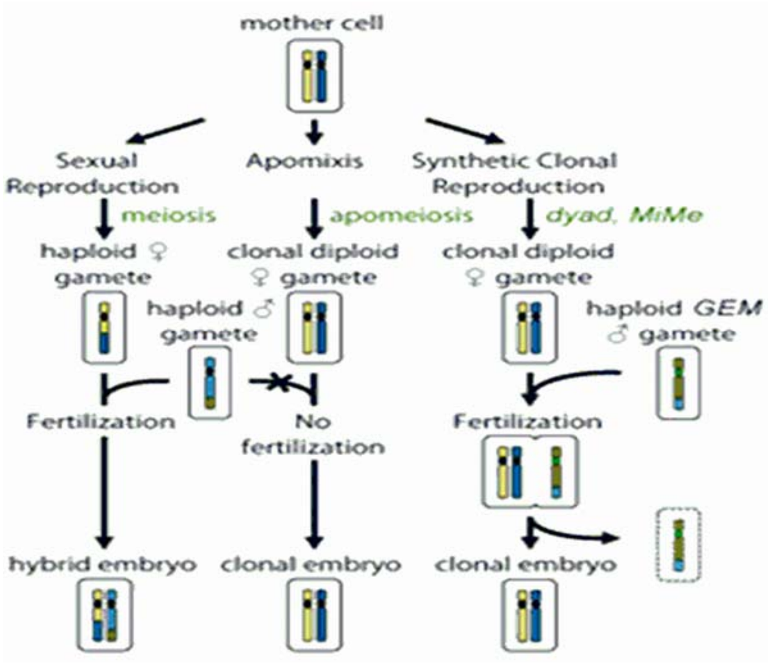

Figure 1. Schematic representation of gametes at sexual reproduction, apomixes and synthetic clonal reproduction (http://www.international.inra.fr/press).

strain whose chromosomes are engineered to be eliminated after fertilization. Up to 34% of the progeny were clones of their parent, demonstrating the conversion of clonal female or male gametes into seeds.

According to Siddiqui, the model plant, *Arabidopsis thaliana* belongs to the mustard family and shown that it is possible to retain hybrid vigour of plants by manipulating known genes that function during normal sexual reproduction and cell division. The hybrids in crops that are made by crossing two varieties lose their vitality over successive generations because of underlying genetic combinations. 'If, however, we can reproduce seeds by apomixis, then hybrid vigour will be maintained as it will be the exact clone of its parent,' Siddiqui explained.

This would reduce the cost of hybrid seed production, and the farmer would be able to multiply his own hybrid seeds and not be compelled to buy them for every planting.

The process will also cut short years of research required in traditional multiplication of hybrid seeds. However, according to CCMB scientists, the application of the fruits of their research to food crops like rice would take 5–10 years.

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Post-mortem of the Japanese earthquake provides new insights

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Much has been written about the 11 March 2011, M_w 9.1 Tohoku-Oki earthquake, that occurred off the northern Japanese coast owing to the unprecedented fury of the tsunami it generated and the destructive impact it had on a coastal nuclear power plant in northern Japan (Figure 1). It will take a long time to contain the fallout from the accident at the Fukushima (Daiichi) Nuclear Power Plant. Apart from the technical and economic challenges of the clean-up, the accident has put a rather large, indelible question mark on the future of the global nuclear power industry, particularly because of the sweeping European reaction which followed in the aftermath of the disaster, targeting the long-term closure of such critical facilities. In any case, the Japanese earthquake is a watershed event in the history of natural disasters, as it puts similar future potential coastal threats in an entirely new perspective, requiring out-of-the-box solutions.

From a scientific point of view, this earthquake has become a cause célèbre of sorts among seismologists, not in the least for the fact that it is one of the better monitored and recorded earthquakes in history. The three papers (http://scim.ag/MSimons, http://scim.ag/S-Ide and http://scim.ag/M-Sato) are but the first instalment in the expected series of papers that will be read and discussed in various forums in the years to come. These papers[1–3] analyse the earthquake

