Tsunami hazard assessment in the Makran subduction zone

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Received: 19 March 2018 / Accepted: 18 December 2019 / Published online: 2 January 2020
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Abstract
The lack of offshore seismic data caused uncertainties associated with understating the behavior of future tsunamigenic earthquakes in the Makran subduction zone (MSZ). Future tsunamigenic events in the MSZ may trigger significant near-field tsunamis. Tsunami wave heights in the near field are controlled by the heterogeneity of slip over the rupture area. Considering a non-planar geometry for the Makran subduction zone, a range of random $k^{-2}$ slip models were generated to hypothesize rupturing on the fault zone. We model tsunamis numerically and assess probabilistic tsunami hazard in the near field for all synthetic scenarios. The main affected areas by tsunami waves are the area between Jask and OrMara along the shorelines of Iran and Pakistan and the area between Muscat and Sur along the Oman coastline. The maximum peak-wave height along the shores of Iran and Pakistan is about 16 m and about 12 m for the Oman shoreline. The slip distributions control the wave height along the Makran coastlines. The dependency of tsunami height on the heterogeneity of slip is higher in the most impacted areas. Those areas are more vulnerable to tsunami hazard than other areas.

Keywords Makran subduction zone · Wave height · Heterogeneity of slip · Numerical tsunami modeling · Probabilistic tsunami hazard assessment

1 Introduction

The Makran subduction zone (MSZ) is a convergent plate boundary between the Arabian Plate and the overlying Eurasian Plate with an average convergent rate of about 4 cm/yr. It extends about 900 km from southeastern Iran to southern Pakistan. The 1945 Makran...
tsunami and the possibility of generating future tsunamigenic events by the Makran subduction zone have motivated researches recently to study tsunami hazard in the northwestern Indian Ocean (e.g., Okal and Synolakis 2008; Heidarzadeh et al. 2008a; Rajendran et al. 2008; Heidarzadeh and Kijko 2011; Rehman et al. 2013; El-Hussain et al. 2016; Hoechner et al. 2016).

The occurrence of the 1945 Makran and the evidence of earlier historic earthquakes (e.g., 1008 and 1483) have proved earthquake and tsunami potential of the Makran subduction zone (Byrne et al. 1992; Heidarzadeh et al. 2008a; Smith et al. 2013). It is seismically active, being capable of generating large earthquakes. However, it is segmented into the western and eastern parts from the seismic potential point of view. The active eastern segment generated the 1945 tsunamigenic earthquake ($M_w 8.1$) which caused a regional tsunami with maximum wave heights of 10m and about 4000 human losses (Heidarzadeh et al. 2008b; Rajendran et al. 2013). The potential of the western segment for generating tsunamigenic earthquakes is puzzling due to its apparent aseismicity and the lack of historical data. There has been some confusion in the studies on which behavior can explain the current status of the western Makran. The presence of sediment layers may be the cause of the unusual seismic behavior of western Makran. Until the end of 2004, previous investigations have suggested that the Sumatra subduction zone, at least the northern part, was considered to be sleeping from which tsunamigenic events would not be expected. The lack of historic data on major seismic events during the last 200 years was supporting this misconception. The gigantic 2004 Sumatra-Andaman earthquake strongly disproved this belief. After more thorough investigations, the traces of major tsunamis have been found in sediment deposits on the horizon of 1000 years. The same story may happen to the MSZ, especially for the western segment. The duration of our seismic records and observations is not enough to predict reliably earthquakes in the long term. Another example is the recent Tohoku 2011 tsunamigenic event. The Fukushima nuclear plant was protected against tsunamis, but the chosen tsunami design height was twice smaller than the real wave which hit the plant. One can assume that the western segment is currently locked and capable of generating future plate boundary earthquakes (Musson 2009; Rajendran et al. 2013). This assumption leads to a serious reconsideration of the entire Makran rupturing scenario. Makran subduction zone is characterized as a shallow subduction zone which can increase coupling and provide a suitable condition to release large earthquakes (Gutsch and Westbrook 2009; Smith et al. 2012).

The 2004 Indian Ocean and 2011 Tohoku tsunamis have demonstrated that the scale and impacts of tsunamis can be significantly larger than expected (Suppasri et al. 2013; Satake 2014), showing the need for increasing attention to the hazard potential of subduction zones for worst-case scenarios.

