Past Earthquake Outbreaks in the Shimanto Belt and Their Use in Forecasting the Occurrence of the Next Nankai Earthquake

四万十帯における過去の地震発生帯と来るべき南海地震発生時期の予測

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Abstract

The basement rock in the southern part of Tokushima Prefecture, the so-called Shimanto belt, is composed mainly of an accretionary complex deposited on the trench from the Cretaceous to the Paleogene Periods. In recent years, the existence of pseudotachylyte, a particular type of rock formed as a result of frictional heat during fault movements, has been reported in the geological faults of the Shimanto belt. A marine terrace in the vicinity of Muroto Cape in the southeastern part of Kochi Prefecture is thought to have been formed by past earthquake activity. Furthermore, by using the proportional relationship between the interval of two successive earthquakes and the amount of coseismic uplift caused by the preceding earthquake observed in the harbor, a time-predictable model, which forecasts the occurrence of the next earthquake (1), has been proposed. In this study, we review the recent progress of geological studies in the Mugi Mélange in the southern part of Tokushima Prefecture. We also introduce a method of forecasting the anticipated Nankai Earthquake by utilizing data from land uplifts due to the last three earthquakes recorded in Murotsu Harbor.

Key words: Shimanto belt, Mugi Mélange, Pseudotachylyte, Time-predictable model of earthquake

要旨

徳島県南部地域は四万十帯と呼ばれる中生代白亜紀から新生代第三紀の海溝で堆積した岩石が分布している．近年、四万十帯の中の過去の地震断層から断層の摩擦発熱によって形成されたシュードタキライトという特異な岩石の存在が報告された．また、高知県南部の室戸岬周辺には過去の地震活動などで形成された海成段丘の存在が知られている．さらに港の海水面変動（として記録された地震時隆起の蓄積量）と地震発生時刻の関係を用いて、次の地震発生時間を予測するモデルが提案されている[例えば（1）]．本研究では、徳島県南部の牟岐メランジュを観察し、著者が居住する地域が過去の地震発生帯であることを確認するとともに、高知県室津港の地震による隆起量のデータを用いて来るべき南海地震の発生時期の予測方法の紹介を行う．

重要語句：四万十帯、牟岐メランジュ、シュードタキライト、地震発生時期予測モデル

Introduction

On March 11th, 2011, the magnitude 9.0 Great Tohoku-Oki Earthquake occurred. The strong quake and the subsequent massive tsunami brought about major destruction across the Tohoku and Kanto regions. This calamity is known as the Great East Japan Disaster. In this geographical region, earthquakes known as the Sanriku offshore earthquakes have occurred repeatedly between the plates. The oceanic plate is subducting beneath the continental plate in the subduction zone. (See the schematic diagram of the accretionary wedge shown in Fig. 1.) Ordinarily, the continental plate is gradually submerged as it is dragged downwards by the motion of the oceanic plate. However, when a large earthquake occurs on the plate interface, the continental plate rebounds upward. Hence, based on the amount of crustal movements recorded in the continental plate, we are able to generate a time-predictable model to forecast the occurrence of the next earthquake. In addition to this, advance preparation and sufficient disaster prevention/mitigation methods can greatly reduce the resulting damage.

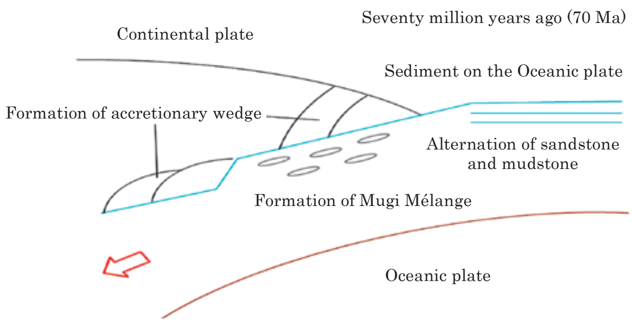

Fig.1. Schematic diagram of the accretionary wedge.

