The Global Positioning System observations on the 2011 Tohoku M9 earthquake genesis process with Physical Wavelets

Fumihide Takeda¹, ²,*

¹ Takeda Engineering Consultant Inc., 2-14-23 Ujina Miyuki, Hiroshima city 734-0015, Japan
² Earthquake Prediction Institute, 3-4-56 Go-shin-yashiki-cho, Imabari city 794-0826, Japan
* Email: f_takeda@tec21.jp

Tohoku is at the eastern edge of a continental tectonic plate overriding a subducting oceanic plate. The GPS observations on the 2011 Tohoku M9 earthquake are the daily displacements at the stations in Tohoku and the Northwest Pacific Ocean. For the noisy and non-differentiable time series, a mathematical tool named Physical Wavelets defines the equations quantifying the earthquake genesis process of nine months and the event predictability. Tohoku is still under the 2011 event. As of May 22, 2021, the GPS observations on the Pacific and the Philippine Sea Plate suggest no imminent megathrust ruptures in the subduction zones.

Contents

1 ABSTRACT 4
2 SUMMARY 5
3 THE FORESHOCKS, AFTERSHOCKS, AND CO-SEISMIC SHIFTS OF THE TOHOKU M9 6
   Fig.3. GPS stations, vertical co-seismic displacement, foreshocks, and aftershocks of the M9 EQ. 6
4 THREE DISTINCTIVE PHASES OF THE TOHOKU CRUSTAL DEFORMATION 7
   Fig. 4. Three phases of crustal deformation (a megathrust EQ genesis process). 7
5 THE CRUSTAL DISPLACEMENT AND THE EQUATIONS OF MOTION 8
   5.1 DISPLACEMENT TIME SERIES 8
   Fig. 5-1. Displacement d (c, j) at Chichijima station. 9
   5.2 THE EQUATIONS OF MOTION 9
6 THE ABNORMAL MOTION OF THE SUBDUCTING NORTHWESTERN PACIFIC PLATE 10
   6.1 CHICHIJIMA STATION (ON THE WESTERN EDGE OF THE SUBDUCTING NORTHWESTERN PACIFIC PLATE) 11
   Fig. 6-1. The abnormal westward motion at Chichijima station. 13
   6.2 CHICHIJIMA-A STATION (ON THE WESTERN EDGE OF THE SUBDUCTING NORTHWESTERN PACIFIC PLATE) 16
   Fig. 6-2. The abnormal westward motion at Chichijima-A station. 17
   6.3 HAHAJIMA STATION (ON THE WESTERN EDGE OF THE SUBDUCTING NORTHWESTERN PACIFIC PLATE) 18
Fig. 6-3. The abnormal westward motion at Hahajima station.

6.4 MINAMITORISHIMA STATION (ON THE NORTHWESTERN PACIFIC PLATE)

Fig. 6-4. The abnormal westward motion at Minamitorishima station.

6.5 SUMMARY OF THE ABNORMAL MOTION

Table 1 (Abnormal motion of the subducting northwestern Pacific Plate)

7 A BULGE DEFORMATION OBSERVATION

7.1 BULGE ON THE EAST COAST (ONAGAWA STATION)

7.1.1 Until March 10, 2011 (Figs. 7-1a and 7-1b), one day before the Tohoku M9 event

Fig. 7-1. The bulge and M9 observations at Onagawa station.

7.1.2 On and After the Tohoku M9 event (Figs. 7-1c – 7-1e)

7.2 BULGE ON THE WEST COAST (RYOUTSU2 STATION)

7.2.1 Until March 10, 2011 (Figs. 7-2a – 7-2d), one day before the Tohoku M9 event

Fig. 7-2. The bulge and M9 observations at Ryoutsu2 station on an island off the west coast.

7.2.2 On and After the Tohoku M9 event (Figs. 7-2e – 7-2g)

7.3 BULGE ON THE TOP (MURAKAMI STATION)

7.3.1 Until March 10, 2011 (Figs. 7-3a – 7-3d), one day before the Tohoku M9 event

Fig. 7-3. The bulge and M9 observations at Murakami station.

7.3.2 On and After the Tohoku M9 event (Figs. 7-3e – 7-3g)

7.4 SUMMARY ON THE BULGE DEFORMATION AND CO-SEISMIC SHIFTS

Table 2 (Three phases of the bulge deformation over Tohoku)

Table 3 (Co-seismic shifts and current states on the Tohoku M9 EQ)

8 THE CURRENT GPS OBSERVATIONS ON THE NORTHWESTERN PACIFIC PLATE AND TOHOKU

9 DETERMINISTIC PREDICTION OF IMMINENT MEGATHRUST EQS

Fig. 9. Schematics of repeating large EQs (faults), trenches, troughs, and GPS stations.

10 ACKNOWLEDGMENTS

11 REFERENCES

12 APPENDIX A (A MATHEMATICAL TOOL)

12.1 PHYSICAL WAVELETS (P-WS)

12.1.1 INTRODUCTION

Fig. 12-1. The layouts of square waves to construct Physical Wavelets.

12.1.2 PHYSICAL WAVELETS (P-WS)

12.1.3 EQUATIONS OF STOCHASTIC MOTION

12.1.4 AUTOMATED POWER MONITORING

12.1.5 REFERENCES ON APPENDIX A

13 APPENDIX B (CURRENT OCEANIC PLATE OBSERVATIONS AS OF MAY 22, 2021)
13.1 THE OCEANIC PLATES AND THE OVERRIDING TECTONIC PLATES

13.1.1 THE SUBDUCTING NORTHWESTERN PACIFIC PLATE, THE PHILIPPINE SEA PLATE, AND THEIR PLATE BOUNDARIES

Fig. 13-1-1. The horizontal displacements at website https://mekira.gsi.go.jp/index.en.html.

13.1.2 GEOLOGICAL CONFIGURATIONS OF OVERRIDING PLATE BOUNDARIES AND OCEANIC PLATE MOTIONS

Fig. 13-1-2. The vertical displacements at website https://mekira.gsi.go.jp/index.en.html.

13.1.3 CHICHIJIMA-A STATION ON THE SUBDUCTING NORTHWESTERN PACIFIC PLATE

Fig. 13-1-3a. Chichijima-A from December 4, 2007 (j = 1) to November 14, 2020 (j = 4691).
Fig. 13-1-3b. Chichijima-A’s D (c, τ) – V (c, τ) path.

13.1.4 MINAMIDAITO-JIMA STATION ON THE PHILIPPINE SEA PLATE

Fig. 13-1-4a. Minamidaito-Jima from December 4, 2007 (j = 1) to November 14, 2020 (j = 4612).
Fig. 13-1-4b. Minamidaito-Jima’s D (c, τ) – V (c, τ) path.

13.2 THE SUBDUCTING NORTHWESTERN PACIFIC PLATE

13.2.1 THE OVERRIDING TECTONIC PLATE (THE TOHOKU AREA)

Fig. 13-2-1. The vertical displacements at website https://mekira.gsi.go.jp/index.en.html.

13.2.2 THE WESTWARD MOTION OF THE SUBDUCTING PACIFIC PLATE (CHICHIJIMA-A STATION)

Fig. 13-2-2a. Chichijima-A from December 4, 2007, to November 14, 2020.
Fig. 13-2-2b. Chichijima-A’s D (E, τ) – V (E, τ) path, from December 4, 2007, to November 14, 2020.

13.2.3 POWER MONITORING PW (E, τ) ON THE WESTWARD MOTION AT CHICHIJIMA-A

Fig. 13-2-3a. PW (E, τ) from August 4, 2009, to December 4, 2011.
Fig. 13-2-3b. PW (E, τ) with w = 7 and s = 20, from August 4, 2009, to December 4, 2011.
Fig. 13-2-3c. PW (E, τ) and M6.4 on August 4, 2019, as of January 2, 2021.
Fig. 13-2-3d. PW (E, τ), D (E, τ) – V (E, τ) path, M7.3, and M6.9, as of April 24, 2021.
Fig. 13-2-3e. D (E, τ) – A (E, τ) path, M7.3, and M6.9, as of April 10, 2021.
Fig. 13-2-3f. D (E, τ) – A (E, τ) path with w = 7 and s = 20 at Chichijima station for Fig. 6-1b.
Fig. 13-2-3g. D (E, τ) – A (E, τ) path with A (E, τ) = K × D (E, τ) for Fig. 6-1b.
Fig. 13-2-3h. D (E, τ) – A (E, τ) path with w = 6 and s = 15 for Fig. 6-1b.
Fig. 13-2-3i. A magnified D (E, τ) – A (E, τ) path for the last three months before the Tohoku M9.

13.2.4 THE NORTHWARD MOTION OF THE SUBDUCTING PACIFIC PLATE (CHICHIJIMA-A STATION)

Fig. 13-2-4a. Chichijima-A from December 4, 2007, to November 14, 2020.
Fig. 13-2-4b. Chichijima-A’s D (N, τ) – V (N, τ) path from December 4, 2007, to November 14, 2020.

13.2.5 POWER MONITORING PW (N, τ) ON THE NORTHWARD MOTION AT CHICHIJIMA-A

Fig. 13-2-5a. PW (N, τ) and M8.1 on May 30, 2015 (j = 2703).
Fig. 13-2-5b. PW (N, τ) from November 7, 2019, to January 2, 2021.
Fig. 13-2-5c. PW (N, τ) and M7.3 and M6.9 on March 20, 2021 (j = 4817).

13.2.6 CURRENT EASTWARD AND NORTHWARD MOTIONS AT CHICHIJIMA-A, AS OF MAY 22, 2021

Fig. 13-2-6a. PW (E, τ) on the eastward motion as of May 22, 2021.
Fig. 13-2-6b. PW (N, τ) on the northward motion as of May 22, 2021.
13.3 THE PHILIPPINE SEA PLATE

13.3.1 THE OVERRIDING TECTONIC PLATE (THE MAIN ISLAND’S WESTERN PART)

Fig. 13-3-1. The vertical displacements at website https://mekira.gsi.go.jp/index.en.html.

13.3.2 THE WESTWARD MOTION OF THE PHILIPPINE SEA PLATE (MINAMIDAITO-JIMA STATION).

Fig. 13-3-2. Minamidaito-Jima from December 4, 2007, to November 14, 2020.

13.3.3 POWER MONITORING \( PW (E, T) \) ON THE WESTWARD MOTION AT MINAMIDAITO-JIMA

Fig. 13-3-3a. \( PW (E, t) \) and M6.2 on August 22, 2010 (\( j = 973 \)).

Fig. 13-3-3b. \( PW (E, t) \) from February 1, 2019, to May 22, 2021.

13.3.4 THE NORTHWARD MOTION OF THE PHILIPPINE SEA PLATE (MINAMIDAITO-JIMA STATION)

Fig. 13-3-4. Minamidaito-Jima from December 4, 2007, to November 14, 2020.

13.3.5 POWER MONITORING \( PW (N, T) \) ON THE NORTHWARD MOTION AT MINAMIDAITO-JIMA

Fig. 13-3-5a. \( PW (N, t) \) and M8.1 on May 30, 2015 (\( j = 2618 \)).

Fig. 13-3-5b. \( PW (N, t) \) and M6.3 on October 24, 2018 (\( j = 3860 \)).

Fig. 13-3-5c. \( PW (N, t) \) from June 1, 2019, to May 22, 2021.

13.4 REFERENCES ON APPENDIX B

14 APPENDIX C (ISSUES IN MEDIA AND JAPAN’S CABINET OFFICE)

14.1 REFERENCES ON APPENDIX C

1 Abstract

This article updates the Global Positioning System observations on the 2011 Tohoku M9 earthquake genesis process, part of an earthquake prediction patent [1]. Tohoku is at the eastern edge of a continental tectonic plate overriding the subducting northwestern Pacific Plate. The observed daily displacement at every GPS station in Tohoku and the Northwest Pacific Ocean is a noisy and non-differentiable time series. A mathematical tool named Physical Wavelets defines the equations of motion, quantifying the observations.

1) A bulge deformation of a few millimeters over Tohoku started an initial phase of three processes in January 2010.

2) In June 2010, the east coast changed the deformation to the next phase and, in one month, began pulling the subducting Pacific Plate westward, nine months before the M9 event on March 11, 2011.

3) The motion gradually gained westward speed, and it reached an abnormal 0.69 mm/day on December 22, 2010, three times higher than normal.

4) About one month before the highest speed observation, the east coast began the final deformation phase of an upheaval growing.

5) Its linear growth decelerated, stopped, and began reversing the westward motion by two weeks before the event.

6) The upheaval grew to 1.2 mm over 115 days and released an enormous reaction force to rupture the megathrust.
They suggest such megathrust events are predictable. Tohoku is still under the 2011 event. As of May 22, 2021, the Pacific Plate and the Philippine Sea Plate’s motions are ordinary, suggesting no imminent megathrust ruptures [2].

2 Summary

Japan has 1300 Global Positioning System (GPS) stations [3] and the 20 km-mesh Seismograph Network [4]. Tohoku is the main island’s northern part, at the eastern edge of a continental tectonic plate overriding the subducting northwestern Pacific Plate. The Tohoku M9 earthquake (EQ) on March 11, 2011, had foreshocks, aftershocks, and vertical co-seismic displacements, as in Fig. 3, suggesting that a fault of 500 km length and 200 km width held the two plates together.

The GPS observations on the 2011 Tohoku M9 EQ are the daily displacements at the GPS stations in Tohoku and the Northwest Pacific Ocean. Each displacement time series is noisy and non-time-differentiable. A mathematical tool named Physical Wavelets (Appendix A) defines the equations to draw the phase plane paths with the displacement resolution of 0.1 mm, 4 orders of magnitude greater than the daily vertical displacement noise level of ± 20 mm, and the rate change resolution 0.01 – 0.0001 mm per day. The paths in Fig. 6-1 – Fig. 7-3 suggest that a cross-sectional deformation process at the northern latitude of about 38 degrees in Fig. 3 is the simplified schematic of Fig. 4, showing the genesis process of the 2011 Tohoku EQ.

The tectonic plate-driving forces had pushed the west and east coasts of Tohoku upward and downward, respectively, as in Fig. 4a. On the west coast, the upward rate was 1.5 mm per year. On the east coast, the subsidence rate was 6 mm per year. They were the regular deformation rates over an approximate distance of 500 km along both shores of Tohoku. The GPS stations in the small islands in the Northwest Pacific Ocean (on the subducting northwestern Pacific Plate) were moving westward and northward at their average rate of 0.1 mm per day and 0.03 mm per day over ten years, respectively. The 0.1 mm per day is approximately our fingernail’s growth rate.

The regular deformation started to change to a bulge deformation of 1 – 3 mm over Tohoku in January 2010, as in section 7. The deformation grew in an initial, first, second (final) phase, as in section 7.4. A simplified schematic is Fig. 4b. At the first phase, Tohoku’s east coast began to pull the subducting plate by their fault coupling on July 11, 2010, nine months before the Tohoku M9 EQ, as in section 7.1. The dotted arrow over the fault (Fig. 4b) shows its pulling action by the eastern edge of the overriding plate. The pulling started to accelerate the plate’s westward motion, as in Figs. 6-1e, 6-1f, 6-1h, and 13-2-3f – 13-2-3i (Appendix B). The motion (at an island’s GPS station on the plate) gained an abnormally increased speed of 0.69 mm/day by December 22, 2010, approximately three times higher than that on July 11, 2010, as in Fig 6-1. A summary of the abnormal motion is in Table 1.

About one month before the highest speed observation on December 22, 2010, the bulge began the final phase with an upheaval growing along the east coast (section 7.1). As it grew, the oceanic plate’s westward motion decelerated and stopped by February 21, 2011. In four days, the motion reversed direction, and the eastward speed reached 0.06 mm/day by March 8, 2011. By March 10, 2011 (one day before the Tohoku M9
event), the upheaval grew to 1.2 mm over 115 days from November 14, 2010. The GPS observations suggest the linear growth generated and released an enormous reaction force, as in Fig. 4c. An observed geophysical process of the upheaval is in sections 7.1 and 7.4.

The three-phase bulge deformation over Tohoku (an overriding tectonic plate’s eastern edge) and the bulge coupling with the subducting oceanic plate motion of nine months are the GPS observed Tohoku M9 EQ genesis process. So-called slow slip events were not in the process (Appendix B). The equations of motion suggest such subduction-zone events are predictable. The current observations show the Tohoku crust motion is still under the M9 EQ influence. As of May 22, 2021, the motion on both the subducting Pacific Plate and the Philippine Sea Plate is ordinary for imminent megathrust EQs (Appendix B). However, the predictable application to the imminent Nankai-trough megathrust ruptures [2] has some issues (Appendices B and C).

3 The foreshocks, aftershocks, and co-seismic shifts of the Tohoku M9

The foreshocks, aftershocks, and vertical co-seismic displacements of the Tohoku M9 EQ are in Fig. 3a [1]. The GPS stations in Fig. 3a observed the co-seismic downward and upward displacement along the east and west coast and the no-displacement along a ridge on Tohoku. The distribution suggests that the EQ’s rectangular fault surface had a 500 km length and a 200 km width. Its rupture decoupled the overriding Tohoku crust (the eastern edge of the continental tectonic plate) from the subducting western edge of the northwestern Pacific Plate.

Fig.3. GPS stations, vertical co-seismic displacement, foreshocks, and aftershocks of the M9 EQ.
(a) The EQ source parameters are from the JMA’s unified hypocenter catalogs [4]. The EQ’s magnitude M is JMA’s magnitude [5]. The M7.5 (2011/3/9) EQ is a foreshock (Appendix C) of the Tohoku M9 EQ (2011/3/11). The M9’s hypocenter and CMT solution were (38.1006°N, 142.8517°E, 24 km) and the reverse faulting of (STR = 193°, DIP = 10°, SLIP = 79°) [5]. The near Chichijima M7.9 (2010/12/22) EQ [1] triggered by the Pacific Plate’s abnormal westward motion is in section 6. The off Tokachi M8 (2003/9/23) EQ [7] is in Fig. 9. The
vertical co-seismic displacements over the 500 km distance are the downward (Down), upward (Up), and no change (No change) displacement at each GPS station. Three GPS stations above 38 degrees north latitude-line, used in sections 4 and 7, are Ryoutsu2 (Up) at (38.0633° N, 138.4717° E, west coast), Murakami (No change) at (38.2307° N, 139.5069° E), and Onagawa (Down) at (38.4492° N, 141.4412° E, east coast). The M9 EQ (2011/3/11) is on the 38-degree N line. The GPS stations in the Northwest Pacific Ocean are Chichijima, Hahajima, and Minamitorishima stations. Chichijima and Hahajima stations are on the subducting western edge of the northwestern Pacific Plate, whereas Minamitorishima station is on the northwestern Pacific Plate (far right below). (b) A google earth map with Fig.3a overlaid.

The Chichijima, Hahajima, and Minamitorishima GPS stations in the Northwest Pacific Ocean observed the identical abnormal oceanic plate motion (section 6) coupled with the bulge deformation along the Tohoku east coast (section 7.1). We first summarize the observed coupling at the Tohoku crust cross-section along about 38 degrees north latitude and the subducting oceanic plate as the schematics in Fig. 4. The Tohoku M9 EQ hypocenter is on the 38-degree N line.

4 Three distinctive phases of the Tohoku crustal deformation

In the schematics of Fig. 4, the east and the west coast face the Northwest Pacific Ocean and the Japan Sea. The top is the location of the no-displacement-ridge-line in Fig. 3.

Fig. 4. Three phases of crustal deformation (a megathrust EQ genesis process).
(a) Regular slow deformation. (b) A bulge deformation pulled the subducting Pacific Plate by a coupling force (dotted arrow). (c) The deformation of an upheaval growth activated an enormous reaction (dotted arrow) to rupture the megathrust EQ and a tsunami to follow.
Tohoku had three distinctive phases of crustal deformation. The bulge deformation in section 7.4, coupled with the subducting northwestern Pacific Plate motion, generated an enormous reaction force to rupture the megathrust EQ.

The regular slow deformation in Fig. 4a is the schematic of subsidence on the east coast by the subducting oceanic plate-driving force (a westward-arrow) and an upward displacement on the west coast by the continental plate-driving force (an eastward-arrow). For example, Onagawa station in Fig. 3 had a subsidence rate of 6 mm per year. Ryoutsu2 station had an upward rate of 1.5 mm per year. The GPS stations observed the regular deformation over about 500 km along the east and west coasts of Tohoku.

A few millimeter bulge deformation is the schematic of Fig. 4b, which changed from the regular deformation in January 2010. The deformation over Tohoku had a three-phase process, as in section 7.4. As the bulge phase changes, as in section 7.1, the east coast of the overriding tectonic plate began pulling the subducting Pacific Plate westward by their fault coupling. The pulling force on the westward motion is the dotted arrow over the fault, which started on July 11, 2010 (Fig. 6-1e). The action accelerated the motion whose westward speed reached the highest speed of 0.69 mm/day on December 22, 2010, as in section 6.

About one month before the highest speed observation, the bulge phase changed to an upheaval growing process on the east coast, as in Figs. 7-1a and 7-1b. The linear growth decelerated the westward motion of the subducting Pacific Plate. The motion stopped by February 21, 2011, and stayed motionless for another four days.

After February 25, the upheaval growth reversed the westward motion. The eastward speed reached 0.06 mm/day only three days before the M9 event on March 11, 2011, as in Fig. 6-1c. The upheaval linearly grew to 1.2 mm over 115 days from November 14, 2010, as in section 7.1. The 1.2 mm growth generated and released an enormous reaction force on the megathrust, as Fig. 4c.