The effect of far-field tsunamis can be suitably evaluated knowing the seismic moment $M_0$ of the submarine earthquake (Dutykh et al. 2012). However, the tsunami hazard of tsunamigenic events in the near field depends on several factors which have increased the researchers’ interest recently (e.g., Dutykh et al. 2011, 2012; Lay et al. 2011; Yamazaki and Cheung 2011; Yamazaki et al. 2011). Although the tsunami propagation per se is well modeled and understood, it can be still problematic due to uncertainties in the rupture details (Greenslade and Titov 2008). As a lesson from the 2004 Indian Ocean and 2011 Tohoku tsunamis, the tsunami generation process and its relationship with seismogenic subduction zones need to be investigated in more detail (Fujii et al. 2011; Ide et al. 2011). The tsunami generation simulation is the controlling step in modeling the life stages of tsunamis and their effects on coastal areas. In the case of tectonic-generated tsunamis, rupture geometry, focal mechanism, seismic moment, and coseismic slip distribution describe
the tsunami generation process. They are required to compute the 3D seafloor deformation caused by rupturing on an underwater fault. Tsunami numerical modeling may fail to predict the true effects of tsunamis by assuming simple uniform slip distributions. Heterogeneity of slip over the fault controls local tsunami wave amplitude variations (Geist and Dmowska 1999), which is necessary to model near-field tsunamis accurately and assess their hazard.

Tsunami hazard can be assessed in three different approaches (González et al. 2009): (1) Probabilistic Tsunami Hazard Assessment (PTHA), (2) worst-case scenario approach (deterministic), and (3) sensitivity analysis. The last one (see e.g., Tang et al. 2006; Barkan et al. 2009) studies the sensitivity of wave amplitude to the characteristics of tsunami sources which does not consider the probability of each scenario (González et al. 2009; Dutykh et al. 2011).

Deterministic approach (e.g., Parsons 2008; Priest et al. 2009) considers particular scenarios (usually the worst-case scenario) to calculate their effect on specific areas. Probabilistic Tsunami Hazard Assessment (PTHA) provides a useful tool to evaluate tsunami risk by considering the probabilities of tsunamis. It determines the likelihood of tsunami severity usually in terms of tsunami wave height for a range of possible sources. PTHA computes the probability of tsunami wave height at a given location that exceeds a certain level in a specified time period. It was developed by Lin and Tung (1982), Rikitake and Aida (1988), and Downes and Stirling (2001) by modifying the probabilistic seismic hazard assessment (PSHA). Increased attention has been paid recently to PTHA, especially after the 2004 Indian Ocean tsunami (e.g., Geist and Parsons 2006; González et al. 2009; Grezio et al. 2012; Sørensen et al. 2012; Horspool et al. 2014). PTHA in Makran has been also a subject of interest to some researchers (e.g., Heidarzadeh and Kijko 2011; El-Hussain et al. 2016; Hoechner et al. 2016).

In our previous study (Rashidi et al. 2018), the evolution of kinetic, potential, and total energies in the near field was studied for a multi-segment source model of the Makran subduction zone. An empirical relationship between the moment magnitude and tsunami wave energy in the Makran subduction zone was obtained. In the current study, we model hypothetical earthquakes generated by the entire Makran subduction zone and perform PTHA. Heterogeneous slip distribution patterns are considered to represent the complexity of earthquakes. Spatial non-uniform slip models are a better approximation of the rupture complexity to model seismic sources (Ruiz et al. 2015); however, it is ignored in many tsunami studies assuming simple source models (Geist 2002). The current study is focused on the $k^{-2}$ rupture model, introduced by Bernard and Herrero (1994) and developed by Gallovič and Brokešová (2004). The distributions of wave height along the shores of Iran, Pakistan, and Oman are used in our analysis and assessment.

