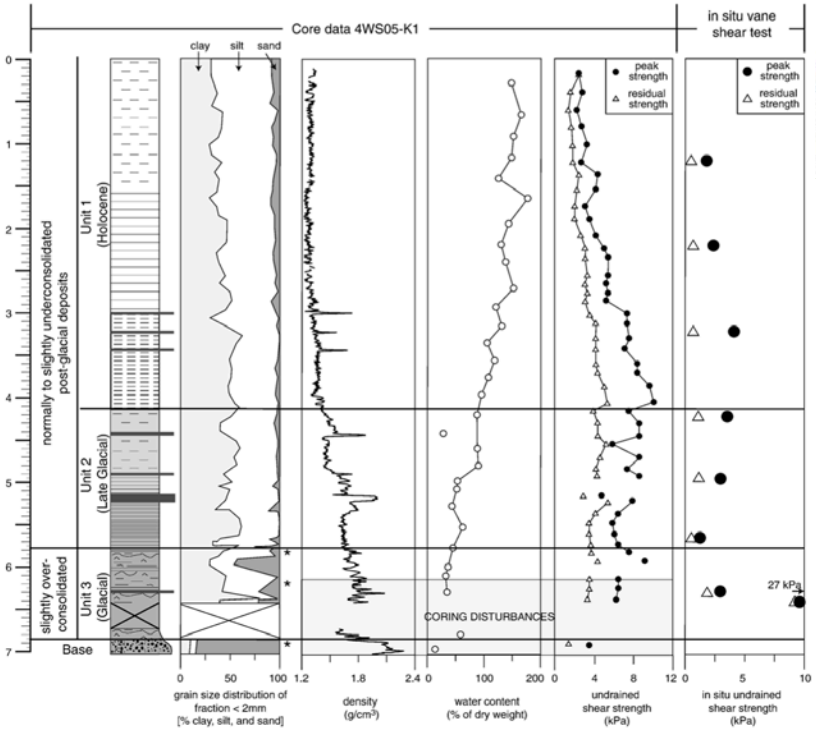


Fig. 6. Data obtained from core 4WS05-K1 and from in situ tests summarizing sedimentological and geotechnical characteristics of the undisturb continuous glacial-to-postglacial sedimentary succession covering the sub-lacustrine slope offshore St. Niklausen. The site is located immediate upslope the failure scar (see Figs. 2 and 3B for location). Asterisks indicate the presence of material with grain size >2 mm (that are not considered this plot).

