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# Observation of rapid long-range seismic bursts in the Japan Trench subduction leading to the nucleation of the Tohoku earthquake

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ABSTRACT

Earthquake precursory phenomena like foreshocks are common but the physical processes which produce them and lead to rupture are poorly understood. Looking for clues about these processes, we explore here the long-term evolution of seismicity in a broad section of the Japan Trench slab around the 2011 Tohoku earthquake location and report the existence of long-range seismic bursts moving rapidly (~1-2 days or less) between the deep and the shallow slab. Their presence is evidenced by synchronizations of deep and shallow seismic activities in the slab. Probabilities that these synchronizations could be due to chance are infinitesimal ($<10^{-5}$). We show that a significant part of the activity in this subduction occurs during these bursts and that they are responsible for the foreshock sequence which preceded the earthquake. These observations support the existence of fluid channels connecting the deep slab, where water is released during dehydration, to the shallow seismogenic zone.


## 1. Introduction

The clearest information that a process of large scale in space and time preceded the rupture of the giant 2011 Tohoku, Japan, earthquake is the presence of a long (~2 months) foreshock sequence (Hirose et al., 2011; Kato et al., 2012). This pre-earthquake phase first became notable when the first M ≥ 4 foreshock occurred on January 13, 2011. The foreshock crisis intensified in mid-February and culminated on March 9, two days before the megathrust rupture, when a M7.3 shock occurred, followed by several M6 shocks (Marsan and Enescu, 2012). This foreshock sequence has been interpreted as indicative of slow slip migrating with time (Kato et al., 2012). Until the M7.3 shock, foreshocks have relatively small magnitudes out of scale with the large zone they illuminate, showing that slip or deformation is small but covers a broad area, a feature also consistent with a phase of slow slip (Brodsky and Mori, 2007; Gomberg et al., 2010). If slow slip produces the foreshocks, this raises the question of what makes it spread so rapidly across a vast area of the previously locked plate interface.

A second information, more difficult to decipher but coming from converging measurements of strainmeter, ocean bottom seismometers and ocean-bottom pressure gauges, is the occurrence in the weeks before the earthquake of a slow slip event (SSE) and tremors in the zone lying between the future epicenter and the trench (Ito et al., 2013, 2015; Katakami et al., 2018). The significance of these observations is reinforced by the fact that an SSE had only been observed once and tremors never before in this Japan Trench subduction.

Another measurement supporting a large scale process comes from the analysis of GPS time series in North Honshu. These geodetic observations concord that a long-term decrease in the rate of deformation began in the Tohoku region around 2003 (Ozawa et al., 2012; Heki and Mitsui, 2013; Mavrommatis et al., 2014; Yokota and Koketsu, 2015; Marill et al., 2021). This rate change has been interpreted as a decrease in coupling of the plate

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interface in the Tohoku region after 2003. A slip rate increase based on the analysis of small repeating earthquakes, consistent with a decrease in coupling, was also reported near the trench in the ∼3 years preceding the earthquake (Uchida and Matsuzawa, 2013).

Although almost all pre-earthquake investigations have been limited to what happens in the shallow seismogenic zone (depth $< 50$ km), the involvement of the deep slab in a pre-earthquake process is supported by some observations (Bouchon et al., 2016; Panet et al., 2018). While the first paper showed the existence of some synchronicity between deep and shallow seismic activities in the months preceding the earthquake, the second one reported the development over the same period of a gravity anomaly originating from deep in the slab and interpreted as an indication of rapid large-scale mass transfers in the subduction.

We explore here aspects of slab seismic activity seldom investigated. We largely rely on small seismicity whose investigation is made possible by the exceptional qualities of the Japanese seismic network and catalog (www.jma.go.jp/en/quake/) and their stability in time (Nanjo et al., 2010). We make this choice because small seismicity is our best proxy to investigate small slab deformation at large depth. We explore this seismicity in a slab segment several hundred kilometers long surrounding the earthquake epicentral area.

## 2. Observations

A map of activity during the two-months long foreshock period is shown in Fig. 1a. Events which are the most clustered in space (large dots) are emphasized relatively to more isolated events (small dots). The way this separation is done is straightforward: The average event spatial density over these two months is first evaluated. Then for each event the number of neighbors within the corresponding radial distance is counted. Events with more than two neighbors are considered as clustered (a comparison using different parametrizations to extract clustered events is in Fig. S1). In spite of the scatter, two alignments that trend nearly parallel to the direction of plate convergence are notable. Differentiating between shallow (depth $< 50$ km, red) and deep (depth $> 50$ km, blue) events shows that the most active deep cluster in the region is associated with the best-marked seismic alignment (Fig. 1b). This cluster was the seat of the largest intermediate-depth earthquake in instrumental time in Honshu (2003 M7.1, Okada and Hasegawa, 2003). The second alignment is visually associated with the location of two other large intermediate-depth earthquakes (1987 M6.6, 2008 M6.8). These three earthquakes are the largest ones at intermediate-depth on record in the region.

Intermediate-depth earthquakes are thought to be produced by metamorphic dehydration of slab minerals (Raleigh and Paterson, 1965; Green and Houston, 1995; van Keken et al., 2011). The peak dehydration occurs in the 60 km to 120 km depth range, releasing large amounts of water at these depths. The place of the two alignments of Fig. 1a-b directly in line with the locations of the largest known intermediate-depth earthquakes in the region is notable. The location of the Tohoku hypocenter up-slip from the most active cluster of intermediate-depth events and the presence of a seismic alignment nearly connecting the two are intriguing.

Fig. 1c-d presents two snapshots of seismic activity during the intensification of the foreshock crisis in late February 2011. Surprisingly, a large part of the seismicity in this period appears organized in lineations. At first, one might think that these lineations are mere coincidental patterns. However several characteristics suggest that they are not random: They emanate from the most active deep clusters. They occur concomitantly with a 7-days long (February 21-28) episode of tremors whose activity peaks on February 26 (Katakami et al., 2018). Several of them converge to the location where these tremors are detected and where foreshocks are occurring. It is also notable that February 26 is when the largest number of small high-frequency events, spatially distant but correlated in time, are detected in the seismic noise in the foreshock area (Gardonio et al., 2019). A map of the seismicity pattern over 20 yr (Fig. S2) shows that the alignments observed in Fig. 1 before Tohoku are not new features but occur along pre-existing lines of denser seismicity.

Exploring seismic activity in short time windows, during which regular background activity is not overwhelming, shows the recurrent presence of rapid transient lineations extending almost continuously between the deep slab and the shallow seismogenic zone (Fig. 2). These lineations mostly consist of small to very small events (M1-2). While most of them cross the locations of the 2003 or 2008 intermediate-depth earthquakes, others originate from further south as also observed in Fig. 1c-d. Some of their features like their long distance continuity, their burst-like nature, their repeated association with the locations of the past deep earthquakes, their tendency to converge towards the Tohoku epicentral zone suggest that they are not coincidental. One of the clearest lineations linking the epicentral zone to the deep cluster below is on January 25. It is notable that this is the day when tremor waveforms, never observed before in NE Japan, begin to be recorded on OBSs (Ito et al., 2015; Katakami et al., 2018). This tremor episode peaks on January 26 and around this time an SSE, which will last until the M7.3 foreshock, is detected on ocean-bottom pressure gauges and on-shore strainmeter (Ito et al., 2013). Another characteristic of the lineations is their tendency to repeat the same pattern at a few days or a few weeks interval (Fig. S3).