## 2 Methodology

### 2.1 Earthquake source models

Heterogeneity of slip in plate boundary events greatly impacts the vertical seabed displacement and thus the tsunami generation (Geist 2002). The lack of offshore seismic data has limited our understanding of the present-day behavior of the Makran subduction zone and insight into the complexity of slip distribution of possible future events. Alternatively, synthetic slip models can be useful tools to exhibit the complexity of tsunamigenic sources
and to understand their effects in the Makran region. Using \( k^{-2} \) stochastic source models, we generate digital static tsunamigenic ruptures to model near-field tsunamis. Bernard and Herrero (1994) proposed the so-called kinematic self-similar rupture model in which spectral amplitudes of a random slip distribution decay as the power of 2 at high wave numbers \( k \) beyond the corner wave number \( k_c = 1/L_c \), where \( L_c \) is the characteristic dimension of the fault (usually the length) (Gallovič and Brokešová 2004). The slip does not depend on \( k \) below \( k_c \). In the case of a rectangular fault with a length of \( L \) and a width of \( W \), the 2D slip distribution \( D(k_x, k_z) \) can be written as its spatial Fourier spectrum (Gallovič and Brokešová 2004)

\[
D(k_x, k_z) = \frac{\Delta \bar{u} L W}{\sqrt{1 + \left( \frac{k_x L}{K} \right)^2 + \left( \frac{k_z W}{K} \right)^2}} e^{i\Phi(k_x, k_z)},
\]

where \( \Delta \bar{u} \) is the mean slip and \( \Phi(k_x, k_z) \) is the phase spectrum, \( k_x \) and \( k_z \) are the wave number components along the \( x \) and \( z \) directions, and \( K \) is a dimensionless constant which determines the smoothness of slip distribution (Gallovič and Brokešová 2004). Based on Somerville et al. (1999), \( K < 1 \) is suggested, which corresponds to smoother slip distributions.

To define rupture scenarios, a non-planar fault geometry (Fig. 1) is constructed by modifying the plate interface and deformation front from Smith et al. (2013). The southwest apex of the fault is located at 24.62°N and 57.68°E. The depth of the upper edge is 6km, and the fault bottom reaches 18 km depth. The width of the fault is 210 km, which correspond to the limit of significant offshore seismicity (Smith et al. 2013). The total length of the fault is about 900 km. The fault is divided into 1024 (64 × 16) subfaults, each with a dimension of 14 km × 13 km. The parameters of the mechanism of earthquake sources used in this study are: strike 251° – 287°, dip 2° – 8°, and rake 90°. Smith et al. (2013) presented three potential rupture scenarios in the Makran region including the full length of the Makran subduction zone, eastern Makran segment, and Sistan suture zone to Little Murray Ridge. They considered a coseismic slip of 10m for each scenario. Motivated by this work and considering a range of uncertainty, 100 random heterogeneous \( k^{-2} \) slip distributions are generated for hypothetical earthquakes using \( 10 \pm 1 \) m of mean coseismic slip and \( K = 0.5 \pm 0.2 \). Figure 2 shows one of \( k^{-2} \) slip distributions for the Makran subduction rupture, for instance.

2.2 Tsunami numerical modeling

To provide the initial condition for tsunami modeling of earthquake scenarios, the seabed static deformation is computed using the Okada solution (Okada 1985) (Fig. 2). We simulate tsunamis using the ComCot numerical model (Liu et al. 1998) which uses explicit staggered leapfrog finite difference schemes to solve both linear and nonlinear shallow water equations in both spherical and Cartesian coordinates. ComCot is a well-known and validated numerical tool that is used widely for investigating near-field and far-field tsunamis (e.g., Wang and Liu 2005, 2006; Barkan and ten Brink 2010; Heidarzadeh and Satake 2014). All simulations are performed for a total run time of 10h with a time discretization step of 2s. The bottom friction is considered in the simulations. A small constant Manning’s roughness coefficient of 0.013 is specified for our simulations, which has been used in different studies to model tsunamis by ComCot for water areas (e.g., Huang et al.
Fig. 1 Upper panel: seismicity of the Makran subduction zone (for M4.0+ and between 1926 to 2016 from the ISC catalog). The star shows the epicenter of 1945 Mw 8.1 Makran earthquake. The white outline represents the estimate of the approximate rupture area of the 1945 event (Byrne et al. 1992). The color of circles indicates the depth of events. The red line is the deformation front by Smith et al. (2013). The thick black line orthogonal to the deformation front denotes the cross section. The non-planar mesh is the rupture geometry. Lower panel: cross section of the fault geometry (black line) and the plate interface (dashed red line) from Smith et al. (2013)

Fig. 2 An example of a $k^{-2}$ slip model for the Makran subduction zone (left panel) and the resulting vertical seafloor deformation (right panel). The non-planar mesh is the rupture geometry
Nonlinear shallow water equations are discretized in spherical coordinates. Tsunami inundation on dry land is not computed due to the lack of high-resolution local bathymetry and topography data. Therefore, we have to use a global bathymetry grid for our purpose. The GEBCO 30arcsec bathymetry data (Smith and Sandwell 1997; Becker et al. 2009), available at http://www.gebco.net/, are used for our simulations.