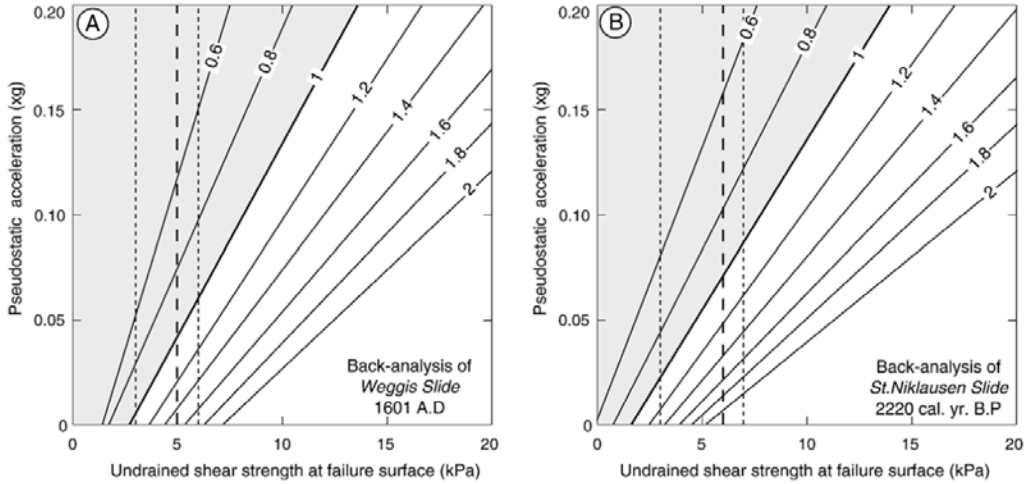
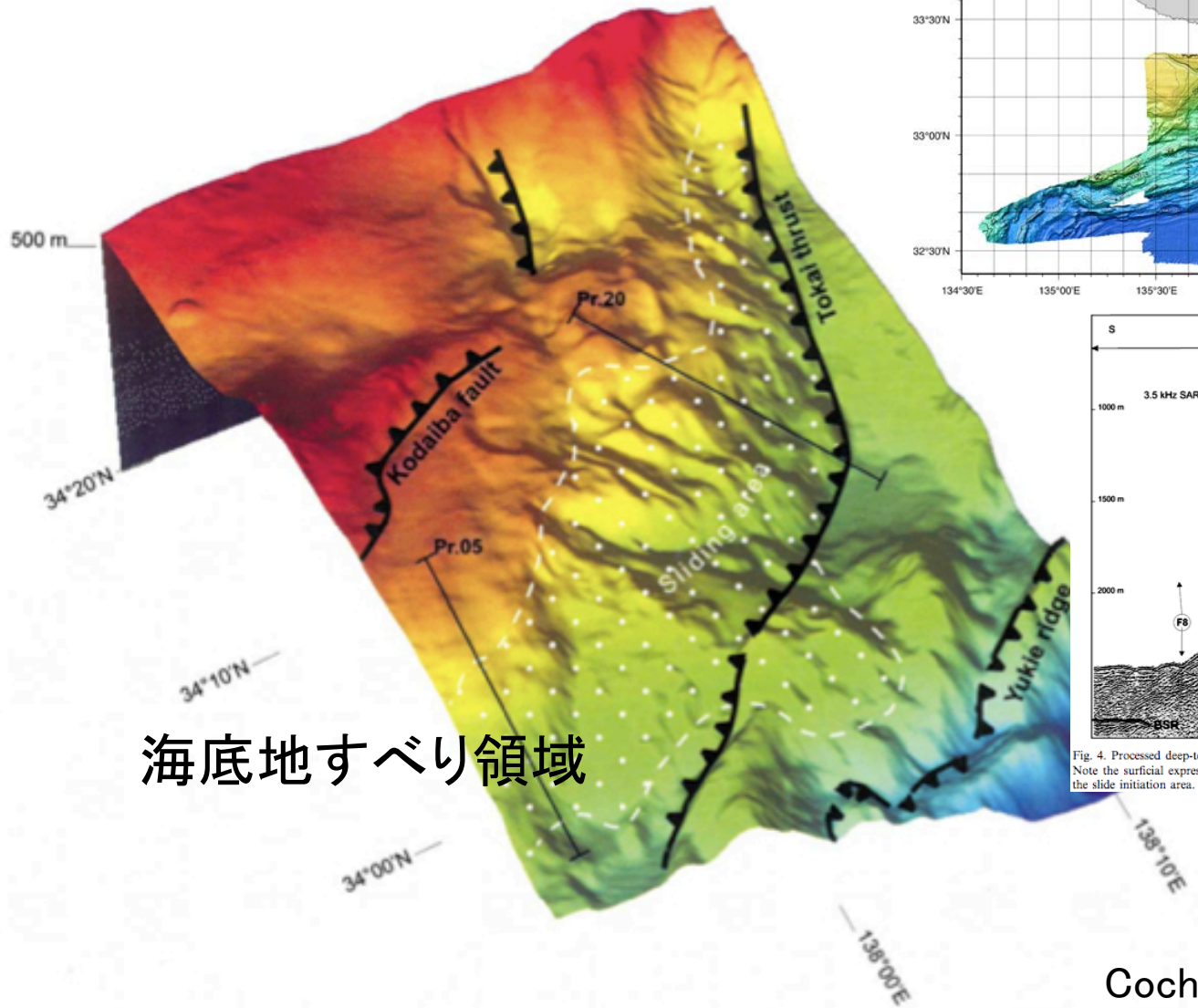
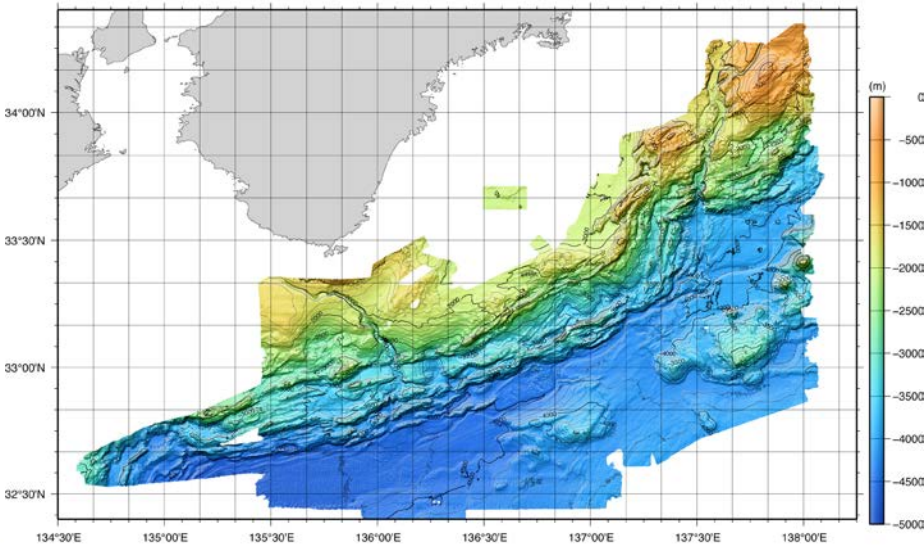


