

# Seismogenic Potential of the Subduction Zone in Northern Chile

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## ABSTRACT

The northern Chile region of the Nazca subduction zone ruptured in an  $M_w \sim 8.5$ – $9.0$  earthquake in 1877, which induced a tsunami. The various magnitude estimates of this event are based on the evaluation of historical records, seismic intensities, and/or tide gauge information; however, its actual along-strike extent is debated. Based on geodetic data, the previous studies have suggested that this region has the potential for an  $M_w$  8.2–8.8 event. We re-evaluate the seismic potential of the region, accounting for the buildup rate of moment deficit along the megathrust, the earthquake magnitude–frequency distribution, and the physics of earthquakes. We combine an improved probabilistic estimate of moment deficit rate with results from dynamic models of the earthquake cycle, testing, in particular, the influence of a potential aseismic barrier near the city of Iquique, which may influence the extent and magnitude of large events in this region. We find that  $M_w$  8.8 is the most probable maximum magnitude earthquake in the region, and that the potential barrier likely has a limited impact considering uncertainties. We discuss the effect of the moment deficit rate on the fault, the  $b$ -value, and the importance of postseismic processes on our results.

## KEY POINTS

- Probabilistic estimate of the seismic potential of the Nazca subduction zone in northern Chile.
- An  $M_w$  8.8 is the most probable maximum magnitude earthquake considering four physical and statistical constraints.
- The potential frictional barrier near Iquique has a limited impact on our estimates considering uncertainties.

## Supplemental Material

## INTRODUCTION

Prior to the 1995 Antofagasta earthquake, the last  $M_w > 8$  megathrust earthquake that ruptured the Nazca subduction zone in northern Chile (latitude  $25^\circ$ – $19^\circ$  S) occurred in 1877, and the subsequent tsunami devastated the Chilean–Peruvian coast and reached throughout the Pacific (Lomnitz, 2004). The along-strike extent of the earthquake is poorly constrained, but most studies agree that this event did not rupture south of the Mejillones peninsula (e.g., Kausel, 1986; Métois *et al.*, 2013; Ruiz and Madariaga, 2018). Although debated, the northern extent of this event probably lies between the southern limit of the 1868  $M_w \sim 8.8$  earthquake and the city of Iquique (Métois *et al.*, 2012; Villegas-Lanza *et al.*, 2016; Fig. 1a). The 1877 event magnitude has been estimated using historical records, seismic intensities and tide gauges, and ranges from  $M_w$  8.5–9.0 (Montessus de Ballore, 1916; Abe, 1979; Kausel, 1986; Ramirez, 1988; Comte

and Pardo, 1991; Ruiz and Madariaga, 2018; Vigny and Klein, 2022).

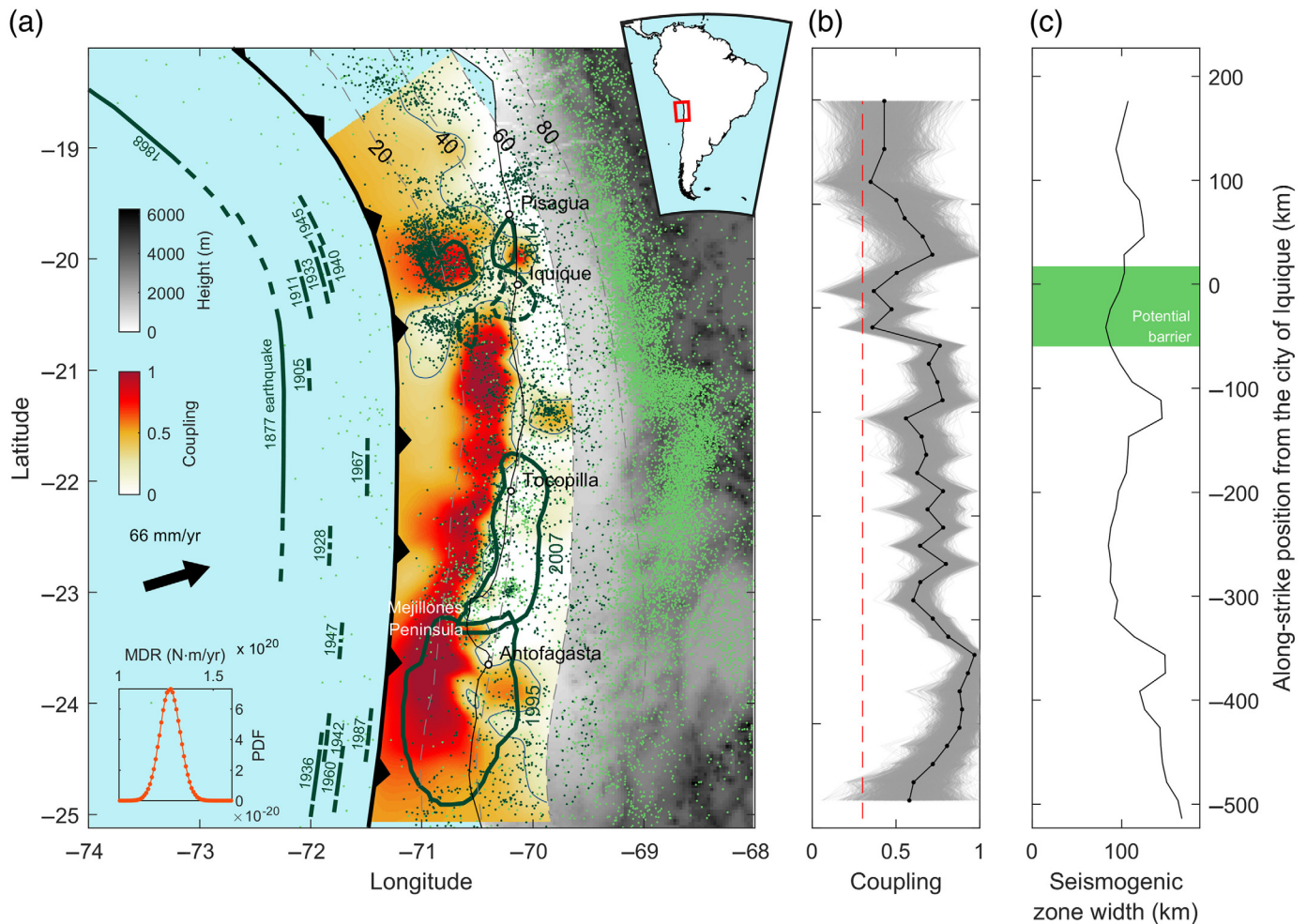
Since then the region hosted multiple  $M_w > 7.5$  earthquakes (Roth *et al.*, 2017), including four events since 1995 and the advent of geodetic measurements. Those events highlight the potential segmentation of the fault, whether along strike or along dip. The 1995  $M_w$  8.1 Antofagasta earthquake ruptured almost the full along-dip extent ( $< 50$  km depth) south of the Mejillones peninsula (Chlieh *et al.*, 2004; Pritchard *et al.*, 2007) and induced postseismic slip below the coseismic slip distribution (Fig. 1a), suggesting that no slip deficit is accumulating below  $\sim 50$  km depth in the area. The 2007  $M_w$  7.7 Tocopilla earthquake, located just north of the Mejillones peninsula, ruptured instead between  $\sim 30$  and 50 km depth, leaving most of the shallow extent of the megathrust locked (Béjar-Pizarro *et al.*, 2010; Schurr *et al.*, 2012). Only a relatively small along-strike portion of the shallow section of the megathrust ( $\sim 50$  km of the event's 150 km length) seems to have hosted postseismic processes (i.e., aftershocks and afterslip), whereas

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the down-dip region from the 2007 coseismic event stayed relatively quiet (Schurr *et al.*, 2012). Finally, the 2014  $M_w$  8.1 Iquique earthquake occurred on the northern part of the megathrust and ruptured two asperities: one shallow and the other at 30–50 km depth (Jara *et al.*, 2018). This earthquake was followed by an  $M_w$  7.7 aftershock three days later with a similar along-dip pattern but located south of the coseismic slip distribution (Duputel *et al.*, 2015).