5 The crustal displacement and the equations of motion

5.1 Displacement time series

We used the Geospatial Information Authority of Japan (GSI)’s F3 solutions for the GPS stations’ daily positions, open to the public with two-week latency by GSI [3]. The relative change of the position from a reference is the displacement vector. Its components are along the geological axis $c$ denoted by $E$ (west to east), $N$ (south to north), and $h$ (down to up) in right-handed coordinates $(E, N, h)$. The time history of each component is the time series,

\[ \{c\} = \{d(c, 0), d(c, 1), d(c, 2), \ldots, d(c, j), \ldots\}. \]

The $j$ is the chronological event index of time in days. If the reference is the first day’s position, the first component is zero, $d(c, 0) = 0$, where the first day is $j = 0$. The reference position may be arbitrary. If such a case, the first day is $j = 1$ for which $\{c\}$ begins with $d(c, 1)$. Each displacement series $\{c\}$, as in Fig. 5-1, is too noisy to define its time derivatives. However, a mathematical tool named Physical Wavelets (Appendix A) defines the equations for the noisy time series $\{c\}$. 

Fig. 5-1. Displacement $d(c,j)$ at Chichijima station.

Chichijima station started its operation on March 21, 1996, and ended it on March 8, 2011, three days before the M9 event. The GSI has replaced Chichijima with Chichijima-A.

The $\{c\}$ is very noisy for the first four years, including a deficiency of four-month data in 1999. Thus, January 1, 2000, is the first day for $\{c\}$. We removed several scattered and two-week-long deficiency days and re-indexed $\{c\}$. The two-week deficiency was at $j = 3078$ in October 2008. The $d(N,j)$, $d(E,j)$, and $d(h,j)$ are in the first, second, and third windows from the top, respectively. Each ordinate is each displacement $d(c,j)$ in meters. Since each displacement is zero at $j = 0$, each graphical origin has the offset value from zero for the graphics of $\{c\}$. Their values are 0.06 m, –0.2 m, and –0.01 m from the top window. The northward, eastward, and upward displacements from the origin are positive. The magnifications on each offset scale are 8000, 2500, and 10000 times. Each column height shows its last $d(c,j)$ from the reference with its value. The $d(N,j)$ at $j = 3940$, 0.11825 m, is the net displacement. The northward moving rate of the subducting Pacific Plate is 0.03 mm per day (1.1 cm per year) over 3940 days. The $d(E,j)$ has the net downward (westward) amount of –0.3888 m. The westward-moving rate is 0.1 mm per day (3.60 cm per year). Small variations in $d(N,j)$ and $d(E,j)$ are indistinguishable from various GPS environmental noises. The noise level for $d(h,j)$ is approximately between ±200, 40 mm by its magnification of m/10000 (0.1 mm).

5.2 The equations of motion

Physical Wavelets (P-Ws) are the operators satisfying the position and derivatives’ time reversal property (Appendix A). Thus, the cross-correlation of P-Ws with the non-time-differentiable $\{c\}$ defines displacement $D(c,\tau)$, velocity $V(c,\tau)$, and acceleration $A(c,\tau)$ at time $\tau$ as follows.

$$D(c,\tau) = \frac{1}{2w+1} \sum_{j=-w}^{w} d(c,\tau+j),$$

(1)

$$V(c,\tau) = \frac{D(c,\tau+s/2) - D(c,\tau-s/2)}{s},$$

(2)

and
\[ A(c, \tau) = \frac{D(c, \tau + s) - 2D(c, \tau) + D(c, \tau - s)}{s \times s} \]  \hspace{1cm} (3)

In these definitions, \( D(c, \tau) \) has \( d(c, j) \) averaged over a time \( j = \tau \pm w \), as in Eq. (1). The \( d(c, j) \) is noisy, and the GPS time series \( \{c\} \) has periodically fluctuating components. The specific extraction is significant if the mutual correlation between P-Ws and \( \{c\} \) is strong (Appendix A). Equation (1) has a low pass filter, Eq. (2) a bandpass filter, and Eq. (3) another bandpass filter. The \( w \) and \( s \) can be any integer by which to filter out the selected frequency components of \( D(c, \tau), V(c, \tau), \) and \( A(c, \tau) \). The relations between the \( D(c, \tau), V(c, \tau), \) and \( A(c, \tau) \), are the equations of motion for the observed \( \{c\} \).

We define a time-rate change of the kinetic energy (velocity squared) by the product of \( V(c, \tau) \) and \( A(c, \tau) \), which is the power, \( PW(c, \tau) \). We then reassign them as \( V(c, j) \) and \( A(c, j) \) at real-time \( j = \tau + w + s \), defined for \( A(c, \tau) \) (Appendix A). The power is then \( PW(c, j) = V(c, j) \times A(c, j) \). Monitoring the oceanic plate and the Tohoku crust’s motions with \( PW(c, j) \geq \) some predetermined threshold, finds any unexpected motion and its onset. The threshold level adopts the observed \( PW(c, j) \)’s maximum amplitude during expected standard motions.

6 The abnormal motion of the subducting northwestern Pacific Plate

Three islands in the Northwest Pacific Ocean near the Japan Trench have GPS stations: Minamitorishima, Hahajima, and Chichijima (replaced with Chichijima-A) station (Figs. 3 and 9). Minamitorishima station is on the northwestern Pacific Plate. Chichijima and Hahajima stations are located below the Japan Trench and on the western edge of the Ogasawara Plateau [3, Fig. 13-1-1 (Appendix B)]. Their qualitatively identical GPS displacement time series \( \{c\} \) suggests that Chichijima and Hahajima stations are under the motion of the western edge of the subducting northwestern Pacific Plate and Minamitorishima station under the northwestern Pacific Plate’s motion.

The displacement \( \{c\} \) of the subducting oceanic plate motion is always under the lunar synodic tidal force loading. We define the \( D(E, \tau), V(E, \tau), \) and \( A(E, \tau) \) with \( w = 7 \) and \( s = 20 \) to observe the responses of the oceanic plate motion to the synodic loading of period 30 (29.5) days. Any external force coupling with the overriding eastern edge may change the periodic lunar responses in amplitudes and phases.

An unexpectedly increased westward speed appeared on the \( D(E, \tau) - V(E, \tau) \) path at every station, as in Figs. 6-1 – 6-4. A trend-change on \( D(E, \tau) \) in July 2010 preceded the abnormal motion. The westward speed \( V(E, \tau) \) at every station reached its highest on December 22, 2010, 76 days before the Tohoku M9 EQ. They were \(-0.69 \) mm/day for Chichijima, \(-0.78 \) mm/day for Chichijima-A, \(-0.84 \) mm/day for Hahajima, and \(-1.15 \) mm/day for Minamitorishima, each of which was approximately three times higher than each standard westward speed, as in Table 1. A rapid deceleration then followed, and it stopped the westward motion by around February 21, 2011. In about four days, the moving direction reversed, and the subducting plate moved eastward until the Tohoku M9 events on March 11, 2011.

The \( PW(E, j) \) monitoring with \( w = 7 \) and \( s = 20 \) detected the onset for both the trend-change and the abnormal motion to follow, as in Figs. 6-1d and 6-1e.
The $D(E, \tau) - A(E, \tau)$ paths are available for quantifying the observed motion under the external force $F(E, \tau)$ by an equation, $F(E, \tau) \approx A(E, \tau) \approx K \times D(E, \tau)$ with a time and synodic-cycle dependent constant $K$ (positive or negative), as in Figs. 13-2-3f – 13-2-3i in Appendix B.

We removed the lunar synodic loading with $w = 15$ and $s = 40$ as in Fig. 6-1f. The $PW(E, j)$ monitoring detected the anomaly onset more clearly, as in Figs. 6-1g and 6-1h. The unexpected trend-change on $D(E, \tau)$ was in July 2010 in Fig. 6-1h, which was the first response of the subducting oceanic plate to the overriding eastern edge’s bulge formation (section 7.1).

The low-frequency selection accompanies some onset-detection delay in real-time $j$, as in Figs. 6-1d and 6-1g. However, the equations with $w \approx 200$ and $s \approx 300$, even with a much longer real-time delay, are requisite for quantifying the Tohoku’s crustal-bulge deformation in a three-phase process by minimizing the yearly and seasonal variations and environmental noises in \{c\} ($c = h$), as in section 7. The first-phase bulge deformation on the east coast, as in sections 7.1 and 7.4, generated every abnormal westward motion to follow by the fault coupling, as in Fig. 4.

Observing the lunar fortnightly tidal force loading in regional \{h\} requires parameters $w \approx 2$ and $s \approx 7$. The $PW(h, j)$ monitoring had detected unusual loading a few weeks before EQs of magnitude larger than about five in the region if the two blocks separated by the fault plane have an upward and downward co-seismic shift [6, 7]. Namely, the fault type is not pure strike-slip. The GPS observations suggest that the crustal reactions to the lunar tidal force loadings are standard unless the earth’s crust is in a critical state with an imminent significant EQ in the region.

Thus, the $PW(c, j)$ monitoring of the crustal responses to the periodic lunar tidal force loadings is an observational and analytical tool for any anomaly detection.

6.1 Chichijima station (on the western edge of the subducting northwestern Pacific Plate)

The GSI closed Chichijima station (27.0956° N, 142.1846° E) after March 8, 2011. The last observation was three days before the Tohoku M9 EQ on March 11, 2011.
Fig. 6-1. The abnormal westward motion at Chichijima station.

(a) The original $\{c\}$ is from $j = 0$ (January 1, 2000), to $j = 3940$ (March 8, 2011). Parameters $w = 7$ and $s = 20$ are for $D(c, \tau)$, $V(c, \tau)$, and $A(c, \tau)$. The $D(E, \tau) - V(E, \tau)$ plane is (24 cm, 1 mm/day). Its origin is $D(E, \tau) = -0.2$ m, the offset reference ($-0.2$ m) at scale 0 from the first-day position ($j = 0$). The $V(E, \tau)$ origin is 0 mm/day. The right half of the $D(E, \tau) - V(E, \tau)$ plane is east from the offset origin. The upper half is eastward and positive $V(E, \tau)$. The lower half is westward and negative. The M7.9 (2010/12/22) event is on $D(E, \tau)$ at $\tau = 3864$
and the (24 cm, 1 mm/day) path. The $d(c, j)$ is in green, $D(c, \tau)$ in red and $V(c, \tau)$ in black. The $V(c, \tau)$ is in a relative scale from the graphical origin 0. (b) The expanded time-window is from $j = 3500$ (December 23, 2009), to $j = 3940$ (March 8, 2011). The (4 cm, 1 mm/day) plane has an offset origin at the blue-line-scale $-50$, $D(E, \tau) = -0.22$ m ($-0.2 - 50/2500$). The $V(E, \tau)$ and $A(E, \tau)$ are in relative scales from the same graphical origin 0. The lunar synodic tidal force loading of the 29.5-day-period has label 30 days on the blue $A(E, \tau)$. The date label 2010/07/11 is the $D(E, \tau)$ trend-change at $\tau = 3700$ (July 11, 2010). (c) The window is from $j = 3500$ (December 23, 2009), to $j = 3940$ (March 8, 2011). A magnified (2 cm, 0.2 mm/day) plane has the offset origin at the blue-line-scale $-100$, $D(E, \tau) = -0.39$ m ($-0.35 - 100/2500$). The path ended at $V(E, \tau) = +0.06$ mm/day. (d) The window is from $j = 3500$ (December 23, 2009), to $j = 3940$ (March 8, 2011) with a $PW(E, j)$ monitoring. The relative power scales are on the right column. The monitoring with $PW(E, j) \geq 400$ detected an anomalous lunar synodic loading on $\{E\}$. The predetermined 400 was about twice the expected standard power level at arrow 1. Level 400 is at the red scale at arrow 2. Arrow 3 was the first anomaly detection at $j = 3847$ (December 5, 2010). At the detection, $PW(E, j)$ rose from 378 (at $j = 3846$) to 440 (at $j = 3847$), showing the red column height. Arrow 4 was the second detection at $j = 3877$ (January 4, 2011). The anomalous $V(E, j)$ and $A(E, j)$ were bold under $PW(E, j) \geq 400$. (e) The window is from $j = 3500$ (December 23, 2009), to $j = 3940$ (March 8, 2011). $PW(E, j) \geq 160$ found the westward trend-change at real-time $j = 3735$ on August 15, 2010. In time $\tau$, the change was at $\tau = 3708$ (at arrow 0) on July 19, 2010. The detecting level 160 at arrow 2 adopted the standard power level at arrow 1. By shifting real-time $j$ back to time $\tau$, the displays are $D(E, \tau)$, $V(E, \tau)$, $A(E, \tau)$ and $PW(E, \tau)$. (f) The time-window is from $j = 3500$ (December 23, 2009), to $j = 3940$ (March 8, 2011). Parameters $w = 15$ and $s = 40$ removed the 30-day-period oscillation. The (4 cm, 0.5 mm/day) plane has the offset-origin, $D(E, \tau) = -0.37$ m ($-0.35 - 0.02$) at the blue-line scale $-50$. The $D(E, \tau)$ trend-change has date-label 2010/7/11. (g) The window is from $j = 3500$ (December 23, 2009), to $j = 3940$ (March 8, 2011) with $w = 15$ and $s = 40$. Arrow 3 was the anomaly detection at $j = 3869$ (December 27, 2010) by $PW(E, j) \geq 400$. The threshold 400 is at the red scale pointed by arrow 2. The threshold adopted the standard power level at arrow 1. The power column height change in red is from 400 (at $j = 3868$) to 442 (at $j = 3869$) at the anomaly detection. The black column height shows the last $PW(E, j)$ (just above level 0) on March 8, 2011 ($j = 3940$). (h) The window is from $j = 3500$ (December 23, 2009), to $j = 3940$ (March 8, 2011) for the $D(E, \tau)$ trend-change detection. Up-arrow 0 was the trend-change detection at real-time $j = 3751$ (August 31, 2010) by $PW(E, j) \geq 160$ with $w = 15$ and $s = 40$. In time $\tau$, the change is at arrow 0, $\tau = 3696$ on July 7, 2010. Arrow 1 is the standard power level, for which the unexpected level 160 was about twice the standard level.

Figure 6-1a is Fig. 5-1 with the analyzed data overlaid. Series $\{E\}$ in the second window has the $D(E, \tau)$ and $V(E, \tau)$ relation expressed as a path on the (24 cm, 1 mm/day) plane. At the highest westward (downward) speed, the M7.9 EQ ruptured in the Pacific about 187 km away from the station (Fig. 3). The event had normal faulting (STR = 340°, DIP = 57°, SLIP = −56°) [5], which suggests the abnormal westward motion triggered the event, as in Fig. 13-2-3i (Appendix B) [1]. In Fig. 6-1b, the $D(E, \tau)$, $V(E, \tau)$, and $A(E, \tau)$ show the lunar synodic tidal force loading (the 29.5-day-period) on the subducting Pacific Plate (Chichijima station). The path leads an eastward protruding by the amount of 0.2 mm/day from the westward speed at −0.23 mm/day. Dividing the 6 mm separation between the two
protruding peaks by the 30 days, the westward speed estimation is −0.2 mm/day. The westward trend of $D(E, \tau)$ changed at around $\tau = 3700$ (July 11, 2010), whose change has the arrowed label 2010/07/11 on the $D(E, \tau)$. The trend-change onset was in an insufficient synodic tidal loading on the $D(E, \tau)$, $V(E, \tau)$, and $A(E, \tau)$ segments that are roughly linear. The onset divided the $D(E, \tau) - V(E, \tau)$ path into two small linear segments. The first linear segment preceding the trend-change has an explicit equation $A(E, \tau) = K \times D(E, \tau)$ with a positive constant $K$ on the $D(E, \tau) - A(E, \tau)$ path-segment, as in Figs. 13-2-3f – 13-2-3i (Appendix B). The constant $K$ under effective lunar synodic tidal loading is negative, obeying the oscillatory motion. Following the trend-change, the motion became anomalous and reached the highest westward speed of $V(E, \tau) = −0.69$ mm/day at $\tau = 3864$ on December 21, 2010, approximately three times faster than $V(E, \tau) = −0.25$ mm/day at $\tau = 3700$ on July 11, 2010. After this, the westward motion shows a rapid deceleration until it stopped at $\tau = 3908$ on February 4, 2011.

Figure 6-1c shows a magnified path changing $V(E, \tau)$ positive on February 8. The reversed motion reached the eastward speed of $V(E, \tau) = +0.06$ mm/day, and the eastward displacement of 1.6 mm at time $\tau = 3918$ on February 14, 2011. In real-time $j$, it was March 8, 2011, three days before the March 11 M9 EQ, because $j$ is in advance of $\tau$ by 17 days ($j = \tau - s/2 - w$).

Figure 6-1d shows the $PW(E, j) \geq 400$ monitoring detected the anomaly by a predetermined threshold level of 400. Level 400 is an unexpected power level twice the standard $PW(E, j)$ amplitudes at dot-arrow 1. The threshold adoption can be automatic or manual during the power monitoring. Arrow 3 and Arrow 4 were then the first at $j = 3847$ (December 5, 2010) and second at $j = 3877$ (January 4, 2011) anomaly detection, respectively. At each detection, $V(E, j)$ and $A(E, j)$ become bold, and they stay bold while $PW(E, j) \geq 400$. They are negative, which means the anomalous acceleration and move were westward.

Figure 6-1e shows that the unexpected westward motion started at the upward arrow 0. The $PW(E, j) \geq 160$ monitoring found the westward trend-change at real-time $j = 3735$ on August 15, 2010. In time $\tau (\tau = j - s - w)$, it was 3708 on July 19, 2010. We shifted real-time $j$ back to time $\tau$ to draw $D(E, \tau)$, $V(E, \tau)$, $A(E, \tau)$ and $PW(E, \tau)$, for which the position and derivatives’ time reversal property satisfy. As for anomalies 3 and 4, the negative $A(E, \tau)$ precedes negative $V(E, \tau)$ so that the anomalous acceleration (oceanic tectonic driving force) and the motion to follow are westward.

In Fig. 6-1f, we define the $D(E, \tau)$, $V(E, \tau)$, and $A(E, \tau)$ with $w = 15$ and $s = 40$, which masked the lunar synodic loading. The $D(E, \tau) - V(E, \tau)$ path shows the abnormal $V(E, \tau)$ more apparent than that in Fig. 6-1d.

Figure 6-1g shows that the $PW(E, j) \geq 400$ monitoring with $w = 15$ and $s = 40$ detected the abnormal motion at arrow 3 (at $j = 3869$ on December 27, 2010). The power change is the red column height. The $V(E, j)$ and $A(E, j)$ in bold are negative so that the abnormal motion was by the westward $A(E, j)$.

Figure 6-1h shows the $PW(E, \tau) \geq 160$ monitoring with $w = 15$ and $s = 40$ detecting the westward trend-change without the effective synodic tidal force loading on $D(E, \tau)$. It shows that the trend-change is independent of the lunar tidal force loading. The geophysical origin for the trend-change was a transition from the regular subsidence deformation on the east coast of Tohoku to the bulge formation, as in section 7.1. The abnormal westward motion of the subducting northwestern Pacific Plate followed the trend-change.
The \(PW(E, j)\) monitoring for the low-frequency \(D(E, \tau)\), \(V(E, \tau)\), and \(A(E, \tau)\) accompanies the anomaly-onset-detection delay in real-time \(j\). However, the delay allowance depends on the detecting objectives. For example, the unexpected \(V(E, j)\) and \(A(E, j)\) detection time in Fig. 6-1d was \(j = 3847\) (December 5, 2010), whereas, it was \(j = 3869\) (December 27, 2010) with \(w = 15\) and \(s = 40\) in Fig. 6-1g. The detection date, December 5, may be useful to predict the imminent M7.9 event on December 22. However, the detection of December 27 and the preceding \(D(E, \tau)\) trend-change was for the Tohoku M9 events on March 11, 2011. An automated power monitoring with multiple frequencies and thresholds for any abnormal event detection is always available.

6.2 Chichijima-A station (on the western edge of the subducting northwestern Pacific Plate)

Chichijima-A station (27.0675° N, 142.1950° E) started its observation on December 4, 2007, as in Fig. 6-2. It shows the same abnormal motion as Chichijima station.
Fig. 6-2. The abnormal westward motion at Chichijima-A station.

(a) The original \{c\} is from \(j = 1\) (December 4, 2007) to \(j = 4533\) (June 6, 2020). An environmental spike noise of the M9 event is on the \(d(E, j)\) at \(j = 1175\) (March 11, 2011). Parameters \(w = 7\) and \(s = 20\) are for \(D(E, \tau)\), \(V(E, \tau)\), and \(A(E, \tau)\). The \(D(E, \tau) - V(E, \tau)\) plane is (24 cm, 0.8 mm/day). The path has the M9 event labeled. The \(V(E, \tau)\) and \(A(E, \tau)\) are in relative scales from the graphical offset-origin. (b) The expanded time-window is from \(j = 660\) (October 4, 2009) to \(j = 1430\) (November 23, 2011). The magnified plane is (2 cm, 0.8 mm/day). The path shows the highest westward speed was \(V(E, \tau) = -0.78\) mm/day at \(\tau = 1096\) on December 22, 2010. (c) The window is from \(j = 660\) (October 4, 2009) to \(j = 1430\) (November 24, 2011). We removed the M9 spike noise as a data deficiency at label 1 & 2 (M9) on the \(d(E, j)\). Two events 1 and 2 are before and after the M9 event on the magnified path. The \(V(E, \tau)\) is +0.12 mm/day at \(\tau = 1174\) (March 10, 2011, label 1), and +0.10 mm/day at \(\tau = 1175\) (March 12, 2011, label 2). (d) The original \{c\} is from \(j = 1\) (December 4, 2007) to \(j = 1174\) (March 10, 2011). The expanded time window shows the lunar synodic tidal loading on the \(V(E, \tau)\) and \(A(E, \tau)\), labeled as 30 days. The westward trend-change label (2010/07/11) is to note the similar phase relationship among \(D(E, \tau)\), \(V(E, \tau)\) and \(A(E, \tau)\) at \(\tau = 932\) as that of Figs. 6-1b – 6-1d at Chichijima station. A magnified path shows \(V(E, \tau) = +0.12\) mm/day at \(\tau = 1157\) (on February 21, 2011) with the last available data of \(d(E, j)\) at \(j = 1174\) on March 10, 2011.

