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Invited review

The crisis of a paradigm. A methodological interpretation of Tohoku and Fukushima catastrophe

Robin Lacassin [a,*], Sylvain Lavelle [b]

[a] *Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Univ Paris Diderot, CNRS, F-75005 Paris, France*
[b] *ICAM Paris-Sénart, Centre Ethique, Technique & Société (CETS), Ecole des Hautes Etudes en Sciences Sociales (EHESS-GSPR), France*

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ABSTRACT

The 2011 Japanese disaster often presented as a 'new Chernobyl' accumulated the effects of earthquake, tsunami and of the subsequent nuclear accident at Fukushima. In the light of this disaster, we review methodological reasons both from geophysical and philosophical perspectives that lead the scientific and technological communities to flawed conclusions, prime cause of the disaster. The origin of the scientific mistake lies in several factors that challenge a dominant paradigm of seismology: the shallower part of the subduction was considered as weak, unable to produce large earthquakes; a complete breakage of the fault up to the sea-floor was excluded. Actually, it appears that such complete rupture of the subduction interface did characterize megathrust ruptures, but also that hazard evaluations and technical implementation were in line with the flawed consensual paradigm. We give a philosophical interpretation to this mistake by weighing the opposition between a prescriptive account and a descriptive account of the dynamics of research. We finally emphasize that imagination, boldness, and openness (especially to alternatives to consensual paradigms) appear as core values for research. Those values may function as both epistemic and ethical standards and are so essential as rigor and precision. Ability to doubt and to consider all uncertainties indeed appears essential when dealing with rare extreme natural hazards that may potentially be catastrophic.

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1. Introduction

Earthquakes are natural physical events with important human, societal and economic consequences. The destructive character of an earthquake depends primarily on geological and physical parameters, such as location, magnitude and geometry of fault rupture. Anthropological studies offer another perspective. Oliver-Smith (1994) claims that "*disasters do not simply happen; they are caused*", adding that this is because "*disasters occur at the interface of society, technology, and environment and are the outcomes of the interactions of these features*" (Oliver-Smith, 1996). The main implication is that there is no disaster without a context of social-historical-political factors that will set up the vulnerability of human groups and settlements (Revet, 2012). In the aftermath of the Lisbon catastrophe of 1755 -accumulating the effects of the earthquake, fire and tsunami- the relative degree of responsibility of Nature and Humans was already subject of debate between Voltaire (1756) and Rousseau (1756). Dynes (2000) suggests that the "*first social scientific view on disaster*" – by Rousseau – clearly stated that the catastrophe was a social construction and that the urban pattern made a city located in a seismic risk area susceptible to damage. In our modern technocratic countries, the political or societal tasks designed to anticipate effects of natural hazards deserve a variety of studies, debates and controversies. In particular, the case of Nature versus Human responsibility is formalized by combining hazard with vulnerability to quantitatively rate the risk and to settle mitigation solutions. It

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* Corresponding author at: IPGP, 1 Rue Jussieu, 75238 Paris CX 05, France.
E-mail address: lacassin@ipgp.fr (R. Lacassin).

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appears that several human and technical factors – including the way sensible infrastructures are structurally engineered – may impact the vulnerability, but forecasting the hazard itself chiefly rests on the scientific expertise which may be affected by large unknowns. Approaches to take into account the range of scientific ideas have been developed by the reinsurance and catastrophe modeling industry to eventually reach a consensus (e.g., Delphi method, Linstone and Turoff, 1975). In fact, social studies of science and technology (Callon et al., 2009) suggest that the process resulting in a dominant scientific perspective at a given moment – the paradigm on which the expertise is based – may adopt the form of a "social construction" (e.g., Tierney, 2007). With these thoughts in mind, we note that the geophysical community rarely questions its ability to deliver a correct expertise to the rest of the society, nor evaluate related epistemic and ethical issues.

After the 2011 Japanese magnitude 9 earthquake and tsunami, and the ensuing nuclear accident at the Fukushima Daiichi plant, an intense debate rose in the geophysical community (e.g., Avouac, 2011; Geller, 2011; Kerr, 2011; Normile, 2011; Sagiya et al., 2011; Stein and Okal, 2011; Kanamori, 2012; Lay, 2012; Stein et al., 2012; Geller et al., 2015), perhaps summed up by breaking titles in *Nature* magazine such as "*Shake-up time for Japanese seismology*" or "*Rebuilding seismology*" (Geller, 2011; Sagiya et al., 2011). That debate revealed community's unease considering what seems to be a failure to have correctly evaluated the earthquake and tsunami hazards before disaster's occurrence. In the light of the Japanese disaster, it appears crucial to re-evaluate theoretical and practical reasons and founding methodological principles, both from physical and philosophical points of view, that lead the scientific and technological communities to somewhat flawed conclusions and actions – or inaction – that should be considered as the prime cause of the disaster. We'll argue that it enlightens the processes leading scientific paradigms to survive and eventually collapse, and the ways scientific models and their uncertainties are implemented – or not – by the technical and political spheres and understood by the rest of the society.

We thus start with a review of the geophysical, technical and societal context to identify the different mistakes that lead to ravage of NE Japanese coastal settlements and to the Fukushima Daiichi nuclear disaster. We then give a philosophical interpretation of those mistakes, before exploring implications in term of epistemic and ethical values and norms that should be kept in mind while forecasting extreme natural hazards. To ensure readability by a large, geophysical and anthropological community, we use footnotes to explain basic seismological and philosophical lexicon, processes and concepts.