The observation of transient lineations connecting in a short time the deep and the shallow slab leads us to compare the timings of the two activities. Because it would be overwhelming to investigate the whole region, we limit the shallow exploration to a broad zone around the Tohoku epicenter. This zone, that we subsequently call the epicentral/foreshock zone, is defined as a circle centered on the epicenter and covering a depth range from 0 to 40 km. To include all known foreshocks, its radius is set at 75 km. The deep activity is the one occurring below 65 km throughout the geographic area of Fig. 1. The 25 km depth separation between the two populations is meant to clearly differentiate shallow events associated with the slip of the slab and intermediate-depth events associated with its internal deformation. We will show later that reasonable changes in these depth ranges do not affect the results. Analyzing 20 years of seismicity, we observe the irregular but recurrent presence of close synchronizations between the two activities, as shown for three year-long periods in Fig. 3. These synchronizations last for short durations and concern events of all magnitudes. At first, they might be dismissed as coincidental but calculation shows that the probability that they may be due to chance is extremely small. A close look at deep/shallow activities in 2004 (Fig. 4a) shows that, while deep activity which includes aftershocks of the 2003 M7.1 intermediate-depth earthquake is dominant, large events in the future epicentral zone systematically occur in synchronization with some deep activity. Probability to reach such a close synchronization by chance is $<10^{-4}$ (see supplementary material for details). This suggests a link between this near-perfect synchronization and the water release thought to have been produced by the intermediate-depth earthquake below a few months earlier. A map presenting where deep and shallow events take place during these synchronizations (Fig. 4b) shows that the deep activity involved originates from the source of the 2003 intermediate-depth earthquake and from the slab segment south of it. Although it may be coincidental, most of the large ($M \geq 6.5$) interplate earthquakes between 2003 and 2010 occur in the region lying between this slab segment and the future epicentral zone (e.g. Satriano et al., 2014). What is surprising is the

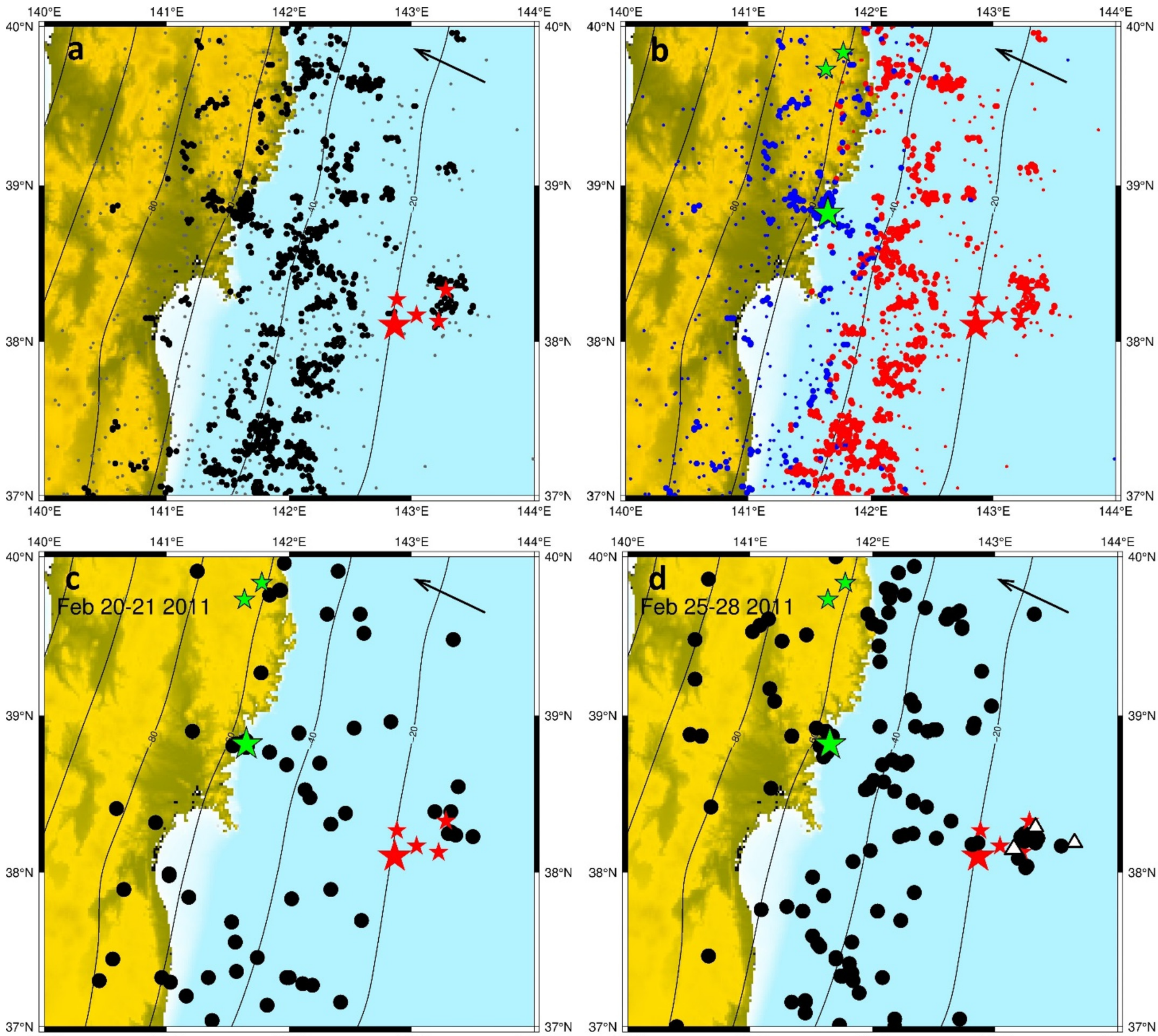


**Fig. 1.** Patterns of seismicity, foreshocks and intermediate-depth activity. **(a)** Map of seismicity in the two months preceding the Tohoku earthquake. All events in the subduction before the March 9 M7.3 foreshock are shown. Afterwards only Mw $\geq$ 6 foreshocks are displayed (red stars). Events spatially clustered (large dots) are emphasized relatively to more isolated events (small dots). Large star is the epicenter. The area surrounding the stars is the foreshock zone. Arrow shows the direction of slab descent (Perfettini and Avouac, 2014). Contour lines show slab interface depth (Hayes et al., 2012). **(b)** Same map differentiating shallow (depth < 50 km, red) and deep (depth > 50 km, blue) events. Green stars are the largest (M $\geq$ 6.5) intermediate-depth earthquakes on record in the region. The biggest one is the 2003 M7.1 event. **(c-d)** Snapshots of seismic activity during the intensification of the foreshock crisis showing the presence of several lineations between the deep and the shallow slab. All subduction events in the JMA catalog during the periods considered are shown. The largest foreshocks prior to the M7.3 shock occur on February 15, 21, 22 and 26. White triangles are OBS stations which recorded an episode of tremors starting on February 21 and ending on February 28 (Katakami et al., 2018). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

long distance range separating deep and shallow events, synchronized in time.