During the interseismic period, the distribution of locked sections of a megathrust fault, referred to as coupling ( $\chi$ ), can be inferred from geodetic data (e.g., Chlieh *et al.*, 2011; Métouis *et al.*, 2012). A coupling of 0 indicates the fault slips at its long-term rate (fully creeping), whereas a coupling of 1 corresponds to a fully locked fault. Wherever the fault is locked, elastic strain builds up and can be interpreted in terms of a deficit of moment, which can at some point be released through earthquakes or other processes (Reid, 1910; Avouac, 2015). Evaluating coupling allows one to infer a direct estimate of the moment deficit buildup rate (MDR). The latest study of the central Andean coupling distribution based on the Interferometric Synthetic Aperture Radar (InSAR, 2003–2010) and the Global Navigation Satellite Systems (GNSS) data (deployed since 2000) uses a Bayesian approach to probe the

**Figure 1.** Regional setting of the northern Chile region of the Nazca subduction zone. (a) Interseismic coupling map (Jolivet *et al.*, 2020). Dots indicate microseismicity since 2001 from the International Seismological Center (ISC) catalog. Dark green dots are earthquakes selected for the seismic potential analysis (<200 km from the subduction trench). Thick green lines offshore indicate the spatial extent of historical large earthquakes ( $M_w > 7$  between 1877 and 1995; Roth *et al.*, 2017). Coseismic slip distribution of recent large earthquakes (since 1995) is indicated by the green contours. The thin solid blue line on the coupling map delimits the bottom extent of the coupled zone, based on a coupling threshold of 0.3. Isodepths of the subduction interface are indicated by the thin gray dashed lines (in kilometers). The bottom left inset shows the probability density function (PDF) of the moment deficit rate. (b) Along-strike distribution of coupling averaged along dip of each of the 245,760 coupling models (gray lines). The black line is the mean value of the 245,760 coupling models. The coupling threshold of 0.3 used in this study is indicated by the red dashed line. (c) Width of coupled zone based on a coupling threshold of 0.3. The potential location of the aseismic barrier is indicated by the green shading. Top right inset shows the location of the study area (red rectangle) in South America. The color version of this figure is available only in the electronic edition.

probability of whether a point of the fault is locked or not on average over the interseismic period (Jolivet *et al.*, 2020). To first order, the coupled regions of the subduction zone (Fig. 1a) overlap with the coseismic slip distributions of the  $M_w > 7.5$

earthquakes since 1995, with the exception of the Tocopilla earthquake, which potentially ruptured the down-dip creeping-locked transition zone (Schurr *et al.*, 2012). In addition, at  $\sim 20.5^\circ$  S, Jolivet *et al.* (2020) infer a reduction in coupling, which may indicate the presence of a frictional barrier (Avouac, 2015) or a geometrical complexity (Jara *et al.*, 2018). The Iquique mainshock and the largest aftershock lie on both the sides of this zone of reduced coupling.

The evaluation of the seismogenic potential of a fault includes evaluating the magnitude of the largest potential earthquake (hereafter referred to as the maximum magnitude)  $M_{\max}$  and its recurrence time  $\tau_{\max}$ . Considering the uncertainties on the 1877 earthquake along-strike extent and magnitude, the potential maximum magnitude that could occur on the megathrust is poorly constrained. On one hand, according to Chlieh *et al.* (2011), the moment deficit buildup rate over the approximate region of the 1877 earthquake ( $[23.5^\circ$  S,  $19.0^\circ$  S] in latitude) is  $1.3 \times 10^{20}$  N·m/yr. Since 1877, the accumulated moment corresponds to an earthquake of  $M_w \sim 8.5$ – $8.8$  (Chlieh *et al.*, 2011). On the other hand, Métois *et al.* (2013) suggest that the 1877 earthquake extended north only up to the city of Iquique ( $\sim 20.3^\circ$  S) for an area with moment deficit equivalent to only  $M_w \sim 8.1$ – $8.3$ .

However, such seismic potential estimates do not fully consider uncertainties, do not include the micro- to moderate-size earthquake productivity, and do not attempt to consider the physics of earthquakes, especially their potential to propagate along strike. For instance, it has been shown that aseismic regions of the megathrust may control the along-strike extent of large megathrust earthquakes, hence their magnitude (Kaneko *et al.*, 2010). In northern Chile, we do not know whether the presence of a low coupling region offshore Iquique significantly impacts the probability of occurrence of large earthquakes. We therefore revisit the seismic potential of the region using earthquake recurrence models fitting both past earthquake frequencies and moment budget (based here on geodetic data)—a strategy that has already been used in previous studies and applied in other regions of the world (Molnar, 1979; Anderson and Luco, 1983; Michel *et al.*, 2018; Mariniere *et al.*, 2021). We do so following a probabilistic approach, and we test, in particular, whether the reduction in coupling observed at  $\sim 20.5^\circ$  S might influence the propagation and thus the magnitude of future large earthquakes. We use statistical results from numerical simulation of the seismic cycle (Kaneko *et al.*, 2010) following a methodology developed, tested, and applied in the Himalayas (Michel *et al.*, 2021). This study is thus a direct application of Michel *et al.* (2021) approach to the northern Chile subduction zone with an emphasis on the evaluation of the maximum potential earthquake within this region, which is debated, and the role of the potential aseismic barrier offshore Iquique. We provide, in addition, a sensitivity test of the parameters controlling the earthquake recurrence models to assess their impact on the

final results. In the following sections, we first describe the concepts and methods, then describe the data available in northern Chile, and apply the methodology to the region before discussing the robustness of our results.

## METHODOLOGY

The methodology is based on Michel *et al.* (2021). The period of seismological observation ( $\sim 100$  yr) is generally too short to evaluate  $M_{\max}$ , as the recurrence time of large events ( $M_w > 8$ ) is often centuries to millennia (e.g., Bollinger *et al.*, 2016; Philibosian and Meltzner, 2020). To circumvent this problem, we build seismicity models representing the long-term magnitude–frequency distribution (MFD) of earthquakes, and test them against four observational and physical constraint to assess which  $M_{\max}$  is the most probable under those assumptions. First, the moment release rate from a seismicity model should balance the observed moment deficit rate on the megathrust. Effectively, we evaluate the budget of available moment. Second, the MFD of observed seismicity catalogs should be a possible outcome of the long-term seismicity model, when sampled over the duration of observation (i.e., we assume the MFD is stable over a period longer than the observation period). Third, earthquakes should follow the moment–area scaling law (Kanamori and Brodsky, 2004; Ye *et al.*, 2016). And fourth, earthquakes should be able to propagate through frictional barriers, which we evaluate based on the statistical outcome of simulations of the seismic cycle (Kaneko *et al.*, 2010).

