Geophysical Journal International

Geophys. J. Int. (2016) **206,** 1761–1783
Advance Access publication 2016 July 6
GJI Seismology

doi: 10.1093/gji/ggw247

Full moment tensors for small events ($M_w < 3$) at Uturuncu volcano, Bolivia

Celso Alvizuri and Carl Tape

Geophysical Institute and Department of Geosciences, University of Alaska, Fairbanks, AK 99775, USA. E-mail: cralvizuri@alaska.edu

Accepted 2016 June 27. Received 2016 June 26; in original form 2015 December 9

SUMMARY

We present a catalogue of full seismic moment tensors for 63 events from Uturuncu volcano in Bolivia. The events were recorded during 2011–2012 in the PLUTONS seismic array of 24 broad-band stations. Most events had magnitudes between 0.5 and 2.0 and did not generate discernible surface waves; the largest event was M_w 2.8. For each event we computed the misfit between observed and synthetic waveforms, and we used first-motion polarity measurements to reduce the number of possible solutions. Each moment tensor solution was obtained using a grid search over the 6-D space of moment tensors. For each event, we show the misfit function in eigenvalue space, represented by a lune. We identify three subsets of the catalogue: (1) six isotropic events, (2) five tensional crack events, and (3) a swarm of 14 events southeast of the volcanic centre that appear to be double couples. The occurrence of positively isotropic events is consistent with other published results from volcanic and geothermal regions. Several of these previous results, as well as our results, cannot be interpreted within the context of either an oblique opening crack or a crack-plus-double-couple model. Proper characterization of uncertainties for full moment tensors is critical for distinguishing among physical models of source processes.

Key words: Inverse theory; Earthquake source observations; Volcano seismology; South America.

1 INTRODUCTION

Seismic waveforms of three-component ground motion contain information about source processes and earth structure. In order to make inferences about the source process, we need to account for how seismic waves propagate through some assumed model of earth structure. In this study, we focus on a data set of seismic waveforms recorded at Uturuncu volcano in Bolivia. We examine a catalogue of events and estimate seismic moment tensors as a first step toward characterizing the source processes at the volcano.

The seismic moment tensor is a 3×3 symmetric matrix that describes the pattern of radiation from a seismic source. Six numbers are needed to describe the moment tensor: three eigenvalues describing the source type and magnitude and three angles (strike, slip, and dip) describing the orientation. For $\mathbf{\Lambda} = (\lambda_1, \lambda_2, \lambda_3)$ and U a rotation matrix, the moment tensors $[\mathbf{\Lambda}]$ and $[\mathbf{\Lambda}]_U$ are defined by

$$[\mathbf{\Lambda}] = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix} \tag{1a}$$

$$[\mathbf{\Lambda}]_U = U\,[\mathbf{\Lambda}]\,U^{-1}. \tag{1b}$$

The notation $M = [\mathbf{\Lambda}]_U$ provides an explicit separation between the source type (with $\mathbf{\Lambda}$) and the orientation (U).

A source type for a moment tensor is its normalized and ordered eigenvalue triple $\mathbf{\Lambda} = (\lambda_1, \lambda_2, \lambda_3)$ ($\|\mathbf{\Lambda}\| = 1$ and $\lambda_1 \geq \lambda_2 \geq \lambda_3$). Due to the normalization and ordering, the source types make up one-sixth of the unit sphere—the lune shown in Fig. 1. Each source type $\mathbf{\Lambda}$ can be specified by its longitude γ and latitude δ on the lune. In beachball terms, $\mathbf{\Lambda}$ determines the coloured pattern on the beachball, but without some physical model for moment tensors it does not determine the actual source process.

The classical model of Aki & Richards (1980) (see also Dufumier & Rivera 1997) describes a moment tensor as an oblique (tensional or compressional) crack and a Poisson parameter for the source region. Alternatively, the moment tensor can be described as a two-process model that is the sum of a crack tensor and a double couple whose fault plane is aligned with the crack (Minson *et al.* 2007). A comparison of the classical model and the crack-plus-double-couple (CDC) model is presented in Tape & Tape (2013), who also elaborate on a more generalized CDC model that was introduced by Julian *et al.* (1998), in which the fault plane of the double couple is not aligned with the crack plane. Without additional constraints on the source process (e.g. the orientation of a crack plane from microseismicity), it is impossible, in the generalized model, to infer the crack and double couple from seismic waveforms.