Another recurrent characteristic of synchronizations is their tendency to cluster in time (Fig. 4c), suggesting a rapid succession of bursts.

We now compare the shallow and deep activities in the months preceding the Tohoku earthquake. Activity in the epicentral zone is now dominated by the foreshock crisis. We first compare it to the deep activity occurring in slab segments of increasing length, sampling the slab further and further away from the epicenter (Fig. 5). As this range increases, a correlation between shallow and deep activities emerges. This correlation takes the form of a close synchronization of the two activities (Fig. 6a). The deep events involved in this synchronization span a surprisingly long segment of slab extending from ~36°N to ~40°N. A zoom on the largest events is presented in Fig. 6b-c (see also Fig. S5).

Unlike Figs. 1 and 2 (as well as Figs. S1, S2, S3 and S6) which present all the JMA catalog events occurring in the periods considered, the time evolutions of the shallow and deep activities presented in Figs. 5 and 6a do not include the very small events (<M2.3). The reason for not including them is seen in Fig. S4: The number of small events is so large (3083 deep and 1562 shallow events are present in this figure) that individual events become difficult to distinguish. Fig. S4 shows the existence of a

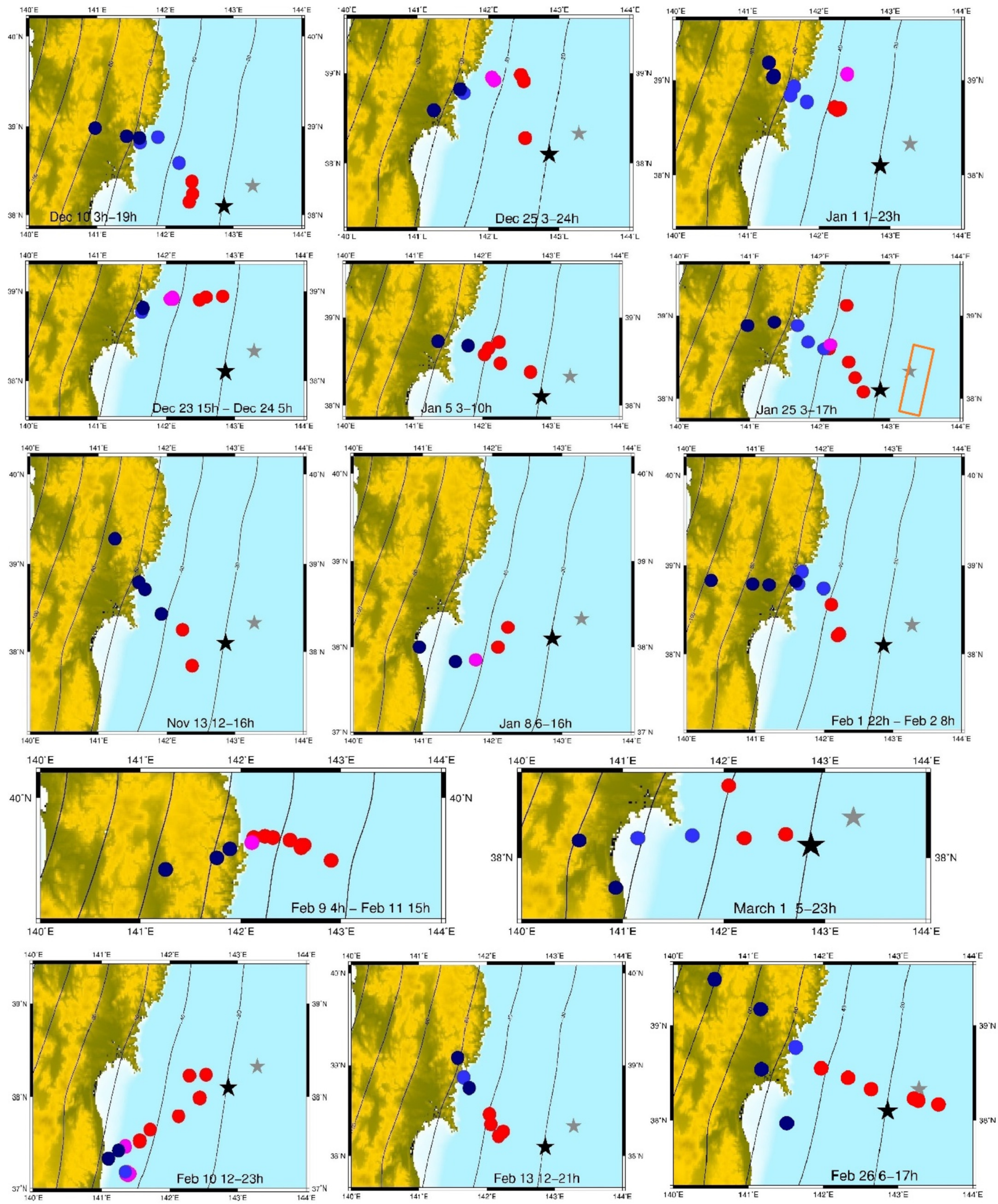


**Fig. 2.** Examples of transient seismic lineaments in the 4 months preceding Tohoku. All the events in the subduction occurring in the time windows indicated are shown (depth < 40 km in red, 40 km < depth < 50 km in pink, 50 km < depth < 70 km in light blue, 70 km < depth in dark blue). The black star is the epicenter, the gray one the M7.3 foreshock. Contour lines show slab interface depth (Hayes et al., 2012). The orange rectangle shown with the seismicity pattern of January 25 is the location of the SSE which preceded Tohoku and began around January 26-27 (Ito et al., 2013).