Regarding the seismicity models, we assume that they represent MFDs of background seismicity and follow a power law form up to  $M_{\max}$  (i.e., Gutenberg–Richter law; Gutenberg and Richter, 1944, 1954). The MFD models are based upon a noncumulative power-law MFD truncated at  $M_{\max}$ , which gives rise to a tapered MFD in the cumulative form (i.e., the traditional display when representing the Gutenberg–Richter law; Rollins and Avouac, 2019). Each model is a function of three parameters: (1)  $M_{\max}$ , (2) the recurrence rate of events of a certain magnitude  $\tau_c$ , and (3) the MFD's  $b$ -value from the Gutenberg–Richter law (i.e., the relative rate of small and large events)  $b$ . We also consider a model with a distribution truncated at  $M_{\max}$  in the cumulative form (i.e., truncated model in Rollins and Avouac, 2019; Michel *et al.*, 2021), which does not affect our results significantly (Text S1; Figs. S1, S2, available in the supplemental material to this article).

We assume that the studied region is an isolated system. Earthquakes that nucleate within the region cannot propagate out of it, and potential earthquakes nucleating outside of it will not propagate within. The results from this study are based on this strong assumption and should be interpreted within this scope.

## Moment budget

To evaluate the budget of moment, we compare the moment released by earthquakes with the moment deficit that builds up on the fault during the interseismic period. On one hand, the



moment deficit rate  $\dot{m}_0^{\text{def}}$  is given as  $\dot{m}_0^{\text{def}} = \int \mu \dot{D}^{\text{def}} dA$ , in which  $\mu$  is the shear modulus,  $\dot{D}^{\text{def}}$  is the slip deficit rate, and  $A$  is the fault's area.  $\dot{D}^{\text{def}}$  is linearly related to coupling on the fault  $\chi$  and to the long-term plate rate  $V_{\text{plate}}$ , as  $\dot{D}^{\text{def}} = \chi V_{\text{plate}}$ . On the other hand, we estimate the total moment released by earthquakes  $\dot{m}_0^{\text{Total}}$  based on the long-term seismicity models. Because the models represent only background seismicity, we add the moment released by aftershocks and aseismic afterslip using a factor  $\alpha_s$ , which represents the proportion of moment released by background seismicity relative to the total moment released (aftershocks and aseismic afterslip included). The total moment release rate is then  $\dot{m}_0^{\text{Total}} = \dot{m}_0^{\text{Bckgrd}}/\alpha_s$ , in which  $\dot{m}_0^{\text{Bckgrd}}$  is the moment rate released by background seismicity. Finally, if  $\dot{m}_0^{\text{Total}} = \dot{m}_0^{\text{def}}$ , the model balances the moment budget.

As derived by Rollins and Avouac (2019) and references therein, the cumulative MFD of seismicity models balancing the moment budget is directly written as

$$N(> M_w) = \frac{1 - \frac{2b}{3} \alpha_s \dot{m}_0^{\text{def}}}{\frac{2b}{3} \dot{m}_0^{\text{max}}} \left[ \left( \frac{\dot{m}_0^{\text{max}}}{\dot{m}_0(M_w)} \right)^{\frac{2b}{3}} - 1 \right], \quad (1)$$

in which  $N(> M_w)$  is the rate of  $>M_w$  events,  $\dot{m}_0^{\text{max}}$  is the moment released by  $M_{\text{max}}$ , and  $\dot{m}_0(M_w)$  is the moment corresponding to magnitude  $M_w$ . The probability of a seismicity model balancing the moment budget  $P_{\text{Budget}}$  is therefore the combination of probabilities of  $M_{\text{max}}$ ,  $b$ ,  $\dot{m}_0^{\text{def}}$ , and  $\alpha_s$ , for which we sample a priori distributions.

## Observed MFD

We evaluate the probability of drawing the observed seismicity catalog (instrumental and/or historical) from the a priori distribution of long-term seismicity models over the time period of observation. We assume that events are independent, hence we evaluate probabilities assuming that background seismicity follows a Poisson process (Gardner and Knopoff, 1974). For events within a bin of given magnitude  $M_i$ , the probability to observe  $n_{\text{obs}}^{M_i}$  events occurring during the time period  $t_{\text{obs}}^{M_i}$ , as characterized by the observed seismicity catalog, assuming the long-term mean recurrence of events is  $\tau_{\text{model}}^{M_i}$ , as defined by a seismicity model, is

$$P_{\text{poisson}}^{M_i}(n_{\text{obs}}^{M_i}, t_{\text{obs}}^{M_i}, \tau_{\text{model}}^{M_i}) = \frac{(t_{\text{obs}}^{M_i}/\tau_{\text{model}}^{M_i})^{n_{\text{obs}}^{M_i}}}{(n_{\text{obs}}^{M_i})!} e^{-t_{\text{obs}}^{M_i}/\tau_{\text{model}}^{M_i}}. \quad (2)$$

We then define the probability of the observed seismicity catalog to be an outcome of the long-term seismicity model,  $P_{\text{Cat}}$ , as  $P_{\text{Cat}} = \prod_i P_{\text{poisson}}^{M_i}$ .

Effectively, we generate 2500 earthquake declustered catalogs considering magnitude uncertainties and the probability of an event being a background seismicity (e.g., acquired from Marsan et al., 2017, method). The probability  $P_{\text{Cat}}$  is the mean probability given by the 2500 catalogs.

## Moment–area scaling law

Global earthquakes statistics show that the moment released by seismic events and the corresponding rupture area are power-law related as  $m_0^{\text{seis}} \propto A^{3/2}$  (e.g., Kanamori and Brodsky, 2004; Ye et al., 2016). Considering the size of a megathrust fault and the distribution of coupling, all earthquakes are not possible according to this scaling. We evaluate the probability of occurrence of a given event  $P_{\text{scaling}}$  by converting its magnitude to an area using the scaling law and by checking whether it fits within the seismogenic area. This constraint is applicable for each magnitude examined and does not depend on the seismicity model tested. We account for the rather large uncertainties of the moment–area scaling (see the Additional parameters needed to implement the scaling law and frictional barrier constraints section).

## Frictional barrier effect

Local reductions in interseismic coupling can be interpreted as frictional heterogeneities acting as barriers to the propagation of earthquakes (Kaneko et al., 2010). We evaluate the influence of these potential frictional barriers from the statistics of seismic cycle simulations (Kaneko et al., 2010; Thomas et al., 2014; Michel et al., 2021) based on the rate–state formalism (Dieterich, 1978; Ruina, 1983). Kaneko et al. (2010) relates the probability of a seismic rupture to pass through a frictional barrier to a nondimensional parameter called the barrier efficiency  $B$ . This criterion depends on the fault constitutive parameters and on the dynamics of the rupture:

$$B = \frac{\Delta\sigma_{VS}(a_{VS} - b_{VS}) \ln(\frac{V_{\text{Dyn}}}{V_i}) D_{VS}}{\beta \Delta\tau_{VW} D_{VW}}, \quad (3)$$

in which  $a_{VS}$  and  $b_{VS}$  are constitutive parameters of the rate-and-state friction law at the barrier, and  $\Delta\sigma_{VS}$  and  $D_{VS}$  are the barrier's effective normal stress and width, respectively.  $V_i$  corresponds to the interseismic slip rate, and  $V_{\text{Dyn}}$  corresponds to the rupture's slip rate.  $D_{VW}$  and  $\Delta\tau_{VW}$  corresponds to the length and mean stress drop of the seismic rupture, while  $\beta$  is the proportion of stress unloaded within the barrier and depends on the geometry of the rupture. We assume here that the seismic rupture uniformly distributes stress at its borders as in Kaneko et al. (2010).