Figure 6-2a shows the observation from December 4, 2007, to June 6, 2020, which has the M9 event on March 11, 2011. The M9 appears as an environmental spike noise on the \(d(E, j)\) at \(j = 1175\). The path shows the anomalous westward motion was only before the M9 event.

Figure 6-2b shows the M9 event on the expanded time-window display with the path. The highest westward speed was \(V(E, \tau) = -0.78\) mm/day at \(\tau = 1096\) on December 22, 2010.

Figure 6-2c has the same time window with the removal of the M9 spike as a data deficiency. Path events 1 and 2 are before and after the M9 event on the magnified path. The \(V(E, \tau)\) is +0.12 mm/day at \(\tau = 1174\) (March 10, 2011, label 1), and +0.10 mm/day at \(\tau = 1175\) (March 12, 2011, label 2).

In Fig. 6-2d, the observed \{c\} is only from December 4, 2007 \((j = 1)\), to March 10, 2011 \((j = 1174)\). The expanded time window shows the lunar synodic tidal loading on the \(V(E, \tau)\) and \(A(E, \tau)\), labeled as 30 days. The westward trend-change label (2010/07/11) is to note the similar phase relationship among \(D(E, \tau)\), \(V(E, \tau)\) and \(A(E, \tau)\) at \(\tau = 932\) as that of Figs. 6-1b – 6-1d at Chichijima station. A magnified path shows \(V(E, \tau) = +0.12\) mm/day at \(\tau = 1157\) (on February 21, 2011) with the last available data of \(d(E, j)\) at \(j = 1174\) on March 10, 2011.
On March 8, 2011, Chichijima-A station observed $V(E, \tau) = +0.08 \text{ mm/day}$, whereas Chichijima station observed the last available $V(E, \tau) = +0.06 \text{ mm/day}$.

6.3 Hahajima station (on the western edge of the subducting northwestern Pacific Plate)

Hahajima station (26.6352° N, 142.1628° E) had data deficiencies from June 16, 2004, to September 23, 2005. Thus, time series $\{c\}$ is from September 24, 2005 ($j = 1$).

Figure 6-3a shows a spike on $d(E, j)$ at $j = 1987$, the M9 event on March 11, 2011. The path has the abnormal motion only before the M9 event.

Figure 6-3b shows the path of the M9 spike event. Before the M9, the path has the highest westward speed $V(E, \tau) = -0.84 \text{ mm/day}$ at $\tau = 1908$ on December 22, 2010, as Chichijima and Chichijima-A stations.
Fig. 6-3. The abnormal westward motion at Hahajima station.

(a) The original \( \{c\} \) is from September 24, 2005 \((j = 1)\), to May 23, 2020 \((j = 5345)\). Parameters \( w = 7 \) and \( s = 20 \) are for \( D(E, \tau) \), \( V(E, \tau) \), and \( A(E, \tau) \). The \( D(E, \tau) - V(E, \tau) \) plane is \((30 \text{ cm}, 1 \text{ mm/day})\). A spike noise is the M9 event on March 11, 2011, at \( j = 1950 \). (b) The time-window is from \( j = 1040 \) (August 4, 2008) to \( j = 2340 \) (February 29, 2012). The magnified \((5 \text{ cm}, 1 \text{ mm/day})\) path shows a sudden change by the M9 spike. (c) The window is from \( j = 1040 \) (August 4, 2008) to \( j = 2340 \) (February 29, 2012). We removed the M9 spike noise as a data deficiency at arrow 1 & 2 (M9) on the \( d(E, j) \). Two events 1 and 2 on the \((2.5 \text{ cm}, 0.5 \text{ mm/day})\) path are before and after the M9. (d) The original \( \{c\} \) is from September 24, 2005 \((j = 1)\), to March 10, 2011 \((j = 1986)\), one day before the Tohoku M9 EQ. The expanded time-window is from \( j = 1050 \) (August 14, 2008) to \( j = 1986 \) (March 10, 2011). Label 2010/7/11 of the trend-change observed at Chichijima stations is on \( D(E, \tau) \) at \( \tau = 3744 \). The \((2.5 \text{ cm}, 0.25 \text{ mm/day})\) path ends at \( V(E, \tau) = 0.20 \text{ mm/day} \) that has the last \( d(E, j) \) on March 10, 2011. It also shows \( V(E, \tau) = 0.13 \text{ mm/day} \) on March 8, 2011.

Figure 6-3c has the same expanded time-window from \( j = 1040 \) to \( j = 2340 \), with the M9 spike removed as a deficit data. Two events 1 and 2 on the path are before and after the M9 event. The \( V(E, \tau) \) is \(+ 0.18 \text{ mm/day} \) at \( \tau = 1986 \) (March 10, 2011, label 1), and \(+ 0.20 \text{ mm/day} \) at \( \tau = 1987 \) (March 12, 2011, label 2).

In Fig. 6-3d, the time series \( \{c\} \) has data only from September 24, 2005 \((j = 1)\), to March 10, 2011 \((j = 1986)\), one day before the Tohoku M9 EQ. The highest speed was \( V(E, \tau) = -0.84 \text{ mm/day} \) at \( \tau = 1908 \) on December 22, 2010. The lunar synodic period of 30 days is on \( A(E, \tau) \) in the expanded time-window from \( j = 1050 \) to \( j = 1986 \) (March 10, 2011). The path, has the eastward speed, \( V(E, \tau) = 0.12 \text{ mm/day} \) on March 8 and 0.20 mm/day on March 10, 2011. The eastward \( V(E, \tau) = 0.12 \text{ mm/day} \) on March 8, 2011, was twice of Chichijima (Table 1).

Label 2010/07/11 points to the trend-change observed at Chichijima station. The onset shows the similar phase relationship among \( D(E, \tau) \), \( V(E, \tau) \), and \( A(E, \tau) \) at \( \tau = 1744 \) on July 11, 2010, like those in Figs. 6-1b – 6-1d, and 6-2d.

The highest speed was \( V(E, \tau) = -0.84 \text{ mm/day} \) at \( \tau = 1908 \) on December 22, 2010, and then the westward motion nearly stopped by February 21, 2011 (in day \( \tau \)). The subducting plate reversed the westward motion.

6.4 Minamitorishima station (on the northwestern Pacific Plate)

Minamitorishima station (N 24.2901, E 153.9787) in the Northwest Pacific Ocean (Figs. 3 and 9) started its operation on July 1, 2004, and had many observational deficits in \( \{c\} \). They are: 1) From May 10, 2005, to May
29, 2005 (at $j = 314$). 2) From August 3, 2005, to September 14, 2005 (at $j = 379$). 3) From October 5, 2006, to November 23, 2006 (at $j = 765$). 4) From July 16, 2008, to August 20, 2008 (at $j = 1362$). 5) From September 30, 2008, to November 26, 2008 (at $j = 1401$). 6) From June 9, 2009, to November 17, 2009 (at $j = 1595$). 7) From August 17, 2010 to September 25, 2010 (at $j = 1865$). 8) From October 13, 2010, to January 1, 2011 (at $j = 1882$). 9) From October 22, 2016, to March 11, 2017 (at $j = 3996$). As of July 25, 2020, the station has stopped observing since March 18, 2020.

Figure 6-4a shows all observed $\{c\}$. Each average moving rate in $\{E\}$ and $\{N\}$ is 7.1 cm per year to the west and 2.3 cm per year to the north.

Figure 6-4b shows the single M9-related-abnormal westward motion on the phase-plane path.

Figure 6-4c shows the M9 spike noise of $d(E, j)$ forcing a stepwise motion on the magnified path.
Fig. 6-4. The abnormal westward motion at Minamitorishima station.

(a) The original \(c\) is from \(j = 1\) (July 1, 2004), to \(j = 5096\) (March 18, 2020). The \(d1\) and \(d2\) on \(E\) are the data deficiencies. The \(d1\) at \(j = 1595\) is from June 9, 2009, to November 17, 2009, and \(d2\) at \(j = 3996\) is from October 22, 2016, to March 11, 2017. A spike noise of M9 at \(j = 1950\) is the Tohoku M9 EQ on March 11, 2011. The vertical displacement \(h\) became very noisy after \(j = 4420\) (May 10, 2018). Therefore, the displacement \(c\) for analyses is from \(j = 1\) (July 1, 2004), to \(j = 4420\) (May 10, 2018). (b) The original \(c\) is from \(j = 1\) (July 1, 2004), to \(j = 4420\) (May 10, 2018), which has the \(d1\) and \(d2\) shifts in Fig. 6-4a smoothed by offsetting. The parameters for \(D(E, r)\), \(V(E, r)\), and \(A(E, r)\) are \(w = 7\) and \(s = 20\). The \(D(E, r) - V(E, r)\) plane is \((50 \text{ cm}, 1.25 \text{ mm/day})\). The spike noise is the M9 event at \(j = 1950\). (c) The expanded time-window is from \(j = 1540\) (April 15, 2009) to \(j = 2090\) (July 30, 2011). The \((5 \text{ cm}, 1.25 \text{ mm/day})\) path makes an abrupt change on the M9 event. (d) The time-window is from \(j = 1540\) (April 15, 2009) to \(j = 2090\) (July 31, 2011). We removed the M9 spike event as a deficiency data at arrow 1 & 2 (M9) on \(d(E, j)\). Two events 1 and 2 on the \((5 \text{ cm}, 1.25 \text{ mm/day})\) path are before and after the M9 event. (e) The original \(c\) is from \(j = 1\) (July 1, 2004) to \(j = 1949\) (March 10, 2011), one day...
before the Tohoku M9 EQ. The expanded time-window is from \( j = 1500 \) (March 6, 2009) to \( j = 1949 \) (March 10, 2011). The lunar synodic loading oscillation of 30 days is on \( A(E, \tau) \), \( V(E, \tau) \) and the (4 cm, 0.5 mm/day) path. The data deficiencies from August 17, 2010 to September 25, 2010 (at \( j = 1865 \)), and from October 13, 2010, to January 1, 2011 (at \( j = 1882 \)), are respectively, at arrow d1 and d2 on \( d(E,j) \) and \( D(E, \tau) \). Label 2010/7/11 of the trend-change observed at Chichijima stations is on \( D(E, \tau) \) at \( \tau = 1830 \), which shows a qualitative agreement.

In Fig. 6-4d, we removed the M9 spike event as a data deficiency in \( \{c\} \). The path became smooth by connecting before (event 1) and after (event 2) the M9. The before-after speeds were \( V(E, \tau) = +0.05 \) mm/day at event 1, and \( V(E, \tau) = +0.10 \) mm/day at event 2. Label 2010/07/11 points to the westward trend-change located at Chichijima station. The onset shows the similar phase relationship among \( D(E, \tau) \), \( V(E, \tau) \) and \( A(E, \tau) \) at \( \tau = 1830 \) on July 11, 2010, like those in Figs. 6-1b – 6-1d, 6-2d, and 6-3d. The trend-change triggered the anomalous \( D(E, \tau) - V(E, \tau) \) path to follow. It reached the maximum speed of \(-1.15 \) mm/day at \( \tau = 1877 \) (October 8, 2010). It was not December 22, as in Chichijima and Hahajima, because there was a data deficiency period from October 13, 2010, to January 1, 2011 (\( j = 1882 \)). The highest eastward speed was \( V(E, \tau) = +0.25 \) mm/day five days after event 2 (March 12, 2011). The plate then moved eastward by 4 mm, returning to the standard lunar synodic loading.

In Fig. 6-4e, the path and \( V(E, \tau) \) show that the anomalous motion started at \( V(E, \tau) = -0.34 \) mm/day on July 11, 2010. The eastward speed on March 10, 2011, was \( V(E, \tau) = +0.05 \) mm/day.

Thus, the path of \( \{E\} \) of the Pacific Plate motion on the M9 event is in good harmony with the motion of Chichijima and Hahajima on the subducting western edge of the Pacific Plate (Fig. 3). However, we note that the speed \( V(E, \tau) = +0.05 \) mm/day on March 10, 2011 increased by five times to \( V(E, \tau) = +0.25 \) mm/day on March 17. The increase after the megathrust rupture suggests some property difference between the Pacific Plate (Minamitorishima with increase) and its subducting western edge (Chichijima and Hahajima without increase).

### 6.5 Summary of the abnormal motion

We summarize the GPS observations with \( w = 7 \) and \( s = 20 \) in sections 6.1 – 6.4 as Table 1. The observed data used for the P-Ws analyses in Table 1 are until March 10, 2011, one day before the Tohoku M9 EQ event. Chichijima station has terminated the operation after March 8. Each movement \( D(E, \tau) \) on March 8 and 10 is the corresponding net displacement from \( D(E, \tau) \) at \( V(E, \tau) = 0.00 \) mm/day to \( D(E, \tau) \) on each date.

#### Table 1 (Abnormal motion of the subducting northwestern Pacific Plate)

| GPS station | \( D(E, \tau) \) trend change | Max \( V(E, \tau) \) | \( V(E, \tau) \) and \( D(E, \tau) \) mm on March 8 and 10 |
|-------------|------------------------------|------------------|--------------------------------------------------|
| Chichijima  | \( 2010/07/11 - 0.25 \)       | \( 2010/12/22 - 0.69 \) | \( +0.06 \) +1.6 mm                              |
| Chichijima-A| \( 2010/07/11 - 0.26 \)       | \( 2010/12/22 - 0.78 \) | \( +0.08 \) +2.0 mm                              |
| Hahajima    | \( 2010/07/11 - 0.28 \)       | \( 2010/12/22 - 0.84 \) | \( +0.12 \) +2.0 mm                              |
| Minamitorishima | \( 2010/07/11 - 0.34 \)   | \( 2010/10/08 - 1.15 \) | \( 0.00 \) 0.0 mm                               |

| No observation after 2011/03/08 |
| No data available; 2010/08/07 ~ 2010/09/25, 2010/10/13 ~ 2011/01/01 |
7 A bulge deformation observation

A regular deformation over Tohoku had been under the two tectonic counter forces’ compression, as schematically drawn in Fig. 4a. The GPS observations show a transition from the regular deformation in June 2010. The transition was a bulge formation characterized by upward displacements of 1 – 3 mm with the further compressed movements of the east and west coasts by -13.2 mm (westward) and + 18.4 mm (eastward) in Fig. 4b. The daily displacement $d(h, j)$ has a background noise of about ± 20 mm. Thus, only the equations of motion with a smooth $D(h, r) - V(h, r)$ path with the parameters $w = 200$ and $s = 300$ in days can quantify the bulge deformation. The path has a resolution of 0.1 mm, 4 orders of magnitude greater than the daily noise level of ± 20 mm. The $D(h, r) - V(h, r)$ path and $A(h, r)$ require displacement $d(h, j)$ ranging from $d(h, r - 350)$ to $d(h, r + 350)$ and from $d(h, r - 500)$ to $d(h, r + 500)$, as in Eqs. (1) - (3).

The deformation had three phases; an initial phase (referred to as Phase 0, Ph-0), the first phase (Phase 1, Ph-1), and the second phase (Phase 2, Ph-2), as summarized in section 7.4 with Table 2. Each stage showed an approximately linear path on the $D(h, r) - V(h, r)$ plane, $V(h, r) \approx k_1 \times D(h, r) + k_2$, where $k_1$ and $k_2$ are constants, and $D(h, r)$ is a displacement from an offset origin. The time rate of $V(h, r)$ is $A(h, r) \approx k_1 \times V(h, r) \approx k_1^2 \times D(h, r) + k_1 \times k_2$. The observed constant $k_1$ and $k_2$ had the same sign in Ph-1 and Ph-2. The bulge deformations in Figs. 7-1b, 7-2c, and 7-3c showed that the $A(h, r)$ was always positive (as also in Table 2). Thus, a condition of $k_1^2 \times D(h, r) > k_1 \times k_2$ holds. The positive acceleration exerted on each GPS station is due to bulging that generated a lifting force on the fault surface. The relative force, $F(h, r) = A(h, r) - k_1 \times k_2 \approx k_1^2 \times D(h, r)$, suggests linear elasticity on the bulge deformation.

7.1 Bulge on the east coast (Onagawa station)

The east coast has an array of GPS stations with co-seismic downward vertical displacements, as in Fig. 3a. Onagawa station (38.4492° N, 141.4412° E) is one of them.

7.1.1 Until March 10, 2011 (Figs. 7-1a and 7-1b), one day before the Tohoku M9 event

The $D(h, r)$ and the $D(h, r) - V(h, r)$ path in Figs. 7-1a and 7-1b show an upheaval of 1.2 mm over 115 days began at dot-arrows, ‘Bulge starts’ and S2. The S2-onset time is $r = 3615$, November 29, 2009, 350 days behind November 14, 2010, in real-time $j$. The date precedes December 22, 2010, on which the westward speed of the subducting northwestern Pacific Plate became abnormal, as in section 6.

The $D(h, r) - V(h, r)$ path in Fig. 7-1b shows three approximately linear segments; S0 in Ph-0 with a nearly zero slope, S1 in Ph-1 with a minus slope in subsidence, and S2 in Ph-2 with a positive slope in upheaval. All segments are under positive $A(h, r)$ that grew linearly in time $r$, suggesting the bulge deformation on the east coast GPS station was under a lifting force.

Segment S1 of the $D(h, r) - V(h, r)$ path has $\Delta D(h, r) = -3.3$ mm (subsidence) and $\Delta V(h, r) = +0.0142$ mm/day over 158 days in time $r$. It is from $r = 3457$ on June 24, 2009, to $r = 3615$ on November 29, 2009, and from $j = 3807$ on June 9, 2010, to $j = 3965$ on November 14, 2010, in real-time $j$. The average acceleration is $+8.99 \times 10^{-5}$ mm/day², exerting the upward acceleration (Force) on the east coast GPS station. The time rate unit conversion is mm/day² $= 1.33959 \times 10^{-11}$ cm/sec².
Segment S2 has $\Delta D(h, \tau) = 1.2$ mm (upheaval) and $\Delta V(h, \tau) = +0.0054$ mm/day over 115 days from $j = 3965$ on November 14, 2010, to $j = 4080$ on March 10, 2011, one day before the M9 event. The averaged acceleration is $+4.7 \times 10^{-5}$ mm/day$^2$.

The $D(h, \tau) - V(h, \tau)$ paths (S0) to S1 in Figs. 7-1a and 7-1b show an approximately constant downward speed of $V(h, \tau) \approx -0.018$ mm/day in the frequency region selected with $w = 200$ and $s = 300$ except for a significant co-seismic displacement. No appreciable changes in $V(h, \tau)$ suggests $A(h, \tau) \approx 0$. The $A(h, \tau)$ in Fig. 7-1b shows a small fluctuation until it began a steady increase at S0. Thus, the regular subsidence deformation at the east coast in Fig. 4a had no significant vertical force component.

The positive average acceleration (lifting force) suggests segments S0, S1, and S3 are part of a bulge deformation under the negatively (westwardly) increasing $V(E, \tau)$ and $A(E, \tau)$, as in Fig. 7-1c. Thus, the well-known elastic-rebound theory cannot explain the sudden appearance of the upward force component ($A(h, \tau) > 0$) nearly normal to the fault line (surface) shown in Fig.4.

The downward (westward) bend on the $D(E, \tau) - V(E, \tau)$ path in Fig. 7-1c started at $\tau = 3434$ on June 1, 2009, which is May 17, 2010, in real-time $j = \tau + 350$. The westward bend-onset referred to as Ph-0 in Table 2 preceded S1-onset by 23 days. The westward movement from Ph-0 was $D(E, \tau) = -13.2$ mm by March 10, 2010, one day before the Tohoku M9 event.

The $D(h, \tau) - V(h, \tau)$ path’s S1 is part of the entire bulge deformation process at Onagawa station. However, we refer to the transition from S1 to S2 as the bulge deformation onset (bulge-onset) or ‘Bulge starts’ for the detection purpose.

Segment S1 has a lifting force twice higher than the S2 force, as summarized in section 7.4. The S1-onset was at time $\tau = 3457$ (on June 14, 2009), including $d(h, j)$ at time $j = 3807$ (on June 9, 2010). The date precedes July 11, 2010, on which the westward motion’s trend-change began, as in section 6. The S1 ends at the bulge-onset, which was $\tau = 3615$, November 29, 2009, 350 days behind November 14, 2010, in real-time $j$. The date precedes December 22, 2010, on which the abnormal westward speed of the subducting Pacific Plate became about three times higher than the standard speed. Thus, the bulge deformation is the geophysical origin for the abnormal westward motion of the subducting oceanic plate.