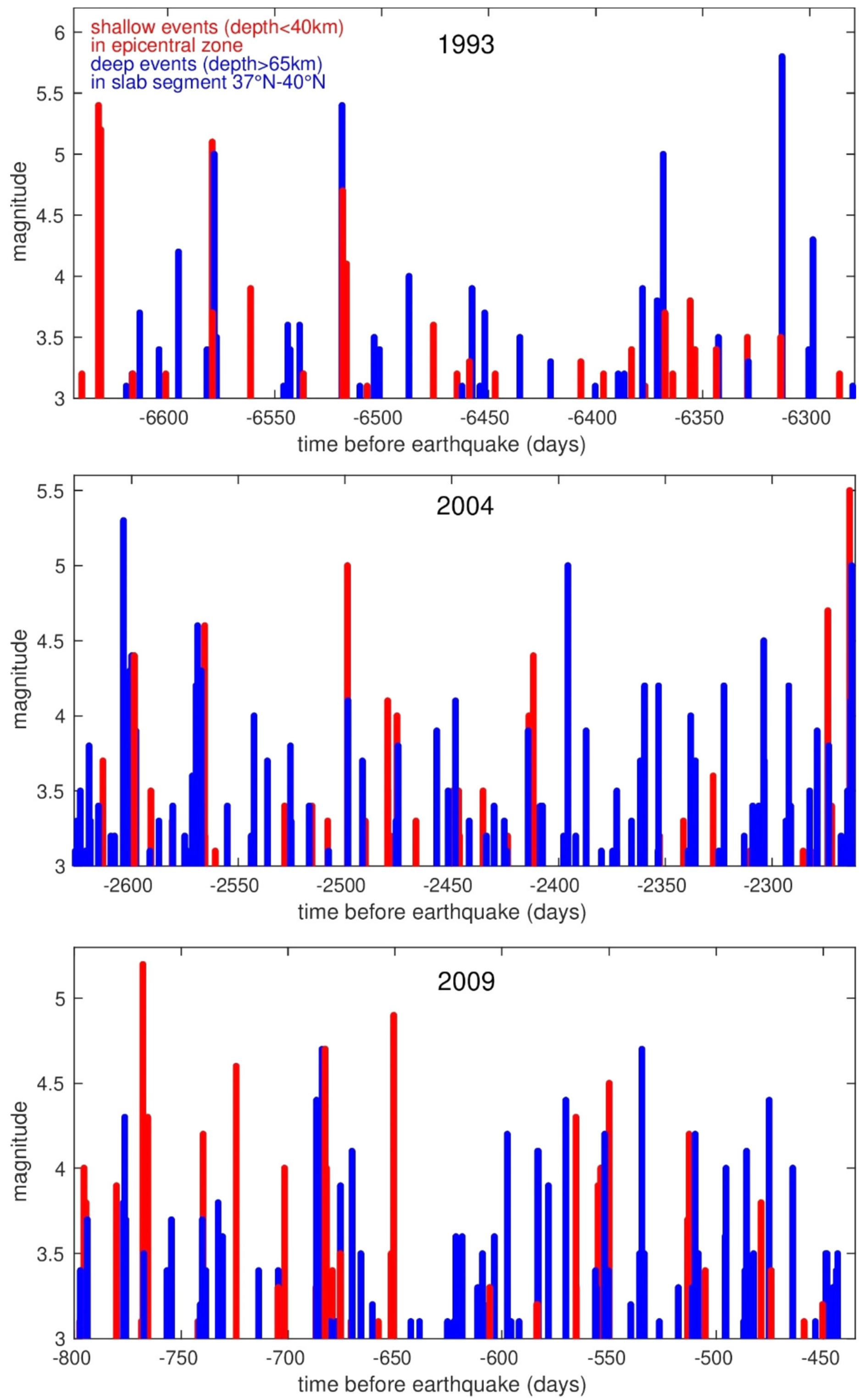


**Fig. 3.** Comparison of the timings of shallow seismic events (depth < 40 km) in the future Tohoku epicentral/foreshock zone with deep activity (depth > 65 km) in the slab in three year-long periods. The close synchronization of a significant portion of the shallow events with some deep activity is notable. This synchronization involves events of all magnitudes. The lateral extent of the slab segment (indicated in blue) over which this synchronization takes place is also remarkable.

near-continuous background of seismic activity in the subduction and the analysis of the temporal evolution of this background would be a challenge not attempted here. The higher magnitude cut-off used in the graphs of Figs. 3 and 4, compared to Figs. 5 and 6a, reflects the longer periods investigated there (∼1 yr), and therefore the larger number of events present in these intervals.

Probability to reach by chance the shallow/deep synchronization observed is $<10^{-3}$ when events down to M2.3 are considered (Fig. 6a), and $<10^{-5}$ when only the larger events are considered regardless of whether the period considered is four months (b) or one-and-a-half month (c) long (see supplementary material). The lower probability obtained for the large events may reflect the fact that this population is well above the background noise and is also