## Seismicity model probability $P_{\text{SM}}$

We define the probability of a seismicity model  $P_{\text{SM}}$  as the product  $P_{\text{SM}} = P_{\text{Budget}} P_{\text{Cat}} P_{\text{scaling}} P_{\text{barriers}}$  (Michel et al., 2021) calculated from the imposed constraints (Methodology section). Based on  $P_{\text{SM}}$ , we then estimate the marginal probabilities of  $M_{\text{max}}$  and of the  $b$ -value, respectively,  $P_{M_{\text{max}}}$  and  $P_b$ . Defining  $M_{\text{mode}}$  as the magnitude at which  $P_{M_{\text{max}}}$  peaks, we evaluate the probability  $P(\tau|M_w = M_{\text{mode}})$  of the rate of  $M_w = M_{\text{mode}}$  events, which accounts for all earthquakes from all of the models (i.e., not only  $M_{\text{max}}$ ).

## DATA AND UNCERTAINTIES

To apply this methodology and evaluate the seismicity models, we explore and sample the constraint parameters within their uncertainties. In this section, we present the data used in this study and describe how uncertainties are estimated.

### Seismicity model constitutive parameters, moment deficit rate, and seismogenic zone

Because of equation (1), we can limit the seismicity model parameter space (Methodology section) to be explored, examining the MDR instead of  $\tau_c$ . The parameter space  $M_{\max}$ ,  $b$ ,  $\alpha_s$  and MDR is then explored through a grid search.  $M_{\max}$  and  $b$  are sampled uniformly over  $M_{\max} \in \mathcal{U}(7.8, 10)$  and  $b \in \mathcal{U}(0.05, 1.50)$ , respectively. The probability density function (PDF) of  $\alpha_s$  is assumed Gaussian with  $\mathcal{N}(80\%, 20\%)$  based on global statistics of earthquake postseismic behavior (Avouac, 2015; Alwahedi and Hawthorne, 2019).

We use the coupling model from Jolivet *et al.* (2020) to calculate the MDR ( $\dot{m}_0^{\text{def}}$ ) and its related uncertainty (see the Moment budget section). Jolivet *et al.* (2020) have sampled the PDF of the coupling models that fit the geodetic data, hence providing 245,760 coupling models based on GNSS and InSAR data. From these models, we build the PDF of moment deficit rate  $\dot{m}_0^{\text{def}}$  following the methodology from the Moment Budget section. The PDF follows a Gaussian distribution with  $\mathcal{N}(1.27 \times 10^{20}, 5.48 \times 10^{18}) \text{ N} \cdot \text{m/yr}$ .

The seismicity model parameter space grid search is proceeded using steps of  $6.36 \times 10^{17} \text{ N} \cdot \text{m/yr}$  for the MDR, 0.1 of magnitude for  $M_{\max}$ , 0.01 for the  $b$ -value, and 10% for  $\alpha_s$ .

In addition, we define the seismogenic zone along-strike extent and width within an isocoupling  $\chi_{\text{thresh}}$  of 0.3. We then discretize the model in thirty seven 17.5 km long segments, and compute the average and standard deviation coupling and width of the seismogenic zone in each bin (Fig. 1).

### Seismicity catalog

We combine two earthquake catalogs: an instrumental one from the International Seismological Center (ISC; Willemann and Storchak, 2001; Bondár and Storchak, 2011; Storchak *et al.*, 2017, 2020; International Seismological Centre, 2022) and an aggregate one from Roth *et al.* (2017) including both instrumental and historical events.

The instrumental ISC catalog is itself a combination of catalogs. Most of the seismic events in northern Chile originate from the Centro Sismológico Nacional catalog (Barrientos, 2018). The type of magnitude in the ISC catalog is heterogeneous. We thus convert the magnitude of each event into moment magnitude ( $M_w$ ; see Text S2 and Figs. S3, S4). We then build two separate catalogs, associated with two different periods of observation, that we decluster using the method of Marsan *et al.* (2017), following the parametrization described by Jara *et al.* (2017) for the region. For the first catalog, we consider events between 2001 and 2021, with an estimated magnitude of completeness ( $M_c$ ) of 3.3

(see Text S2). From the resulting declustering of the catalog, we select events from 2010 (date from which background seismicity rate appears constant) and within 200 km east from the trench to avoid earthquakes related to the orogenic processes within the Andes at  $\sim 100$  km depth (Fig. S5). For the second catalog, we take instead events between 1970 and 2021, with an estimated  $M_c$  5.7. After declustering, we select events from 1980 and also within 200 km east from the trench (Fig. S6). We do not discriminate between events attributed to slip on the subduction interface and events rupturing structures within the overlying forearc for both the catalogs. The elastic loading resulting from coupling along the interface induces strain over a large area, and we assume that seismicity in the arc only results from the corresponding stresses.

The other earthquake catalog is an aggregate of various catalogs combined by Roth *et al.* (2017).  $M_w > 6.5$  earthquakes between 1500 and 1899 are from the Centro Regional de Sismología para América del Sur (CERESIS) catalog (Giesecke *et al.*, 2004), events between 1900 and 2009 are from ISC-Global Earthquake Model (GEM) data (Storchak *et al.*, 2013), and earthquakes after 2009 (which consist of a  $M_w$  6.5 in 2009 and of the  $M_w$  8.1 Iquique earthquake) are included manually (Duputel *et al.*, 2015; Jara *et al.*, 2018). We do not include the largest aftershock of the Iquique earthquake as we use a declustered catalog. We select events since 1877 within the region, excluding the 1877 event, and assume that events spatially straddling the previous earthquakes within a 1.5 yr period are aftershocks and are thus removed. The events magnitude uncertainties are fixed to 0.2 for events before 1995, and 0.1 thereafter. Roth *et al.* (2017) suggest an  $M_c$  of about 7.0, whereas a maximum curvature method (Wiemer and Wyss, 2000) evaluates this  $M_c$  around 7.25. When applying the observational seismicity catalog constraint (see the Observed magnitude–frequency distribution section), we only compare events with  $M_w > 4.25$ ,  $M_w > 6.25$ , and  $M_w > 7.75$  for the first and second catalog from ISC and the aggregate catalog from Roth *et al.* (2017), respectively, to avoid border effect from the  $M_c$  when exploring magnitude uncertainties (Felzer, 2008).