We note that each linearity of S1 and S2 holds for the respective $D(h, \tau) - A(h, \tau)$ path. However, $A(h, \tau)$ at the S2-onset ($\tau = 3615$) requires $d(h, j)$ at $j = 4115$ (> $j = 4080$, March 10, 2011). Thus, the second linear segment is not available.
Fig. 7-1. The bulge and M9 observations at Onagawa station.
(a) The original \{c\} is from January 1, 2000 (\(j = 0\)), to March 10, 2011 (\(j = 4080\)). Sudden large shifts in \{c\} are co-seismic. The events’ magnitudes and dates are at arrows on \(d(c, j)\). The \(w = 200\) and \(s = 300\) are for \(D(c, \tau)\), \(V(c, \tau)\), and \(A(c, \tau)\). The \(D(h, \tau) - V(h, \tau)\) plane is (5 cm, 0.1 mm/day) with the offset origin \(D(h, \tau) = -0.04\) m and \(V(h, \tau) = 0\) mm/day. The bulge-onset is at arrow ‘Bulge starts’ on the \(D(h, \tau)\) at \(\tau = 3615\), November 29, 2009 (November 14, 2010, in real-time \(j\)). (b) The expanded window is from January 13, 2006, to March 10, 2011. The magnified phase-plane is (1 cm, 0.02 mm/day) with the origin \(D(h, \tau) = -0.062\) m (–0.06 m – 0.002 m). Approximately linear segments are S0, S1, and S2 on the phase-plane. Each segment’s onset location is at a dot-arrow with its name. The S2 is the ‘Bulge starts’ in Fig. part a. Arrow Ph-0 between S0 and S1 is the onset location of an anomalous movement on the \(D(E, \tau) - V(E, \tau)\) path in Fig. part c. A horizontal dot-line at the offset origin 0 (-0.06) is the abscissa for \(V(h, \tau)\) and \(A(h, \tau)\); namely \(V(h, \tau) = A(h, \tau) = 0\). The magnitudes of \(V(h, \tau)\) and \(A(h, \tau)\) are in relative scales. (c) The original \{c\} is from January 1, 2000 (\(j = 0\)), to April 30, 2011 (\(j = 4107\)). It includes the M9 event on March 11, 2011 (\(j = 4081\)), arrow M9 on \(d(c, j)\). The \(D(c, \tau) - V(c, \tau)\) planes with the offset origins are (8 cm, 0.2 mm/day) for \(c = N\) and \(E\), and (4 cm, 0.1 mm/day) for \(c = h\). The \(D(c, \tau) - V(c, \tau)\) path shows the doted path jumped by the M9 event. Every \(d(c, j)\) and its column height has the co-seismic shifts saturated by the M9 event with its digital value from the position at \(j = 0\). The southward shift is 1.90 m (–
1.77 – 0.05 – 0.08), the eastward shift is 4.7482 m (4.8882 – 0.10 – 0.04), and the downward shift is 0.9694 m (= – 0.8994 – 0.04 – 0.03). (d) The original \{c\} is from January 1, 2000 (j = 0), to July 18, 2020 (j = 7473). The D(c, r) – V(c, r) planes are (1.25 m, 0.5 mm/day) for c = N, and (5 m, 2 mm/day) c = E, and (50 cm, 0.2 mm/day) for c = h. The D(c, r) – V(c, r) path ends at label 1. The location of the M9 event has arrow M9 on d(c, j) that saturated the D(c, r) – V(c, r) path. (e) The original \{h\} is from January 1, 2000, to July 18, 2020. The time-delayed Vx = V(h, τ – 600) and Vz = V(h, τ) path is on the (0.2 mm/day, 0.2 mm/day) plane. The M 9 event saturated the path. The last V(h, τ) and the corresponding point in the Vx – Vz plane has label 1 on them.

### 7.1.2 On and After the Tohoku M9 event (Figs. 7-1c – 7-1e)

Figure 7-1c shows that the M9 EQ saturated d(c, j) with 1.90 m southward, 4.7482 m eastward, and 0.9694 m downward shifts, summarized in Table 3.

The M9 co-seismic shifts in Fig. 7-1d are the changes in d(c, j) at j = 4081. As of July 18, 2020, the crustal motion is at arrow 1 and label 1 on the V(c, τ) and the phase path, respectively. The path at label 1 has the positive (eastward) V(E, τ), reversed from westward in Fig. 7-1c, suggesting that the state has not returned before the 2011 Tohoku M9. It is in good harmony with the GSI’s eastward observation in Fig. 13-1-1 (Appendix B).

One of the crustal state analyses is a time-delayed Vx – Vz path for which Vx is a time-delayed velocity and Vz is present [7]. An example with Vx = V(h, τ – 600) and Vz = V(h, τ) is in Fig. 7-1e where the path is on the (0.2 mm/day, 0.2 mm/day) plane. The V(h, τ) at label 1 is a 2020s crustal state. The 2020s (Vx, Vz) state is away from the state before the 2011 Tohoku M9, suggesting that the current east coast’s vertical motion is still under the M9 event.

### 7.2 Bulge on the west coast (Ryoutsu2 station)

The west coast is the shore facing the Japan Sea in the schematics of Fig. 4 with the co-seismic upward displacement in Fig. 3a. Although Ryoutsu2 station (38.0633° N, 138.4717° E) is on an island off the west coast, the island is geologically a part of the main island, as seen in Fig. 3b.

#### 7.2.1 Until March 10, 2011 (Figs. 7-2a – 7-2d), one day before the Tohoku M9 event

The path in Figs. 7-2a – 7-2d shows an upheaval of 2.3 mm in \{h\} at Ryoutsu2 station. It started at dot-arrow ‘Bulge starts’ on the D(h, τ) and D(E, τ) in Figs. 7-2a and 7-2b. The time and date is time τ = 4982 on November 13, 2009, (October 29, 2010, in real-time j = 5332).

The D(h, τ) – V(h, τ) path in Fig. 7-2c shows three approximately linear segments, segment 0 (S0), segment 1 (S1), and segment 2 (S2), which respectively correspond to Ph-0, Ph-1, and Ph-2 of the bulge deformation process. Each onset location is at each corresponding dot-arrow, S0, S1, and S2. Segment S0 began with an increasing A(h, τ) whose acting direction changed upward (positive above the horizontal dot-line). The positive A(h, τ) is under a lifting force, as on the east coast. An anomalous V(E, τ) started at dot-arrow Ph-0, as in section 7.4. The Ph-0 preceded to S0. A sharp corner from S1 to S2 on the D(h, τ) – V(h, τ) path is the bulge-onset at dot-arrow S2 on the D(h, τ). The bulge-onset was at τ = 4838 on June 22, 2009, June 7, 2010, in real-time j = 5188. The S2 has an upheaval of 2.3 mm from bulge-onset.
The bulge-onset detection by $PW(h, j) \geq 500$ is in Fig. 7-2d. Threshold 500 at the $PW$ red bar is about twice the maximum power at dot-arrow 1, observed during the regular deformation. Thus, the power level of 500 is high enough to detect any abnormal deformation. The bulge-onset detection is at dot-arrow 3 on October 28, 2010, which changed $V(h, j)$ and $A(h, j)$ in bold. They stay bold under $PW(h, j) \geq 500$. The onset detection by $PW(h, j)$ was one day before the qualitative detection in Figs. 7-2a – 7-2c. After the bulge-onset in Fig. 7-2d, the $PW(h, j)$ continued to rise to $PW = 2322$ until one day before the M9 event on March 11, 2011.

The second window in Fig. 7-2a shows the eastward motion started to slow down after reaching the $D(E, \tau) - V(E, \tau)$ path-peak at $\tau = 4642$ on December 8, 2008, which is November 23, 2009, in real-time $j = 4992$. The $A(E, \tau)$ is zero at the peak and changed negative (westward) to slow down $V(E, \tau)$. The slowing action began at arrow Ph-0 in Fig. 7-2c, preceding the S1 onset by 196 days. The $D(E, \tau)$ net displacement from the slowing-onset (Ph-0) and the S2-onset to one day before the M9 event was +18.4 mm and + 10.0 mm, respectively, as in Table 2.
Fig. 7-2. The bulge and M9 observations at Ryoutsu2 station on an island off the west coast.

(a) The original \{c\} is from March 21, 1996 (\(j = 0\)), to March 10, 2011 (\(j = 5464\)). Parameters \(w = 200\) and \(s = 300\) are for \(D(c, \tau)\), \(V(c, \tau)\), and \(A(c, \tau)\). The \(D(c, \tau) - V(c, \tau)\) planes are (10 cm, 0.06 mm/day) for \(c = N\) and \(E\), and (5 cm, 0.03 mm/day) for \(c = h\). \(V(c, \tau)\) and \(A(c, \tau)\) are in relative scales and their origins are at scale 0 for \(V(c, \tau)\) and 200 (blue line) for \(A(c, \tau)\). (b) The original \{h\} is from March 21, 1996, to March 10, 2011. The \(D(h, \tau) - V(h, \tau)\) plane is (1 cm, 0.03 mm/day). The bulge-onset at dot-arrow ‘Bulge starts’ has time \(\tau = 4982\) on November 14, 2009 (in real-time \(j = \tau + 350\) on October 10, 2010). (c) The expanded time-window is from December 17, 2006, to March 10, 2011. The \(D(h, \tau) - V(h, \tau)\) plane is (2 mm, 0.015 mm/day). The path has three approximately linear segments in white lines, referred to as S0, S1, and S2. The S2 has \((\Delta D(h, \tau) \text{ in m}, \Delta V(h, \tau) \text{ in mm/day}) = (0.0023, 0.0116)\) displayed on the phase plane. The bulge-onset is at the sharp S1-S2 bend. Each onset, S1, S2, and S3, is at each dot-arrow. The Ph-0 dot-arrow is the onset location for Phase 0 in Table 2. A horizontal dot-line is the abscissa for \(V(h, \tau) = A(h, \tau) = 0\) at the level of the offset origin 0 (0.02). The \(V(h, \tau)\) and \(A(h, \tau)\) are in relative scale. The “Bulge starts” in Fig. part b is at dot-arrow S2 of \(\tau = 4982\) (on October 29, 2010), in real-time \(j = 5332\). (d) The expanded time-window is from December 17, 2006, to March 10, 2011. The bulge-onset detection was at \(j = 5331\) (October 28, 2010) by the power monitoring \(PW(h, j) \geq 500\), one day earlier than Fig. part c. Level 500 at the red scale-bar adopted a standard level at arrow 1. The bulge-onset
detection on $V(h,j)$ and $A(h,j)$ is at the vertical dot-arrow 3 that also points to the bulge-onset on the (2 mm, 0.015 mm/day) path. The same linear segment division in Fig. part c is on the path. The S1 has ($\Delta D(h,\tau)$ in m, $\Delta V(h,\tau)$ in mm/day) = (0.0006, 0.0072) displayed on the phase plane. Arrow 2 points to the power change from 420 (at $j = 5330$) to 506 (at $j = 5331$) on the displaced red column. The power on March 10, 2011 ($j = 5464$), is at the black column height. (e) The original $\{c\}$ is from March 21, 1996 ($j = 0$), to April 30, 2011 ($j = 5515$). The M9 event is at $j = 5465$ on March 11, 2011. The $d(N,j), d(E,j)$, and their column heights show the co-seismic shifts saturated by the M9 event. Their digital values are from the position on March 21, 1996 ($j = 0$), to July 18, 2020 ($j = 8858$). The M9 downward spike on $d(h,j)$ at arrow M9 and a vertical dot-arrow is at $j = 5465$ on March 11, 2011. (g) The $\{h\}$ is from March 21, 1996 ($j = 0$), to July 18, 2020 ($j = 8858$). The time-delayed $V_x = V(h, \tau - 600)$ and $V_z = V(h, \tau)$ plane is (0.1 mm/day, 0.1 mm/day). The last $V(h, \tau)$ and the corresponding point in the $V_x - V_z$ plane have label 1.

7.2.2 On and After the Tohoku M9 event (Figs. 7-2e – 7-2g)

Figure 7-2e has the M9 event added on Figs. 7-2a and 7-2b. The M9 moved the west coast station to the south and the east by 0.0734 m and 0.6310 m. The event also lifted the station by 0.0313 m.

In Fig. 7-2f, the Tohoku M9 co-seismic shift is on the $\{c\}$ at $j = 5465$. As of July 18, 2020, the path appears freed from the Tohoku M9 event except for the $\{E\}$ motion. The $D(E,\tau) - V(E,\tau)$ path is not on the same $V(E,\tau)$ level as before the M9.

Figure 7-2g shows a time-delayed $V_x - V_z$ path, for which $V_x = V(h, \tau - 600)$ and $V_z = V(h, \tau)$. The path and $V(h, \tau)$ at arrow 1 is a 2020s state. The present state is similar to that before the 2011 Tohoku M9 event, suggesting that the current $V(h, \tau)$ at arrow 1 is free from the M9 event.

7.3 Bulge on the top (Murakami station)

The top is the peak position in the schematics of Fig. 4, a location of the no-displacement-ridge-line in Fig. 3. Murakami station (38.2307° N, 139.5069° E) is at the top.

7.3.1 Until March 10, 2011 (Figs. 7-3a – 7-3d), one day before the Tohoku M9 event

Figures 7-3a and 7-3b show the bulge-onset location on $D(c,\tau)$ and $V(c,\tau)$ at the Bulge starts dot-arrow for $c = E$ and $h$.

Figure 7-3c shows the $D(h,\tau) - V(h,\tau)$ path divided into four approximately linear segments. The S0 in Ph-0 and S1 in Ph-1 are similar to those at the west coast (Ryoutsu2 station). Phase-2 has the segment divided into S2a and S2b. Each onset location is at each corresponding dot-arrow, S0, S1, S2a, and S2b. The S0 began with an increasing $A(h,\tau)$ whose action shortly changed to lifting the Top (positive above the horizontal dot-line). The bulge-onset is the S2a-onset dot-arrow pointing to $D(h,\tau), V(h,\tau)$, and $A(h,\tau)$. It is at a corner from S1 to S2a on the $D(h,\tau) - V(h,\tau)$ path.
The S2a began at $\tau = 3538$ on September 12, 2009 (August 28, 2010, in real-time $j = 3883$) and changed to S2b. The S2b started at $\tau = 3620$ on December 3, 2009 (November 18, 2010, in real-time $j = 3970$). The net upheaval is 2.5 mm over 199 days before the Tohoku M9 event, as in Table 2.

The $D(E, \tau) - V(E, \tau)$ path in Fig. 7-3a at the first segment’s onset (S1 onset) is at $V(E, \tau) = 0$ mm/day. The bulge grew with the westward motion, and the westward speed reached $V(E, \tau) = -0.0086$ mm/day at $\tau = 3732$ (on March 10, 2011, in $j = 4082$) day before the M9 event. The station moved westward by 1.1 mm from $D(E, \tau)$ at $V(E, \tau) = 0$ mm/day.
Fig. 7-3. The bulge and M9 observations at Murakami station.

(a) The original \{c\} is from January 1, 2000 (j = 0), to March 10, 2011 (j = 4082). Parameters w = 200 and s = 300 are for \(D(c, \tau), V(c, \tau), \) and \(A(c, \tau)\). The \(D(c, \tau) - V(c, \tau)\) plane is \((5 \text{ cm}, 0.04 \text{ mm/day})\) for \(c = N, E, \) and \(h\). The bulge-onset is at the dotted arrows with label Bulge starts. (b) The original \{h\} is from January 1, 2000, to March 10, 2011. The \(D(h, \tau) - V(h, \tau)\) plane is \((4 \text{ mm}, 0.015 \text{ mm/day})\). The bulge-onset is at the dotted arrows with label Bulge starts. (c) The expanded time window is from July 30, 2006 (j = 2400), to March 10, 2011 (j = 4082). The \(D(h, \tau) - V(h, \tau)\) plane is \((2 \text{ mm}, 0.015 \text{ mm/day})\). The path has four approximately linear segments in white lines, referred to as S0, S1, S2a, and S2b. The S2a has \((\Delta D(h, \tau) \text{ in m}, \Delta V(h, \tau) \text{ in mm/day}) = (0.0009, 0.0055)\), and S2b has \((\Delta D(h, \tau) \text{ in m}, \Delta V(h, \tau) \text{ in mm/day}) = (0.0016, 0.0014)\) displayed on the phase plane. The bulge-onset is at a corner from S1 to S2a. Each onset, S0, S1, S2a, and S2b, is at a corresponding dot-arrow. The onset location of an abnormal movement in \(V(E, \tau)\) is at dot-arrow Ph-0. A horizontal dot-line is the abscissa for \(V(h, \tau) = A(h, \tau) = 0\) at the level of the offset origin 0 (0.002) The \(V(h, \tau)\) and \(A(h, \tau)\) are in relative scale. (d) The same expanded time window in Fig. part c. The \(PW(h, j) \geq 500\) monitoring detected a bulge-onset at \(j = 3931\) on October 10, 2010, at arrow 3. The threshold 500 is at the red bar. The detection made \(V(h, j)\) and \(A(h, j)\) bold. The displaced red column height at arrow 2 is the power change from 459 (at \(j = 3930\)) to 504 (at \(j = 3931\)).

The power on March 10, 2011 (\(j = 4082\)), is the column height in black. (e) The original \{c\} is from January 1, 2000 (\(j = 0\)), to April 30, 2011 (\(j = 4133\)). The Tohoku M9 event is at \(j = 4083\) on March 11, 2011. The \(D(c, \tau) - V(c, \tau)\) plane is \((5 \text{ cm}, 0.04 \text{ mm/day})\) for \(c = N, E, \) and \(h\). (f) The original \{c\} is from January 1, 2000 (\(j = 0\)), to July 18, 2020 (\(j = 7494\)). The M9 downward spike noise on \(d(h, j)\) is at \(j = 4083\) on March 11, 2011. The \(D(h, \tau) - V(h, \tau)\) plane is \((12 \text{ cm}, 0.04 \text{ mm/day})\). (g) The original \{c\} is from January 1, 2000 (\(j = 0\)), to July 18, 2020 (\(j = 7494\)). The time-delayed \(Vx = V(c, \tau - 600)\) and \(Vz = V(c, \tau)\) planes are \((0.08 \text{ mm/day}, 0.08 \text{ mm/day})\) for \(c = N\), and \((0.04 \text{ mm/day}, 0.04 \text{ mm/day})\) for \(c = E\) and \(h\). The last \(V(c, \tau)\) and the corresponding point in the \(Vx - Vz\) planes are at label 1.

Figure 7-3d shows the bulge-onset detection by the power monitoring \(PW(h, j) \geq 500\). The threshold is 500 on a relative scale at the \(PW\) scale. The level is about 100 higher than the horizontal dotted level (arrow 1) that is
the maximum power observed at the regular crustal deformation before the unexpected bulge-onset. The detection
changed $V(h, j)$ and $A(h, j)$ bold, and the corresponding location on the phase-path is at the vertical dot-arrow 3.
The unexpected $PW(h, j)$ rose to 1664 and dropped to about 1300 one day before the M9 event.

7.3.2 On and After the Tohoku M9 event (Figs. 7-3e – 7-3g)

The M9 co-seismic shift is 0.1969 m to the south, 1.1607 m to the east, and no abrupt change above the ± 20 mm noise level, saturating the \{N\} and \{E\} displays, as in Fig. 7-3e.

The co-seismic shift at $j = 4083$ is on the \{N\} and \{E\}, as in Fig. 7-3f. The $D(h, \tau) - V(h, \tau)$ path in Fig. 7-3f shows three large downward movements; the first came from the M9 event, including a downward spike noise of M9 on $d(h, j)$ (label M9); however, the second and the third have no clear geophysical origin. The downward trend suggests a recovering state from the bulge deformation.

The time-delayed $V_x - V_z$ path is $V_x = V(c, \tau - 600)$, and $V_z = V(c, \tau)$. In Fig. 7-3g, each time-delayed path and $V(c, \tau)$ at label 1 is the state, as of July 18, 2020. They show a 2020s crustal state characterized by $V(c, \tau)$ is still away from before the 2011 Tohoku M9 event except for $V(h, \tau)$, suggesting only the vertical motion, $V(h, \tau)$, is free from the M9 event.

7.4 Summary on the bulge deformation and co-seismic shifts

We summarize the bulge observations in sections 7.1, 7.2, and 7.3 as in Tables 2 and 3. The E, W, and T in Table 2 are for the East coast (Onagawa station), West coast (Ryoutsu2 station), and Top (Murakami station). We divided the bulge deformation process into three phases, Phase 0 (Ph-0), Phase 1 (Ph-1), and Phase 2 (Ph-2). Each stage has an approximately linear segment on each $D(c, \tau) - V(c, \tau)$ path. An initial phase (Ph-0) characterized by a uniform increase in $A(h, \tau)$ has segment S0. The first phase Ph-1 has segment S1, and the second Ph-2 has segment S2. The S2 for T (Murakami station, the Top) has subdivisions S2a and S2b. The data for S0, S2a, and S2b are in rows below each main row of segments S1 and S2. Segment S2 for T has S2a and S2b combined as a single linear segment.