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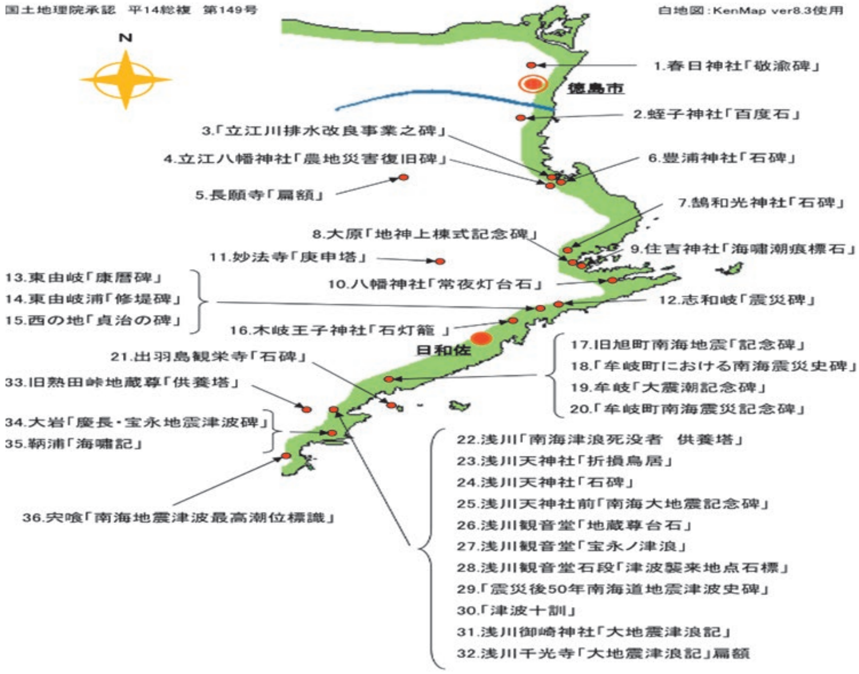

Fig.2. Map of earthquake/tsunami monuments in Tokushima Prefecture (2).

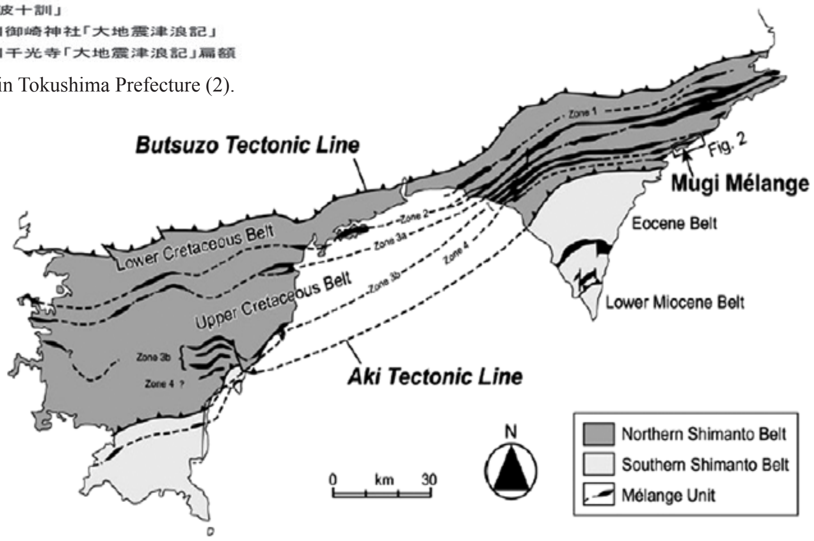

Fig.3. The distribution of the Shimanto belt in Shikoku and the location of the Mugi Mélange (3).

The author is a resident of the southern coastal region of Tokushima Prefecture. This area has suffered serious damage from past tsunamis. In order to hand down tales of the disasters to succeeding generations and make use of the experience to reduce the damage from future earthquakes, numerous stone monuments describing the disasters have been established in various places within the prefecture (Fig. 2). In this region, scientists have warned that the next Nankai earthquake and a huge accompanying tsunami are likely to occur in the near future. The source region of the earthquake will be located offshore from Shikoku and the Kii Peninsula, which runs along the Nankai Trough. Hence, preparing for this event is extremely important.

Results

Geology of the Shimanto Belt: Coherent Unit and Mélange

The Shimanto belt is mainly composed of the accretionary wedge. In other words, sediments derived from the continental plate and rock fragments/layers scraped from the subducting oceanic plate are mixed in the trench, and part of this mix is accreted landward slope of trench at the bottom of previously accreted wedge (or slices) in. Slices pile next to one another with reverse faults. They are characterized by in-

Fig.4. Alternating sandstone and mudstone at Gyoto Cape, Muroto City, Kochi Prefecture, which is an example of the coherent sequence.