### Additional parameters needed to implement the scaling law and frictional barrier constraints

Constraints from the earthquake scaling law and frictional barrier are explored separately from the other two constraints by testing 500,000 events sampled uniformly between  $M_w$  6 and 10. Considering the scaling law, we use the moment–area scaling and associated uncertainty modeled by Michel *et al.* (2021) derived from the database of large subduction earthquakes of Ye *et al.* (2016). We evaluate a linear relationship between the rupture area  $A$  and seismic moment of earthquakes  $m_0$ , such as  $\text{Log}_{10}(m_0) = \frac{3}{2}A + Q$ . Least-squares regression suggests  $Q = 15.15$  (with  $A$  in square kilometers). Earthquake moment is normally distributed around this trend with a standard deviation of  $\sigma_{\text{scaling}} = 0.23$  (Michel *et al.*,

2021), used as the uncertainty on the scaling law in our exploration. Other studies yield different uncertainty estimates on the scaling. Using data from Leonard (2010),  $\sigma_{\text{scaling}}$  reaches 0.5, roughly twice than the one estimated on data from Ye et al. (2016). Such larger uncertainties directly impacts  $P_{\text{scaling}}$  and thus  $P_{M_{\text{max}}}$  (Fig. S7).

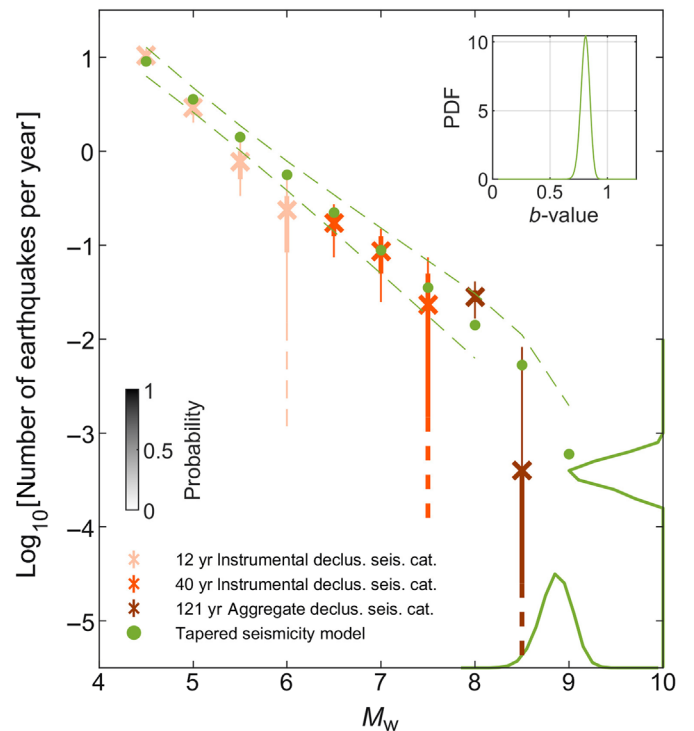
To apply the frictional barrier constraint in a probabilistic manner, we need to evaluate the values and uncertainties of the constitutive, dynamic, and geometric parameters involved in the barrier efficiency. To our knowledge, there are no estimates available for the constitutive parameters  $\Delta\sigma_{VS}(a_{VS} - b_{VS})$  in the northern Chile region of the Andean subduction zone. We assume values and uncertainties from other parts of the subduction zone, including a postseismic study from Weiss et al. (2019) and Frank et al. (2017). The interseismic slip rate  $V_i$  is taken from the coupling model. The rupture properties such as seismic slip velocity  $V_{\text{Dyn}}$  and stress drop  $\Delta\tau_{VW}$  are taken from the literature (Kanamori and Brodsky, 2004; Cocco et al., 2016). The length of an event  $D_{VW}$  depends on the procedure described by Michel et al. (2021). All parameters are summarized in Table S1.

We assume that there is only one potential barrier located offshore Iquique. The barrier width  $D_{VS}$  and related uncertainty are based on the along-strike distribution of coupling and the coupling threshold  $\chi_{\text{thresh}}$  (see the Seismicity model constitutive parameters, moment deficit rate, and seismogenic zone section). From the PDF of coupling, the distribution of possible widths of the barrier is a positive-truncated Gaussian  $\mathcal{N}(5.3, 21.9)$  km, with a nonnegligible probability of being inexistent (Fig. S8).

Finally, the relationship between the barrier efficiency ( $B$ ) and the probability that an event passes a barrier is itself prone to uncertainty. This relationship is indeed based on the statistical outcome from 2D numerical models of the seismic cycle (Kaneko et al., 2010). We model the relationship with a linear regression for  $B \in [0, 1.2]$  and impose a probability equal to 0 for  $B > 1.2$  (Fig. S9). The distribution of the probabilities relative to the model follows to a Gaussian with a standard deviation of 9.3% (Michel et al., 2021; Fig. S9), which we will use as uncertainty for the relationship.

## RESULTS

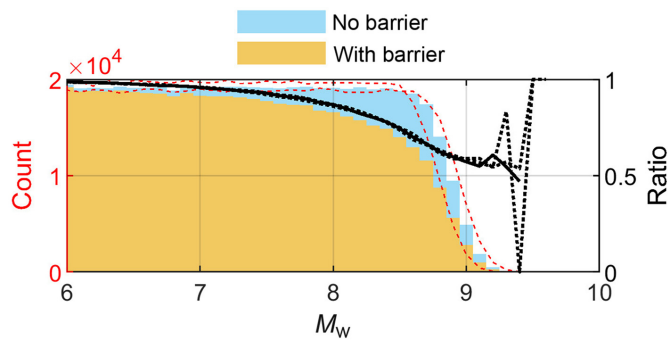
The probability of a given seismicity model  $P_{\text{SM}}$  is shown in Figure 2, with the corresponding marginal probability of the maximum magnitude of an earthquake  $P_{M_{\text{max}}}$ . The maximum magnitude is approximately normally distributed and peaks at  $M_w$  8.85 (median and mean of  $P_{M_{\text{max}}}$  can be found in Table S2). Earthquakes larger than  $M_w$  9.25 are very improbable (less than 1% considering  $P_{M_{\text{max}}}$ ; Fig. 2). The sharp decrease of  $P_{M_{\text{max}}}$  for magnitudes larger than 9.2 is mainly controlled by the moment–area scaling law (Figs. 3, 4a) and to a lesser extent by the barrier effect (see the Frictional barrier effect section). The barrier effects only affects magnitudes larger than  $M_w$  8, cutting the probability of an event by  $\sim 50\%$  above magnitude 9 (black



**Figure 2.** Seismic potential analysis using all constraints: moment budget, observed magnitude–frequency distribution (MFD), moment–area scaling law, and the frictional barrier effect. The rate of occurrence of earthquakes, within their observation period, is indicated by brown (Roth et al., 2017, catalog; events from 1850 to 2022), orange (International Seismological Center [ISC] catalog; 1980–2022 events), and pink (ISC catalog; 2010–2022 events) crosses. The associated thin and thick vertical lines correspond to the catalogs 15.9%–84.1% (one-sigma) and 2.3%–97.7% (two-sigma) quantiles, respectively. Green dots show the mean of the marginal PDF of the long-term seismicity models. Green dashed lines indicate the spread of the 1% best seismicity models. The marginal probability of  $M_{\text{max}}$ ,  $P_{M_{\text{max}}}$ , is indicated by the solid green line on the  $M_w$  axis. The solid green line on the earthquake frequency axis indicates the probability of the rate of events  $\tau$  with magnitude  $M_w$  8.85, thus  $P(\tau|M_w = M_{\text{mode}})$ , which considers all magnitudes in the seismicity models and not only the recurrence rate of  $M_{\text{max}}$ . The top right inset shows the marginal probability of the  $b$ -value. Note that the seismicity MFDs in the figure are not in the cumulative form. The color version of this figure is available only in the electronic edition.

line in Fig. 3a). The effect of the other parameters of the barrier efficiency are shown in Figure S10.  $P_b$ , the marginal probability of the  $b$ -value, is also normally distributed, peaks at  $\sim 0.8$ , and reaches a probability close to 0 at  $b = 0.9$  (inset in Fig. 2).  $P(\tau|M_w = M_{\text{mode}})$ , the probability of the rate of  $M_w$  8.85 events, implies a recurrence time of such events of between  $\sim 1000$  and  $\sim 6300$  yr, with a peak at  $\sim 2500$  yr (Figs. 2, 4b).