The time intervals in days for segment S1 (and S0), segment S2 (and S2a and S2b), and westward movement in all phases are Int-1, Int-2, and Int-3. Each segment’s onset time is the date in time $j = \tau - 350$. Ph-0 referred to an unusual motion that started in advance of segment S1. The movement has a $V(E, \tau)$’s sharp change on the $D(E, \tau) - V(E, \tau)$ path. The onset date preceded Ph-1 by $\Delta$ day (minus) in days. If the onset follows Ph-1 as in Top (T), $\Delta$ day is positive. The $D(c)$ and $V(c)$ are the abbreviations for $D(c, \tau)$ and $V(c, \tau)$. If the change in westward movement is positive, like 18.4 mm in row W (west coast), it is eastward by 18.4 mm. The sign convention obeys the $D(c, \tau) - V(c, \tau)$ plane for $c = E$ and $h$. The mm/day² with Int-1 stands for an average acceleration calculated by $\Delta V(h) / \text{Int-1}$. The time rate conversion from day to sec is 1mm/day = 1.1574⁻⁶ cm/sec, and 1mm/day² = 1.3396⁻¹¹ cm/sec².
The $\Delta D(h) = -2.8$ mm at row S0 on the east coast (E) during the initial phase Ph-0 is unexpected subsidence of $-2.8$ mm over 149 days. The west coast (W) and the Top (T) followed the east coast with $\Delta D(h) = -1$ mm and $\Delta D(h) = -1.5$ mm. It suggests that a massive action in the transition from the regular to bulge deformation made the overriding tectonic plate’s eastern edge take hold of a significant barrier (on fault) in deep. The $\Delta D(h) = -3.3$ mm in Phase 1 (Ph-1), the edge went further down by 3.3 mm to begin pulling the subducting oceanic plate with a lifting (bulging) force on the fault surface. After the pulling in Phase 1, an upheaval in Phase 2 followed. It was 1.2 mm on the east coast, 2.3 mm on the west coast, and 2.5 mm on the Top. The pulling in Ph-1 (S1) on the east and west coasts started on June 9 and June 7 in 2010. The overriding tectonic and the subducting oceanic plate forces of $A(E, \tau)$ compressed Tohoku centered at the ridge (Top) by $-13.2$ mm (westward) and $+18.4$ mm (eastward), respectively. The Top moved $-1.2$ mm (westward). The west coast shows that the $D(E, \tau) - V(E, \tau)$ path on Ph-0 started 173 days earlier than that on the east coast, suggesting the overriding tectonic plate exerted an enormous eastward push on the west coast, activating the bulge deformation. One row below W shows an expected movement with $\Delta \text{day} = -23$ on the $D(E, \tau) - V(E, \tau)$ path under the east coast’s Ph-0 condition. The $\Delta D(h)$ in Ph-1 and $\Delta D(E)$ over the entire deformation phases suggest the schematic as in Fig. 4-b.

Table 3 shows the co-seismic shifts and current states on the Tohoku M9 EQ. The sign conventions are minus – for southward in $d(N)$ and downward in $d(h)$. The current crustal state at each GPS station in 2020 is still under the influence of the Tohoku 2011 EQ. Each component of $d(c)$ under the M9 EQ is in the ‘Under the Tohoku M9’ column.

### Table 3 (Co-seismic shifts and current states on the Tohoku M9 EQ)

| GPS station       | Co-seismic shift (in m) | Under the Tohoku M9 |
|-------------------|-------------------------|---------------------|
|                   | $d(N)$                  | $d(E)$              | $d(h)$              | $d(c)$ |
| E-coast (Onagawa) | -1.9000                 | 4.7482              | -0.9694             | $c = E, N, h$ |
| W-coast (Ryoutsu2)| -0.0734                 | 0.6310              | 0.0313              | $c = E$ |
| Top (Murakami)    | -0.1969                 | 1.1607              | 0.0000              | $c = E, N$ |
8 The current GPS observations on the northwestern Pacific Plate and Tohoku

Chichijima-A and Hahajima stations on the subducting western edge of the Pacific Plate have not observed such an abnormal westward motion since the 2011 Tohoku M9 event, as in Figs. 6-2a and 6-3b. Minamitorishima station on the northwestern Pacific Plate has the last abnormal motion in Fig. 6-4b.

Onagawa station is on the east coast of Fig. 4, which shows that the current crustal state has not returned before the Tohoku M9 event as Figs. 7-1d and 7-1e. Murakami station is on the top of Fig. 4. It has both \( V(E, r) \) and \( V(N, r) \) under the Tohoku M9 influence, as in Fig. 7-3g; however, \( V(h, r) \) is free from the M9 event except for the downward trends, as in Fig. 7-3f. Ryoutsu2 station is on the west coast of Fig. 4, whose \( V(E, r) \) is under the Tohoku M9 influence, as in Fig. 7-2e.

They suggest that Tohoku’s eastern edge of a tectonic plate, overriding the subducting northwestern Pacific Plate, is sliding eastward without considerable constraint.

However, Chichijima-A station showed an abnormal westward motion of the subducting oceanic plate as in Figs. 13-2-3d and 13-2-3e (Appendix B). The motion coupled the M7.3 (ruptured within the subducting plate’s slab) on February 13, 2021, with the M6.9 on March 20, 2021. As for the M6.9, the observation suggests a barrier on the subducting plate unbroken by the 2011 Tohoku M9. The overriding eastern edge then caught hold of the barrier on the subducting plate. The coupling ruptured the M6.9 barrier, as in Fig. 13-2-3e. The rupturing process suggests it was a miniature of the Tohoku 2011 M9 EQ event.

9 Deterministic prediction of imminent megathrust EQs

The cross-correlation of P-Ws with the observed daily displacement time series \( \{ c \} \) defines the relations between the \( D(c, \tau) \), \( V(c, \tau) \), and \( A(c, \tau) \) for the subducting oceanic plate motion coupled with the overriding crustal bulge deformation. The \( D(c, \tau) - V(c, \tau) \) path quantified the genesis process of the 2011 Tohoku M9 EQ, whose schematic is Fig. 4. The process led to an application to predicting imminent megathrust EQs in advance by a few months [1].

The GPS prediction begins with detecting the oceanic plate’s abnormal motion. The power monitoring of \( PW(c, j) \geq \) predetermined thresholds detects the anomaly onset. The current GPS observations to watch for the unexpected motion of the subducting northwestern Pacific Plate and the Philippine Sea plate are in Appendix B. As of May 22, 2021, the observations suggest no imminent megathrust ruptures in the subduction zones of the northwestern Pacific Plate and the Philippine Sea Plate. Detecting any bulge-onset, dividing the \( D(h, \tau) - V(h, \tau) \) path into two linear segments, each of which to obey linear elasticity, is another powerful tool (section 7.1).

Similarly, we have the seismicity observations with a time series, \( \{ c \} = \{ d(c, 1), d(c, 2), \ldots, d(c, j), \ldots \} \), where \( c = LAT, LON, DEP, INT, \) and MAG [1, 7]. Each component \( c \) is the epicenter location (in latitude \( LAT \), longitude \( LON \), and focal depth \( DEP \)), the inter-event-interval (\( INT \)), and magnitude \( MAG \). Time \( j \) is a chronological event index having a unique relationship with the origin time (event time). The time interval between consecutive events (\( INT \)) reflects changes in the regional stress state [8]. The cross-correlation of P-Ws with the observed seismicity time series \( \{ c \} \) find the relations between \( D(c, \tau) \) and \( A(c, \tau) \) for the large EQ.
genesis process of several months [1, 7, 9]. The EQ genesis shows that the imminent large EQ’s fault size and motion, magnitude, and rupture time in the event index are predictable in advance of a few months. An appropriate index conversion to the rupture time in date is necessary [1]. The successful application to significant hindsight EQs is available for anticipated large EQs [1].

A cumulative (moving) sum of \( d(\text{INT}, j) \) and \( d(\text{DEP}, j) \) over a predetermined parameter \( w \) is proportional to the strain energy density stored in the regional crust [1, 9]. Each sum shows a smooth stress accumulation and a rapid release to an imminent large EQ rupture in a selected region [1]. The observation led to the successful hindsight prediction of many significant EQs in Japan within a few days in advance, including the 2011 Tohoku M9 EQ [1, 9]. Thus, the time series analyses of GPS displacement and EQ source parameter with P-Ws are available for predicting such an imminent megathrust EQ [2] in subduction zones, as in Fig. 9 [1].

![Fig. 9. Schematics of repeating large EQs (faults), trenches, troughs, and GPS stations.](image)

A dense network of 1240 GPS stations laid by GSI is in green dots, and the schematic locations of trenches are in brown, the Nankai trough is in green [2], and the faults of repeating large EQs [2] are in red. The trench off northeastern Japan’s east coast was the M9 Tohoku EQ on March 11, 2011, whose fault is label 6. Okinotorisima station is no longer available.

10 Acknowledgments

I used the GPS data opened to the public by the Geospatial Information Authority of Japan (GSI) [3], the EQ source parameters (the unified hypocenter catalogs) [4], the focal mechanism solutions (CMT solutions) by the Japan Metrological Agency (JMA) [5], and a Google Earth map.

To the memory of four late scientists who had mentored and inspired me with facing the scientific challenges of earthquake predictions, I would like to dedicate this study. They are a geophysicist, Professor Keiiti Aki (March 3, 1930 - May 17, 2005), a physicist, and my dissertation [10] advisor, Professor Makoto Takeo (April 6, 1920 - May 23, 2010), a physicist and a member of my dissertation committee, Professor Gertrude Rempfer (January 30, 1912 - October 4, 2011), and a fluid engineer and my father, Professor Rikiya Takeda (September 27, 1923 - March 7, 2011).
The patent (130 pages and 85 figures) has two observations for the claims: seismicity and GPS observations. This article updated the GPS observations. Physical Wavelets analyses of displacement time series \( \{c_t\} \) and their analyzed-data drawing of Fig. 5-1 – Fig.7-3 used an EQ prediction software written for the two patents, [1] and [B1] (Appendix B).

The contents of Figs. 3 and 4 with GPS observations were in four presentations at Japanese and AGU fall meetings. They are A32-11 (Seismological Society of Japan, 2011 Fall Meeting Oct. 14), NH23A-1543 (AGU 2011 Fall Meeting Dec. 6), G23B-0794 (AGU 2013 Fall Meeting Dec. 10), and JpGU-AGU Joint Meeting 2020/Crustal deformations precursory to the Tohoku M9 earthquake and tsunami (atlas.jp), (2020).

[2] Cabinet Office, Government of Japan (2020).
http://www.bousai.go.jp/jishin/nankai/taisaku_wg/
http://www.bousai.go.jp/jishin/nankai/nankaitrough_info.html

[3] The Geospatial Information Authority of Japan, (2020).
https://mekira.gsi.go.jp/index.en.html

[4] National Research Institute for Earth Science and Disaster Resilience, (2020).
https://www.hinet.bosai.go.jp/?LANG=en

[5] Japan Metrological Agency, (2020).
https://www.data.jma.go.jp/svd/eqev/data/mech/cmt/top.html

[6] Takeda, F., Short-term earthquake prediction with GPS crustal displacement time series and Physical Wavelets: Tottori and Akinada earthquakes (S046-P001), Abstracts, 2002 Japan Earth and Planetary Science Joint Meeting, (2002).

An update including the 2016 Kumamoto earthquakes of M6.5 and M7.3 in Kyushu will be in https://arxiv.org/ (2021).

[7] Takeda, F., and M. Takeo, An Earthquake Prediction System Using The Time Series Analyses of Earthquake Property And Crust Motion, AIP Conf. Proc., Vol. 742, pp. 140-151 (2004).
https://aip.scitation.org/doi/abs/10.1063/1.1846470
Dieterich, J., A constitutive law for rate of earthquake production and its application to earthquake clustering, J. Geophys. Res., 99, 2601–2617, 1994.

Takeda, F., Physical laws for precursory phenomena of impending large earthquakes and their applications to predictions, NHESS, (2018)

https://nhess.copernicus.org/preprints/nhess-2017-454/

The preprint’s content is from the seismicity part of the Japanese earthquake prediction patents [1] and [B1] in Appendix B. The patent [1] has peer-reviewed 130 pages and 85 figures in addition to another peer-reviewed prior patent [B1]. However, as the opened review reports and discussions show, two reviewers appear to have a grave misconception about Physical Wavelets and unfamiliar with the seismological observations, including temporal variations of the decay rate of seismic coda waves. Following the editor’s directives for further review was scientifically impossible.

A new preprint with additional sections and improved referencing will be in https://arxiv.org/ (2021) to reduce misconceptions and unfamiliarity.

Takeda, F., Selective reflection of light at a solid-gas interface and its application, Portland State Univ., (1980).

https://pdxscholar.library.pdx.edu/open_access_etds/838/
Suppose we have a particle whose motion is changing its direction and speed discontinuously like a Brownian particle. We have established the well-known Brownian motion’s stochastic differential equations: the Langevin equation and another by Ito’s calculus. A phenomenal description of a large number of such particles is the diffusion equation. However, in deriving the equation, we have ignored the non-differentiability of the particle-probability-distribution function with respect to the particle’s probabilistic position [A1]. On the other hand, a mathematical tool named Physical Wavelets (P-Ws) directly defines the equations of stochastic motion whose path becomes smooth [A2]. Thus, the tool finds the 2011 Tohoku M9 EQ genesis process from the non-differentiable daily displacement time series observed at GPS stations.

12.1 Physical Wavelets (P-Ws)

12.1.1 Introduction

Some examples of P-Ws in time $t$ and $\tau$ are Figs. 12-1a and 12-1b. The inverted $D1W(t)$ of Fig. 12-1a with the narrower width $\Delta t$ is the well-known Haar wavelet. The $DDW(t)$ is then the scaling function for the Haar wavelet. The pair forms a basis of a complete orthonormal set for the most straightforward multiresolution analysis of time series [A3]. On the other hand, the cross-correlation between P-Ws and any non-differentiable path of particle motion defines its position ($D$), velocity ($V$), and acceleration ($A$). Since 1985, the $D1W(t-\tau)$ of Fig. 12-1b has been an imperative tool to extract the real-time rate change ($V$) from noisy pressure fluctuations for an oscillometric on-line-digital-blood-pressure unit design [A4-A6]. Thus, the functions of P-Ws are different from those in the well-known wavelet analysis.

The P-Ws detect any faint anomaly from noisy signals and assign physical laws to it. The detected anomaly is a deterministic and physics-based precursor to an imminent disaster under critical observation. For example, $V$ and $A$’s product defined with P-Ws is proportional to the kinetic energy ($KE$) rate change, which is the power. Monitoring the power by comparing it with predetermined threshold levels automates detecting any abnormally-incresed-rate-change leading to the disaster. The automatic or manual threshold setting is adaptive to the maximum rate change in a routine operation. Such precursor detections have entirely prevented the sudden material fractures of rotating heavy manufacturing machinery a few hundred milliseconds in advance of possible disasters [A7-A9]. The detected precursor has physical laws that help the manufacturing system improve.

The displacements observed at the GPS stations have the crustal responses to the lunar tidal force loading [A2, A10-A12]. The displacement time series show the fortnightly and the synodic period. The automated power monitoring of the time series detects the abnormally increased power of their crustal responses. The anomalies are the sudden deviations from the periodic and regular lunar tidal force loading. Unusual responses near imminent large earthquake (EQ) epicenters were the precursors seen weeks before the EQs [A10-A11].

In studying nonlinear dynamics, the phase space constructed from the observed time series with P-Ws is physically more tractable than the state space reconstructed by so-called time delay embedding, as in Figs. 13-2-3d and 13-2-3e [A8, A13-A14]. An array of $DDW(t)$s can estimate the number of independent variables or the number of dynamical degrees of freedom, creating chaotic time series [A2]. The detection algorithm is the same as finding false nearest neighbors for estimating the minimum embedding dimension of an attractor constructed
by a delay-embedding theorem. The P-Ws may claim that the minimum embedding dimension is the number of independent variables creating time series.

Statistical analyses of time series with P-Ws give us some physical intuition on their extracting quantities. For example, the Allan variance is the two-sample variance taken with the \( DIW(t) \) of Fig. A1a, giving us a statistical \( KE \). The \( KE \) for 1/f fluctuation is finite (constant) regardless of the time width of \( DIW(t) \), which suggests the system with 1/f has an intrinsic constant \( KE \) [A13, A14].

![Figure 12.1](image.png)

**FIG. 12-1. The layouts of square waves to construct Physical Wavelets.**
(a) The interval to take differences for \( D1W(t) \) and \( D2W(t) \) is integer \( \Delta t (= 2w+1) \) that is the width of \( Sa(t) \) or \( DDW(t) \). (b) The interval can be any integer different from the width \( \Delta t \) of \( Sa(t−τ) \). The layouts are for \( D1W(t−τ) \) and \( D2W(t−τ) \) with \( s = 2n \) where integer \( s > Δt \). A few other possible layouts with different conditions among \( s, 2n, \) and \( Δt \) are not shown.

### 12.1.2 Physical Wavelets (P-Ws)

Consider the motion of a virtual particle of unit mass in coordinate space. We first assume its \( c \)-component position, denoted by \( D(c,t) \), is time-differentiable. Denoting a small interval of \( t \) by \( Δt \) \( (\geq 0) \), the conventional definition of the \( c \)-component of the particle velocity is,

\[
V(c,t) = \lim_{Δt \to 0} \frac{[D(c,t+Δt)−D(c,t)]}{Δt} = dD(c,t)/dt . \tag{A1}
\]

The differential operator \( d/dt \) has the time reversal property of \( d/d(−t) = −d/dt \). This time reversal of \( −t \), while keeping the interval \( Δt \) positive, changes the forward difference in Eq. (A1) into, \([D(c,−(t−Δt))−D(c,−t)] = −[D(c, t)−D(c, t−Δt)] \), for which \( D(c, −t) = D(c, t) \). The difference does not obey the time reversal of \( d/dt \). The correct representation is then the central difference,
Using the Dirac delta function $\delta(\tau)$, Eq. (A2) is

$$V(c, t) = \lim_{\Delta t \to 0} \frac{[D(c, t + \Delta t / 2) - D(c, t - \Delta t / 2)]}{\Delta t} = dD(c,t)/dt. \quad (A2)$$

The $\delta(\tau)$ is an even function of time $\tau$ with the property of

$$D(c, t) = \int_{-\infty}^{\infty} D(c, \tau) \delta(\tau - t) d\tau. \quad (A4)$$

The $\delta(t)$ may be replaced with a square wave of $Sa(t)$, as in Fig. A1, whose height and width are $1/\Delta t$ and $\Delta t$, respectively. As $\Delta t \to 0$, $Sa(t)$ has the same property as $\delta(t)$. Replacing $\delta(t)$ with $Sa(t)$, Eq. (A4) is

$$D(c, t) = \lim_{\Delta t \to 0} \int_{-\infty}^{\infty} D(c, t) Sa(t - \tau) d\tau. \quad (A5)$$

Similarly, Eq. (A3) is

$$V(c, \tau) = \lim_{\Delta t \to 0} \frac{[D(c, \tau - \Delta t / 2) - D(c, \tau + \Delta t / 2)]}{\Delta t} = dD(c, \tau)/d\tau. \quad (A3)$$

Assuming $V(c, \tau)$ is differentiable, acceleration $A(c, \tau)$ is then

$$A(c, \tau) = \lim_{\Delta t \to 0} \frac{[V(c, \tau + \Delta t / 2) - V(c, \tau - \Delta t / 2)]}{\Delta t} = dV(c, \tau)/d\tau$$

$$= \lim_{\Delta t \to 0} \frac{[D(c, t) [Sa(t - \tau - \Delta t) - 2Sa(t - \tau) + Sa(t - \tau + \Delta t)] d\tau]}{\Delta t^2} = d^2 D(c, \tau)/d\tau^2. \quad (A7)$$

By removing the limiting process, the differentiability of $D(c, t)$ is not the prerequisite to defining $V(c, t)$ and $A(c, \tau)$. Integrals of Eqs. (A5) - (A7) are the cross-correlation functions between $D(c, t)$ and a set of square waves. The square waves form the observational windows (operators) with which to detect the particle’s motion at time $\tau$. The operator in Eq. (A5) detects the position (or displacement) of the particle exposed over interval $\Delta t$, so it is the displacement detector, $Sa(t - \tau) = DDW(t - \tau)$. Similarly, the operator in Eq. (A6) is the first-order
difference detector, \( Sa(t - \tau - \Delta t/2) - Sa(t - \tau + \Delta t/2) = D1W(t - \tau) \). The operator in Eq. (A7) is the second-order difference detector, \( Sa(t - \tau - \Delta t) - 2Sa(t - \tau) + Sa(t - \tau + \Delta t) = D2W(t - \tau) \). The layouts of these detection windows are in Fig. 12-1 at time \( t = 0 \). The \( D1W(t) \) and \( D2W(t) \) are odd and even functions of time \( t \) to obey each time reversal property of \( d/dt \) and \( d^2/dt^2 \). We denote \( D1W(t - \tau)/\Delta t \) and \( D2W(t - \tau)/(\Delta t)^2 \) by \( VDW(t - \tau) \) and \( ADW(t - \tau) \), respectively. The \( Sa(t) \) in the definitions may be other representations for the \( \delta(t) \).

The \( DDW(t) \) is even, and \( VDW(t) \) is odd, and \( ADW(t) \) is even with respect to \( t \). Therefore, \( DDW(t - \tau) \) and \( VDW(t - \tau) \) are orthogonal to each other at time \( t = \tau \), so are \( VDW(t - \tau) \) and \( ADW(t - \tau) \). However, \( DDW(t - \tau) \) and \( ADW(t - \tau) \) are not. The orthogonality between \( DDW(t - \tau) \) and \( VDW(t - \tau) \) guarantees that \( D(c, \tau) \) and \( V(c, \tau) \) are independent of one another. They completely define the state of the moving particle in the \( D(c, \tau) - V(c, \tau) \) plane (space) at time \( \tau \), and then uniquely defines \( A(c, \tau) \) [A15]. Its subsequent motion will draw the predicted path in the space. We name these detection windows Physical Wavelets.

