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Potential slab deformation and plunge prior to the Tohoku, Iquique and Maule earthquakes

Michel Bouchon[1]★, David Marsan[2], Virginie Durand[3], Michel Campillo[1], Hugo Perfettini[1], Raul Madariaga[4] and Blandine Gardonio[1]

Megathrust earthquakes rupture hundreds of kilometres of the shallow plate interface in subduction zones, typically at depths of less than 50 km. Intense foreshock activity preceded the 2011 M_w 9 Tohoku-oki (Japan) and 2014 M_w 8.2 Iquique (Chile) megathrust earthquakes. This pre-earthquake activity was thought to be generated[1–6] by slow slip in the seismogenic zone before rupture, but where this slow slip originated and how it spread rapidly over long distances are unknown. Here we analyse seismic activity deep in the subduction zone before the Tohoku-oki and Iquique ruptures, as well as before the 2010 M_w 8.8 Maule earthquake in Chile. We find that, before each of these megathrust earthquakes, shallow seismicity occurred synchronously with bursts of seismic activity deep (~100 km) in the subducting slab. The extensional mechanism of these deep shocks suggests that the slab was stretched at depth. We therefore propose that, before these megathrust quakes, the slab might have started to plunge into the mantle below part of the future rupture zone. We speculate that synchronization between deep and shallow seismicity may have marked the nucleation phase for these three giant earthquakes.

While subducting plates slip slowly and continuously below about 50 km, slip above occurs mostly intermittently during subduction earthquakes. The transition zone between the stick–slip and the stable sliding domains is in many places the seat of episodic slow slip and tremors[7–9]. Below this transition zone, earthquakes still occur, but they represent intra-plate deformation and are located within the cold core of the slab. These earthquakes, which in most subductions cluster between depths of 80 and 200 km, are termed intermediate-depth earthquakes. It has long been thought that there is a mechanical connection between these intra-slab events and the subduction earthquakes above. Such a link is suggested by the tendency of some large intermediate-depth earthquakes to precede by a decade or less a large subduction earthquake above[10–14].

Because the resolving power of geodetic instruments decreases rapidly with depth, intermediate-depth seismicity is our only tool to investigate dynamic processes occurring deep in the subduction zone. With this aim, we study the intermediate-depth seismicity before three of the best recorded megathrust earthquakes so far: the 2011 M_w 9 Tohoku-oki earthquake in Japan and the 2014 M_w 8.2 Iquique and 2010 M_w 8.8 Maule earthquakes in Chile.

The 11 March 2011 Tohoku-oki earthquake is the largest earthquake of the past ten years and was preceded by numerous foreshocks[1,15,16]. Figure 1a presents the evolution of the deep (≥80 km) seismic activity in the slab, down-dip below the hypocentral area, in the preceding year. The magnitude cutoff considered ($M > 1$) is the magnitude of completeness of the catalogue for deep events (Supplementary Fig. 1). The figure shows that the rate of activity suddenly increases on 13 January, nearly two months before the earthquake. From then on, this rate will stay high until the earthquake. Remarkably, on the same day, seismic activity begins in the epicentral area (Fig. 1a). Between 13 January and 11 March, numerous foreshocks occur in a wide zone (~50 km) bordering the epicentre[1,15]. This foreshock activity peaks on 9 March, two days before the megathrust, with an M_w 7.3 shock, and stays intense until the earthquake[16]. The spatial distribution of the increase in deep seismicity following the change of trend of 13 January and leading to the 9 March foreshock (Fig. 2a) shows that, during these nearly two months, the slab is slowly deforming and plunging below a large section (~200 km) of the future rupture. The largest increase takes place precisely down-dip from the zone where the shallow foreshocks are concomitantly occurring (Fig. 2b). The timing of the largest events during this period (Fig. 1b) shows that the two largest bursts of foreshock activity before the 9 March foreshock occur within a few hours of the two strongest shocks at depth. These deep shocks lie 160 km and 215 km away from the epicentre (Fig. 1c).