The probability of occurrence of an event with  $M > M_w$  for a time period  $T$ ,  $P(M > M_w|T)$ , is an estimate frequently used in seismic hazard analysis. For northern Chile, the probability of having at least an  $M_w > 8.8$  in a 30, 100, 1000 and 10,000 yr period is of  $\sim 1\%$ , 4%, 29%, and 63%, respectively (Fig. 4c). One could expect a probability closer to 1 for  $T = 10,000$  yr,



**Figure 3.** PDFs of  $M_w$ , expressed in counts, considering only the moment–area scaling law (blue histogram), and considering both the scaling law and potential frictional barrier into account (yellow histogram). The PDFs are evaluated from 880,000 events uniformly sampled between  $M_w$  6 and 10. The effect of the potential frictional barrier, alone, is estimated taking the ratio between the yellow and blue histograms (solid black line). The dashed black lines represent the effect of the potential frictional barrier for a coupling threshold equal to 0.2 and 0.4 (instead of 0.3). The red dashed lines indicate the position of the PDF using the moment–area scaling law constraint only, if taking a coupling threshold equal to 0.2 and 0.4. The color version of this figure is available only in the electronic edition.

considering the recurrence time at  $M_{\text{mode}}$ ; however, a bit less than half of the probable seismicity models have an  $M_{\text{max}}$  below 8.7 and have thus a probability equal to 0 for producing  $M_w > 8.7$  events.

Another estimate of importance for seismic hazard analysis is the probability of the distance between a chosen site and the seismic source. We evaluate this probability, taking the barrier effect into consideration, using the procedure from the [Moment–Area Scaling Law](#) and [Frictional Barrier Effect](#) sections, as we are able to calculate the probability of a point of the fault to be part of an event of magnitude  $M_w$ , Figure 4d shows the difference between the PDFs of  $M_w > 8.5$  events location with and without the barrier effect. The northern segment of the subduction zone, past the city of Iquique, is less prone to be part of an  $M_w > 8.5$  due to the barrier. We can then, for example, calculate the probability of the distance between the cities of Iquique or Tocopilla and an  $M_w > 8.5$  seismic source, taking into account the potential frictional barrier (Fig. 4e). In this study, we evaluate only the distances relative to one seismic source (i.e., the subduction interface), as opposed to the common use in probabilistic seismic hazard analysis that takes into consideration all sources. Nevertheless, the results from this study’s approach could eventually be integrated into such seismic hazard analysis.

## DISCUSSION

### Influence of the parameters of the long-term seismicity model

Under all the assumptions supporting our analysis, our main result suggests that the most probable maximum magnitude

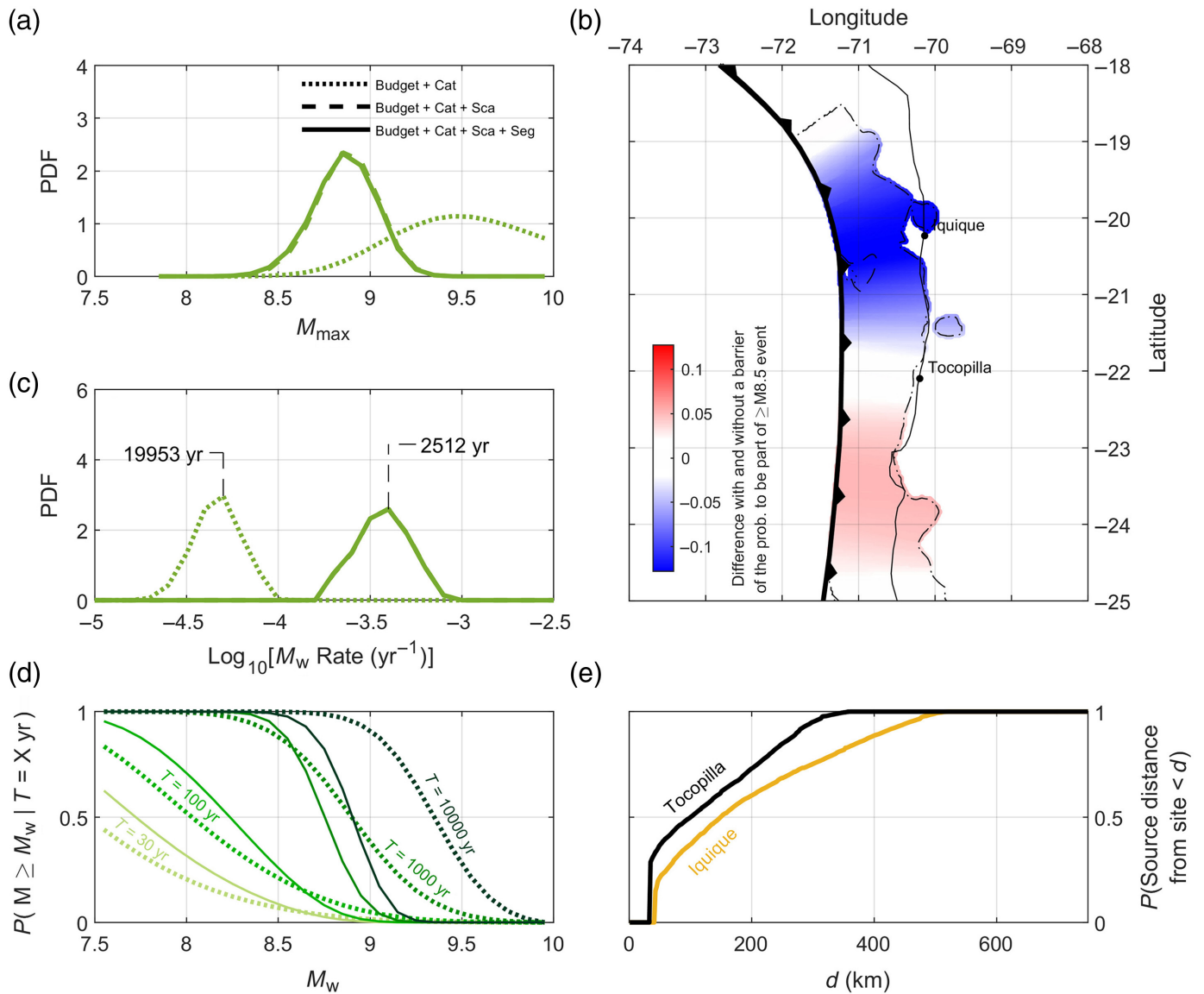
earthquake is 8.8, and that earthquakes larger than  $M_w$  9.1 are very improbable in the region (less than 2% considering  $P_{M_{\text{max}}}$ ), assuming that the region is an isolated system (i.e., earthquakes cannot propagate out of it, and external events cannot propagate within it). In addition, the introduction of a barrier to the propagation of earthquakes and of the scaling law leads to a lowering of the probability of an earthquake rupturing the entire northern Chile seismic gap (from the Mejillones peninsula to the Arica bend). It appears that the barrier effect is less influential than the earthquake scaling law due to the large uncertainties of the barrier efficiency parameters (see the [Frictional barrier effect](#) and [Additional parameters needed to implement the scaling law and frictional barrier constraints](#) sections), and the fact that the barrier is located on one side of the fault and only separates a small portion of the fault. Before introducing these physics-based constraints, the probability of a seismicity model ( $P_{\text{SM}}$ ) and thus  $P_{M_{\text{max}}}$  depends on the MDR,  $b$ -value, and  $\alpha_s$ . We explore the influence of each of these parameters on  $P_{M_{\text{max}}}$  without accounting for the scaling law and barrier constraints to evaluate the effect of the parameters at the core of our method. We will mostly refer to the mode of  $P_{M_{\text{max}}}$ , but the median and mean of the PDF for each of the following scenarios can be found in Table S3.