Fig.5. Blocks in the matrix structure observed in the upper section (unit 3) of the Mugi Mélange, which is an example of the mélange structure.

ward younging in each sheet and overall outward younging. Sediments derived from the continental plate make up the majority of the coherent unit characterized by the alternation of sandstone and mudstone (Fig. 4). The rock fragments/layers scraped from the subducting oceanic plate are mainly found in the mélange zone and are characterized by blocks in their matrix structure. The predominant blocks are pillow lavas, chart, limestone and sandstone, and the matrix is usually composed of mudstone (Fig. 5). In the case of the Shimanto belt, the accretionary wedge was formed in the past trench between the Cretaceous and Paleogene Periods before being exposed to the Earth's surface.

Fig. 4 shows an outcrop of alternating layers of sandstone and mudstone, a so-called coherent sequence, which we observed at Gyoto Cape, Muroto City, Kochi Prefecture. It is believed that this type of rock layering is formed by turbidity current taken place at continental slope due to a force such as an earthquake.

Fig.5 is an outcrop photo of blocks in the matrix structure observed in the upper section (unit 3) of the Mugi Mélange, where elongated lenticular lenses composed mainly of sandstone are randomly distributed within the matrix, which is composed mainly of mudstone.

The Mugi Mélange was exposed to the Earth's surface by erosion of the continental crust enhanced by weathering, and by the recurrence of earthquakes in the subduction zone due to the existence of earthquake faults (Fig. 1), which we will introduce in the following section.

<u>The Mugi Mélange as an Earthquake Fault</u>

Along the coast of Kaifu County, Tokushima Prefecture, between the towns of Mugi and Minami (between the Mugi and Akemaru coasts), one can see the structured Mugi Mélange in a small area between two systematic layers of rock (the northern Hiwasa and southern Kainan Formations) (Figs. 3 and 6)[3].

The characteristic of the Mugi Mélange that deserves special mention is the existence of pseudotachylyte. The 1-2 m thick Minami Awa pseudotachylyte-yielding fault developed at the boundary of the Hiwasa Formation, a turbidite unit in the coherent sequence in the north, and unit 5 in the upper section of the Mugi Mélange in the south (Figs.

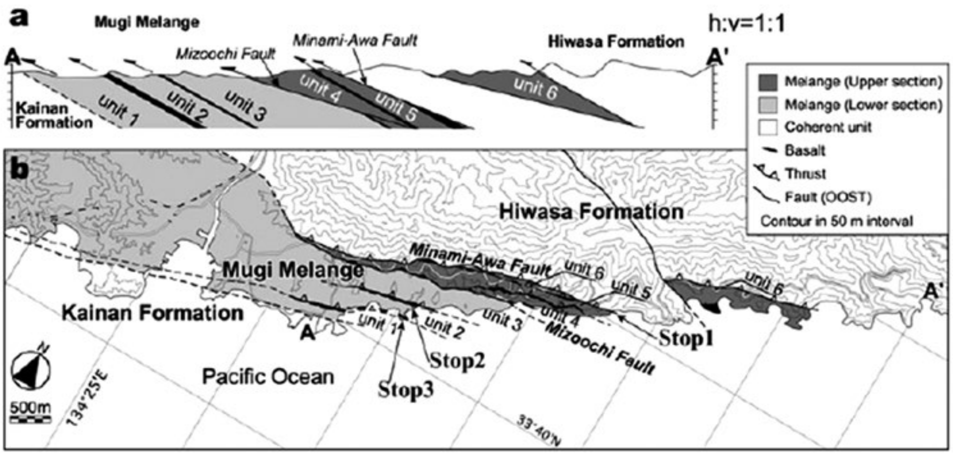

Fig.6. A geological map of the Mugi Mélange (3).