Fig. 10. Results of deterministic limit equilibrium slope stability back-analysis of Weggis (A) and St. Niklausen (B) Slides during the 1601 A.D. M_w ~6.2 earthquake and the 2220 cal yr B.P. earthquake (M_w>6.5), respectively. Contour plots show factor of safety (FS) as a function of the undrained shear strength at the failure surface and the pseudostatic acceleration (fraction of gravitational acceleration g). The gray shaded areas indicate solutions leading to instable conditions (FS<1). The range and reliable in situ values of measured undrained shear strength at the two study sites is shown as a fine dotted and bold dashed line, respectively. See Table 1 for model input data.

海底地形で見えにくい例：東海スラスト上盤



海底地すべり領域



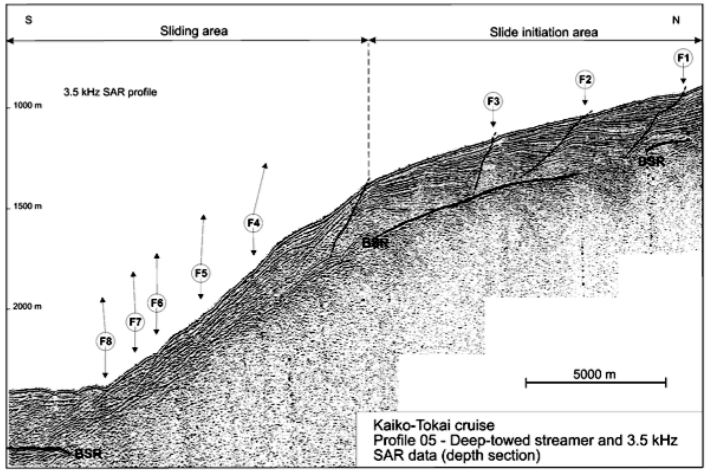


Fig. 4. Processed deep-towed streamer profile (PASISAR), profile 05 and associated subbottom SAR profile. Location on Fig. 2. Note the surficial expression of failures (F4–8) on the 3.5-kHz profile and the 'piggyback basin' shape of each sliding blocks in the slide initiation area.

Cochonat et al. (2002; Mar. Geol.)

Fig. 2. Detailed 3D view of the slope around Tokai Thrust after R/V *l'Atalante* cruise. Dotted zone: location of the local sliding area identified from interpretation of SAR and PASISAR data. Location of profile 05 (Figs. 3 and 4) and profile 20 (Fig. 5).

これからやったら良さそうなこと

- 海底地形を良くみて海底地すべり分布図を作る．場合によっては，周辺の危険斜面もわかったらすばらしい．
- できれば，地震探査記録でクロスチェックする．
- さらにできれば，堆積物によって再来周期を調べる．
- さらに可能ならば，斜面安定解析を行って，次の地震に備える．

もっと興味がある方へ

- 今までお話ししたことは，地質学雑誌2017年12月号に総説「海底地すべりと災害」として掲載しています．興味があったらJ-STAGEから無料ですのでダウンロードしてみてください．