### 2.3 Tsunami hazard assessment

The wave height distributions along the shorelines of Iran, Pakistan, and Oman resulted from tsunami modeling of heterogeneous slip models are used to assess the probabilistic tsunami hazard. Computing annual rate of earthquakes as tsunami generators is required in PTHA. The well-known Gutenberg–Richter law (Gutenberg and Richter 1954) has been the most common expression to estimate the annual rate of occurrence of seismic events. It can be applied in the classic open-ended form (Gutenberg and Richter 1954) or in the truncated form (Cosentino et al. 1977; Weichert 1980). The truncated Gutenberg–Richter model (Cosentino et al. 1977; Weichert 1980) is preferred because it leads to finite energy release rates and finite rupture extents. In this study, the truncated Gutenberg–Richter relation (Cosentino et al. 1977; Weichert 1980) is applied to compute the annual rate of occurrence of the earthquakes (Fig. 3) using events from 1926 to 2016 driven from the ISC catalog (Fig. 1):

\[
v(M) = v(M_{\text{min}}) \left(1 - \frac{1 - e^{-\beta(M-M_{\text{min}})}}{1 - e^{-\beta(M_{\text{max}}-M_{\text{min}})}}\right), \quad \beta = b \ln 10,
\]

(2)

where \(v(M)\) is the annual occurrence rate of earthquakes with magnitude \(\geq M\), \(M_{\text{max}}\) is the maximum magnitude considered in the truncated Gutenberg–Richter relationship, and \(M_{\text{min}}\) is the threshold or completeness magnitude of the earthquake catalog. The \(b\) value is the slope of line in the Gutenberg–Richter relation and represents the relative abundance of large to small events. We consider a maximum magnitude of 9.2 based on Smith et al.

![Figure 3](image-url)  
**Fig. 3** Truncated Gutenberg–Richter (TGR, solid red line) and Gutenberg–Richter (GR, dashed blue line) relationships for the seismicity of Makran subduction zone between 1926 and 2016 from the ISC catalog
Applying the maximum likelihood method (Weichert 1980), the resulting magnitude of completeness is 4.7 and the b value 0.8. In Eq. (2), \( v(M_{\text{min}}) \) is the annual occurrence rate of the events having a magnitude greater than or equal to \( M_{\text{min}} \), that is calculated from the Gutenberg–Richter relationship (Fig. 3).

The occurrence of tsunamigenic earthquake scenarios is assumed to be a Poissonian process. Therefore, the annual probability of a tsunamigenic scenario, \( S_i \), with the annual occurrence rate \( v_i \) can be obtained as follows:

\[
p(S_i) = 1 - e^{-v_i}. \tag{3}
\]

For a total number \( N \) of tsunamigenic sources, the probability of tsunami wave amplitude \( \zeta \) exceeding a specific value \( \zeta_c \) at a given coastline in a time period \( T \) can be written as

\[
P(\zeta \geq \zeta_c) = 1 - \prod_{i=1}^{N} \left[ 1 - (1 - e^{-v_i T}) P(\zeta \geq \zeta_c | S_i) \right] \tag{4}
\]

where \( v_i \) is the annual occurrence rate of \( i \)th scenario \( S_i \) and \( P(\zeta \geq \zeta_c | S_i) \) is the probability that tsunami wave amplitude \( \zeta \) resulted from \( i \)th scenario \( S_i \) exceeds the given value \( \zeta_c \) which is 1 if \( \zeta \geq \zeta_c \) and 0 if \( \zeta < \zeta_c \).