© The Authors 2016. Published by Oxford University Press on behalf of The Royal Astronomical Society.

Figure 1. Four regimes for moment tensors, depicted on the fundamental lune (Tape & Tape 2013, Fig. S1, Supporting Information). The lune is the surface of normalized moment tensor eigenvalue triples $\mathbf{\Lambda} = (\lambda_1, \lambda_2, \lambda_3)$, with $\lambda_1 \geq \lambda_2 \geq \lambda_3$. The three arcs $\lambda_3 = 0$ (red), $\lambda_2 = 0$ (blue) and $\lambda_1 = 0$ (white) divide the lune into four regions. Above $\lambda_3 = 0$, beachballs are all red ($\lambda_3 > 0$). Above and to the right of the arc $\lambda_2 = 0$, moment tensor beachballs have red bands and white caps ($\lambda_2 > 0 > \lambda_3$). Below and to the left of it they have white bands and red caps ($\lambda_1 > 0 > \lambda_2$). Below the arc $\lambda_1 = 0$, beachballs are all white ($\lambda_1 < 0$). Double-couple moment tensors are at the centre of the lune, where $\mathbf{\Lambda} = (1, 0, -1)$. (Although points on the lune have unit norm, we often give them as unnormalized directions; thus $(1, 0, -1)$ instead of $(1, 0, -1)/\sqrt{2}$.)

Table 1. Examples of published studies on full moment tensor inversions. See Table 2 for explanation of columns. See Section 1 for discussion.

			Magnitude	Frequency	Details for moment tensor inversion									
Study	Events	Stations	range	range (Hz)	FMP	BW	SW	WD	AR	1-D/3-D	GS	L	UNC	F11b
This study	63	5–23	0.3–2.8	0.25–10	Y	Y	Y	Y	–	1D	Y	–	B	Y
Boyd *et al.* (2015)	53	39	3.29–4.72	0.02–0.10	Y	–	Y	Y	–	1D	Y	–	C	Y
Ross *et al.* (2015)	7	71–126	4.2–5.4	0.02–0.3	–	Y	Y	Y	–	1D	Y	–	C	–
Aso & Ide (2014)	38	5	1.2–2.1	≤10	–	Y	–	Y	–	1D	Y	Y	–	–
Stähler & Sigloch (2014)	1	17–41	5.7	–	–	Y	–	Y	–	1D	–	–	A	–
Stierle *et al.* (2014)	33	35	2.5–4.3	0.5–35	–	Y	–	Y	–	1D	Y	–	B	–
Chiang *et al.* (2014)	3	3–4	5.21–5.25	0.01–0.08	Y	–	Y	Y	–	1D	Y	–	B	–
Guilhem *et al.* (2014)	15	30	3.31–4.43	0.5–2.5	Y	Y	–	Y	–	1D	–	Y	B	–
Nayak & Dreger (2014)	62	5	1.3–1.6	0.1–0.2	Y	–	Y	Y	–	1D	Y	–	B	–
Pesicek *et al.* (2012)	7	10–12	1.0–2.3	2–10	Y	–	–	–	Y	3D	Y	Y	C	Y
Ford *et al.* (2012)	1	8	3.5	0.02–0.1	–	–	Y	Y	–	1D	–	Y	B	–
Vavryčuk (2011)	71	7–22	≤3.7	1–35	–	Y	–	–	–	1D	–	Y	C	Y
Eisner *et al.* (2010)	4	980	0.4–0.7	–	–	–	–	–	–	1D	–	–	–	–
Baig & Urbancic (2010)	147	–	–	–	–	–	–	–	–	–	–	–	–	–
Julian *et al.* (2010)	38	36	0.3–2.6	≤5	Y	–	–	–	Y	–	–	Y	–	–
Walter *et al.* (2010)	14	24		20–70	–	Y	–	Y	–	1D/3D	Y	Y	–	–
Ford *et al.* (2010)	2	6–8	4.2–4.8	0.02–0.1	–	–	Y	Y	–	1D	Y	–	B	–
Ford *et al.* (2009)	32	16–52	3.3–5.4	0.02–0.1	–	–	Y	–	–	1D	–	Y	–	–
Šilený *et al.* (2009)	24	8	−2 to −1.4	–	Y	Y	–	–	–	1D	–	Y	–	–
Walter *et al.* (2009)	13	–	−2.6 to −1.3	5–60	–	Y	–	Y	–	1D	Y	–	–	–
Minson & Dreger (2008)	18	9	3.7–6.5	0.02–0.05	–	–	Y	–	–	1D	Y	–	–	Y
Šilený & Milev (2008)	5	12	2.0–3.0	≥3	–	–	–	Y	–	1D	–	Y	C	–
Minson *et al.* (2007)	13	3–9	4.5–6.2	≤0.05	–	–	Y	–	–	1D	Y	Y	–	Y
Šilený & Milev (2006)	5	16	–	4.5–20	–	Y	–	–	Y	–	–	–	C	–
Foulger *et al.* (2004)	26	65	0.4– 3.1	≤5	Y	–	–	–	Y	1D	–	Y	–	Y
Horálek *et al.* (2002)	70	6–9	0.3 –3.0	≥0.5	–	Y	–	–	Y	1D	–	Y	–	–
Vavryčuk (2001)	36	9	0.5–3.0	–	–	–	–	–	–	–	–	–	–	Y
Miller *et al.* (1998b)	70	30	–	≤5	Y	Y	–	–	Y	3D	–	Y	–	–
Dahm & Brandsdóttir (1997)	15	4–21	1.1–2.3	1.5–7.0	Y	Y	–	–	Y	–	–	Y	–	–