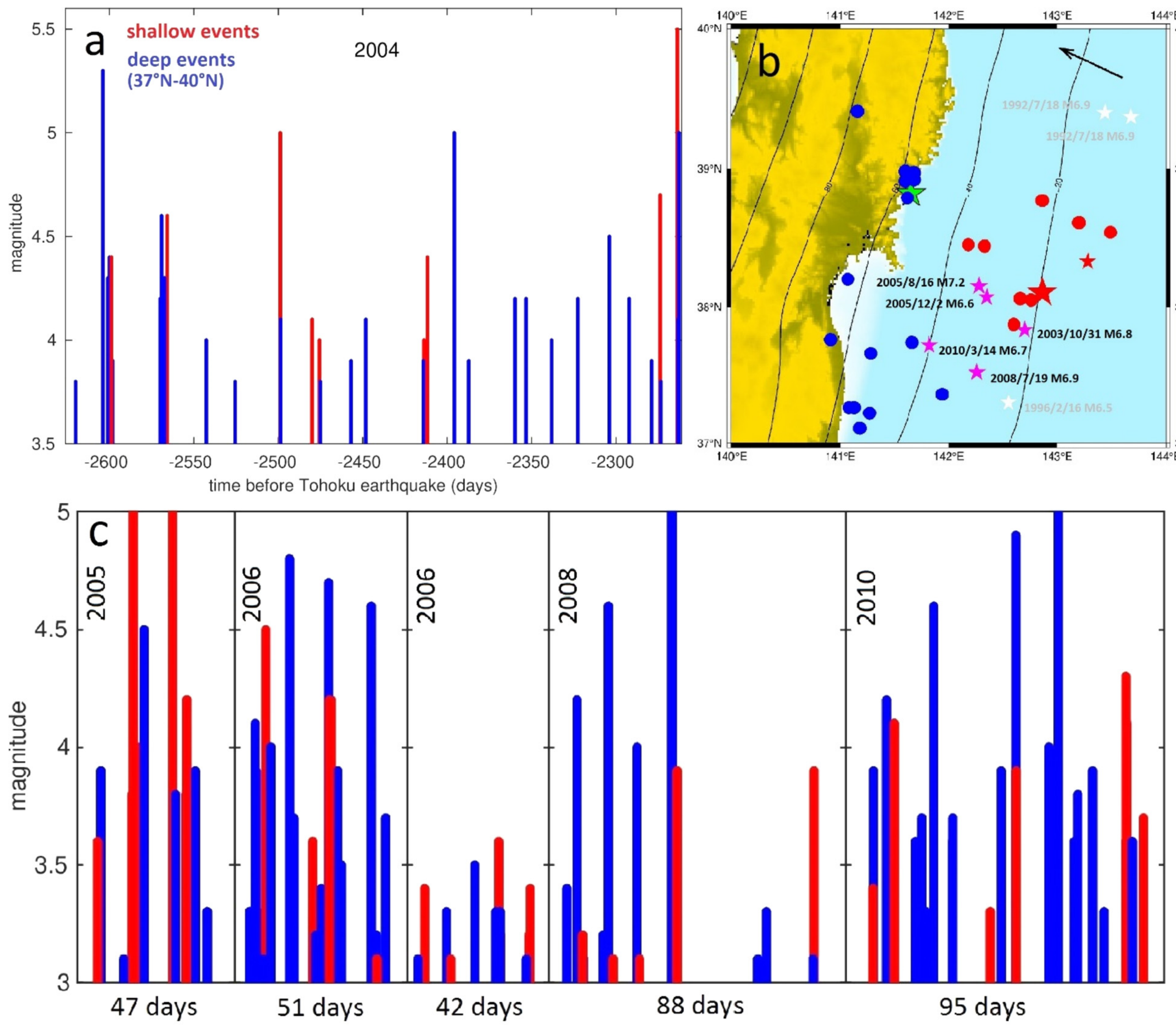


**Fig. 4.** Observation of periods where shallow events occur in quasi-systematic synchronization with some deep activity. **(a)** Comparison of the timings of large events in the future epicentral zone and in the deep slab in 2004, a few months after the M7.1 intermediate-depth earthquake occurred. **(b)** Map showing the locations of events during these 2004 synchronizations. Deep events are in blue, shallow events in red. Green star is the M7.1 2003 earthquake. Red stars are the Tohoku epicenter (large one) and its $M \geq 6$ foreshocks. Pink and white stars are the $M \geq 6.5$ interplate earthquakes in the region between 1990 and 2011. Pink stars are after the 2003 intermediate-depth earthquake, white stars are before. **(c)** Examples of months-long periods of recurrent synchronizations. These synchronizations concern all magnitude ranges. Years of occurrences are indicated.

less likely to contain aftershocks. The smallness of these values is surprising and may be due to a characteristic of many bursts which are not just made up of two single events but of multiple deep and shallow events interweaved together within a short time as seen in Fig. 6c, a characteristic difficult to be reproduced by chance.

## 3. Interpretation

Fluids have long been recognized to play a major role in the occurrence and mechanics of earthquakes (Sibson, 1992; Miller et al., 1996). It is now well established that large volumes of water are released during the slab descend into the mantle (Raleigh and Paterson, 1965; Peacock, 1990; Green and Houston, 1995; Kawano et al., 2011; van Keken et al., 2011; John et al., 2012; Angiboust et al., 2014; Guillot et al., 2015; Plümper et al., 2016). The channelization of their escape from dehydration zones is visible in the metamorphosed veins preserved in exhumed slabs (e.g. Plümper et al., 2016). Subsequent fluid ascent through the subduction is thought to be localized in space and time once fluid volumes exceed a critical size (John et al., 2012; Angiboust et al., 2014; Plümper et al., 2016; Taetz et al., 2018). This results from the recognized insufficiency of low rock permeability at large depth to drain subducting plates and the necessity of a high-flux transport system for fluids to escape (Kawano et al., 2011; Plümper et al., 2016).

The observations we report are in line with the findings of these studies. The characteristics of the seismic lineations observed support that they are the water channels hypothesized. The synchronizations of the shallow seismic activity with activity deep in the slab support the circulation of overpressured water pulses in these channels. A logical mechanical model emerges from these complementary observations. Once water is released in the deep slab, it begins to be transported upwards by the small veins seen in exhumed rocks. Extended networks of veins and pockets of water develop as more water is released. When and where water pressure exceeds local confining pressure and rock strength, hydrofracturing extends the water path up-dip. These slow processes occur at different scales and places. When barriers break, overpressure pulses propagate suddenly up-dip while deep water pressure drops towards hydrostatic value and water is expelled upward. Once pressure has stabilized, water pressure at depth has dropped and can no longer sustain the confining pressure of the rocks. The channel closes as rapidly as it has come to be. This explains the ra-

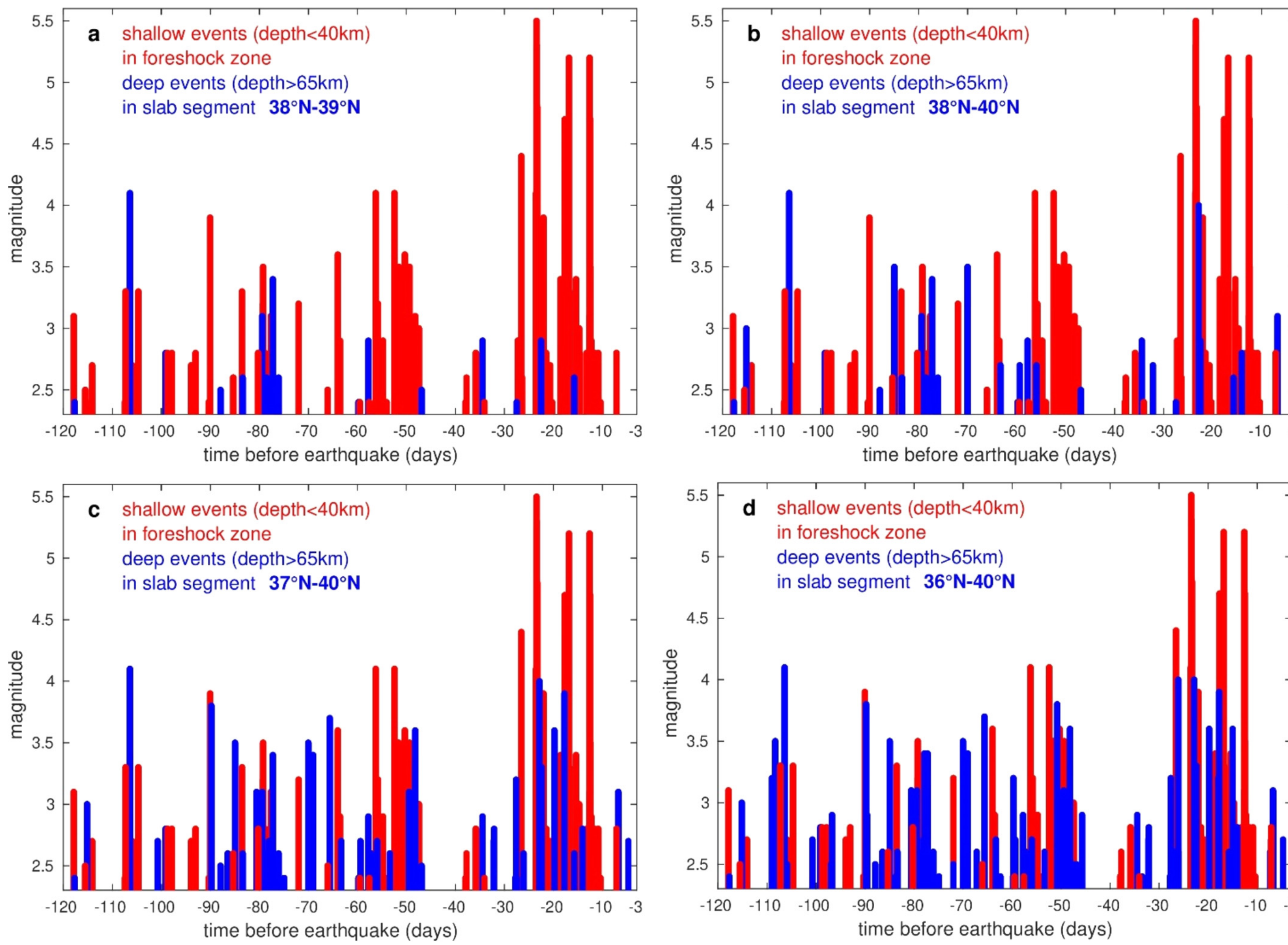


**Fig. 5.** Comparison of the timings of shallow events in the foreshock/epicentral zone (a circle of 75 km around the epicenter) with events occurring deep in the slab in the 4 months preceding the Tohoku earthquake. The slab section considered for the deep activity increases from (a) to (d) and is indicated in each panel. As the length of the slab section increases, a synchronization emerges between the two activities.