### 12.1.3 Equations of stochastic motion

We now assume the particle motion changes its direction and speed discontinuously. We denote its \( c \)-component position at time \( t \) by \( d(c, t) \) and its non-differentiable path by the observed data \( \{ c \} = \{ d(c, 0), d(c, 1), d(c, 2), ..., d(c, j), ... \} \) where integer \( j \) is the chronological event index at the observation time \( t \). We have the \( c \)-component position of the particle motion smoothed over \( \Delta t = 2w+1 \), for which integer \( w \geq 1 \). It is

\[
D(c, \tau) = \int_{-\infty}^{\infty} \{ c \} DDW(t - \tau) dt = [1/(2w+1)] \sum_{j=-w}^{w} d(c, \tau + j).
\]  

(A8)

The interval to take differences in \( D1W(t - \tau) \) and \( D2W(t - \tau) \) is \( \Delta t = 2w+1 \). Let the interval be an integer of \( 2n \) for \( D1W(t - \tau) \) and another integer \( s \) for \( D2W(t - \tau) \). Their layouts are in Fig. 12-1b. The P-Ws find \( V(c, \tau) \) and \( A(c, \tau) \) for \( s = 2n \) as,

\[
V(c, \tau) = \int_{-\infty}^{\infty} \{ c \} VDW(t - \tau) dt = [D(c, \tau + s/2) - D(c, \tau - s/2)]/s
\]

(A9)

and

\[
A(c, \tau) = \int_{-\infty}^{\infty} \{ c \} ADW(t - \tau) dt = [D(c, \tau + s) - 2D(c, \tau) + D(c, \tau - s)]/s^2.
\]

(A10)

In these definitions, each square wave, \( Sa(t) \) of Fig. 12-1b, collects \( d(c, j) \) as in Eq. (A8).
The relations between Eq. (A8), Eq. (A9), and Eq. (A10) are the equations of motion [A15] for the particle motion changing its direction and speed discontinuously, which may carry the periodically fluctuating components embedded in \( \{c\} \).

The extraction of specific periodicity from \( \{c\} \) is significant if the mutual correlation between P-Ws and \( \{c\} \) is high. In the fluctuation (frequency) domain, the Fourier transform of P-Ws is the extracting function by the correlation theorem. The respective Fourier transforms of \( DDW(t) \), \( VDW(t) \), and \( ADW(t) \) are then:

\[
DDW(f) = \frac{\sin(\pi f \Delta t)}{\pi f \Delta t}, \tag{A11}
\]

\[
VW(f) = 2 \frac{\sin(\pi f \Delta t)}{i f \Delta t s} \sin(\pi f s) \tag{A12}
\]

and

\[
ADW(f) = -4 \frac{\sin(\pi f \Delta t)}{\pi f \Delta t s^2} \sin^2(\pi f s). \tag{A13}
\]

The frequency \( f \) is in 1/day. The symbol \( i \) in Eq. (A12) is a complex number, \( i \times i = -1 \). Equation (A11) works as a low pass filter, Eq. (A12) as a bandpass filter, and Eq. (A13) as another bandpass filter. A functional alternative to \( Sa(t) \) improves these filtering functions. Therefore, Eqs. (A8) – (A10) have the respective filters. The \( w \) and \( s \) can be any integer by which to filter out the selected frequency components of \( D(c, \tau) \), \( V(c, \tau) \), and \( A(c, \tau) \). These extracted components then draw the \( D-A, D-V, V-V \), and \( A-A \) path [A8, A9, A11, A13].

12.1.4 Automated power monitoring

If an anomaly is a change comparable to the amplitudes of the observed fluctuations in \( \{c\} \), it will be indistinguishable from the background fluctuations. It may appear as the changes in their phases and magnitudes. The following method can detect such anomalies in real-time [A7-A10].

We define a time-rate change of the kinetic energy by the product of \( V(c, \tau) \) and \( A(c, \tau) \) in Eq. (A9) and Eq. (A10), which is the power, \( PW(c, \tau) \). We then reassign the \( V(c, \tau) \) and \( A(c, \tau) \) at time \( \tau \) to \( V(c, j) \) and \( A(c, j) \) at the current time \( j = \tau + w + s \), defined for \( A(c, \tau) \). The power at time \( j \) is

\[
PW(c, j) = V(c, j) \times A(c, j) = \frac{1}{s} KE(c, j) \times \left( 1 - \frac{V(c, j-s)}{V(c, j)} \right). \tag{A14}
\]

The \( KE(c, j) \) is the kinetic energy, defined as the \( V(c, j) \) squared. Velocity \( V(c, j) \) extracts mainly the fluctuations of period \( 2s \) for which \( D(c, j) \) and \( D(c, j-s) \) will have the opposite sign to each other. The \( KE(c, j) \)
magnifies the relative velocity change in parentheses in Eq. (A14). Thus, power $PW(c,j)$ becomes maximum near either troughs or peaks of the periodic fluctuations of $2s$ in $A(c,j)$. The larger the amplitude of $A(c,j)$ with the localized $2s$ becomes, the larger $PW(c,j)$ becomes. Thus, any anomaly becomes the corresponding large $PW(c,j)$. A predetermined threshold detects the rising $PW(c,j)$, which becomes higher than the threshold level and gives the anomaly-onset time. The threshold level may automatically adopt the $PW(c,j)$’s maximum amplitude during the standard condition.

12.1.5 References on Appendix A

[A1] Takeo, M., *Disperse systems*, Wiley-VCH. ISBN 3-527-29458-9, pp. 43 – 46, (1999)

[A2] Takeda, F., Large and Great Earthquake prediction method, system, program, and recording medium, Japanese Patent 5798545 (2015).

https://www.j-plain inventor of patents/inventor sos0100

https://patents.google.com/patent/JP5798545B2/en

[A3] Daubechies, I., *Ten Lectures on Wavelets*, Philadelphia, SIAM. ISBN 0-89871-274-2, pp. 10-16, (1992).

[A4] Takeda, F., Acquisition of arterial response process for pulsating blood flow and its blood pressure measuring method, United States Patent 5,222,020 (1993).

http://patent.uspto.gov/netahtml/PTO/index.html

The patent has 107 cited references. The $D1W(t – \tau)$ of Fig. A1b was programed (masked) onto a 4-bit LSI (T8649EBI, TMP47C220AF, 4075) Toshiba Co. (1985), for an online unit that had ECG function and other physiological monitoring [A5, A6].

[A5] Takeda, F., Blood pressure measurement apparatus and associated method, United States Patent 5,425,372 (1995).

http://patent.uspto.gov/netahtml/PTO/index.html

[A6] Takeda, F., Blood pressure measurement apparatus and associated method, United States Patent 5,626,141 (1997).

http://patent.uspto.gov/netahtml/PTO/index.html

[A7] Takeda, F., The detection apparatus of motion changes, Japanese Patent 2787143 (1998).

https://www.j-plain inventor of patents/inventor sos0100

[A8] Takeda, F., A new real-time signal analysis with wavelets and its possible application to diagnosing the running condition of vehicles on wheels, JSME Inter. J. Ser. C, 37(3), 549-558 (1994).

[A9] Takeda, F., S. Okada, M. Imade, and H. Miyauchi, Diagnosing abnormal operating conditions of rotational machineries and machine tools with physical wavelets, in Proc. SPIE 4222, *Process Control and Inspection for Industry*, 417-426 (2000).
The primary concept of P-Ws in Appendix A is how to define the equations of stochastic motion. The definition also gives us the most straightforward answer to why the position and velocity in classical mechanics are independent of one another. Their independence completely determines the system state and its subsequent motion, as discussed on pp. 1-2.
13 Appendix B (Current oceanic plate observations as of May 22, 2021)

The daily crustal displacement time series, \( \{ \mathbf{c} \} = \{ d(\mathbf{c}, 1), d(\mathbf{c}, 2), \ldots, d(\mathbf{c}, j), \ldots \} \) is the relative change from a reference chosen for graphics, not the first day position at \( j = 0 \). Thus, the chronological event index \( j \) starts from \( j = 1 \) unless specified. The geological axis \( c \) is \( E \) (west to east), \( N \) (south to north), and \( h \) (down to up) in right-handed coordinates (\( E, N, h \)), as Fig. 5-1.

The observation at Minamitorishima station in the Northwest Pacific Ocean (Figs. 3 and 9) is imperative in detecting the genesis of the imminent megathrust ruptures off Nemuro (label 4, in Fig. 9). The analyses require the station’s stable operation and an increased number of GPS stations around and within the Russian border to detect a bulge deformation, as in section 7.1. The current Minamitorishima operation appears unstable. Therefore, we only update the observed \( \{ \mathbf{c} \} \) at Chichijima-A station on a western edge of the subducting northwestern Pacific Plate and Minamidaito-Jima station on the Philippine Sea Plate with the earthquake prediction software [B1, B2].

As of May 22, 2021, the subducting northwestern Pacific Plate and the Philippine Sea Plate’s motion in the subduction zone of Tohoku and western Japan are normal for imminent megathrust ruptures. However, the motion of Chichijima-A was abnormal after January 2, 2021, until April 10, 2021. During the abnormal period, the M7.3 and the M6.9 ruptured off the Tohoku east coast on February 13, 2021, and March 20, 2021. The abnormal motion was a shortened and miniature version of the 2011 Tohoku M9 event, as in Figs. 13-2-3d and 13-2-3e.

We define the \( D(\mathbf{c}, \tau), V(\mathbf{c}, \tau), \) and \( A(\mathbf{c}, \tau) \) with \( w \approx 6 \) and \( s \approx 15 \) (\( w = 6 \) and \( s = 15 \), and \( w = 7 \) and \( s = 20 \)), to extract the lunar synodic fluctuations of period 29.5. The updates follow those graphics in Figs. 5-1 and 6-1. The oceanic plate’s \( \{E\} \) and \( \{N\} \) observations have shown that:

1) The horizontal displacement is under the lunar synodic tidal loading (29.5-day period).

2) The westward-moving speed triggering large EQ events becomes approximately twice higher than the standard one. As of May 22, 2021, the observed large EQ events are M6.9, M6.4, M7.9, M8.1, M7.3, and M6.9. The M6.9 and M7.3 were the coupled events stated above. The M8.1 was west off Ogasawara, 681.7 km deep, one of Wadati–Benioff zone EQs (Figs. 46 – 49, in [B2]).

3) As for the M7.9 on December 22, 2010, the bulge deformation (section 7.1) pulled the subducting Pacific Plate westward by their fault coupling, as in Fig. 4b. The westward speed increased approximately three times higher than usual. The elastic reaction to the pulling triggered the 2011 Tohoku M9 events, as in Fig. 4c. Thus, the M7.9 event was part of the M9 EQ triggering process, as in sections 6.1 and Figs. 13-2-3f – 13-2-3i.

4) However, the geophysical origin for the increased speed, triggering the other large EQs, is unclear. It may have coupled with so-called slow slip events in subduction zones [B3], as discussed in sections 13.2.4, 13.2.5, and 13.3.5.

5) The GPS observations on the 2011 Tohoku M9 EQ suggest that so-called slow slip events are not in the megathrust EQ genesis process in subduction zones.
6) The power monitoring shows that the M7.9 and M8.1 events ruptured after a few consecutive abnormal responses to the synodic loading (in sections 13.2.3 and 13.3.4). The two cases suggest the first anomalous response is the precursor to the upcoming event larger than about M8. A power monitor is an automated tool with which to detect any unusual motion in real-time.

13.1 The oceanic plates and the overriding tectonic plates

13.1.1 The subducting northwestern Pacific Plate, the Philippine Sea Plate, and their plate boundaries

![Map of oceanic plates](https://mekira.gsi.go.jp/index.en.html)

**Fig. 13-1-1. The horizontal displacements at website https://mekira.gsi.go.jp/index.en.html.**

Each displacement over five years at the GPS stations is from a reference at the station labeled in the square (Hagi1). The abnormal movements at Ioto Island (below Chichijima Island) are due to the volcano activities [B4].

Before the 2011 Tohoku M9 EQ, the eastward motion along Tohoku’s east coast was the opposite. The M9 event has reversed the direction. Thus, Tohoku’s east coast is still under the 2011 M9 EQ event.

The Chichijima-A station (Chichijima Is) is on the subducting northwestern Pacific Plate, and Minamidaito-Jima station (Minami Daitojima Is) is on the Philippine Sea plate.

13.1.2 Geological configurations of overriding plate boundaries and oceanic plate motions

The Pacific Plate moves approximately perpendicular to the northern main-island (Tohoku) eastern shoreline of about 500 km (as in Fig. 13-1-1), for which the enormous fault coupling pulled down the entire shoreline (as in Fig. 4a). As the crustal deformation along the shoreline turned to bulging (Phase 1 in section 7.4), it started accelerating the westward motion of the subducting oceanic plate, as in Fig. 4b. Phase 2 in section 7.4 then decelerated and stopped the motion. The enormous reaction to Phase 2 pushed back the entire shoreline, as in Fig. 4c, to rupture the megathrust, the Tohoku M9 EQ and tsunami to follow. We may estimate the 500 km fault length’s rupture to be the M9 EQ by an empirical magnitude relation of $M = 2 \times (\log_{10} (500 \text{ Km}) + 1.8) = 9$ [B5].

On the other hand, the Philippine Sea Plate moves roughly parallel to the 600 km east coastline of the southern main-island and Shikoku, as in Fig. 13-1-1. The coastline’s subsidence is local, appearing only in Tokai, Tonankai, and Nankai, as in Fig. 13-1-2. The entire coastline’s subsidence coupled with the subducting Philippine Sea Plate, necessary for the Nankai-trough Mw 9.1 EQ and 34-meter high tsunami [B6], is missing. Thus, the locally scattered subsidence along the entire coastline suggests the Nankai-trough Mw 9.1 events are implausible.
We may also estimate this unrealistic EQ of 600 km fault length to be M9.2 by the empirical relation of $M = 2 \times (\log_{10} (600\text{ Km}) + 1.8) = 9.2$ [B5].

Fig. 13-1-2. The vertical displacements at website https://mekira.gsi.go.jp/index.en.html. Each vertical displacement over five years at the GPS stations is from a reference at the station labeled in the square (Hagi1).

13.1.3 Chichijima-A station on the subducting northwestern Pacific Plate

Fig. 13-1-3a. Chichijima-A from December 4, 2007 ($j = 1$) to November 14, 2020 ($j = 4691$).

The GPS station had a 39-day-deficit out of the total 4730-day-observation. The deficits include the removed spike data of March 11, 2011.

As in Fig. 5-1, the $d(N, j)$, $d(E, j)$, and $d(h, j)$ are in the first, second, and third windows from the top, respectively. Each abscissa is time $j$ and $\tau$ from December 4, 2007 ($j = 1$). Each ordinate is each displacement $d(c, j)$ (green) and $D(c, \tau)$ (red) in meters. Each graphical origin has its offset assigned for the entire display of $\{c\}$. Their values are 0.03 m, –0.11 m, and 0 m from the top window. The northward, eastward, and upward displacements from the origin are positive. The magnifications on each offset scale are 10000, 2500,
and 5000 for the entire drawing of $d(c,j)$ in green. Each mercury manometer-like column has the last offset
displacement at its bottom, which is 0.0872 m, – 0.3460 m, and 0.0186 m.

Parameters $w$ and $s$ to define $D(c,\tau)$, $V(c,\tau)$ and $A(c,\tau)$ are $w = 6$ ($W = 13 = 2w + 1$) and $s = 15$ ($S = s$). The black $V(c,\tau)$ and blue $A(c,\tau)$ are in relative scales with their origins at scales 0 (red) and 200 (blue),
respectively. $D(c,\tau)$ is in red. Time $\tau$ lags behind real-time $j$, $j = \tau + w$ for $D(c,\tau)$, $j = \tau + w + s/2$ for $V(c,\tau)$, and $j = \tau + w + s$ for $A(c,\tau)$.

The four to one magnification ratio for \{N\} and \{E\} shows that the average horizontal direction of motion is
approximately 14 degrees from the west to the north. We note that the two to one ratio for \{N\} and \{h\} makes
their environmental-noise fluctuation amplitudes are similar. Thus, the \{N\} and \{h\} paths in the $D(c,\tau) - V(c,\tau)$
plane become similar without the northward moving trend in Fig. 13-1-3b. The large EQs (M6.9, M7.9, and M6.4
in Fig. 13-1-3a) are in section 13.2.

Fig. 13-1-3b. Chichijima-A’s $D(c,\tau) - V(c,\tau)$ path.

As for the graphical parameters on Fig. 13-1-3b, the parameters are $W = 13 = 2w + 1$ ($w = 6$) and $S = s =
15$. The $(D = 650, V = 90)$ has the respective scale conversion;

for $c = N$, (6.5 cm, 0.6 mm/day) by the magnification 10000 for $d(N,j)$,

for $c = E$, (26 cm, 2.4 mm/day) by the magnification 2500 for $d(E,j)$,

for $c = h$, (13 cm, 1.2 mm/day) by the magnification 5000 for $d(h,j)$.

The origin of the $D(c,\tau) - V(c,\tau)$ plane has each offset values; 0.03 m for $D(N,\tau)$, – 0.104 m for $D(E,\tau)$, 0 m for $D(h,\tau)$. The $(D/4, V/1, A/1, PW/4)$ is the reduced magnification for the respective drawing. The threshold (Th) explanation is in section 13.2.3. The right-side scales are for $PW(c,\tau)$ and $PW(c,j)$ as in Fig. 6-1d.
The GPS station has a scattered 118-day-deficit mainly during 2011 and 2012 out of the total 4730-day-observation. Their deficits include the spike of March 11, 2011. The $d (N, j)$, $d (E, j)$, and $d (h, j)$ are in the first, second, and third windows from the top, respectively. Each abscissa is time $j$ and $\tau$ from December 4, 2007 ($j = 1$). Each ordinate is each displacement $d (c, j)$ (green) and $D (c, \tau)$ (red) in meters. Each graphical origin zero has an offset assigned for the entire display of $\{c\}$. Their values are 0.34 m, –0.58 m, and 0 m from the top window. The northward, eastward, and upward displacements from the origin are positive. Each offset scale has 5000, 2500, and 5000 magnification for the entire graphing of $d (c, j)$. Each mercury manometer-like column has the last offset displacement at its bottom, which is 0.4888 m, –0.8376 m, and 0.0234 m.

Parameters $w$ and $s$ to define $D (c, \tau)$, $V (c, \tau)$ and $A (c, \tau)$ are $w = 6$ ($W = 13 = 2w + 1$) and $s = 15$ ($S = s$). The black $V (c, \tau)$ and blue $A (c, \tau)$ have the same drawings as Fig. 13-1-3a. They are in relative scales with their origins at scales 0 (red) for $V (c, \tau)$ and 200 (blue) for $A (c, \tau)$. Time $\tau$ lags behind time $j$, $j = \tau + w$ for $D (c, \tau)$, $j = \tau + w + s/2$ for $V (c, \tau)$, and $j = \tau + w + s$ for $A (c, \tau)$. The two to one magnification ratio for $\{N\}$ and $\{E\}$ shows that the average horizontal direction of motion is approximately 27 degrees from the west to the north. The magnifications of $\{N\}$ and $\{h\}$ are the same; however, the environmental-noise fluctuation amplitudes of $\{h\}$ become larger, so are those of $V (h, \tau)$ and $A (h, \tau)$. The M7.9 is the M7.9 EQ in sections 6.1 and 13.2.
The parameters are $W = 13 = 2w + 1$ ($w = 6$) and $S = 15 = s$. Phase Space ($D = 800$, $V = 90$) for the respective $D (c, \tau) - V (c, \tau)$ is:

- for $c = N$, (16 cm, 1.2 mm/day) by the magnification 5000 for $d (N, j)$,
- for $c = E$, (32 cm, 2.4 mm/day) by the magnification 2500 for $d (E, j)$,
- for $c = h$, (16 cm, 1.2 mm/day) by the magnification 5000 for $d (h, j)$.

The origin of the $D (c, \tau) - V (c, \tau)$ plane has each offset values: 0.34 m for $D (N, \tau)$, –0.58 m for $D (E, \tau)$, 0 m for $D (h, \tau)$. The ($D / 5$, $V / 1$, $A / 1$, $PW / 4$) is the reduced magnification for the respective drawing. The threshold (Th) is in section 13.2.3. The right-side scales are for $PW (c, \tau)$ and $PW (c, j)$.

### 13.2 The subducting northwestern Pacific Plate

#### 13.2.1 The overriding tectonic plate (the Tohoku area)

Before the 2011 Tohoku M9 EQ, Tohoku’s east coast vertical motion was downward as Figs. 4 and 7-la. The M9 event has reversed the vertical direction, as in section 7.1.2. Figure 13-2-1 shows that the displacement along the east coastline is still upward over 500 km, namely under the 2011 Tohoku M9 EQ event.
It shows the displacement over five years at the GPS stations from the fixed station labeled in the square, Ryoutsu1 station, just above Ryoutsu2 station in section 7.2. The Tohoku area is still under the 2011 M9 EQ event.

**13.2.2 The westward motion of the subducting Pacific Plate (Chichijima-A station)**

Figure 13-2-2a is the update of Fig. 6-2a. Label 1 & 2 (M9) points to the deficit of the M9 EQ on March 11, 2011, between $j = 1174$ and 1175. The unexpected westward and eastward motions on the path with $w = 7$ and $s = 20$ triggered EQs.

The eastward speed $V(E, \tau) = +0.39$ mm/day at $\tau = 91$ (March 6, 2008) triggered the M6.9 EQ of the reverse faulting (STR 31°, DIP 69°, SLIP 74°) in the Kurile island region [B7].