2. The geophysical, technical and societal context

The Mw[1] 9.0 2011 Tōhoku-oki earthquake broke a ~500 km long segment of the subduction megathrust[2] that marks the boundary between the Pacific and Okhotsk tectonic plates (Figs. 1, 2). The fault, which dips west beneath Japan, broke from depth ≥ 40 km to its emergence at the sea floor. Coseismic slip[3] was particularly strong on the shallower parts of the fault close to the Japan trench (several tens of meters, possibly more than 50 m, see Fig. 2c), causing large vertical displacements of the sea-bottom just above the fault and provoking huge tsunami waves (e.g., Lay et al., 2011; Simons et al., 2011; Ozawa et al., 2011; Kodaira et al., 2012; Satake et al., 2013; Tajima et al., 2013). On the coast facing the Japan trench, tsunami inundation reached heights typically larger than 15 m, locally 30–40 m, above average sea level (Mori et al., 2011), killing more than 15,000, drowning the Fukushima Daiichi nuclear plant (Fig. 3) and provoking the subsequent nuclear accident. In the past sixty years before that event, at least four Mw 9+ earthquakes – Kamtchatka 1952 Mw 9, Chile 1960 Mw 9.5, Alaska 1964 Mw 9.2, Sumatra 2004 Mw 9.1 to 9.3, and possibly Aleutians 1957 Mw 8.6 to 9.1[4] – broke various subduction megathrust segments worldwide (Fig. 1, see also Fig. 4). As a consequence, the risk of occurrence of such Mw 9+ events on any subduction zone in the World was correctly identified by few authors (e.g., McCaffrey, 2008), although dismissed or ignored by most of the geophysical community. Indeed, the scientific consensus before Tōhoku was that each subduction zone has its own, complex, segmentation and mechanical properties,[5] and that many subduction zones in the World will never produce a Mw 9+. This was admitted for the part of the Japan trench that eventually broke in 2011, where erroneous estimates of potential magnitudes and rupture segmentation resulted in bottom level estimates of the hazards (e.g., Fujiwara et al., 2006; Fujiwara and Morikawa, 2012). But, as noted a posteriori by Stein and Okal (2011), "*the size of the 2011 Tōhoku earthquake need not have been a surprise*". We identify several interwoven causes to what should be considered as a scientific mistake.

Hazard estimates were only based on the detailed analytical record of local past events, which were considered over a too short period of time. The Mw ~ 7.5 earthquakes of the past decades were taken as characteristic of the seismic potential of the subduction offshore Tōhoku. A model of segmented, patchy subduction interface was thus deduced (Fig. 2a) and used for earthquake and tsunami hazard calculations with the aim to produce the official hazard maps (Fujiwara et al., 2006; Yanagisawa et al., 2007; Fujiwara and Morikawa, 2012). It appears that the 2011 event largely overcame that segmentation (Fig. 2c). It is worth noting that those hazard estimates based on the short-term local analytical record were not put in perspective of the worldwide memory of giant megathrust events. Specifically, close to the N in Kamtchatka, the same subduction interface than in NE Japan hosted a very large magnitude (Mw ~ 9) earthquake in 1952 (Fig. 1). The fault segment facing the Tōhoku coast has the same first-order geometrical characters than the one that broke in 1952 offshore Kamtchatka. This should have hint for the potential of earthquakes with much larger rupture zones and magnitudes along the Japan trench.[6] Indeed, the millenary historical record implies that very large events broke the subduction offshore NE Japan in the past. The largest of these events appears to be the 869 AD Jōgan earthquake that gave rise to a tsunami with effects comparable to those of the 2011 Tōhoku-oki event (e.g., Sugawara et al., 2012a, 2012b). Other strong tsunami hit the NE Japan coast in the past centuries (e.g. 1611, 1793, 1896, 1933). Perhaps also akin to 2011's, the 1611 AD Keicho earthquake and tsunami, known from historical and geological records, inundated many places along the Japan coast

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[1] The moment magnitude, noted Mw, is a physical measure of the energy released by the earthquake. Its scale is logarithmic, not linear. A Mw 7 event has 30 times the energy of a Mw 6 (the same relation exists between Mw 8 and 7 or Mw 9 and 8 for example). Here we note Mw9+ for earthquakes with magnitudes ≥ 9.

[2] Subduction megathrusts are extremely large geological faults marking the interface of converging tectonic plates. They dip relatively gently (~10–30°) below the upper plate (Japan in our case) while the lower plate (here the Pacific plate) is sliding downward at a pluri-centimetric rate. The upper part of the megathrust, from depth ~40 km to its emergence at the oceanic trench, moves in a stick–slip way on century time-scale, a process called the seismic cycle. Between large earthquakes, the fault stays locked, and, on each side, upper and lower plates deform and store plate convergence in an elastic (reversible) way. Stresses thus accumulate and eventually reach a yield point generating a massive seismic slip on the fault – itself causing the earthquake – releasing part or totality of the stored elastic strain. Those processes – strain accumulation and catastrophic release – are now accurately measured by geodesy using GPS or other techniques.

[3] The "coseismic slip" represents the amount of slip on the fault that accumulated quasi-instantaneously (tens of seconds to minutes) during the earthquake. That slip generates destructive seismic waves and vertical motion of the sea floor responsible for the tsunami.

[4] Magnitude of the 1957 Aleutian earthquake varies significantly from one study to another.

[5] The magnitude of an earthquake depends on the size of the broken fault or fault segment, and on the coseismic slip. In addition these two parameters are linked by scale-laws. This implies that a small fault, or a very segmented fault will thus be unable to generate large earthquakes.

[6] The same subduction zone also caused large Mw 8+ earthquakes in 1963 and 2006 offshore the Kuril islands (Mw 8.5 and 8.3).