The literature summarized in Table 1 provides context for our study. These studies estimated full moment tensors in a variety of settings: geothermal and volcanic regions (Dahm & Brandsdóttir 1997; Miller *et al.* 1998b; Minson *et al.* 2007; Julian *et al.* 2010; Pesicek *et al.* 2012; Guilhem *et al.* 2014), mines (Šilený & Milev 2008, 2006; Ford *et al.* 2009), hydraulic fracturing (Foulger *et al.* 2004; Šilený *et al.* 2009; Baig & Urbancic 2010; Eisner *et al.* 2010; Julian *et al.* 2010), landslides (Nayak & Dreger 2014), glaciers (Walter *et al.* 2010, 2009), explosions (Minson & Dreger 2008; Ford *et al.* 2009, 2010, 2012; Chiang *et al.* 2014), and earthquakes

(Vavryčuk 2001; Horálek *et al.* 2002; Vavryčuk 2011; Stähler & Sigloch 2014; Stierle *et al.* 2014; Ross *et al.* 2015). See also the review by Julian *et al.* (1998) and Miller *et al.* (1998a) for previous studies, and see Chouet & Matoza (2013) for a review of studies specific to volcanic settings.

Table 1 also compares the choice of seismic data and the approach to moment tensor inversion in different studies. For larger events (say, $M_w > 3$), we see that lower frequency waveforms ($f < 0.2$ Hz or $T > 5$ s) can be used to estimate moment tensors, whereas smaller events require using higher frequency waveforms or using only the polarity of the first-motion *P* wave. Once the time windows of waveforms have been selected, one must decide how to compute synthetic seismograms and then how to measure the waveform difference between observations and synthetics. Finally, there is a choice of how to estimate the best-fitting moment tensor, either using a linearized inversion or using a grid search over the model parameter space.

We also examine in Table 1 how previous studies have addressed uncertainties of moment tensors. We label each study according to: (A) whether formal uncertainties are addressed (e.g. Stähler & Sigloch 2014), (B) whether the misfit function is represented on the space of moment tensors (e.g. Ford *et al.* 2010), (C) whether some other approach was used, such as perturbing synthetic seismograms to see the perturbations on estimated moment tensors (e.g. Riedesel & Jordan 1989; Šilený & Milev 2006), and (–) whether uncertainties were not addressed or not reported (Table 2).

In this study, we examined 63 events with magnitudes 0.3–2.8. Such small events produce relatively high frequencies. For most events, we were only able to use high-frequency (2–10 Hz) *P* waveforms; for the largest events we used surface waves (0.25–0.50 Hz). We used a grid-search algorithm to obtain the moment tensor whose synthetic seismograms provide the best fit to observed seismograms (Zhu & Helmberger 1996; Zhu & Ben-Zion 2013). We use the source-type representation on the lune (Tape & Tape 2012) (Fig. 1) to outline regions of solutions that are allowed by first-motion polarity observations, and we use the waveform misfit to highlight regions of confidence around the best-fitting moment tensor. Our graphical display of misfit in the model parameter space of full moment tensors is a step toward obtaining formal uncertainties. These displays are particularly important for small events where only a limited portion of the seismic wavefield can be used and hence uncertainties are larger. Within our catalogue of 63 events are several events requiring non-double-couple mechanisms.