Like the Tohoku earthquake, the 1 April 2014 M_w 8.2 Iquique earthquake in Chile was preceded by intense foreshock activity[2–6,17]. This activity began in early January, nearly three months before the megathrust, surprisingly far (~130 km) from the epicentre, and was also characterized by bursts of seismic events (Fig. 3a) occurring over a very wide area (~150 km). The comparison of the foreshock occurrences with the deep intermediate-depth seismicity down-dip below in the slab shows that the two activities are closely correlated in time. The first foreshock burst of 4–8 January is accompanied by a first burst at depth on 7 January. The second foreshock burst begins on 30 January, shortly after a second seismic burst at depth on 29 January. The next significant increase of activity at depth occurs on 14 March. One day later, the shallow seismicity is reactivated, and on 16 March the largest foreshock (M_w 6.7) occurs and shallow activity spreads. The next burst of activity at depth takes place on 31 March, when the largest intermediate-depth shock of the year in the zone (M_w 5.6) occurs. This deep shock (115 km) is followed the next day by the megathrust. The spatial distribution of the activity (Fig. 3b) shows that, during each burst, the deep shocks occur down-dip from the zones where the foreshocks occur. The southern foreshock cluster which starts the pre-earthquake activity in early January is concomitant with deep activity below. The 150 km-long jump to north of foreshock activity at the end of January follows, by a few hours, the start of deep activity to the

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[1]Université de Grenoble Alpes and Centre National de la Recherche Scientifique, ISTerre, BP 53, 38041 Grenoble, France. [2]Université de Savoie, ISTerre, 73376 Le Bourget du Lac, France. [3]Institut de Physique du Globe de Paris, 1 rue Jussieu, 75005 Paris, France. [4]Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris, France. *e-mail: Michel.Bouchon@ujf-grenoble.fr