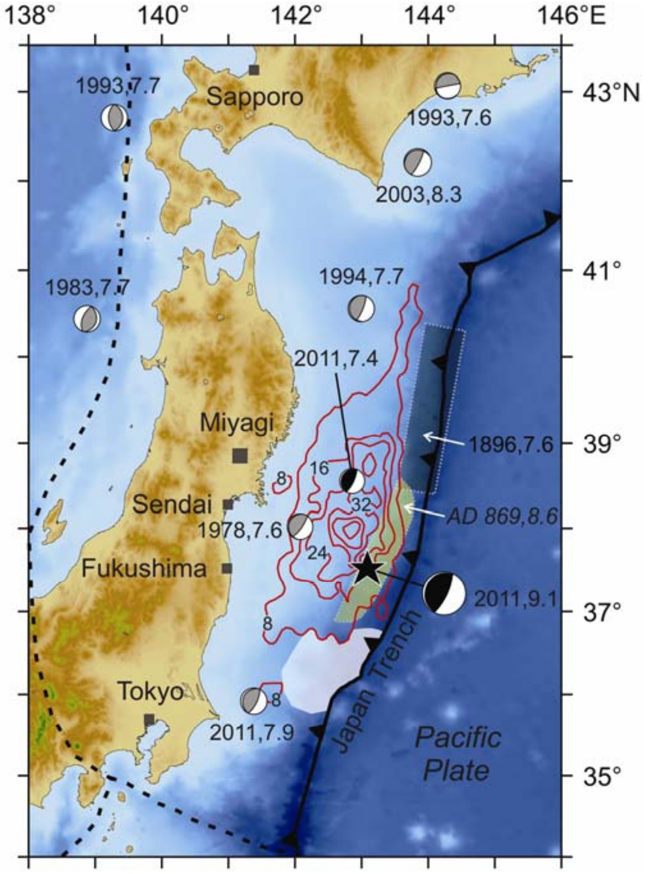

Figure 1. Area shown here covers the southern Hokkaido and Honshu Islands of Japan with four major cities and the Miyagi prefecture marked by dark grey squares. Line with saw tooth pattern is the Japan Trench, where the Pacific Plate subducts northwest – beneath the Eurasian Plate. The dashed line marks the boundary between two microplates, the Phillippine Sea Plate to the South and the Okhotsk Plate to the North. Black star denotes the location of the 2011 mainshock (M_w 9.1). Beach balls represent focal mechanisms (with compressional quadrants in grey) of the $M_w > 7.5$ earthquakes occurred since 1977 (source: the Harvard Centroid Moment Tensor (CMT) database). Focal mechanisms for the March 2011 foreshock (M_w 7.4) and mainshock with compressional quadrants in black are also shown. The red lines indicate the modelled coseismic slip contours at 8 m intervals, after Simons *et al.*[3]. The tsunami source regions for two historical events discussed in the text AD 1896 (M 7.6) Sanriku and the AD 869 ($\geq M$ 8.6) Jōgan events are marked in yellow and grey shades, after Tanioka and Seno, and Minoura *et al.*[5,9] respectively. The white shaded region marks an asperity with high seismic hazard potential[3].

rupture characteristics and coseismic displacements, along with their modelled outcomes and consequences. What emerges from these studies is surprising in the sense that the causative fault appears to be highly heterogeneous and complex rather than simple, in terms of its surface properties. Consequently, the amount and the speed of the fault slip were not uniform, which has a strong bearing not only on the intensity of shaking but also on the size of the tsunami that followed. The earthquake occurred at the plate boundary of the North American and the Pacific plates, and the maximum slip during the earthquake was calculated to be greater than 20–30 m based on the data generated from campaign-mode seafloor geodetic measurements before and after the earthquake[2]. But the models based on regional geodetic and seismological data suggest that the plate boundaries in this region slipped past each other by more than 50 m in some places (Figure 1)[3]. This rate of displacement is high by any known standards.

Unlike the 2004 Andaman–Sumatra and 2010 Maule, Chile events, the Tohoku-Oki earthquake had a sequence of foreshocks. The largest of these was the M_w 7.3 earthquake that occurred 45 km away from the mainshock. Due to its size, location and similar faulting style, Ide *et al.*[1] in their paper used the seismic characteristics of this foreshock to understand the fault plane properties of the mainshock, employing an approach that involves using an empirical Green's function. This commonly used method involves deconvoluting the teleseismic and regional broadband data for a small event from the corresponding signals at the same stations for a large mainshock. The deconvolution corrects each mainshock seismic record for path effects and instrument complexities and if the faulting mechanisms and focal depths are identical, it provides relative source time functions for the mainshock that includes the rupture directivity. This method is much more convenient, compared to numerically simulating synthentic seismograms of the event, as it requires no modelling of the structural complexities of the source region of the earthquake. By inverting broadband data from 50 Global Sesimographic Network stations, Ide *et al.*[1] reconstructed the temporal and spatial variations of the slip distribution during the Tohoku-Oki earthquake. The results suggest that the rupture was initially slow and picked up speed as it propagated updip toward the trench axis. A 30 m slip, the highest according to their model, was concentrated at shallow depths from where high-frequency waves were weakly radiated vis-à-vis the deeper part of the rupture zone where the slip was minimal.

According to Ide *et al.*[1], the earthquake is characterized by two rupture modes: a deep energetic phase and a shallow slow phase – a property that may be intimately related to the frictional properties of the subduction interface. In terms of the rupture mode, the Tohoku-Oki earthquake is, therefore, different from the earlier historical tsunamigenic earthquakes of lesser magnitude in the vicinity (e.g. the 1896 and the 1994 Sanriku-Oki M_w 7.6 events that had anomalously high tsunamis for their magnitudes; Figure 1), whose updip rupture propagation speeds were considered to be slower at shallow depths[4]. According to Ide *et al.*[1] a large slowly propagating slip at shallow depths without an energetic slip at greater depths is what resulted in the Sanriku-Oki earthquakes having unusually high tsunamis (for their seismic slip). Slow earthquakes may include a component of aseismic deformation at the top of the trench interface that may involve the deformation of the sedimentary prism[5]. Doubts have been raised whether the 2004 Andaman–Sumatra event was also a tsunami earthquake[6].