The westward speed $V(E, \tau) = -0.77$ mm/day at $\tau = 1096$ (December 22, 2010) triggered the M7.9 EQ of the normal faulting (STR 340°, DIP 57°, SLIP −56°) near Chichijima island [B7].

The westward speed $V(E, \tau) = -0.534$ mm/day at $\tau = 4228$ (August 4, 2019) triggered the M6.4 EQ of the reverse faulting (STR 198°, DIP 21°, SLIP 87°) off the Fukushima coast [B7].
Fig. 13-2-2b. Chichijima-A’s $D(E, \tau) - V(E, \tau)$ path, from December 4, 2007, to November 14, 2020.

Phase Space ($D = 600, V = 45$) is $(24 \text{ cm}, 1.2 \text{ mm/day})$ for the $D(E, \tau) - V(E, \tau)$ plane by the magnification 2500 for $d (E, j)$. The Ref $= -0.104$ ($= -0.104 \text{ m} + 0 / 2500 \text{ m}$) is the reading $D(E, \tau)$ at the blue line on the left scale 0. It becomes the offset origin for the $D(E, \tau) - V(E, \tau)$ plane. The W and S parameters are $W = 13 = 2w + 1 \ (w = 6)$ and $S = 15 = s$. The $(D / 4, V / 1, A / 1, PW / 4)$ is the reduced magnification for the respective drawing.

Label 1 & 2 (M9) points to the deficit of the M9 EQ on March 11, 2011.

The unexpected motions on the path show the large $V(E, \tau)$ amplitudes triggering M6.9, M7.9, and M6.4. Their large amplitudes create the corresponding large $PW(E, \tau)$, as detailed in Appendix A 12-1-4.

13.2.3 Power monitoring $PW(E, \tau)$ on the westward motion at Chichijima-A

The observation at Chichijima station of Fig. 6-1b has the $D(E, \tau) - A(E, \tau)$ paths in Figs. 13-2-3f – 13-2-3i to show the equations. We begin updating the Chichijima-A observations.
Fig. 13-2-3a. $PW(E, \tau)$ from August 4, 2009, to December 4, 2011.

Phase Space ($D = 100, V = 45$) is (4 cm, 1.2 mm/day) for the $D(E, \tau) - V(E, \tau)$ plane by the magnification 2500 for $d(E,j)$, whose offset-origin is $Ref = 0.02 (= 0.06 \text{ m} - 0.04 \text{ m})$ read at the blue line on the left scale $-100 \times \text{m}/2500$. Parameters $W$ and $S$ are $W = 13 = 2w + 1$ ($w = 6$) and $S = 15 = s$.

The path shows that the M7.9 event raptured at $V(E, \tau) = -0.9670 \text{ mm/day}$ at $\tau = 1096$ (on December 22, 2010). Its path-point is $(0.0169, -0.9670)$, where 0.0169 m is the westward location from the offset-origin 0.02 m. The abnormal $V(E, \tau)$ triggered the normal faulting M7.9 EQ (STR $340^\circ$, DIP $57^\circ$, SLIP $-56^\circ$) near Chichijima [B7].

The threshold (Th) for the abnormal power (AP) detection is $Th = 350$. The AP (195; 400) and @ 993 on the right is that $PW(E, j) \geq 350$ detected the AP changing from 195 to 400 at $j = 993$ ($\tau = 971$). There are three APs; the third corresponds with the abnormal westward $V(E, \tau)$, triggering M7.9 EQ. The power monitoring $PW(E, j)$ has detected the unusual first response to the lunar synodic loading at $j = 993$ on September 10, 2010, about three months in advance of the M7.9 EQ event.

In Fig. 13-2-3a, we shifted real-time $j$ back to time $\tau$ to show $D(E, \tau), V(E, \tau), A(E, \tau)$ and $PW(E, \tau)$, as in Fig. 6-1e. The $V(E, \tau)$ and $A(E, \tau)$ are bold while $PW(E, \tau) \geq 350$.

Fig. 13-2-3b. $PW(E, \tau)$ with $w = 7$ and $s = 20$, from August 4, 2009, to December 4, 2011.

Phase Space ($D = 100, V = 50$) is (4 cm, 1 mm/day) with the offset-origin of $Ref = 0.02 \text{ m} (= 0.06 \text{ m} - 100/2500 \text{ m})$. Parameters $W$ and $S$ are $W = 15 = 2w + 1$ ($w = 7$) and $S = 20 = s$.

The path shows that the M7.9 event raptured at $V(E, \tau) = -0.7735 \text{ mm/day}$ at $\tau = 1096$ on December 22, 2010. Its path-point reading is $(0.0166, -0.7735)$, where 0.0166 m is the westward location from the offset origin 0.02 m and $V(E, \tau) = -0.7735 \text{ mm/day}$.

The threshold is $Th = 350$. The AP (324; 400) and @ 1078 is that $PW(E, j) \geq 350$ detected the first AP changing from 324 to 400 at $j = 1078$. The $V(E, \tau)$ and $A(E, \tau)$ are bold while $PW(E, \tau) \geq 350$. 

56
The $PW(E, \tau)$ shows that the M7.9 ruptured at the second anomalous synodic loading. It suggests the first loading at $j = 1078$ (on December 4, 2010) is a precursor to the normal faulting M7.9 EQ (STR 340°, DIP 57°, SLIP −56°) at $\tau = 1096$ (on December 22, 2010) near Chichijima [B7].

We may set the other $w$, $s$, and adoptive threshold (Th) for the $PW(E, j) \geq Th$ monitoring to re-observe the 2011 Tohoku M9 events. We then apply them to the automatic detection of any plate’s motion precursory to the anticipated megathrust ruptures.

Fig. 13-2-3c. $PW(E, \tau)$ and M6.4 on August 4, 2019, as of January 2, 2021.

Phase Space ($D = 100, V = 45$) is (4 cm, 1.2 mm/day) with the offset-origin of Ref = −0.318 m (= −0.27 m −120/2500 m). The parameters to extract the lunar synodic loading are $W = 13 = 2w + 1 (w = 6)$ and $S = 15 = s$.

The threshold is Th = 350. The AP (308; 375) and @ 3858 is that $PW(E, j) \geq 350$ detected the first AP changing from 308 to 375 at $j = 3858$. The $V(E, \tau)$ and $A(E, \tau)$ are bold while $PW(E, \tau) \geq 350$.

The westward speed $V(E, \tau) = −0.6951$ mm/day at $\tau = 4228$ (August 4, 2019) triggered the M6.4 EQ of reverse faulting (STR 198°, DIP 21°, SLIP 87°) off the Fukushima coast [B7].

As of January 2, 2021, the subducting northwestern Pacific Plate’s $\{E\}$ is normal, namely, no anomaly rupturing any megathrust.

Fig. 13-2-3d. $PW(E, \tau), D(E, \tau) − V(E, \tau)$ path, M7.3, and M6.9, as of April 24, 2021.
Figure 13-2-3d updates Fig. 13-2-3c, which shows M7.3 at \( j = 4782 \) (on February 13, 2021), and M6.9 at \( j = 4817 \) (on March 20, 2021) in the subduction zone. The M7.3 was the reverse faulting of (STR 191°, DIP 55°, SLIP 78°) with the epicenter in the subducted slab off Fukushima [B9]. The M6.9 was the reverse faulting of (STR 183°, DIP 20°, SLIP 72°) off Miyagi [B10].

A four-day segment in \{c\}, starting from February 20, 2021 \( (j = 4789 \sim 4793) \), had a uniform displacement shift for which the segment has the offset smoothing in Figs. 13-2-3d, 13-2-3e and 13-2-5c. Hahajima station also had the same shift in its \{c\}.

The \( D(E, \tau) - V(E, \tau) \) path shows an unusual westward motion, which coupled the M7.3 with the M6.9 event, as suggested in Fig. 13-2-3e. The highest westward speed of \( V(E, \tau) = -0.7223 \) mm/day \((w = 6 \text{ and } s = 15)\) is at \( \tau = 4795 \) on February 26, 2021 (on March 11, 2021, in real-time \( j = 4803 \)). The westward speed with \( w = 7 \text{ and } s = 20 \) was \(-0.5670 \) mm/day, nearly reaching the maximum of \(-0.78 \) mm/day in Table 1.

Chichijima-A and Hahajima stations are on the western edge of the Ogasawara Plateau (a western edge of the subducting Pacific Plate) as in Fig. 13-1-1. On the other hand, Hahajima showed the highest westward speed of \( V(E, \tau) = -0.3738 \) mm/day with \( w = 7 \text{ and } s = 20 \) for the abnormal motion, about half the maximum of \(-0.84 \) mm/day as in Table 1. Two stations responded differently to the fault (barrier) coupling with the Tohoku eastern edge near the M6.9 epicenter. The fault length estimation is \( L = 44.7 \) km by an empirical relation \( M = 2 \times (\log_{10}(L \text{ Km}) + 1.8) \) [B5].

![Fig. 13-2-3e. D (E, \( \tau \)) – A (E, \( \tau \)) path, M7.3, and M6.9, as of April 10, 2021.](image)

Figure 13-2-3e shows the \( D(E, \tau) - A(E, \tau) \) path in Fig. 13-2-3d with \{c\} until April 10, 2021. The \( D(E, \tau) \) and \( A(E, \tau) \) relation is on the \((4 \text{cm}, 0.08 \text{ mm/day}^2)\) plane with the same coordinate system for the \( D(E, \tau) - V(E, \tau) \) plane. The \( A(E, \tau) \) on the upper half-plane is positive and eastward. The last phase point is \( \tau = 4838 \) on April 10, 2021, (March 20, 3021, in real-time \( j = 4817 \)). The \( A(E, \tau) \) at the GPS station is proportional to the net external force \( F(E, \tau) \) by the plate subduction, the overriding eastern edge’s dragging, and the lunar synodic tidal force loading.

The \( D(E, \tau) - A(E, \tau) \) path shows an oscillatory motion by the synodic tidal loading under the subducting plate’s westward uniform movement. If the path has a series of uniformly dispersed points, the lunar tidal force loading is significant. The densely packed points on the path are the plate’s movement under constraint. Each
oscillation shows an equation, \( F(E, \tau) \approx A(E, \tau) \approx K \times D(E, \tau) \) with a time and synodic-cycle dependent constant \( K \) (positive or negative). The observed equation on three oscillations (referred to as three segments) suggests two different kinds of forces ruptured M7.3 and M6.9.

Force 1 (F1) on segment 1 (a westward movement with \( K = 0.0102 /\text{day}^2 \)):

The \( D(E, \tau) - A(E, \tau) \) path to the M7.3 at \( \tau = 4782 \) (on February 13, 2021), shows \( A(E, \tau) \approx K \times D(E, \tau) \) with a weak lunar synodic tidal modulation like a trend-change on \( D(E, \tau) \) for the Tohoku M9 event in section 6.1. The segment over the modulation has a linear change \( (\Delta D(E, \tau), \Delta A(E, \tau)) = (-5.7 \text{ mm}, -0.0582 \text{ mm/day}^2) \) from December 31, 2020 \( (A(E, \tau) = 0.0229 \text{ mm/day}^2 \text{ at } \tau = 4838) \). The minus in the change is westward, which finds positive \( K = 0.0102 /\text{day}^2 \). The time rate unit conversion is \( \text{mm/day}^2 = 1.33959 \times 10^{-11} \text{ cm/sec}^2 \).

The \( K \) is positive due to two insufficient synodic loadings under the westward movement. The westward force (negative \( A(E, \tau) \)) suppressed the lunar synodic tidal force loading by some constraint and ruptured the M7.3. Force 1 was abnormal, as shown with \( PW(E, \tau) \geq 350 \). The onset detection time is \( j = 4805 (\tau = 4783) \) two days after the M7.3 event.

Force 2 (F2) on segment 2 (a westward movement with \( K = -0.0084 /\text{day}^2 \)):

The \( D(E, \tau) - A(E, \tau) \) path-segment after the M7.3, shows a good linear relation, \( A(E, \tau) = K \times D(E, \tau) \). The change \( (\Delta D(E, \tau), \Delta A(E, \tau)) = (-10.9 \text{ mm}, 0.0914 \text{ mm/day}^2) \) finds \( K = -0.0084 /\text{day}^2 \). The observation on \( V(E, \tau) = -0.7223 \text{ mm/day at } \tau = 4795 \) on February 26, 2021, which is very similar to the abnormal motion on the Tohoku M9 event in section 6, suggests that Force 2 is a pulling action by the Tohoku eastern edge. The edge might have caught hold of an unbroken barrier left on the subducting oceanic plate and pulled it.

Force 3 (F3) on segment 3 (an eastward movement with \( K = -0.0336 /\text{day}^2 \)):

The \( D(E, \tau) - A(E, \tau) \) path to the last phase point of M6.9 at \( \tau = 4817 \) (March 20, 2021) shows \( A(E, \tau) \approx K \times D(E, \tau) \). The linear-change \( (\Delta D(E, \tau), \Delta A(E, \tau)) = (2.1 \text{ mm}, -0.0706 \text{ mm/day}^2) \) finds \( K = -0.0336 /\text{day}^2 \). Force 3 ruptured the M6.9 with the large \( K \).

Force 1 has \( A(E, \tau) \approx K \) (positive) \( \times D(E, \tau) \) relation on the M7.3 with the reverse faulting within the subducted slab. A barrier unbroken by the 2011 Tohoku M9 was on the subducting plate. Force 2 is in phase with the effective lunar synodic tidal force loading, significantly reducing constrain (dispersed points along the path). It pulled the subducting plate by -10.9 mm (westward), a miniature version of the 2011Tohoku M9 EQ. Force 3 is the reaction to Force 2 under the lunar tidal force loading. The overriding tectonic plate’s eastern edge begun to push back the barrier on the subducting plate, opposite to the expected direction of the oceanic plate motion. The reaction (Force 3) moved the subducting plate eastward with the barrier, triggering the M6.9 EQ on March 20, 2021.

A suggestive reason for establishing an \( A(E, \tau) \approx K \) (positive) \( \times D(E, \tau) \) relation in Force 1 is a non-effective synodic loading due to constraint as catching hold of a barrier on the subducting plate by the overriding eastern edge. A similar \( A(E, \tau) \approx K \) (positive) \( \times D(E, \tau) \) preceded the trend-change in Fig. 6-1b is in Figs. 13-2-3f and
13-2-3g. Thus, the Tohoku M9 in section 6.1 suggests a miniature coupling of the Tohoku eastern edge with the subducting oceanic plate. The overriding edge pulled the subducting oceanic plate at the abnormal westward speed of $V(E, \tau) = -0.7223 \text{ mm/day}$, as in Table 1.

Fig. 13-2-3f. $D(E, \tau) - A(E, \tau)$ path with $w = 7$ and $s = 20$ at Chichijima station for Fig. 6-1b.

Fig. 13-2-3g. $D(E, \tau) - A(E, \tau)$ path with $w = 7$ and $s = 20$ at Chichijima station for Fig. 6-1b.

Figure 13-2-3f is Fig. 6-1b with the $D(E, \tau) - A(E, \tau)$ path. The westward trend-change at arrow 2010/07/11 shows a linear segment of the $D(E, \tau) - A(E, \tau)$ path, as a white line in Fig. 13-2-3g.

The linear change is $(\Delta D(E, \tau), \Delta A(E, \tau)) = (-0.0021, -0.0081)$ in (m, mm/day$^2$) from $A(E, \tau) = 0.0039 \text{ mm/day}^2$ at $\tau = 3681$ on June 22, 2010, as shown below the time scale (-0.3562, 0.0039 in (m, mm/day$^2$)). Thus, $A(E, \tau) \approx K \times D(E, \tau)$ has $K = 0.0039 /\text{day}^2$. The (3700, −0.3578) in $(\tau, \text{m})$ below the PW scale shows $D(E, \tau)$ at the trend-change.

The segment in a white line in Fig. 13-2-3g preceded the trend-change at label 2010/07/11. It had a positive $K$ in $A(E, \tau) \approx K \times D(E, \tau)$. The positive $K$ shows a weak response of the subducting plate to the lunar synodic tidal force loading, as in Fig. 13-2-3e.

An insufficient synodic tidal loading on the segment appears on the $D(E, \tau) - A(E, \tau)$ path with $w = 6$ and $s = 15$, as in Fig. 13-2-3h. Thus, the positive $K$ in Fig. 13-2-3g is due to the tidal response constrained by coupling the subducting plate motion with the bulge formation on the overriding eastern edge (the Tohoku east coast).
Fig. 13-2-3h. $D(E, \tau) - A(E, \tau)$ path with $w = 6$ and $s = 15$ for Fig. 6-1b.

Fig. 13-2-3i. A magnified $D(E, \tau) - A(E, \tau)$ path for the last three months before the Tohoku M9.

Figure 13-2-3i shows four linear segments of the $D(E, \tau) - A(E, \tau)$ path in indexed order for Fig. 6-1b. The $A(E, \tau)$ has the corresponding indexes. They are the last part of the M9 EQ genesis process. Segment 1 started at $\tau = 3844$ (on December 2, 2010). Segment 4 has two sub-portions. Each segment has $A(E, \tau) \approx K \times D(E, \tau)$.

Segment 1: $(\Delta D(E, \tau), \Delta A(E, \tau)) = (0.1 \text{ mm}, -0.0330 \text{ mm/day}^2)$ and $K = -0.0330 /\text{day}^2$.

Segment 2: $(\Delta D(E, \tau), \Delta A(E, \tau)) = (-8.7 \text{ mm}, 0.0434 \text{ mm/day}^2)$ and $K = -0.0050 /\text{day}^2$.

Segment 3: $(\Delta D(E, \tau), \Delta A(E, \tau)) = (-0.2 \text{ mm}, -0.0247 \text{ mm/day}^2)$ and $K = 0.1235 /\text{day}^2$.

Segment 4-1: $(\Delta D(E, \tau), \Delta A(E, \tau)) = (-1.6 \text{ mm}, 0.0034 \text{ mm/day}^2)$ and $K = -0.0213 /\text{day}^2$.

Segment 4-2: $(\Delta D(E, \tau), \Delta A(E, \tau)) = (1.5 \text{ mm}, -0.0068 \text{ mm/day}^2)$ and $K = -0.0453 /\text{day}^2$.

Segment 2 started at $\tau = 3854$ on December 12, 2010, and triggered the M7.9 at $\tau = 3864$ on December 22, 2010, as arrowed on the $D(E, \tau) - A(E, \tau)$ path. Segment 3 began at $\tau = 3878$ on January 5, 2011, with the most significant positive $K$. Segment 4-1 and 4-2 started at $\tau = 3890$ on January 17, 2011, and $\tau = 3894$ on January 21, 2011, respectively.
13.2.4 The northward motion of the subducting Pacific Plate (Chichijima-A station)

Only 3% of the average Pacific Plate horizontal motion has the northward component \( N \). The \( N \) has its environmental-noise fluctuation amplitude about a half of \( h \) as shown in Figs. 13-1-3a and 13-1-3b. The observation of M7.9 at the downward (southward) \( V(N, \tau) \) arrowed in Fig. 13-2-4a shows that the 3% of the lunar synodic southward loading was a part of the normal faulting M7.9 EQ (STR 340°, DIP 57°, SLIP −56°) near Chichijima [B7].

The M8.1 (STR 32°, DIP 25°, SLIP −44°) on May 30, 2015, [B7] was on the lunar synodic loading, as arrowed on the \( V(N, \tau) \) in Fig. 13-2-4a and the \( V(N, \tau) \) and the path in Fig. 13-2-4b. Its \( PW(N, \tau) \) and \( PW(N, j) \) detection are Fig. 13-2-5a.

However, the other large EQ events’ identifications in the lunar synodic loading of \( V(N, \tau) \) and \( A(N, \tau) \) require noise separation path analyses. The paths are on the \( V(N, \tau) - V(E, \tau) \) and the \( V(N, \tau) - V(h, \tau) \), and the \( A(N, \tau) - A(E, \tau) \) and the \( A(N, \tau) - A(h, \tau) \) planes. Their observations and analyses will be arXiv [B8].

![Fig. 13-2-4a. Chichijima-A from December 4, 2007, to November 14, 2020.](image)

The \( d(N,j) \) excludes the M9 EQ’s spike data on March 11, 2011 (between \( j = 1174 \) and 1175). The drawing follows the eastward displacement \( \{E\} \) in Figs. 13-2-2a and 13-2-2b.

![Fig. 13-2-4b. Chichijima-A’s \( D(N, \tau) - V(N, \tau) \) path from December 4, 2007, to November 14, 2020.](image)
Phase Space \((D = 700, V = 90)\) is \((7 \text{ cm}, 0.6 \text{ mm/day})\) by the magnification 10000 for \(d(N,j)\). The \(\text{Ref} = 0.03\) (in meters) is the reading at the blue line on the left scale 0. It becomes the offset origin for the \(D(N, \tau) - V(N, \tau)\) plane. Parameters \(W\) and \(S\) are \(W = 13 = 2w + 1 (w = 6)\) and \(S = 15 = s\). The \((D / 4, V / 1, A / 1, PW / 4)\) is the reduced magnification for the respective drawing.

The path shows the localized northward and southward fluctuating motions whose amplitudes are approximately equal, suggesting the lunar synodic loading on \(\{N\}\) dominates the fluctuations. They include some sudden northward shifts of about 1 cm before and after the M8.1 event. They appear some co-seismic shifts; however, the geophysical origin is unclear. It may be a so-called slow slip event [B3]. Some details are in Figs. 13-2-5b and 13-2-5c for the Pacific Plate’s subduction zone, and Figs. 13-3-5a and 13-3-5b for the Philippine Sea Plate’s subduction zone.