1.1 Uturuncu volcano

The Altiplano of the central Andes is a broad plateau characterized by substantial relief (elevations 3.5–4.7 km) and overlying a 70-km-thick crust (Isacks 1988). Cerro Uturuncu, within the Altiplano, is a stratovolcano that was last active 270 ka (Sparks *et al.* 2008). Uturuncu volcano is part of a large regional cluster of volcanoes, nested calderas and ignimbrite sheets termed the Altiplano-Puna volcanic complex (APVC; de Silva 1989). The region experienced

Table 2. Explanation of columns for Table 1.

FMP	Used first-motion polarities
BW	Used body waves
SW	Used surface waves
WD	Used waveform difference
AR	Used amplitude ratios
1-D/3-D	Computed Green's function's using 1-D or 3-D structural model
GS	Used grid search
L	Used linearized inversion
UNC	Addressed uncertainties
	[A] posterior probability density over moment tensor (or eigenvalue) space
	[B] show misfit function over full eigenvalue space
	[C] approximate posterior probability density over moment tensor (or eigenvalue) space
F11b	Data plotted in Fig. 11b

Table 3. Moment tensor results for the example event for different subsets of data and different allowable subsets of moment tensors. Each row lists the optimal moment tensor solution as six parameters: magnitude M_w, lune longitude γ, lune latitude δ, strike κ, dip θ, and rake σ. The percent variance reduction is VR. The weights (10, 01, or 00) for the waveform components for each inversion are listed for *P*-wave vertical (PV), *P*-wave radial (PR) and surface waves (Surf). The number of first-motion polarities used in the inversion are listed under Npol. The label 'subset' denotes whether the moment tensor inversion assumes the full moment tensor space ('–') or is restricted to specific physical models by setting $\gamma = 0°$ and $\delta = 0°$ for the double couple (DC), $\gamma = -30°$ for tensional crack (C+), and $\gamma = 30°$ for compressional crack (C–). Figures associated with each inversion are listed in the last two columns.

M_w	γ	δ	κ	θ	σ	VR	PV	PR	Surf	Npol	Subset	Figures	
2.8	10	−10	150	76	−75	22.1	10	01	10	11	–	6, 7a	4, S8
2.8	5	−13	145	73	−70	22.4	10	01	10	–	–	7b	S9
2.9	20	−23	145	66	−80	30.9	10	01	00	11	–	7c	S10
3.0	20	−26	130	58	−80	32.8	10	01	00	–	–	7d	S11
3.0	20	−23	145	66	−80	47.6	10	00	00	11	–	8a	S12
2.2	0	0	10	5	−75	15.2	00	01	00	11	–	8b	S13
2.8	15	3	150	73	−55	21.7	00	00	10	11	–	8c	S14
2.7	[0]	[0]	170	90	−85	21.2	10	01	00	11	DC	S24b	S21
2.7	[−30]	34	50	50	75	11.4	10	01	00	11	C+	S24c	S22
3.1	[30]	−30	345	35	−90	24.2	10	01	00	11	C–	S24d	S23

extensive magmatism starting 11 Ma (de Silva 1989) in eruptive episodes, with rates up to 31 km^3 ka^{-1}, generating over 12 000 km^3 of ignimbrites (Salisbury *et al.* 2011).

The crust beneath the APVC is characterized by geophysical anomalies, such as very low seismic velocities and high seismic attenuation (Zandt *et al.* 2003), low electrical resistivities (Haberland *et al.* 2003; Comeau *et al.* 2015), and negative gravity anomalies and low densities (del Potro *et al.* 2013). A regional-scale mid-crustal magma reservoir termed Altiplano-Puna Magma Body (APMB) was identified beneath the APVC at depth of about 15 km (19 km below the surface) (Chmielowski *et al.* 1999). A recent seismic study using surface wave dispersion and receiver functions estimates that the APMB is about 200 km wide, 11 km thick, is at depths 4–25 km, and has a volume of about 500 000 km^3 (Ward *et al.* 2014).

Geodetic satellite observations in the region have identified ongoing surface uplift centred at Uturuncu volcano at a rate of 10–15 mm yr^{-1} (Pritchard & Simons 2002) and peripheral subsidence (Fialko & Pearse 2012). These studies have concluded that the deformation may be linked with the APMB, and suggest a mid-crust source above a depth of 20 km. Active fumaroles (Sparks *et al.* 2008) and geothermal fields in the region also suggest active magmatic activity (de Silva 1989).