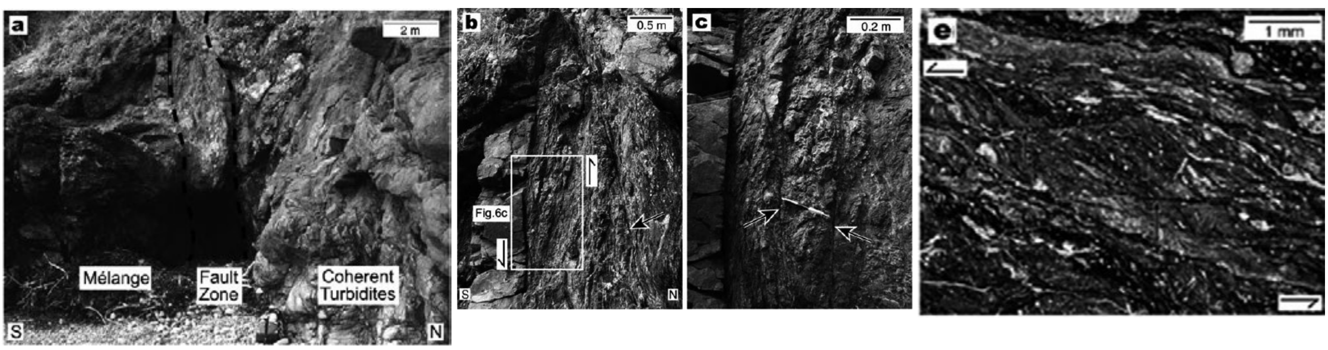

Fig.7. Microstructure of the Mugi Mélange (3).

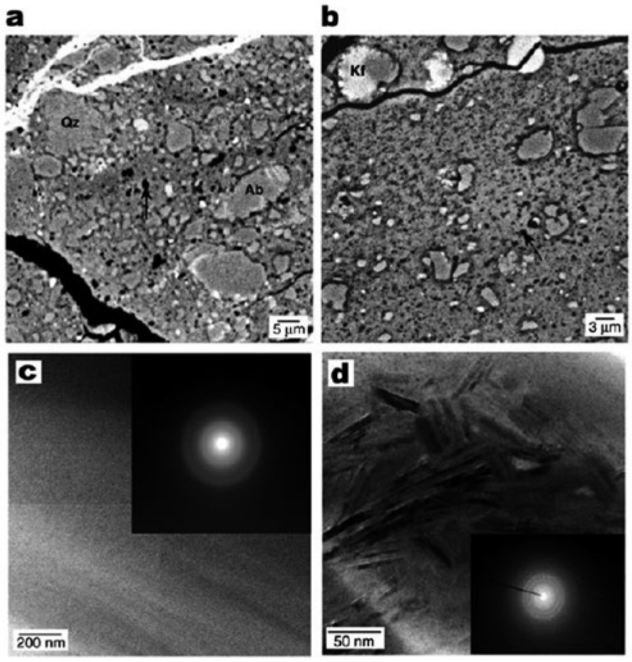

Fig.8. Electron micrographs of melanocratic veins in the Mugi Mélange (3).

6 and 7a).

Fig. 7b shows the asymmetrical structure of sheared planar cataclasite, a fault rock that has a finer-grained matrix, revealing a leftward deviation within the boundary fault. It also depicts the presence of continuous, dark (melanocratic) veins less than a few millimeters wide as indicated by the arrows (magnified in Fig. 7c). We were able to identify the above structures through our study.

One of the criteria for pseudotachylyte formation is the existence of quenched partial melt formed by the heat generated by friction during earthquake fault movement. The partial melt can penetrate and fill cracks in the surrounding rock and form a vein structure. When the melt experiences sudden cooling, part of the melt cannot crystalize and remains amorphous. The result of the microstructure study of the melanocratic veins conducted by Yamaguchi *et al*. (3) is introduced in Fig. 8.

Figs. 8a and 8b are scanning electron micrographs of the melanocratic vein (backscattered electron images). Bubbles (dark holes indicated by black arrows), fragments of quartz (Qz), albite (Ab), and potassium feldspar (Kf) are identified within the matrix. These mineral grains are the main constituents of sandstone, and their shapes are irregular with an embayed outer edge, indicating that these grains were partially melted.

Figs. 8c and 8d are transmission electron micrographs and X-ray diffraction patterns. The latter indicates that the matrix is made of an amorphous substance (upper right inset in Fig. 8c). The euhedral minute crystal in the matrix is identified as mullite ($Al_9Si_3O_{19.5}$) based on the electron diffraction pattern and crystal shapes (Fig. 8d). Mullite is presumably derived from clay minerals through heating (3). The crystallization of mullite requires a temperature of over 1100°C. Those data suggest that the melanocratic vein was once partially melted by the fault friction, and therefore it is considered to be pseudotachylyte.