### 3 Results

Figure 4 shows wave height distributions from all scenarios along the coastlines of Iran and Pakistan. The computed mean, lower, and upper wave height bounds along the coastlines of Iran and Pakistan are also represented in Fig. 4. The same results for the coastline of Oman are shown in Fig. 5. The mean wave height along the shores of Iran and Pakistan ranges between 0 and 7m, while it changes between 0 and 6m along the Oman coast. The maximum wave height reaches a value of \( \sim 16 \)m along the shores of Iran and Pakistan and \( \sim 12 \)m for the Oman shoreline. The tsunami wave height attenuates to the west and east of the Iran–Pakistan shoreline. The highest wave heights along the shore are observed near the ports of Chabahar and Jiwani. In the case of Oman coast, an area between Muscat and south of Sur encounters the largest wave heights. Tsunami wave heights attenuate to the south of Oman coastline, especially around the Masirah Island. Table 1 shows the estimated mean and maximal wave heights in some major coastal cities along the shores of Iran, Pakistan, and Oman.

Figure 6 shows the histograms of wave heights along the coastlines of Iran, Pakistan, and Oman and at several selected ports. About 90% of tsunami waves cause a wave height up to 4m. Among the selected locations, Chabahar is impacted by a larger number of higher wave heights. Jask is exposed to the least hazard with maximum wave heights mainly from 1 to 2m.

The results of PTHA are presented in Figs. 7, 8, 9 and 10. Figures 7 and 8 illustrate the tsunami probability maps for thresholds of 0.5m and 3m wave heights. The threshold values of 0.5m and 3m are selected based on Horspool et al. (2014) that correspond to a tsunami warning and a major tsunami warning, respectively. A major tsunami warning is related to a tsunami that can lead to major land inundation and put coastal communities in serious danger (Horspool et al. 2014).

In Fig. 7, we display the probability of tsunami wave height exceeding the 0.5 m threshold along the coastlines of Iran, Pakistan, and Oman over a period of 50, 250, and 1000
Fig. 4 Wave height distributions simulated in this study (gray lines) and mean (black dashed line), lower (blue dotted line) and upper (red dot-dashed line) wave height bounds along the coastlines of Iran and Pakistan.

Fig. 5 Wave height distributions simulated in this study (gray lines) and mean (black dashed line), lower (blue dotted line) and upper (red dot-dashed line) wave height bounds along the coastline of Oman.
years. Unless for an area around the Masirah Island, the probability to exceed the 0.5m tsunami amplitude is uniformly distributed along the entire coastlines of Oman, Iran, and Pakistan in different time periods. The estimated probability of tsunami wave height exceeding 0.5m in 50 years is close to 0.6 for most areas along the Iran–Pakistan and Oman shorelines. The results show that the probability of a tsunami wave exceeding 0.5m for time periods of 250 and 1000 years reaches 1 along the coastlines of Iran, Pakistan, and Oman.

### Table 1

| City      | Mean estimated wave height (m) | Maximal wave height (m) |
|-----------|-------------------------------|-------------------------|
| Jask      | 1                             | 2                       |
| Konarak   | 4                             | 11                      |
| Chabahar  | 5                             | 10                      |
| Jiwani    | 2                             | 5                       |
| Pasni     | 3                             | 6                       |
| Ormara    | 4                             | 8                       |
| Muscat    | 5                             | 8                       |
| Sur       | 5                             | 9                       |

![Fig. 6](image1.png) Histograms of wave heights along the coastlines of Iran–Pakistan (a) and Oman (b) and for selected ports (c)
Figure 8 shows the probability of tsunami wave amplitude exceeding 3m evaluated for coastlines of Iran, Pakistan, and Oman in time periods of 50, 250, and 1000 years. Distributions of the exceedance probability in 50, 250, and 1000 years illustrate a relatively
similar pattern along the shorelines. The probability of exceeding 3m increases with time. However, its changes in the west and east of Iran–Pakistan shoreline and west of Muscat are insignificant. For a region between Jask and Ormara along the Iran–Pakistan shoreline, the probability of exceedance is high. It ranges from 0 to 0.56 in 50 years and reaches 1 in 1000 years for most locations between Jask and Ormara. The exceedance probability is significant between Muscat and Sur, ranging from 0 to 0.99 (~1) in 250 years. It decreases to less than 0.11 to the west of Muscat.