Uturuncu volcano was the focus of the second part of a multidisciplinary project known as PLUTONS, which was active 2009–2015 and was supported by the Continental Dynamics programme of the National Science Foundation. [The acronym PLUTONS, with a few extra letters, stands for: Probing Lazufre and Uturuncu TOgether: Nsf (usa), Nerc (uk), Nserc (canada), Sergeotecmin (bolivia), Sernageomin (chile), observatorio San calixto (bolivia), universidad nacional de Salta (argentina), universidad mayor de San andres (bolivia), universidad de potoSi (bolivia), Sernap (bolivia), chilean Seismological service, and universidad de San juan (argentina).] An array of broad-band stations was installed at Uturuncu volcano (West & Christensen 2010) in order to record the local activity associated with volcanic (and tectonic) deformation.

We use seismic data from the PLUTONS project to estimate moment tensors for events beneath Uturuncu volcano. The goal of our study was to estimate full moment tensors for all possible events at Uturuncu volcano, along with their uncertainties. As far as we can tell, these are the first moment tensors—full or double couple—examined for this volcano. Double-couple moment tensors for the larger region are available from, for example, Chinn & Isacks (1983) and Devlin *et al.* (2012, see their table 1).

2 METHODS

2.1 Selection of events

The objective of our study is to estimate full moment tensors using the best available seismic data at Uturuncu volcano. Therefore we focus on shallow events that are inside the station array. We ignore events in the underlying slab, for which the station array forms a much smaller aperture. Fig. 2 summarizes the seismicity catalogue for the PLUTONS project, and it also highlights our selection of events for analysis.

We focus on events at Uturuncu volcano that are between longitudes -67.4° and -66.9° and latitudes -22.6° and -22.1° and above a depth of 60 km. (All depths listed are with respect to sea level, not the topographic surface, unless explicitly stated.) The PLUTONS seismicity catalogue (Keyson & West 2013) is complete through 2012 March 9 and contains 1433 events within this region, spanning the time period from 2009 April 26 to 2012 March 9 and including stations from both Lazufre volcano (Jay *et al.* 2011) and Uturuncu volcano. We focus on the time period of the Uturuncu stations only, from 2010 April 12 to 2012 March 9 (Fig. 2b). Within this time period, there are 421 events, the majority of which occurred at a depth of 4–6 km; since the mean station elevation is 4.6 km, these events occur at about 10 km below the surface.

Uturuncu volcano did not produce many sizable earthquakes during the time period of the PLUTONS project. Based on the frequency–magnitude distribution for the 421 events in our region of interest (Fig. 2c), we expect one $M > 2.5$ event per two years and about 100 $M > 0$ events per year. The magnitude of the catalogue completeness is $M_c = 0.0$.

In order to isolate the most promising events for moment tensor inversion, we reduce the set of 421 to 101 events by forming two subsets. The first is the set of the 21 events with $M \geq 1$. The second is the set of 80 events with $M \geq 0$ and having $\geq$20 recording stations. For the small events, we could only use *P* waveforms and polarities, so we restricted the subset to have the most stations. We chose the large events in order to try to model surface waves, even if only a limited number of stations were recording. The set of 101 events was reduced to 72 using the criterion that an event must have $\geq$5 first-motion polarities that have arrival times that are consistent with a simple velocity model. The set of 72 events was reduced to 63 by excluding outlier events from a scatter plot of *P* traveltime (from the catalogue) versus hypocentral distance (Fig. S2, Supporting Information). The 63 events that we analyse represent a subset of all events within the PLUTONS catalogue that we deem to be suitable for full moment tensor inversions.

2.2 First-motion polarity measurements

Given the small size of the events at Uturuncu volcano, we could not rely on waveform-only comparisons to obtain reliable moment tensors, as do studies with regional seismic networks recording large ($M \geq 4$) events (e.g. Tan *et al.* 2010). First-motion polarity measurements have been used in a number of studies of full moment tensors (Table 1), and they proved to be valuable for the small events in our study.