pidity with which fluid escape begins and ends and why it cannot be continuous in time but naturally occurs in bursts. In analogy, overpressure pulses propagate in the kilometers-long fluid-filled boreholes of centimeter diameter drilled for oil exploration at velocity of ∼1.5 km/s (e.g. Bouchon, 1993). A simple chronology between deep and shallow events should not be expected because an upward propagating overpressure is necessarily associated with a downward propagating decompression and the complex geometry of channels results in multiple upward and downward propagating pulses during a burst, reminiscent of the observed back and forth propagation of tremors (Ghosh et al., 2010; Ide, 2010). The tendency of many lineations to repeat themselves is also a tremor characteristic (Ambruster et al., 2014). Fluids have long been suspected to play a major role in the mechanisms of tremors and slow slip events (Kao et al., 2007; Shelly et al., 2007; Beroza and Ide, 2009; Ghosh et al., 2010; Gomberg et al., 2010; Ide, 2010; Peng and Gomberg, 2010; Vidale and Houston, 2012; Shapiro et al., 2018). The burst-like nature of tremor and slow slip activities is also a recently recognized characteristic (Frank et al., 2018).

An alternative mechanism which might be involved in the synchronicity observed is dynamic triggering, an event being produced by the stress field radiated by a distant event. Two characteristics of the observations, however, make such a mechanism unlikely: The first one is the small magnitude of many of the events showing this synchronicity, sometimes even very small (M∼1-2) in the case of the events making up the lineations. The second one is the long distance separating synchronized events (typically 150 km or more).

The large water release expected during and following the M7.1 intermediate-depth earthquake of 2003 under Tohoku may have accelerated this process. This is suggested by the clear observation of seismic bursts in the year following the earthquake. This scenario is strengthened by concordant observations of a decrease of the rate of compression in the Tohoku region in the period 2003-2011 relatively to previous years (Ozawa et al., 2012; Heki and Mitsui, 2013; Mavrommatis et al., 2014), interpreted as a decrease in plate coupling, a phenomenon expected from the presence of water along the plate interface. A cross-section map of slab seismicity (Fig. S6) shows that much of the deep pre-Tohoku activity was still highly localized in the source area of the 2003 earthquake. This is the zone that most of the transient lineations were recurrently crossing (Figs. 1c-d, 2). A map showing, at the scale of Honshu, the location of the largest intermediate-depth earthquake in instrumental time there (M7.1 2003) and the location and slip of the Tohoku earthquake (Fig. 7) underlines the geometric connection between the intermediate-depth slab where water is released and the shallow seismogenic zone where large earthquakes nucleate. Other occurrences of large intermediate-depth earthquakes followed a few years or a decade later by a large subduction earthquake directly above have been reported (Mal-

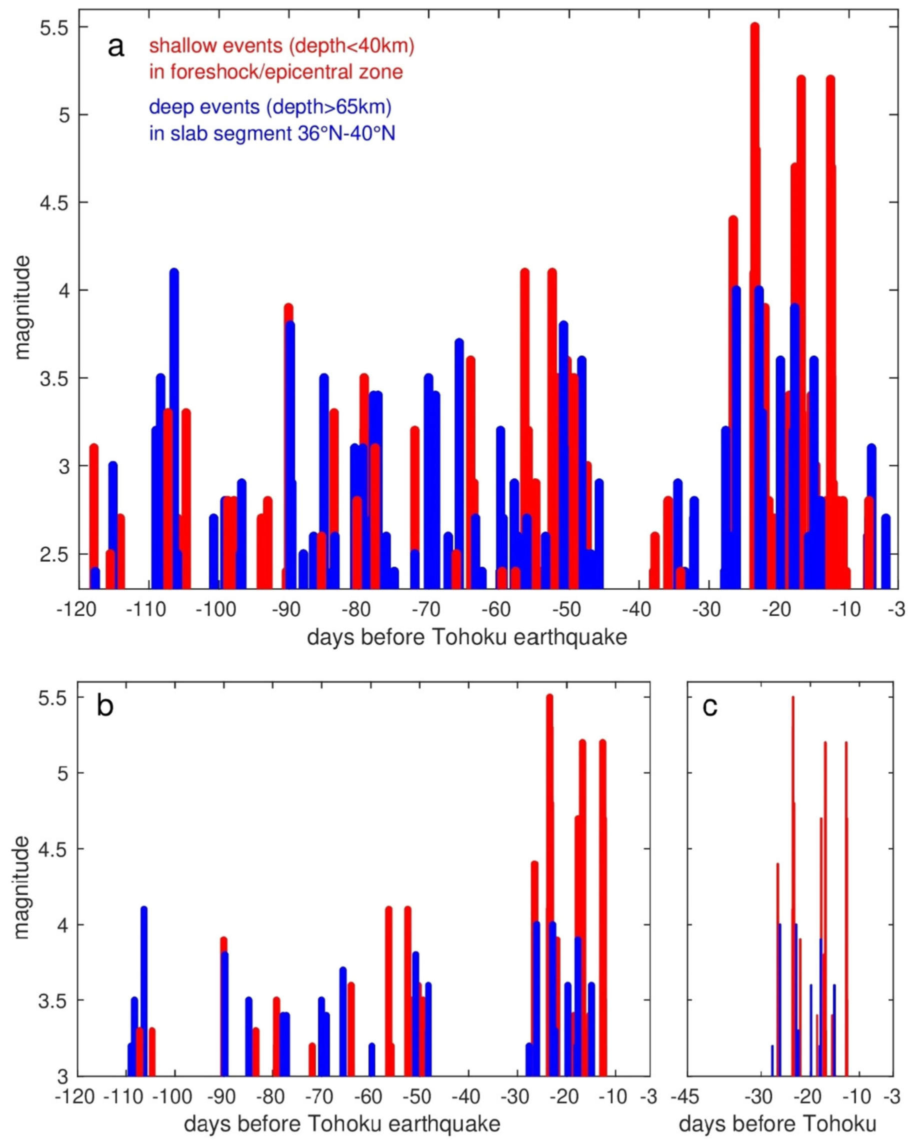


**Fig. 6.** Comparison of the timings of shallow events in the epicentral zone (i.e. foreshocks) with deep activity in the slab in the months preceding the earthquake. **(a)** Events down to magnitude 2.3 are displayed. The time window considered ends before the M7.3 foreshock after which activity is dominated by its numerous aftershocks. **(b)** Same but focusing on the larger events. **(c)** Zoom on the last 45 days at a finer resolution scale showing that each burst is made up of multiple interweaved deep and shallow events.

grange and Madariaga, 1983; Astiz and Kanamori, 1986; Dmowska et al., 1988; Jara et al., 2017). In this respect it is notable that in the Hellenic subduction the largest subduction earthquake on record occurred directly up-dip and only 40 days after the largest intermediate-depth earthquake on record (Durand et al., 2014). This rapidity of interaction may be explained by the roll-back of the slab which characterizes the Hellenic subduction and would logically facilitate water ascent.