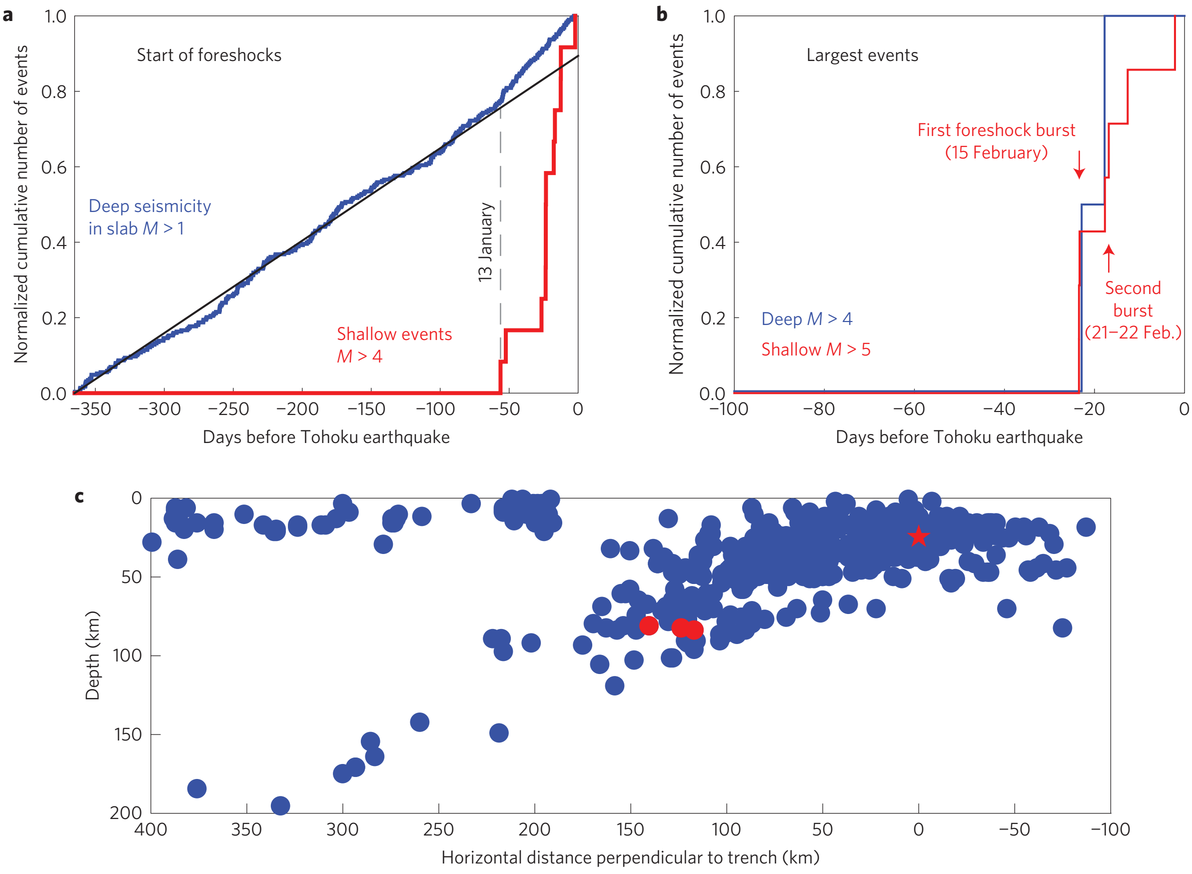

Figure 1 | Compared evolutions of foreshock activity and deep seismicity before Tohoku. **a**, Time evolution of shallow ($\leq$40 km) foreshocks and deep ($\geq$80 km) seismicity before the earthquake. Events after the M_w 7.3 foreshock of 9 March are not included. The black line is the least-square fit before the foreshocks start on 13 January. **b**, Timing of the largest deep and shallow events occurring in the 100 days before the earthquake. **c**, Vertical cross-section perpendicular to the trench of the one-year-long pre-earthquake seismicity. The Tohoku hypocentre is the red star and the three largest deep pre-shocks are the red dots.