First, we explore the effect of the estimate of the moment deficit rate. We compare three cases: (1) a megathrust fully locked down to 60 km depth, (2) the MDR from [Jolivet et al. \(2020\)](#) divided by 2 (keeping the same uncertainty), and (3) the MDR of [Jolivet et al. \(2020\)](#) divided by 5 (Fig. 5a). Those scenarios are quite radically different from our setup and have a strong effect on  $P_{M_{\text{max}}}$ . Although the fully locked fault results in a PDF peaking at  $M_w > 10$ , lower moment deficit rate tends to saturate at  $M_w$  8.3, constrained by the aggregate earthquake catalog (seismicity models with  $M_{\text{max}}$  below the observed maximum magnitude of the catalog will be highly improbable).

Second, we explore the influence of the assumed moment contribution of postseismic and aseismic deformation. Figure 5b shows tests for  $\alpha_s = 0.8, 0.67, 0.50$ , and  $0.40$ , which corresponds to a ratio between postseismic processes and background seismicity moment release of 0.25, 0.5, 1.0, and 1.5, respectively (in our main model,  $\alpha_s$  is normally distributed around a mean of 80% with a standard deviation of 20%). Decreasing  $\alpha_s$ , which increases the percentage of moment released by postseismic processes relative to background seismicity, decreases the amount of moment released by background seismicity needed to balance the moment budget, thus  $M_{\text{max}}$ .

Third, we explore the effect of the  $b$ -value (Fig. 5c). Fixing this parameter to a single value is a strong assumption due to the observed seismicity catalog constraint and will have an important impact on  $P_{M_{\text{max}}}$ . The lower the  $b$ -value, the smaller the probable  $M_{\text{max}}$ . However, seismicity models with  $b$ -value around 0.8 will fit the observed MFD of earthquakes more easily (most probable  $b$ -value using only the moment budget and catalog constraints).



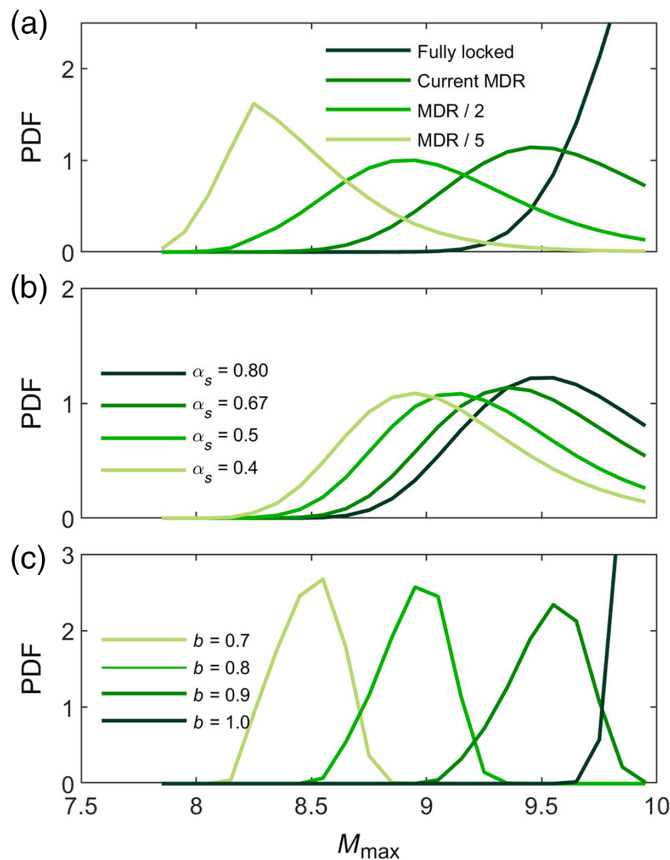


In conclusion, the MDR is relatively well-constrained observationally from geodetic data. Although end-member hypothesis shows significant influence on the results, we can confidently say that such hypotheses are quite improbable. The  $b$ -value has also a strong influence but is constrained by the earthquake catalogs. The large uncertainties on the magnitude of the catalog events (up to 0.5) allow for a broad possible range of  $b$ -value, between 0.7 and 1.0 before applying the scaling law and barrier constraint, and between 0.7 and 0.9 after. For the poorly constrained parameter, namely the ratio of post- versus coseismic slip, we observe that significant variations in  $\alpha_s$  changes the most probable maximum magnitude to some extent with variations contained between 8.95 and 9.55. However, adding the scaling law constraint diminishes the impact of  $\alpha_s$  restraining instead  $P_{M_{\max}}$  mode between 8.75 and 8.95, thus not affecting our conclusions. The two types of long-term seismicity models explored here (i.e., tapered and truncated models; see the [Methodology](#) section,

**Figure 4.** (a) Marginal PDF of  $M_{\max}$  for three combinations of constraints. (b) Difference of the probability of rupture extent with and without the barrier for  $M_w > 8.5$  earthquakes using only the scaling law and the potential frictional barrier constraints into account. (c) Same as panel (a) but for the marginal PDF of the recurrence time of events with  $M_w = M_{\text{Mode}}$ ,  $P(\tau|M_w = M_{\text{Mode}})$ . (d) Probability of occurrence of earthquakes of magnitude larger than  $M_w$  over a period of  $X$  years. We show that the probability of occurrence of such events for four time periods, 30, 100, 1000, and 10,000 yr. In panels (a,c,d), dotted lines represent the marginal PDFs considering both the moment budget and seismicity catalog constraint, the dashed lines indicate the PDFs when adding the earthquake scaling constraint (not shown in panel d), whereas the continuous lines indicate the PDFs using all constraints. (e) Cumulative PDF of  $M_w > 8.5$  source distance from the cities of Iquique and Tocopilla. The color version of this figure is available only in the electronic edition.

Text S1, and Figs. S1, S2) provide similar results. This is not necessarily the case in other regional setting (e.g., in the Ecuador–Colombian subduction; [Mariniere et al., 2021](#)).