## 4. Conclusions

We have shown the existence of a synchronization between shallow and deep seismic activities in the Japan Trench subduction. This synchronization is confirmed by statistics and concerns a significant part of the slab seismic activity. It supports the existence of rapid long-range seismic bursts in the subduction. The observations we report show that these bursts are associated with the foreshock sequence which preceded the Tohoku earthquake. The most mechanically logical interpretation of these bursts is that they are produced or triggered by pulses of overpressured fluids propagating in fluid channels. The existence of such channels and the rapidity and short duration of the fluid transport in them are supported by recent mineralogical and geochemical studies on the slab dehydration process.

## CRediT authorship contribution statement

Michel Bouchon: Conceptualization; Anne Socquet: Validation, Investigation; David Marsan: Formal analysis; Stephane Guillot: Investigation; Virginie Durand: Methodology; Blandine Gardonio: Methodology; Michel Campillo: Validation; Hugo Perfettini: Validation; Jean Schmittbuhl: Investigation; Francois Renard: Graphics; Anne-Marie Boullier: Discussions and validation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

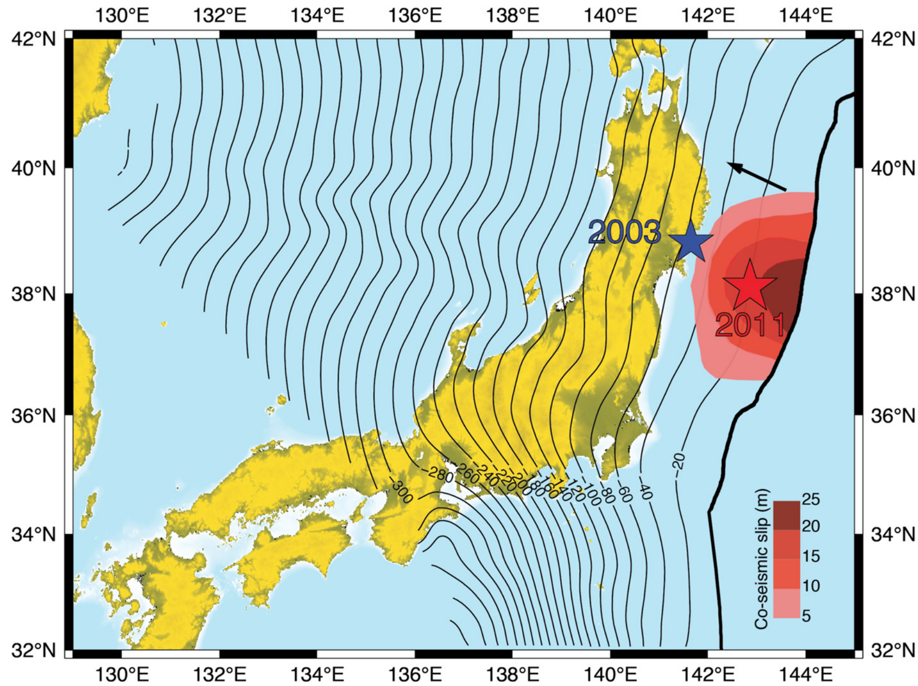


**Fig. 7.** Locations of the largest intermediate-depth earthquake (M7.1 in blue) and the largest subduction earthquake (M9.0 in red) in instrumental time in Honshu. The Tohoku coseismic slip determined from the inversion of GPS data by Perfettini and Avouac (2014) is shown in reddish colors. Contour lines show slab interface depth (Hayes et al., 2012). The thick black line is the trench. Arrow indicates the direction of slab descent.

## Data availability

The data used in this study are open and available at www.jma.go.jp/en/quake/ or at www.isc.ac.uk.

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## Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2022.117696.

## References

Ambruster, J.G., Kim, W.Y., Rubin, A.M., 2014. Accurate tremor locations from coherent S and P waves. J. Geophys. Res. 119, 5000–5013.
Angiboust, S., Pettke, T., de Hoog, J.C.M., Caron, B., Oncken, O., 2014. Channelized fluid flow and eclogite-facies metasomatism along the subduction shear zone. J. Petrol. 55, 883–916.
Astiz, L., Kanamori, H., 1986. Interplate coupling and temporal variation of mechanisms of intermediate-depth earthquakes in Chile. Bull. Seismol. Soc. Am. 76, 1614–1622.
Beroza, G.C., Ide, S., 2009. Deep tremors and slow quakes. Science 324, 1025–1026.
Bouchon, M., 1993. A numerical simulation of the acoustic and elastic wavefields radiated by a source in a fluid-filled borehole embedded in a layered medium. Geophysics 58, 475–481.
Bouchon, M., et al., 2016. Potential slab deformation and plunge prior to the Tohoku, Iquique and Maule earthquakes. Nat. Geosci. 9, 380–383.
Brodsky, E.E., Mori, J., 2007. Creep events slip less than ordinary earthquakes. Geophys. Res. Lett. 34, L16309.
Dmowska, R., Rice, J.R., Lovison, L.C., Josell, D., 1988. Stress transfer and seismic phenomena in coupled subduction zones during the earthquake cycle. J. Geophys. Res. 93, 7869–7884.
Durand, V., Bouchon, M., Floyd, M.A., Theodulidis, N., Marsan, D., Karabulut, H., Schmittbuhl, J., 2014. Observation of the spread of slow deformation in Greece following the breakup of the slab. Geophys. Res. Lett. 41, 7129–7134.
Frank, W.B., Rousset, B., Lasserre, C., Campillo, M., 2018. Revealing the cluster of slow transients behind a large slow slip event. Sci. Adv. https://doi.org/10.1126/sciadv.aat0661.
Gardonio, B., et al., 2019. Seismic activity preceding the 2011 Mw9.0 Tohoku earthquake, Japan, analyzed with multidimensional template matching. J. Geophys. Res. 124, 6815–6831.
Ghosh, A., et al., 2010. Rapid continuous streaking of tremor in Cascadia. Geochem. Geophys. Geosyst. 11, Q12010.
Gomberg, J., et al., 2010. Slow slip phenomena in Cascadia from 2007 and beyond: a review. Geol. Soc. Am. Bull. 122, 963–978.
Green, H.W., Houston, H., 1995. The mechanics of deep earthquakes. Annu. Rev. Earth Planet. Sci. 23, 169–213.
Guillot, S., Schwartz, S., Agard, P., Renard, B., Prigent, C., 2015. Tectonic significance of serpentinites. Tectonophysics 646, 1–19.
Hayes, G.P., Wald, D.J., Johnson, R.L., 2012. Slab1. 0: a three-dimensional model of global subduction zone geometries. J. Geophys. Res. 117, B01302.
Heki, K., Mitsui, Y., 2013. Accelerated Pacific plate subduction following interplate thrust earthquakes at the Japan trench. Earth Planet. Sci. Lett. 363, 46–49.
Hirose, F., Miyaoka, K., Hayashimoto, N., Yamazaki, T., Nakamura, M., 2011. Outline of the 2011 off the Pacific coast of Tohoku earthquake (Mw 9.0) – Seismicity: foreshocks, mainshock, aftershocks, and induced activity. Earth Planets Space 63, 513–518.
Ide, S., 2010. Striations, duration, migration, and tidal response in deep tremor. Nature 466, 356–359.
Ito, Y., et al., 2013. Episodic slow slip events in the Japan subduction zone before the 2011 Tohoku-Oki earthquake. Tectonophysics 600, 14–26.
Ito, Y., Hino, R., Suzuki, S., Kaneda, Y., 2015. Episodic tremor and slip near the Japan Trench prior to the 2011 Tohoku-Oki earthquake. Geophys. Res. Lett. 42, 1725–1731.
Jara, J., Soquet, A., Marsan, D., Bouchon, M., 2017. Long-term interactions between intermediate depth and shallow seismicity in North Chile subduction zone. Geophys. Res. Lett. 44.
John, T., et al., 2012. Volcanic arcs fed by rapid pulsed fluid flow through subducting slabs. Nat. Geosci. 5, 489–492.
Kao, H., Shan, S.J., Rogers, G., Dragert, H., 2007. Migration characteristics of seismic tremors in the northern Cascadia margin. Geophys. Res. Lett. 34, L03304.
Katakami, S., Ito, Y., Ohta, K., Hino, R., Suzuki, S., Shinohara, M., 2018. Spatiotemporal variation of tectonic tremor activity before the Tohoku-Oki earthquake. J. Geophys. Res. 123, 9676–9688.