The discovery of pseudotachylyte in the Mugi Mélange outcrops confirms that the southern region of Tokushima Prefecture and the offshore region of Shikoku has been an active earthquake zone since the Cretaceous Period.

Model for Forecasting the Occurrence of the Next Nankai Earthquake

The amounts of sea floor uplift caused by past Nankai earthquakes in the Murotsu harbor in Kochi Prefecture were recorded. The amounts of uplift for the last three major earthquakes are as follows:

Name of Earthquake	Occurrence date	Amount of uplift (meters)
• Hoei Earthquake	October 28th, 1707	1.8
• Ansei Earthquake	December 24th, 1854	1.2
• Showa Earthquake	December 21st, 1946	1.15

In this region, the coseismic land uplift is produced by an earthquake caused by the rebound of the continental plate to its original height after having settled from being dragged by the oceanic plate year after year.

As shown by the plot of the cumulated coseismic uplift against the time of earthquake occurrences in Fig. 9, we can see that the interval between two successive earthquakes is proportional to the amount of coseismic uplift of the preceding earthquake. We can use this information to construct a time-predictable model (1), which can predict the occurrence of the next earthquake.

According to the time-predictable model, the three points ①, ②, and ③ in Fig. 9 are almost collinear. Point ④, which goes through the extended portion of this line, tells us the time when the next earthquake will occur. First, we apply a least squares method to estimate this line which passes through the three points ①, ②, and ③.

Point① $(x_1, y_1) = (1707.8 , 0.0)$

Point② $(x_2, y_2) = (1855.0 , 1.8)$

Point③ $(x_3, y_3) = (1947.0 , 3.0)$

x indicates the year of earthquake occurrence, and y indicates the cumulated coseismic uplift.

The regression line passing through three points is determined by the least squares method. This regression line has the form:

$$y = a\,x + b$$

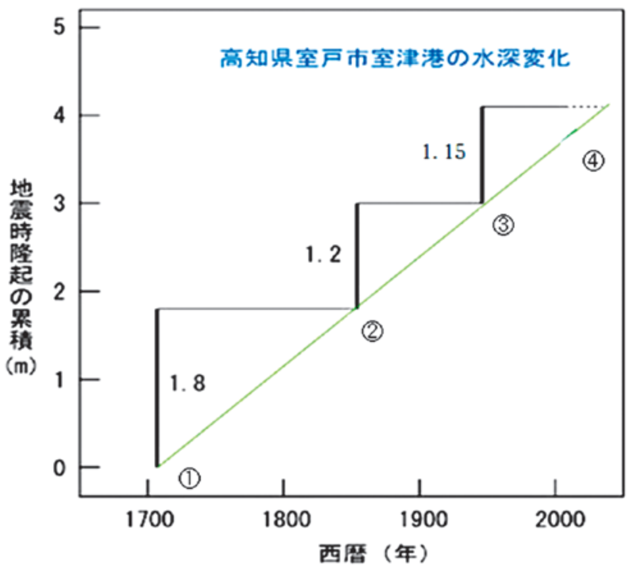

Fig.9. Time-predictable model (1, 4).

where a and b are the parameters to be determined.
We define residuals as:

$$e_1=y_1-(ax_1+b),\ \ e_2=y_2-(ax_2+b),\ \ e_3=y_3-(ax_3+b)$$

and we obtain the sum of squared residuals as:

$$E2 = e_1^2 + e_2^2 + e_3^2 = A + a^2B + 3b^2 - 2bC - 2aD + 2abE.$$

Here A, B, C, D and E are:

$$A=y_1^2+y_2^2+y_3^2,\ B=x_1^2+x_2^2+x_3^2,\ C=y_1+y_2+y_3,$$

$$D=x_1y_1+x_2y_2+x_3y_3,\ E=x_1+x_2+x_3.$$

We minimize $E2$ to determine the two parameters a and b. If fixing b, $E2$ is considered to be a quadratic function of a, and since $B>0$, there is a minimum value.