For all seismograms in this study, we deconvolved the instrument response over the frequency range 0.05–20 Hz. First-motion polarity measurements were made on the vertical-component waveforms; in the case of some of the smallest events, we applied an $f > 1$ Hz high-pass filter to enhance the signal-to-noise level. An 'upward' (or 'outward') measurement corresponds to a compression; a 'downward' (or 'inward') measurement corresponds to a dilatation. If a waveform did not have a discernible first motion—either due to poor signal-to-noise or due to a non-abrupt *P* wave—it was not used in the inversion. Three seismologists picked the first-motion polarities; any discrepancies among the three choices were resolved following collective discussion and analysis.

2.3 Grid-search moment tensor inversion

Estimating moment tensors using a grid search requires a choice of model parameter space, a choice of a seismic velocity model, the calculation of synthetic seismograms, a choice for a misfit function to compare observed and synthetic seismograms, and an algorithm to determine the minimum of the misfit function.

Figure 2. Stations and events near Uturuncu volcano. (a) Map showing stations and all events with depths less than 60 km in the Uturuncu catalogue (Keyson & West 2013). Our region of interest is inside the station array and ranges between longitudes −67.4° and −66.9° and between latitudes −22.6° and −22.1°. There are 421 events in this region, 63 of which (red circles) meet our selection criteria in this study (Section 2.1). Top and right plots show the seismicity projected onto vertical cross-sections. The histogram shows the distribution of events with depth; it reveals a predominance of event depths near 5 km. (b) Top: number of PLUTONS stations active as a function of time. The vertical lines mark the time period of events considered in our study, 2010 April 12–2012 March 9. Bottom: events as a function of time; the red circles are the 63 events in our study. (c) Frequency–magnitude distribution for 421 crustal events in the region of interest. The relationship implies the occurrence of one $M \geq 2.5$ earthquakes per two years in this region.

Our space of model parameters has six dimensions, consistent with the number of entries in a 3 × 3 symmetric matrix. Our six parameters, however, are not the matrix entries but rather strike angle, rake angle, dip angle (all for the closest double couple), lune latitude δ, lune longitude γ and moment magnitude (Table S3, Supporting Information). The strike, rake and dip angles determine the moment tensor orientation, and δ and γ determine the source type.

Our moment tensor inversion method is the 'cut-and-paste' algorithm (Zhao & Helmberger 1994; Zhu & Helmberger 1996), which has recently been extended to full moment tensors by Zhu & Ben-Zion (2013). The source time function is assumed to have the simple form of a trapezoid function. Synthetic waveforms are precomputed in a layered model (or homogeneous model) over a range of distances and event depths using the frequency–wavenumber method (Zhu & Rivera 2002). The basic premise of the moment tensor inversion algorithm is that *P* waves (vertical and radial components) and surface waves (Love and Rayleigh) are windowed separately and filtered separately. Within each time window, a time-shift is applied to the synthetic waveforms with the intention of correcting for errors due to the user-input velocity model. Then within each time window a direct waveform difference is measured. We force the time-shift for the *P* wave to be the same on the vertical and radial components, and we force the time-shift for the Rayleigh wave to be the same on the vertical and radial components.

Our main adaptation to the code of Zhu & Helmberger (1996) is the use of the L1 norm (eq. 2a), as described in Silwal & Tape (2016). The misfit function is

$$\Phi(M) = \sum_{j=1}^{N} \sum_{i=1}^{5} \phi_{ij}(M) \tag{2a}$$

$$\phi_{ij}(M) = \left[\left(\mathbf{u}_{ij} - \mathbf{s}_{ij}(M)\right)^T \mathbf{W}_{ij} \left(\mathbf{u}_{ij} - \mathbf{s}_{ij}(M)\right) \right]^{1/2}, \tag{2b}$$

where i is the index over five possible waveform sections, j is the index over N stations, $\mathbf{u}_{ij}$ is the observed seismogram, $\mathbf{s}_{ij}(M)$ is the discretized seismogram for moment tensor M, $\phi_{ij}(M)$ is the L2-norm waveform difference within each time window, weighted by matrix $\mathbf{W}_{ij} = w_{ij}\mathbf{I}$ (see Section 2.4). Variance reduction is a normalized measure that provides a better comparison from one event to the next. This is computed as

$$\mathrm{VR}(M) = 100 \times \left(1 - \left(\frac{\Phi(M)}{\|\mathbf{u}\|_{L1}}\right)^2\right) \tag{3}$$

where

$$\|\mathbf{u}\|_{L1} = \sum_{j=1}^{N} \sum_{i=1}^{5} \sqrt{\mathbf{u}_{ij}^T \mathbf{W}_{ij} \mathbf{u}_{ij}} \tag{4}$$

is the data normalization factor that is independent of M. Variance reduction can be negative; its range is VR $\leq$ 100.