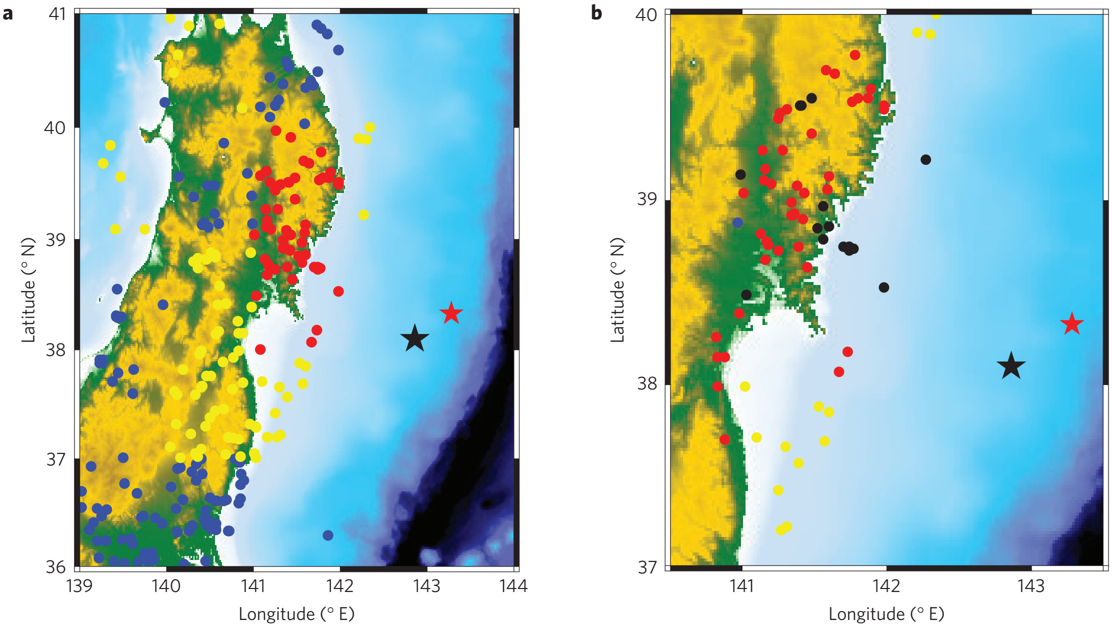

Figure 2 | Plunge/deformation of the slab below northeastern Japan before Tohoku, imaged by the spatial distribution of deep activity increase between 13 January and 9 March 2011. **a**, Events $M > 1$ deeper than 80 km. The area is divided into zones of 1° × 1° in latitude/longitude and events are coloured according to the activity increase in their zone, measured relatively to the activity rate in the preceding year: blue (decrease), yellow (0–50% increase), red (50–100% increase), black (>100% increase). Stars show the earthquake (black) and M_w 7.3 foreshock (red) epicentres. **b**, Zoom on events located within 2° of the epicentre. The area is divided into finer zones of 0.5° × 0.5°. Scaling is the same as in **a**.

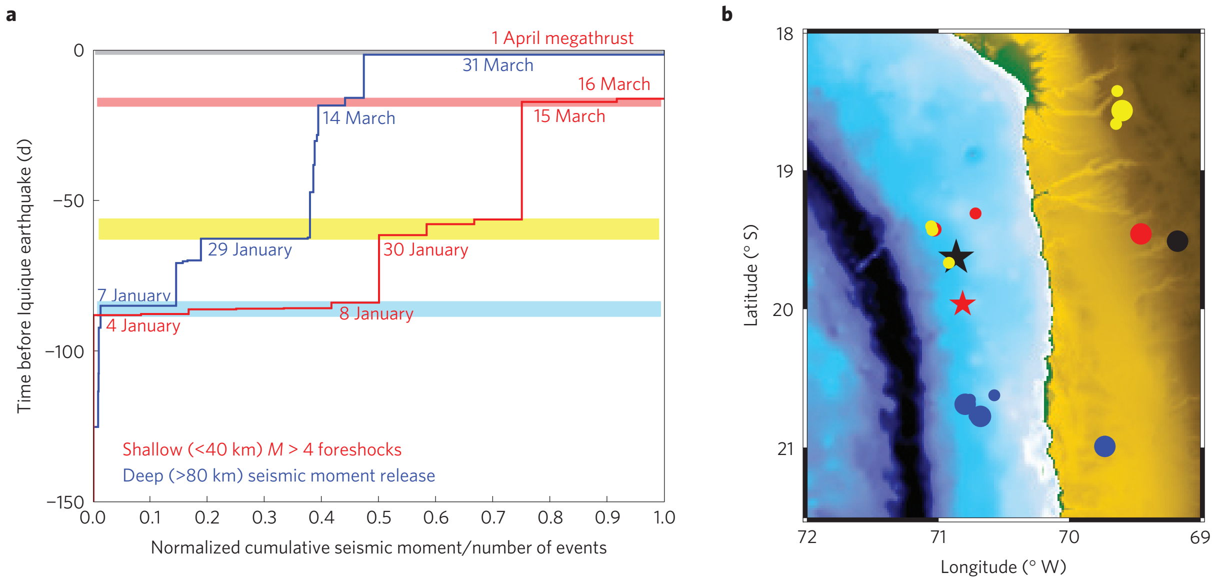

Figure 3 | Evolution of deep and shallow activity before Iquique. a, Comparison of the large foreshock occurrences with activity deep in the slab. Shallow seismicity following the 16 March M_w 6.7 foreshock is not included. The four coloured bands represent the periods of most intense activity. **b**, Spatial distribution of events during the four activity bursts shown in **a**: 4–8 January, blue; 29 January–4 February, yellow; 14–16 March, red; 31 March–1 April, black. Stars show the earthquake (black) and largest foreshock (red) epicentres. Shallow seismicity is confined below sea. Deep activity occurs below land. To avoid inclusion of regular background seismicity, only $M \geq 4$ events are considered. The largest circles are $M \geq 4.9$ events.