**Figure 5.** Marginal PDF of  $M_{\max}$ ,  $P_{M_{\max}}$ , for different values of (a) moment deficit rate, (b)  $\alpha_s$ , the proportion of moment released by aftershocks and aseismic afterslip relative to the total moment released, and (c)  $b$ -value. The color version of this figure is available only in the electronic edition.

We finally explore the influence of the coupling threshold within which we define the seismogenic zone. This threshold has a small impact on the moment–area scaling law constraint, shifting  $P_{\text{scaling}}$  of 0.05 magnitude when taking coupling thresholds of 0.2 or 0.4 (red lines in Fig. 3a). An extreme scenario, which we already explored above, would be to assume the fault completely locked (coupling equal to 1) down to 60 km depth. Such scenario would significantly increase the width and along-strike extent of the seismogenic zone. Such scenario results in  $P_{M_{\max}}$  starting to increase at  $M_w$  8.75, peaking at  $M_w$  9.15, and dying out at  $M_w$  9.45 (Fig. S11), thus larger  $M_{\max}$  than when using the coupling map. However, such scenario is not consistent with geodetic data over the interseismic period (Métois *et al.*, 2016; Jolivet *et al.*, 2020).

### Comparison with earlier estimates of seismogenic potential

Chlieh *et al.* (2011) estimate a moment deficit rate of  $1.3 \times 10^{20} \text{ N} \cdot \text{m/yr}$  over their proposed 1877 earthquake spatial extent, roughly from the city of Arica in the north to the city of Antofagasta in the south. Their estimate

slightly overestimates ours using roughly the same area ( $9.1 \times 10^{19} \pm 0.4 \times 10^{19} \text{ N} \cdot \text{m/yr}$ ) for a difference in equivalent magnitudes of  $\sim 0.1$ . Assuming that the 1877 earthquake extended only up to the city of Iquique, Métois *et al.* (2013) evaluate a moment deficit rate of  $\sim 1.5\text{--}2.9 \times 10^{19} \text{ N} \cdot \text{m/yr}$ , corresponding to an equivalent magnitude of  $M_w$  8.1–8.3. Within this area, the MDR from the coupling map from Jolivet *et al.* (2020) indicates  $\sim 6.2 \times 10^{19} \text{ N} \cdot \text{m/yr}$ , which will produce a difference of 0.3 in terms of magnitude.

The magnitude of the 1877 event was actually recently reestimated as an  $M_w$  8.5 based on the re-evaluation of intensity maps and tsunami heights by Vigny and Klein (2022). This value is on the edge of the PDF of  $P_{M_{\max}}$  we estimate (see the Results section), and the recurrence time from Vigny and Klein (2022) differs from ours ( $\sim 150$  yr instead of  $\sim 800$  yr for  $M_w$  8.5 events). Uncertainties, whether on the magnitude or recurrence time, are in any case relatively large (Fig. 2).

### Megathrust segmentation

We interpreted the low coupling near the city of Iquique (Fig. 1a) as a frictional barrier, assuming a local variation in rheological properties of the megathrust are responsible for this reduction in coupling. However, other complexities might be at the origin of such feature (Jara *et al.*, 2018; Maksymowicz *et al.*, 2018). For instance, geometry or fluids are known to influence the dynamics of slip along faults (Sibson, 1973; Noda and Lapusta, 2010; Romanet *et al.*, 2018). One would therefore need to reconsider the probability of an earthquake rupturing such low coupling region under the physical constraints imposed by these mechanisms.

We also note that the 1877 event probably stopped south at about the northern extent of the 1995 Antofagasta earthquake, while no drop in coupling is observed at this location (Fig. 1a). This apparent segmentation might originate from the stress shadow imposed by an earthquake that ruptured the same region than the 1995 Antofagasta earthquake, although this is speculative. In any case, this highlights the role of historical seismicity and, in particular, the slip distribution of past earthquakes, which we do not account for in this methodology. Indeed, background seismicity, including  $M_w > 7.5$  earthquakes, is viewed as independent events. Such assumption is probably not applicable for large events, as their occurrence is surely dependent on their interactions in time and space. Finally, our study only considers along-strike heterogeneity, although there is evidence for along-dip segmentation (i.e., Lay *et al.*, 2012; Jara *et al.*, 2018; Ruiz and Madariaga, 2018).

Finally, we acknowledge that our study only accounts for a finite region of the subduction zone. Large earthquakes could effectively propagate out of this region, because it has been recently proposed based on geoarcheological evidence, which suggests the potential occurrence of an M 9.5 event 3800 yr ago (Salazar *et al.*, 2022).

## CONCLUSION

We propose a probabilistic evaluation of the seismogenic potential of the northern Chile subduction zone, taking into account the moment budget of the megathrust, the MFD of observed earthquakes, the moment–area scaling law, and the effect of a potential frictional barrier. We find that, given the uncertainties, an  $M_w \sim 8.8$  event is the most probable maximum magnitude earthquake (between  $\sim 8.5$  and  $9.1$ , considering the 5th and 95th percentile of the cumulative PDF of  $P_{M_{\max}}$ ), events with such magnitude tend to occur every  $\sim 2500$  yr if taking all probable seismicity models into account (between 1500 and 6300 yr considering the 5th and 95th percentile of  $P(\tau|M_w 8.85)$ ), and the potential barrier near the city of Iquique has a limited impact considering its uncertainty. The methodology presented in this study does not take into account the history of large events and is thus time independent. Since the 1877 earthquake, the moment deficit accumulated on the fault north of the city of Antofagasta is equivalent to an  $M_w 8.6$ . However, the 2014 Iquique earthquake and its aftershock might have released moment deficit at its location and potentially left a stress shadow that might hinder the propagation of future large events. Nevertheless, following this scenario, the moment deficit accumulated between the city of Antofagasta and Iquique since 1877 is equivalent to an  $M_w 8.5$ .

## DATA AND RESOURCES

We use the instrumental seismicity catalog from the International Seismological Center (ISC, <http://www.isc.ac.uk/iscbulletin/search/catalogue/>, last accessed January 2023). The historical seismicity data are taken from Roth *et al.* (2017). The coupling model data are taken from Jolivet *et al.* (2020). The moment and area data of subduction earthquakes are taken from Ye *et al.* (2016). The relationship between the barrier efficiency and the probability of an earthquake to pass a frictional barrier is given by Kaneko *et al.* (2010). The supplemental material contains (1) a description of the results of northern Chile seismogenic potential using a truncated seismicity model (Text S1), (2) information about the process followed to decluster the instrumental catalog (Text S2), (3) figures illustrating the difference between the tapered and truncated seismicity models (Figs. S1, S2), (4) figures describing the magnitude type conversion of the instrumental catalog events into moment magnitude (Figs. S3, S4), (5) figures describing the instrumental catalog and its declustering (Figs. S5, S6), (6) figure showing a comparison between using Leonard (2010) and Ye *et al.* (2016) data on the scaling law constraint (Fig. S7), (7) figures describing the uncertainties on the size of the potential barrier near the city of Iquique and on the probability of an event to pass a barrier (Figs. S8, S9), (8) a figure showing the effect of the frictional barrier constraint on the parameters of the barrier efficiency (Fig. S10), and (9) a figure showing the results of northern Chile seismogenic potential taking a fault fully coupled down to 60 km depth (Fig. S11).

## DECLARATION OF COMPETING INTERESTS

The authors acknowledge that there are no conflicts of interest recorded.

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