For the small-magnitude events in this study, it was challenging to fit the observed *P* waveforms with synthetic waveforms. We filtered the *P* waveforms between 2 and 10 Hz to provide the best signal-to-noise. Even in cases where the observed and synthetic *P* waveforms have similar shapes, it is possible for the synthetic waveform to be matched with a different observed waveform that has a higher cross-correlation value; this misalignment of waveforms is known as cycle-skipping. To minimize the chances of cycle-skipping, we forced the synthetic *P* waveform to start at the time of the *P* onset in the catalogue (Keyson & West 2013). We then allowed time-shifts to the synthetics of $|\Delta T| \leq 0.05$ s. The variable **s** in eq. (2b) is taken to be the discretized version of the time-shifted synthetic seismogram.

We also use first-motion polarities during the grid search. For each moment tensor M, we calculate how many predicted polarities $n(M)$ do not match the observed polarities:

$$n(M) = \frac{1}{2} \sum_{j}^{N} \left| k_j^{\mathrm{obs}} - k_j(M) \right| \tag{5}$$

where k_j^{obs} is the observed first-motion polarity (1 or −1) at the jth station and $k_j(M)$ is the predicted first-motion polarity (1 or −1). Thus, $n(M)$ is at least zero (all measurements match) and at most N (all measurements mismatch).

In our inversions, we discard any moment tensor with $n(M) > 0$, that is, any moment tensor whose predicted polarities did not match all of the observed polarities. This is a strong constraint that emphasizes the first-motion polarities. An alternative would be to use a misfit function that combines the waveform misfit $\Phi(M)$ with the polarity misfit $n(M)$. The main reason for using first-motion polarities is due to the challenges of fitting waveforms for small-magnitude events in structurally complex regions. By allowing synthetic waveforms to be time-shifted to match observed waveforms, there is always a danger of cycle-skipping. The inclusion of first-motion polarities reduces the chance of cycle-skipping for the *P* waveforms.

2.4 Choice of velocity model and weights for misfit function

The seismic velocity structure at Uturuncu volcano is not well known. Regional studies (Zandt *et al.* 2003; Ward *et al.* 2014) provide 1-D models with layers so thick that most of our events are within the uppermost layer. We performed full moment tensor inversions for 63 events using a local 1-D model (Shen *et al.*, in preparation) and a homogeneous model. The homogeneous model is described by $V_{\mathrm{P}} = 4800$ m s^{-1}, $V_{\mathrm{S}} = 2820$ m s^{-1}, $\rho = 2306$ kg m^{-3}, $Q_{\mathrm{P}} = 1000$ and $Q_{\mathrm{S}} = 500$; values for V_{P} and V_{S} were obtained from the upper layer of a tomography study by West *et al.* (2013); values for ρ, Q_{S}, and Q_{P}, where $\rho = 0.77 + 0.32\,V_{\mathrm{P}}$, are set by default while computing synthetic waveforms with the frequency–wavenumber method (Zhu & Rivera 2002). The moment tensor solutions obtained with the homogeneous model provided a better fit to the observed data, as discussed in Section 5. However, when using the homogeneous model we needed to adjust the misfit function used in the inversion, as described next.

Ray paths for a homogeneous model are straight lines. The presence of a shallow slow layer will refract the ray with a steeper incident angle at the station. Therefore, the synthetic amplitude ratio between the vertical component and radial component of the *P* wave will increase if a slow uppermost layer is added to a homogeneous model.

For each station and for each event, we calculated the amplitude of the *P* wave on the vertical and radial components for both the observed and synthetic waveforms. These quantities allowed us to examine two different amplitude ratios: (1) $\ln(A_{\mathrm{obs}}/A_{\mathrm{syn}})$, the ratio between observed and synthetic *P*-wave amplitudes (either vertical or radial component), (2) $\ln(Z/R)$, the ratio of the vertical-component *P*-wave amplitude to the radial component amplitude. We used these amplitude ratios to guide our choice of velocity model and our choice of weights in the inversion.