Here is an interesting question. What created the condition of the slow updip propagation of the rupture? In this regard, I think it is equally important to understand more about the 1896 Sanriku earthquake, which was considered a slow earthquake, with a rupture speed of 1–1.5 km/s compared to the rupture speed of about 3 km/s of a normal earthquake. The slowness of rupture may not be the only condition for the generation of large tsunamis. An additional uplift of the sediment at the toe of the trench also needs to be considered[5]. Although the paper by Ide *et al.*[1] does not say so explicitly, the question that arises naturally is whether we, in fact, deal with two classes of earthquakes in this region: the more frequent Sanriku-type shallow tsunami earthquakes and the Tohoku-type deeper but infrequent mega-earthquakes that overlap the rupture zones of the smaller events. Is it possible that an amplified uplift of the accretionary prism occurred during the Tohoku-Oki earthquake?

The results of the companion paper by Simons *et al.*[3] suggest that most of the fault slip may not have 'extended below this (the active accretionary prism) zone' except in the central part of the rupture area where a maximum slip of 5–15 m is modelled. Though the amplified deformation of the accretionary sediment wedge may not be apparent from these studies, Simons *et al.*[3], who use the regional geodetic (including seafloor pressure gauge data) and seismological data for their model, also agree that for the Tohoku-Oki earthquake, the deeper parts of the slipped area witnessed a more energetic rupture compared to the shallow regions. Overall, they state that the energy radiation was slow compared with say, the 2010 Maule, earthquake. To develop an image of the rupture process, these authors use the inversion of teleseismic array waveforms, a technique different from Ide *et al.*[1]. Both these teams obtain similar results, in so far as the variation in energy radiation in the deeper versus shallow parts of the rupture zone is concerned. The second paper, however, goes more into the interpretational aspects. For example, Simons *et al.*[3] suggest that efficient radiation of energy at the deeper part of the fault plane is due to the presence of frictional heterogeneities near the brittle-plastic transition zone: the reason why the 2010 Maule event, a lesser magnitude but a deeper earthquake, showed high frequency (HF) excitation.

Another interesting aspect of this study is their identification of a small region within the rupture area showing a high stress drop, which essentially suggests a long-living unbroken patch where more stress accumulation is expected. It gives us a clue as to what probably happened and why the Tohoku-Oki earthquake became a segment-breaking mega-earthquake – it was born when this stronger barrier (or asperity) broke and the surrounding areas (although broken earlier) with lower thresholds of failure, were caught up in the breaking spree. The authors suspect that a subducted sea mount defining the asperity may be present in the central part of the rupture zone. Further, they predict that such a mechanism could be active south of the southern extremity of the Tohoku-Oki rupture zone, located close to Tokyo. Though the Tohoku earthquake did not rupture the shallow part of the fault in this region, it might have transferred some stress, thus increasing the overall stress in that portion of the fault. We have two possibilities that arise from this conclusion; either the fault is slipping aseismically or it is locked and will break at an appropriate time, when sufficient stresses have accumulated. It is not difficult to find recent examples of major earthquakes that follow mega-earthquakes, due to these stress transfer processes. Nearer home, we have had the 2005 M_w 8.6 Nias–Simeulue event, to the south of the 2004 Andaman–Sumatra earthquake rupture, triggered by the stress transfer processes associated with the 2004 mainshock. Models for this event show two distinct well-constrained primary ruptures to the north and south of the hypocentre, with a deeper coseismic slip of 8 and 11 m respectively, but little seafloor movement. No tsunami followed this earthquake[7]. I do not want to bet on this issue: it is equally possible that the anticipated stress transfer may not occur on the southern part of the 2011 Japanese earthquake. It is worth noting that the rupture propagation in the case of the 2004 event was unidirectional, unlike the Japanese earthquake.

What emerges from these studies is the overriding importance of the frictional properties of the fault plane in the nucleation processes of earthquakes. The heterogeneities, which include subducted sea mounts or just rheological properties within the trench interface to a large extent, determine the seismogenic characteristics of a subduction zone. That the Japanese Trench part of the subduction zone has a history of magnitude 7 and 8 earthquakes is known[8]. What surprised scientists is the fact that it had the capacity to generate a magnitude 9+ earthquake. Simons *et al.*[3] underscore the fact that there were undetected huge stress accumulators like the unbroken patch within the rupture zone of the Tohoku-Oki earthquake, which may have broken about 1000 years ago, during AD 869 (ref. 9). However, they consider that the concept of a characteristic earthquake with roughly the same slip is not useful for subduction-zone earthquakes. Interestingly, the type area which helped in formulating the concept of characteristic time-dependent earthquakes was the Nankai Trough on the southern part of the Japanese Trench[10]. Studies of the Tohoku-Oki earthquake favour a strong nonlinearity of strain build-up, which in fact corresponds to the heterogeneities of a fault plane. But the fact remains that we have only infrequent 9+ magnitude earthquakes possibly with a 1000 yr recurrence interval. Understanding the geology and physics of structural complexities of the fault zone is the way forward.

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