$$E2(a) = Ba^2 + 2(bE-D)a + A + 3b^2-2bC$$

$$=B\{a-(D-bE)/B\}^2+A+3b^2-2bC-(D-bE)^2/B$$

Therefore, if we set

$$a-(D-bE)/B=0\rightarrow Ba+Eb=D \quad (1),$$

$E2(a)$ takes a minimum value. Similarly, for b, we can write

$$E2(b)=3b^2+2(aE-C)b+A+a^2B-2aD$$

$$=3\{b-(c-aE)/3\}^2+A+a^2B-2aD-(C-aE)^2/3.$$

Additionally, in this case, in order to take a minimum value, we set

$$b-(C-aE)/3=0\rightarrow Ea+3b=C \quad (2).$$

From the simultaneous equations (1) and (2), we obtain

$$a=(CE-3D)/(E^2-3B) \quad (3)$$

$$b=(DE-BC)/(E^2-3B) \quad (4).$$

By substituting the x and y values from the points ①, ② and ③ into B, C, D and E in Eqs. (3) and (4), we obtain:

a=0.012512639029323
b=-21.38071284125379
$y=ax+b$
y=0.012512639029323x-21.38071284125379.

Since the point ④ has the y value

y_4=4.15,

the corresponding x value becomes

x_4=2040.4.

As described above, we can forecast the time when the next earthquake will occur. However, this model uses only three data points. Therefore, the number 2040.4 is not necessarily correct. For this reason, I discuss the uncertainty of the forecast below. First, I show residuals which are defined as the actual years of the last three earthquake occurrences minus the calculated ones.

Residuals of occurrence years for the last three Nankai earthquakes

EQ name	(1)*	(2)*	(3)*
Hoei Earthquake	(1707.8)	(1708.7)	+0.9
Ansei Earthquake	(1855.5)	(1852.6)	−2.4
Showa Earthquake	(1947.0)	(1948.5)	+1.5

(1)* Actual occurrence year
(2)* Calculated occurrence year
(3)* Residuals: (1) – (2)

Second, I show the years when the next Nankai earthquake is forecast to occur, based not on the line passing through the three points, but on the line passing through the three combinations of two points.

	Forecasted year
Calculated from points ① and ②	2047.2
Calculated from points ② and ③	2035.2
Calculated from points ③ and ①	2038.7

Discussion

The Shimanto belt was formed as an accretionary complex/prism in the past trench and is believed to be an active earthquake zone based on several lines of evidence, including a fault accompanied by pseudotachylyte. At present, the Nankai accretionary complex/prism is formed in the offshore region of Shikoku, where the next Nankai earthquake is expected. Therefore, the Shimanto accretionary complex/prism is an onland analog of the present active earthquake zone, and a comprehensive study of the Shimanto belt is indispensable to understanding the phenomenon taking place at the plate boundary in the subduction zone. This study will facilitate disaster prevention.

A time-predictable model that employs uplift data can forecast the occurrence of the next Nankai earthquake. The estimated uncertainty of the forecast time is small, ranging from a few to several years. However, the credibility of such simple estimates is questionable because the number of available data is so small that we cannot make statistical arguments. Furthermore, as noted by Shimazaki & Nakata (1), the datum for the 1707 Hoei earthquake is based on two measurements conducted before and 52 years after the event, and the amount of the coseismic uplift is extrapolated using the subsiding rate observed in the present day. To increase the certainty of the forecast, we need to construct other models based on other data related to earthquake reoccurrences. We can thus understand the characteristics of these models, and we need to improve the model, which provides us a basis for mitigating the great disaster likely to be caused by the next Nankai earthquake.

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References

1. Shimazaki, K. & T. Nakata. Time-predictable recurrence model for

large earthquakes. Geophys. Res. Lett. 7: 279–282. (1980).

2. Tokushima University Research Center for Management of Disaster and Environment. Nankai Jishin wo shiru – Tokushima ken no jishin·tsunami hi, <http://www.jishin.go.jp/main/bosai/kyoiku-shien/13tokushima/material/tksm_22_3.pdf> [accessed 10 Sept. 2015]. (2008).
3. Yamaguchi, A., T. Shibata, K. Ujiie & G. Kimura. Deformation and fluid flow in seismogenic subduction zone: The Mugi Mélange in the Shimanto Belt. Jour. Geol. Soc. Japan 115 (supplement): 21–36. (2009).
4. Time-predictable model. <http://sc1.cc.kochi-u.ac.jp/~mako-ok/nankaia/time/time.html> [accessed 15 Sept. 2015].