Kato, A., et al., 2012. Propagation of slow slip leading up to the 2011 Mw 9.0 Tohoku-Oki earthquake. Science 335, 705–708.
Kawano, S., Katayama, I., Okazaki, K., 2011. Permeability anisotropy of serpentine and fluid pathways in a subduction zone. Geology 39, 939–942.
van Keken, P.E., Hacker, B.R., Syracuse, E.M., Abers, G.A., 2011. Subduction factory: depth-dependent flux of $H_2O$ from subducting slabs worldwide. J. Geophys. Res. 116, B01401.
Malgrange, M., Madariaga, R., 1983. Complex distribution of large thrust and normal fault earthquakes in the Chilean subduction zone. Geophys. J. R. Astron. Soc. 73, 489–505.
Marill, L., Marsan, D., Socquet, A., Radiguet, M., Cotte, N., Rousset, B., 2021. 14-year acceleration along the Japan Trench. J. Geophys. Res. 2020JB021226.
Marsan, D., Enescu, B., 2012. Modeling the foreshock sequence prior to the 2011, MW9.0 Tohoku, Japan, earthquake. J. Geophys. Res. 117, B06316.
Mavrommatis, A.P., Segall, P., Johnson, K.M., 2014. A decadal-scale deformation transient prior to the 2011 Mw 9.0 Tohoku-Oki earthquake. Geophys. Res. Lett. 41, 4486–4494.
Miller, S.A., Nur, A., Olgaard, D.L., 1996. Earthquakes as a coupled shear stress-high pore pressure dynamical system. Geophys. Res. Lett. 23, 197–200.
Nanjo, K.Z., Ishibe, T., Tsuruoka, H., Schorlemmer, D., Ishigaki, Y., Hirata, N., 2010. Analysis of the completeness magnitude and seismic network coverage of Japan. Bull. Seismol. Soc. Am. 100, 3261–3268.
Okada, T., Hasegawa, A., 2003. The M7.1 May 26, 2003 off-shore Miyagi prefecture earthquake in northeast Japan: Source process and aftershock distribution of an intra-slab event. Earth Planets Space 55, 731–739.
Ozawa, S., et al., 2012. Preceding, coseismic, and postseismic slips of the 2011 Tohoku earthquake, Japan. J. Geophys. Res. 117, B07404.
Panet, I., Bonvalot, S., Narteau, C., Remy, D., Lemoine, J.M., 2018. Migrating pattern of deformation prior to the Tohoku-Oki earthquake revealed by GRACE data. Nat. Geosci. 11, 367–373.
Peacock, S.M., 1990. Fluid processes in subduction zones. Science 248, 329–337.
Peng, Z., Gomberg, J., 2010. An integrated perspective of the continuum between earthquakes and slow-slip phenomena. Nat. Geosci. 3, 599–607.
Perfettini, H., Avouac, J.P., 2014. The seismic cycle in the area of the 2011 Mw9.0 Tohoku-Oki earthquake. J. Geophys. Res., Solid Earth 119, 4489–4515.
Plümper, O., John, T., Podladchikov, Y.Y., Vrijmoed, J.C., Scambelluri, M., 2016. Fluid escape from subduction zones controlled by channel-forming reactive porosity. Nat. Geosci. 10, 150–155.
Raleigh, C.B., Paterson, M.S., 1965. Experimental deformation of serpentinite and its tectonic implications. J. Geophys. Res. 70, 3965–3985.
Satriano, C., Dionicio, V., Miyake, H., Uchida, N., Vilotte, J.O., Bernard, P., 2014. Structural and thermal control of seismic activity and megathrust rupture dynamics in subduction zones: lessons from the Mw 9.0, 2011 Tohoku earthquake. Earth Planet. Sci. Lett. 403, 287–298.
Shapiro, N.M., Campillo, M., Kaminski, E., Vilotte, J.P., Jaupard, C., 2018. Low-frequency earthquakes and pore-pressure transients in subduction zones. Geophys. Res. Lett. 43, 11083–11094.
Shelly, D.R., Beroza, G.C., Ide, S., 2007. Complex evolution of transient slip derived from precise tremor locations in western Shikoku, Japan. Geochem. Geophys. Geosyst. 8, Q10014.
Sibson, R.H., 1992. Implications of fault-valve behavior for rupture nucleation and recurrence. Tectonophysics 18, 1031–1042.
Taetz, S., John, T., Bröcker, M., Spandler, C., Stracke, A., 2018. Fast intraslab fluid-flow events linked to pulses of high pore fluid pressure at the subducted plate interface. Earth Planet. Sci. Lett. 482, 33–43.
Uchida, N., Matsuzawa, T., 2013. Pre- and postseismic slow slip surrounding the 2011 Tohoku-Oki earthquake rupture. Earth Planet. Sci. Lett. 374, 81–91.
Vidale, J.E., Houston, H., 2012. Slow slip: A new kind of earthquake. Phys. Today 65, 38–43.
Yokota, Y., Koketsu, K., 2015. A very long-term transient event preceding the Tohoku earthquake. Nat. Commun. 6. https://doi.org/10.1038/ncomms6934.