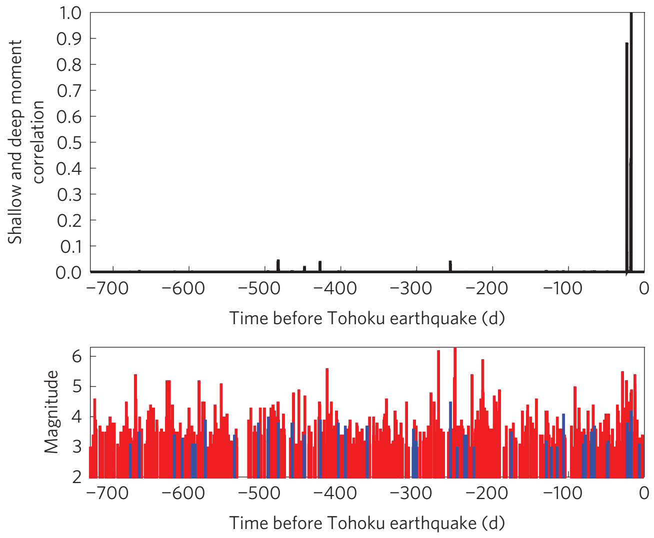

Figure 4 | Correlation of shallow (≤40 km) and deep (≥80 km) seismicity occurring in a zone of 2° (222 km) radius around the Tohoku epicentre, in the two years preceding the earthquake. This correlation is made over a one-day-long moving window and represents the product of the shallow and deep seismic moments released in the same time window. It is normalized to its peak value. The magnitude of the largest shallow (red) and deep (blue) events is shown below. The period considered ends just before the M_w 7.3 foreshock of 9 March, two days before the earthquake.

north. The largest foreshock (M_w 6.7) on 16 March and the 1 April megathrust both closely follow a burst of activity precisely down-dip below. A probability estimation, based on Poisson statistics and on the rate of deep seismicity in the three months before the beginning of foreshock activity, yields a value of less than 0.01% that the occurrence of four deep shocks of $M \geq 4.9$, as is observed in Fig. 3b, in the zone and periods considered, is due to chance.

The 27 February 2010 M_w 8.8 Maule earthquake in Chile, which is the second largest megathrust of the past ten years, was also preceded by foreshocks[18], but this precursory activity was less intense than before Tohoku and Iquique. The recorded activity began on 14 January, 10 h after a burst of activity at depth, and lasted for a week (Supplementary Fig. 2). The largest four foreshocks ($M > 4$) occurred on 14 and 21 January, and are synchronized, within a few hours or a day, with activity below down-dip in the slab.

While the mechanisms of the shallow foreshocks are characterized by low-angle thrusting, similar to the subduction earthquake and indicative of the down-slip of the slab in the epicentral area, the few deep pre-shocks for which the mechanism is known (http://www.isc.ac.uk) are representative of intra-slab extensional deformation. This mechanism of down-dip extension, typical of intermediate-depth earthquakes[10–14], shows that the slab is stretched at depth along its plunge direction, while shallow foreshocks are occurring above. It seems to logically indicate that its deep part is plunging while its locked upper part is resisting the plunge. This would mean that the slip of the slab at depth has accelerated from its steady-state subduction rate. The shallow foreshocks then show the progressive unlocking of the interface, which begins to slip locally under the deep pull of the plunging slab. In the majority of our observations, the deep burst precedes the shallow one, but sometimes it is opposite. This may reflect the limit of resolution of the catalogues, because the beginning of a burst may involve events too small to be recorded.