13.2.5 Power monitoring \(PW(N, \tau)\) on the northward motion at Chichijima-A

![Fig. 13-2-5a. \(PW(N, \tau)\) and M8.1 on May 30, 2015 (\(j = 2703\)).](image)

The magnified date window is from November 28, 2014, to November 24, 2015. Phase Space \((D = 100, V = 90)\) is \((1 \text{ cm, 0.6 mm/day})\) by the magnification 10000 for \(d(N,j)\). The \(\text{Ref} = 0.035 (= 0.05 \text{ m} - 150 / 10000 \text{ m})\) is the reading at the blue line on the left scale – 150 \((\times \text{ m/10000})\). It becomes the offset origin for the \(D(N, \tau) - V(N, \tau)\) plane. The parameters to extract the synodic loading are \(W = 13 = 2w + 1 (w = 6)\) and \(S = 15 = s\). The magnification is 10000 for \(d(N,j)\), four times \(d(E,j)\) so that \(V(N, \tau)\) and \(A(N, \tau)\) also become four times \(V(E, \tau)\) and \(A(E, \tau)\). Thus, the \(PW(N, \tau)\) threshold to detect an abnormal power (AP) loading in real-time \(j\) is sixteen times of \(PW(E, \tau)\)’s 350, which is 5600. The \((D / 1, V / 3, A / 3, PW / 50)\) is the reduced magnification for the respective drawing.

The AP (3034; 5656) and \(@ 2607\) is that \(PW(N,j)\) detected the first AP changing from 3034 \((j = 2606)\) to 5656 \((j = 2607)\) on February 23, 2015. The \(V(N, \tau)\) and \(A(N, \tau)\) are bold for \(PW(N, \tau) \geq 5600\). The M8.1 event was on May 30, 2015 \((at \ j = 2703)\), at a little off downward (southward) peak of \(A(N, \tau)\) dotted-arrowed at \(\tau = 2703\). The location on the \(D(N, \tau) - V(N, \tau)\) plane was at \((0.0378, -0.4796)\); namely, the offset location is 0.0378 m, and the southward speed (negative) – 0.4796 mm/day. The triggering motion is in harmony with the M8.1 EQ’s normal faulting \((\text{STR} 32^\circ, \text{DIP} 25^\circ, \text{SLIP} -44^\circ)\) [B7]. The first AP detection suggests it was a precursor three months in advance of the M8.1 EQ.
Fig. 13-2-5b. \( PW(N, \tau) \) from November 7, 2019, to January 2, 2021.

Phase Space \((D = 100, V = 90)\) is \((1 \text{ cm}, 0.6 \text{ mm/day})\) by the magnification 10000 for \(d(N,j)\). The \(\text{Ref} = 0.083 \approx (0.08 \text{ m} + 0.03 \text{ m})\) is the reading at the blue line on the left scale \(30 \times \text{m/10000}\). It becomes the offset origin for the \(D(N,\tau) - V(N,\tau)\) plane. The parameters to extract the synodic loading are \(W = 13 = 2w + 1 \quad (w = 6)\) and \(S = 15 = s\). The magnification is 10000 for \(d(N,j)\), four times \(d(E,j)\). Thus, the \(PW(N,j)\) threshold for detecting the abnormal power (AP) loading in real-time \(j\) is 3500 sixteen times of \(PW(E,j)\)’s 350. The \((D/1, V/3, A/3, PW/50)\) is the reduced magnification for the respective drawing.

The \(D(N,\tau) - V(N,\tau)\) path shows the fluctuating motion under the lunar synodic loading on \(\{N\}\). The sudden northward shift of about 1 cm accompanies one synodic oscillation during the jump so that the change is not co-seismic but maybe a so-called slow slip event in the subduction zone [B3]. The \(D(N,\tau) - V(N,\tau)\) path with \(w = 15\) and \(s = 50\) shows the same jumping motion without the synodic oscillation.

As of January 2, 2021, the subducting northwestern Pacific Plate’s \(\{N\}\) is normal; namely, no anomaly to rupture any imminent megathrust in the subduction zone.

Fig. 13-2-5c. \(PW(N, \tau)\) and M7.3 and M6.9 on March 20, 2021 \((j = 4817)\).

Figure 13-2-5c updates Fig. 13-2-5b with the phase Space \((D = 100, V = 105)\) of \((1 \text{ cm}, 0.7 \text{ mm/day})\) by the magnification 10000 for \(d(N,j)\). The \(\text{Ref} = 0.088 \approx (0.08 \text{ m} + 0.08 \text{ m})\) is the reading at the blue line on the left scale \(80 \times \text{m/10000}\). It is the offset origin for the \(D(N,\tau) - V(N,\tau)\) plane.
Figure 13-2-5c shows M7.3 at $j = 4782$ (on February 13, 2021), and M6.9 at $j = 4817$ (on March 20, 2021) in the subduction zone. The M7.3 was the reverse faulting of (STR 191º, DIP 55º, SLIP 78º) within the subducted slab off Fukushima [B9], suggesting the abnormal power detected at $j = 4757$ (on January 19, 2021) might have been the precursory stress loading to the slab. The second AP (abnormal power) implies the coupling of M7.3 and M6.9, as in Fig. 13-2-5e.

13.2.6 Current Eastward and Northward motions at Chichijima-A, as of May 22, 2021

![Image 1](image1)

**Fig. 13-2-6a.** $PW(E, r)$ on the eastward motion as of May 22, 2021.

![Image 2](image2)

**Fig. 13-2-6b.** $PW(N, r)$ on the northward motion as of May 22, 2021.

Figures 13-2-6a and 13-2-6b updated Figs. 13-2-3d and 13-2-5c as of May 22, 2021. Some minor changes in the updates are due to the updates by GSI [B4].

As of May 22, 2021, the subducting northwestern Pacific Plate’s $\{E\}$ and $\{N\}$ show no imminent megathrust ruptures. The abnormal power in $\{N\}$ has no clear geophysical origin, as discussed in sections 13.2.4, 13.2.5, and 13.3.5.

13.3 The Philippine Sea plate

Minamidaito-Jima station is on the Philippine Sea Plate as in Fig. 13-1-1.
13.3.1 The overriding tectonic Plate (the main island’s western part)

As discussed in section 13.1.2, Tohoku’s entire eastern shoreline of about 500 km had a downward displacement by coupling the whole 500 km length fault with the subducting northwestern Pacific Plate motion. The fault coupling was the prerequisite condition for the 2011 Tohoku M9 EQ and tsunami.

On the other hand, the GPS observation along the eastern shoreline of about 600 km, as in Fig. 13-3-1, shows the downward displacement in Tokai, Tonankai, Nankai, and the islands near Kozushima. The scattered subsidence spots along the southern coast of the main island and Shikoku suggest that the Eurasian Plate’s eastern edge (the Amurian Plate), overriding the Philippine Sea Plate [B2], has three separate independent faults, Tokai (label1), Tonankai (label 2), and Nankai (label 3) in Fig. 9. Thus, even with their simultaneous chain ruptures, generating an enormous reaction force along the entire 600 km long coastline is unlikely without the fault coupling as in the 2011 Tohoku events. Namely, the anticipated Mw 9.1 EQ and 34 m-height tsunami to follow [B6] will not occur. The non-scientific presumption may come from the fact that Japan’s cabinet office could not prepare for the Tohoku M9 events, as in Appendix C.

![Fig. 13-3-1. The vertical displacements at website https://mekira.gsi.go.jp/index.en.html.](image)

We present the Philippine Sea Plate’s motion. Each scattered fault coupling with the oceanic plate motion will be at arXiv [B8].

13.3.2 The westward motion of the Philippine Sea Plate (Minamidaito-Jima station).

![Fig. 13-3-2. Minamidaito-Jima from December 4, 2007, to November 14, 2020.](image)
The $d(E, j)$ excludes the M9 EQ's spike data on March 11, 2011 (between $j = 1730$ and 1731). Phase Space ($D = 750$, $V = 25$) is (30 cm, 0.5 mm/day) by the magnification 2500 for $d(E, j)$. The Ref $= \ -0.59$ ($= -0.43$ m $- 0.16$ m) is the reading at the left scale $-400$ ($\times$ m/2500). It is the offset origin, ($-0.59$, $0$ m/day), for the $D(c, \tau) - V(c, \tau)$ plane. The parameters to extract the lunar synodic loading are $W = 15 = 2w + 1$ ($w = 7$) and $S = 20 = s$. The ($D / 4$, $V / 1$, $A / 1$, $PW / 2$) is the reduced magnification for the respective drawing.

The path shows the unusual westward speed, $-0.4288$ mm/day, whose action triggered M6.2 EQ on August 22, 2010 ($j = 973$), as detailed in Fig. 13-3-3a.

13.3.3 Power monitoring $PW(E, \tau)$ on the westward motion at Minamidaito-Jima

![Fig. 13-3-3a. $PW(E, \tau)$ and M6.2 on August 22, 2010 ($j = 973$).](image)

Phase Space ($D = 50$, $V = 25$) is (2 cm, 0.5 mm/day) by the magnification 2500 for $d(E, j)$. The Ref $= -0.43$ ($= -0.41$ m $- 0.02$ m) is the reading at the blue line on the left scale $-50$ ($\times$ m/2500). It is the offset origin of the $D(E, \tau) - V(E, \tau)$ plane.

The parameters to extract the synodic loading are $W = 15 = 2w + 1$ ($w = 7$) and $S = 20 = s$. The threshold for detecting the abnormal power (AP) loading in real-time $j$ is Th $= 350$. The ($D / 1$, $V / 1$, $A / 1$, $PW / 2$) is the reduced magnification for the respective drawing.

The AP (306; 400) and @ 999 on the right show the detected AP was from 306 (at $j = 998$) to 400 (at $j = 999$). The $V(E, \tau)$ and $A(E, \tau)$ become bold under $PW(E, \tau) \geq 350$. The M6.2 EQ ruptured at the abnormal $A(E, \tau)$ downward peak, as arrowed at $\tau = 973$. The M6.2 rupturing location on the path is ($-0.4288$, $-0.1828$), $-0.4288$ m eastward from the offset origin $-0.43$ m, and $V(E, \tau) = -0.1828$ mm/day at $\tau = 973$ (August 22, 2010).

The AP shows that the abnormal downward force $A(E, \tau)$ triggered the normal faulting M6.2 EQ (STR $326^\circ$, DIP $63^\circ$, SLIP $-85^\circ$) at depth 31km, $19^\circ 58.6'$ N, and $147^\circ 15.3'$ E [B7], far below Chichijima in Fig. 3.
Fig. 13-3-3b. $PW\ (E, \tau)$ from February 1, 2019, to May 22, 2021.

Phase Space ($D = 50, V = 25$) is (2 cm, 0.5 mm/day) by the magnification 2500 for $d\ (E, j)$. The Ref = – 0.836 (= – 0.78 m – 0.056 m) is the reading at the blue line on the left scale – 100 ($\times$ m/2500). It is the offset origin for the $D\ (E, \tau) – V\ (E, \tau)$ plane.

The parameters to extract the synodic loading are $W = 15 = 2w + 1$ ($w = 7$) and $S = 20 = s$. The threshold for detecting the AP is $Th = 350$. The ($D / 1, V / 1, A / 1, PW / 2$) is the reduced magnification for the respective drawing.

The present Philippine Sea Plate’s $\{E\}$ is normal as of May 22, 2021.

13.3.4 The northward motion of the Philippine Sea Plate (Minamidaito-Jima station)

Fig. 13-3-4. Minamidaito-Jima from December 4, 2007, to November 14, 2020.

The $d\ (N, j)$ excludes the M9 EQ’s spike data on March 11, 2011 (between $j = 1730$ and 1731).

Phase Space ($D = 800, V = 50$) is (16 cm, 0.5 mm/day) by the magnification 5000 for $d\ (N, j)$. The Ref = 0.334 (= 0.44 m – 0.096 m) is the reading at the blue line on the left scale – 480 ($\times$ m/5000). It is the offset-origin for the $D\ (N, \tau) – V\ (N, \tau)$ plane. The parameters to extract the synodic loading are $W = 15 = 2w + 1$ ($w = 7$) and $S = 20 = s$. The ($D / 4, V / 1, A / 1, PW / 2$) is the reduced magnification for the respective drawing.

The M8.1 EQ on May 30, 2015 ($j = 2618$) [B7] is at $V\ (N, \tau) = – 0.4741$ mm/day, as arrowed M8.1 a little off the downward peak. It is the same M8.1 EQ in Figs. 13-2-4a, 13-2-4b, and 13-2-5a.
The $D (N, \tau) - V (N, \tau)$ path shows the fluctuating motion with the sudden northward shifts of about 1 cm as those in Fig. 13-2-4b. The detailed changes before the M8.1 and M6.2 event are in Fig. 13-3-5a and Fig. 13-3-5b, respectively.

### 13.3.5 Power monitoring $PW (N, \tau)$ on the northward motion at Minamidaito-Jima

![GPS Displacement Analysis](image)

**Fig. 13-3-5a.** $PW (N, \tau)$ and M8.1 on May 30, 2015 ($j = 2618$).

The magnified date window is from February 21, 2014, to October 10, 2015. Phase Space ($D = 100$, $V = 50$) is (2 cm, 0.5 mm/day) by the magnification 5000 for $d (N, j)$. The Ref = 0.35 (= 0.36 m – 0.01 m) is the reading at the blue line on the left scale – 50 ($\times m/5000$), which is the $D (N, \tau) - V (N, \tau)$ plane’s offset-origin. The parameters to extract the synodic loading are $W = 15 = 2w + 1$ ($w = 7$) and $S = 20 = s$. The magnification is 5000 for $d (N, j)$, which is twice $d (E, j)$. Thus, $V (N, \tau)$ and $A (N, \tau)$ also become twice $V (E, \tau)$ and $A (E, \tau)$. The $PW (N, j)$ threshold for detecting the abnormal power (AP) loading in real-time $j$ is then four times of $PW (E, j)$’s 350, which is $Th = 1400$. The $(D / 1, V / 2, A / 2, PW /12)$ is the reduced magnification for the respective drawing.

The AP (1344; 1764) and @ 2525 is that $PW (N, j)$ detected the first AP changing from 1344 (at $j = 2524$) to 1764 (at $j = 2525$) on February 26, 2015. The $V (N, \tau)$ and $A (N, \tau)$ are bold under $PW (N, \tau) \geq 1400$. The M8.1 event was on May 30, 2015 ($j = 2618$), at a little off downward (southward) peak of $A (N, \tau)$ dotted-arrowed at $\tau = 2618$. The M8.1 EQ triggering motion is in harmony with that of the northwestern Pacific Plate, generating the normal faulting (STR 32°, DIP 25°, SLIP −44°) [B7].

The $D (N, \tau) - V (N, \tau)$ path shows the sudden northward shift of about 1 cm before the M8.1 event, accompanying a weak synodic oscillation. Thus, the non-co-seismic change may be a so-called slow slip event in the subduction zone [B3].
Fig. 13-3-5b. \( PW(N,\tau) \) and M6.3 on October 24, 2018 \((j = 3860)\).

The magnified date window is from October 4, 2018, to January 2, 2021. Phase Space \((D = 180, V = 50)\) is (3.6 cm, 0.5 mm/day) by the magnification 5000 for \( d(N,j) \). The \( Ref = 0.46 (= 0.48 m - 0.02 m) \) is the reading at the blue line on the left scale \(- 100 (\times m/5000). \) It is the \( D(N,\tau) - V(N,\tau) \) plane’s offset origin. Parameters \( W \) and \( S \) are \( W = 15 = 2w + 1 \) \((w = 7)\) and \( S = 20 = s\). The \( PW(N,\tau) \) threshold is \( Th = 1400\). The \((D / 1, V / 2, A / 2, PW / 12)\) is the reduced magnification for the respective drawing.

The AP \((1258; 1520)\) and \( @3867\) is that \( PW(N,j) \) detected the abnormal power \( (AP) \) changing from 1258 \((at j = 3866)\) to 1520 \((at j = 3867)\) on October 31, 2018. The \( V(N,\tau) \) and \( A(N,\tau) \) are bold for \( PW(N,\tau) \geq 1400\). The M6.3 event was on October 24, 2018 \((j = 3860)\), after the upward \( (northward) \) peak of \( V(N,\tau) \) dotted-arrowed at \( \tau = 3860\). The M6.3 EQ was at depth 28km, 23°58.1’N, and 122°36.1’E (North West off Ishigakijima Island) with the reverse faulting \( (STR 50^\circ, DIP 77^\circ, SLIP 41^\circ) [B7] \). A foreshock of M6.1 to the M6.3 was on October 23, 2018 [B7].

The \( D(N,\tau) - V(N,\tau) \) path shows the sudden northward shift of about 1 cm before the M6.3 event, with the lunar synodic oscillation. Thus, the non-co-seismic change may be a so-called slow slip event in the subduction zone [B3].

Fig. 13-3-5c. \( PW(N,\tau) \) from June 1, 2019, to May 22, 2021.

Figure 13-3-5c is the update of Fig. 13-3-5b, which shows the present Philippine Sea Plate’s \( \{N\} \), as of May 22, 2021, is normal; namely, no abnormal motion precursory to the imminent megathrust ruptures in the subduction zone.
13.4 References on Appendix B

[B1] Takeda, F., Earthquake prediction method, earthquake prediction system, earthquake prediction program, and recording medium, Japanese Patent 4608643 (2011).
https://www.j-platpat.inpit.go.jp/s0100
https://patents.google.com/patent/JP4608643B2/en

[B2] Takeda, F., Large and Great Earthquake prediction method, system, program, and recording medium, Japanese Patent 5798545 (2015).
https://www.j-platpat.inpit.go.jp/s0100
https://patents.google.com/patent/JP5798545B2/en

[B3] For example, Caltech, Earthquakes in slow motion: Studying ‘slow-slip’ events could shed light on destructive temblors.
https://phys.org/news/2019-10-earthquakes-motion-slow-slip-events-destructive.html

[B4] Geospatial Information Authority of Japan (GSI), (2020).
https://mekira.gsi.go.jp/index.en.html

[B5] Utsu, T., Statistical features of seismicity, in International Handbook of Earthquake and Engineering Seismology, Academic Press, Amsterdam, 719–732 (2002).

[B6] Cabinet Office, Government of Japan (2020).
http://www.bousai.go.jp/jishin/nankai/taisaku_wg/
http://www.bousai.go.jp/jishin/nankai/nankaitrough_info.html

[B7] Japan Metrological Agency (JMA), (2020).
https://www.data.jma.go.jp/svd/eqev/data/mech/index.html

[B8] Takeda, F., to be in https://arxiv.org/ (2021).

[B9] https://www.hinet.bosai.go.jp/topics/off-fukushima210213/?LANG=ja , (2021)
https://www.data.jma.go.jp/svd/eqev/data/mech/cmt/fig/cmt20210213230750.html , (2021)

[B10] https://www.hinet.bosai.go.jp/topics/off-miyagi210320/?LANG=ja , (2021)
https://www.data.jma.go.jp/svd/eqev/data/mech/cmt/fig/cmt20210320180944.html , (2021)
Appendix C (Issues in media and Japan’s cabinet office)

The issues on a questionable media’s role in the 2011 Tohoku M9 EQ and Japan’s new disaster countermeasures had been as follows.

Seismologists in a nation of earthquakes (Japan) had asperity models of M8 class EQs off Tohoku. They could not anticipate the M9 EQ (Fig. 3 and label 6 in Fig. 9). Therefore, the Japanese government did not have any disaster countermeasures against the M9 event and tsunami to follow. Instead, they had some countermeasures against only M8 class events off the east coast of Tohoku and tsunamis.

On March 9, 2011, at 11:45, Japan had M7.5 in the anticipated area, one of the large foreshocks to the March 11 M9 EQ. This event stirred great anxiety about the imminent M8 throughout the nation. Therefore, the country and the news media needed a reliable seismological opinion on the M7.5 concerning the anticipated M8 event. NHK, Japan’s national public broadcasting organization, had asked only the earthquake research institute’s public relations at the University of Tokyo for the seismological opinion under the obligation to broadcast emergency reporting. Although the institute’s view was just an asperity model out of complex EQ phenomena, NHK broadcasted it on the prime-time national evening news on March 9 as if the opinion were absolute. The public opinion was that the M7.5 event was nothing to do with the anticipated M8 class event. Thus, the news relieved the great anxiety from many communities prepared for the imminent M8 event and tsunami.

Japan had been anticipating three other repeating M8 class events along the Nankai-trough [C1]. Their past independent schematic fault lines are label 1, 2, and 3 along the green Nankai-trough in Fig. 9. Similarly labeled are other significant fault lines including off the east coast of Hokkaido.

The nation’s seismologists and Japan’s cabinet office could not anticipate the Tohoku M9 events. They now assume the simultaneous chain ruptures of three independent faults and their subsequent 600 km length fault (Mw 9.1) to generate a tsunami of 34 m in height [C1] without any scientific confirmation. Japan’s cabinet office laid out disaster countermeasures against the assumed Mw 9.1 events, stirring unprecedented anxiety among many communities in Japan’s western part. The concern includes an assumed 4 m height tsunami onto the city of Osaka [C2].

14.1 References on Appendix C

[C1] Cabinet Office, Government of Japan (2020).
http://www.bousai.go.jp/jishin/nankai/taisaku_wg/
http://www.bousai.go.jp/jishin/nankai/nankaitrough_info.html

[C2] http://www.pref.osaka.jp/kikikanri/bukai/