Figure 9 shows the probability of exceeding different wave heights at one or more locations along the coastlines of Iran–Pakistan (left panel) and Oman (right panel). Solid lines indicate robust fitting.
4 Discussion and conclusions

Taking into account a range of near-field source models, our tsunami simulations show that the maximum wave height reaches 16m along the coastlines of Iran and Pakistan. The minimum bound of tsunami wave height exhibits a relative uniform distribution which can match with wave height from a uniform slip distribution (Ruiz et al. 2015). The results of our simulations show that near-field tsunami height along the coastlines depends on the slip distribution of tsunamigenic events. Different slip models result in different patterns of wave height along the shores, especially for the zones located parallel to the rupture area. The patterns of wave height from non-uniform slip distributions are more complex than uniform slip distributions. Moreover, the resolution of bathymetry can largely affect wave heights. Clearly, the higher the resolution bathymetry grid has, the more the accurate wave height computation is. Besides the different slip distributions, the non-uniform shape of the Iran–Pakistan coastline due to the presence of different coastal features influences the pattern of wave amplitude. A high variability of tsunami wave heights can be seen between 58.5°E and 65.3°E, which corresponds to the concentration of slip over the rupture area. This part of the shore is the most affected area by tsunamis. To the west and east of Iran–Pakistan shoreline, the dependency of tsunami wave height to the heterogeneity of slip relatively decreases. It reflects a lower uncertainty of tsunami height in these areas.

For the coast of Oman, the variability of wave height is high in an area between Muscat and Sur. The uncertainty of tsunami wave height showed by lower and upper wave height bounds is lower in other parts of the Oman shore. To the south of Oman’s eastern tip, wave heights are highly attenuated around the Masirah Island because of the tsunami waves scattering. However, it seems that tsunami heights amplify locally to the south of the Masirah Island due to multiple reflections of tsunami waves.

The probabilistic tsunami hazard for the central part of Iran–Pakistan shoreline and the area between Muscat and Sur is quite considerable. Tsunami waves deplete their energy mainly along those areas. The location of western and eastern parts of Iran–Pakistan shoreline and the west of Muscat with respect to the extent of slip on the fault area causes very weaker wave amplitudes and thus lower levels of tsunami hazard in comparison with the central areas. Scattering of tsunami waves around Oman’s eastern tip can dissipate tsunami waves energy and cause attenuated wave height to the south of Oman. While the tsunami hazard probability increases with time along the most affected areas, it stays nearly constant in other areas. The short-term (50 years), midterm (250 years), and long-term (1000 years) tsunami hazards along the main affected areas are significant which make them highly vulnerable to tsunami hazard. Other areas are less susceptible to tsunami hazard. Tsunami hazard variability with time depends on the size and magnitude of the tsunamigenic scenario. This study presumes a certain size of the Makran rupture area with a limited range of magnitudes. Considering different sizes of rupture areas with different magnitudes will change the results. In general, Iran is more vulnerable than Pakistan and Oman to tsunami hazard from the entire Makran subduction zone. High tsunami wave heights are distributed along a broader area for the Iranian part of the shoreline.

This study takes into account the effect of slip heterogeneity on tsunami hazard along the shorelines of Iran, Pakistan, and Oman considering a range of uncertainty for mean slip value and slip distribution. Future works should consider the effects of other factors on tsunami wave height along those coastlines (e.g., fault parameters, the dynamic
bottom motion, other near-field and far-field tsunamigenic sources, etc.). Besides, high-resolution site-specific bathymetric/topographic maps are required to improve the results of our study and to compute the tsunami inundation of dry land.

The high-level long-term tsunami hazard of Makran subduction zone indicates the need of preparedness for future events, especially by developing a regional tsunami early warning system for Makran coastlines. Special attention needs to be paid to the central part of Iran–Pakistan shoreline and the area between Muscat and Sur. Local authorities might be interested to use the results of this study alongside other relevant publications in order to increase the protection level of coastal facilities. The Makran subduction zone is a common threat for different countries, especially Iran, Oman, Pakistan, and India. Collaborative studies, sharing data, and tsunami awareness education can constructively mitigate the Makran tsunami hazard.

Acknowledgements

We would like to thank the developers of COMCOT numerical model (Liu et al. 1998). Figures were drawn using the GMT software (Wessel and Smith 1991). We would like to express special thanks to the Editor, Prof. Thomas Glade and two anonymous reviewers for their constructive and thoughtful comments. A. Rashidi would like to acknowledge the hospitality of the Department of Earth Sciences, Uppsala University, Sweden, and the Laboratory of Mathematics (LAMA UMR 5127), University Savoie Mont Blanc, France.

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