These observations also confirm that most large interplate earthquakes are preceded by a preparation phase which involves the slow aseismic slip of the plate interface, with foreshocks representing the breaking of frictional asperities resisting this slow slip[1–6,19,20]. This activity is not continuous in time, but is characterized by bursts with quieter periods in between. This characteristic is reminiscent of the patterns of alternate activity and quiescence that have long been reported before some large earthquakes[21–23].

The synchronization observed between deep seismicity and shallow foreshocks may provide the means to detect the nucleation phase of these giant earthquakes, days or weeks in advance of the rupture. The correlation, over a 1-day-long window, of shallow

($\leq$40 km) and deep ($\geq$80 km) seismicity occurring in a zone of 2° (222 km) radius around the Tohoku epicentre in the two years preceding the earthquake is presented in Fig. 4. It shows that the information that the slab had started to plunge below the seismogenic zone was there, in the seismic data, three weeks before the catastrophic earthquake/tsunami. This type of detection may help mitigate risk in the future.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

M.B. and D.M. originated and developed the study. V.D. contributed to the methodology. M.C., H.P., R.M. and B.G. contributed to the data analysis and interpretation.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.B.

Competing financial interests

The authors declare no competing financial interests.

Methods

Data. This study uses the best known and most complete catalogue of world seismicity. This catalogue is made by the International Seismological Centre (ISC, http://www.isc.ac.uk) and is the result of long-lasting cooperation between over 130 national and regional agencies worldwide in charge of monitoring seismic activities. For events in Japan, this catalogue provides the JMA (Japan Meteorological Agency) locations and magnitudes that we use almost exclusively. For events in Chile, most of the data we use originate from the Centro Sismologico Nacional of Chile.

Analysis. The shallow seismicity shown in Figs 1 and 3 includes the events located in a circle which corresponds closely to the extent of the reported zone of foreshocks. For the Tohoku earthquake, this circle has a radius of 0.5° (55 km) and is centred on the epicentre of the large 9 March M_w 7.3 foreshock, which lies in the middle of the foreshock area, rather than on the 11 March epicentre, which lies at its edge[1,15,16]. For the Maule earthquake (Supplementary Fig. 2), the same size circle centred on the epicentre is considered. For the Iquique earthquake, where the farthest reported foreshocks are located 130 km away from the epicentre[3,4], this zone has a radius of 130 km and is centred on the epicentre. In depth, this shallow seismicity zone extends between 0 and 40 km. Because regular background seismicity is low in and around this zone for the three cases considered, its spatial extent is not critical, as long as it is large enough to include all known foreshocks.

The deep seismicity shown in Figs 1a,b and 3, and Supplementary Fig. 2 corresponds to events deeper than 80 km located within 2° (222 km) of horizontal distance from the epicentres. As we are interested in the part of this zone which lies down-dip from the hypocentre, we limit it for the Tohoku and Maule earthquakes to the sector which lies within an angle of 45°, measured at the epicentre, from the direction in which the slab plunges. For the Iquique earthquake, where the foreshock area is very large, the whole zone is considered. The 2° radius is chosen because it is large enough to include intermediate-depth seismicity, but the particular value considered is not critical. Our choice of two well-separated depth ranges, $0 >$ depth ≥ 40 km for shallow events, and ≥ 80 km for deep events, is to clearly separate the two populations and to avoid uncertainties in depth location possibly mixing the two populations.

The deep background seismicity of Fig. 1a contains 330 $M > 1$ events. The location of the three largest deep Tohoku pre-shocks (16 Feb. $M4$, 21 Feb. $M4.2$, 4 March $M3.1$) is shown in Fig. 1c.

The correlation of shallow (≤ 40 km) and deep (≥ 80 km) seismicity presented in Fig. 4 includes all the seismic events located within 2° (222 km) of horizontal distance from the Tohoku epicentre. This correlation is made over a 1-day-long moving window and represents the product of the shallow and deep seismic moments released in the same time window. It is normalized to its peak value. The zone considered is nearly as wide as the one which will rupture during the earthquake.