Whether we assume a homogeneous model or a 1-D model, the take-off angles of ray paths from the source are low-angle (with

Figure 3. *P*-wave amplitude ratios, $\ln(A_{\mathrm{obs}}/A_{\mathrm{syn}})$, for all 656 windows for all 63 events and for two different sets of weights. (a) Amplitude ratios for moment tensor inversions using equal weights for the vertical-component *P* wave, the radial component *P* wave, and the surface waves. On the left is the amplitude ratio for the vertical-component *P* wave; on the right is the ratio for the radial component. With this choice of weights, the histogram for the radial component is approximately centred on zero, whereas the histogram for the vertical component is skewed toward positive values, indicating that the vertical-component synthetic amplitudes are small relative to observations. (b) Same as (a), but for this set of moment tensor inversions the radial component was downweighted relative to the vertical-component *P* wave and the surface waves. For these weights, we see that the vertical-component *P* wave amplitude ratios are centred on zero, whereas the radial component ratios are skewed to negative values, indicating that the radial synthetic amplitudes are larger than the observations. Note that the moment tensor solutions in (b) are not identical to those in (a), since a different misfit function has been used. Figs S4–S7 provide an extended analysis of amplitude ratios.

respect to horizontal). Our assumption of a homogeneous model results in predictions of higher amplitude *P* waves on the radial component compared to the vertical component (Fig. S4, Supporting Information). However, our *P*-wave amplitudes are larger on the vertical component, indicating steeper incident angles at the station than would be expected for a homogeneous model. In order for our synthetic amplitudes to better match observed ones, we could have added a shallow slow layer. Instead, we preferred to keep the simpler homogeneous model, and we obtained the better match by adjusting the weights for the waveforms in the inversion.

With equal weights for fitting the vertical and radial components of *P* waves, we discovered that the amplitude ratios were centred for the radial component but skewed for the vertical component (Fig. 3a). It appears that the artificially high amplitudes of the radial component *P* waves were leading to moment tensor solutions with worse-than-desired amplitude fits for the vertical-component *P* waves.

Since our first-motion polarity measurements were made on the vertical component, we wanted to fit the vertical-component waveforms above all. We achieved this by downweighting the waveform fitting of the radial component *P* waves within the inversion. The result on the moment tensor inversion is shown in Fig. 3(b), where the amplitude ratios are centred for the vertical component but skewed for the radial component.

3 FULL ANALYSIS FOR AN EXAMPLE EVENT

We display results for one event in Figs 4–8. This event, with magnitude M_{w} 2.8, is the largest in the data set and generates large enough surface waves to be compared with synthetic seismograms. Our grid search over six parameters (magnitude, lune longitude, lune latitude, strike, dip and rake) results in the moment tensor M_0 shown at the top of Fig. 4. (The moment tensor M_0 is not to be confused with the scalar seismic moment, also usually denoted by M_0.) The grid search is limited to moment tensors whose predicted first-motion polarities all match the observations.

The waveform fits for the event in Fig. 4 have room for improvement, as the waveforms do not match wiggle-for-wiggle. Furthermore, the actual amplitude differences are larger than they appear in Fig. 4, where we have scaled each waveform in each window in order to best view the waveform shapes (Fig. S8 in the Supporting Information shows the unscaled waveforms). These differences in waveform fits, especially due to amplitudes, are to be expected for events of this magnitude ($M \leq 3$) and with waveforms filtered at these frequencies: 2–10 Hz for *P* waves and 0.25–0.50 Hz for surface waves. From our standpoint, what is most important is that we can use more than just the first-motion polarity to estimate the moment tensor. For all events in our study, we try to fit the shapes

Figure 4. Moment tensor solution M_0 and waveform comparisons for the example event (20100516063454464) in this study. Each column is a different section of the three-component waveform: PV = vertical-component P wave, PR = radial component P wave, SurfV = vertical-component Rayleigh wave, SurfR = radial component Rayleigh wave, and SurfT = transverse component Love wave. The stations are ordered by increasing epicentral distance from the top row. The observed waveforms are plotted in black, the synthetic waveforms are plotted in red. The body waves are filtered between 2 and 10 Hz, and the surface waves are filtered between 0.25 and 0.50 Hz (2–4 s). Each observed and synthetic waveform is scaled to fill the plotting window; Fig. S8 in the Supporting Information shows the same record section with absolute amplitudes. The numbers below each station name are, from top to bottom, the station epicentral distance, the station azimuth, and the sign of the first-motion polarity (1 is upward and −1 is downward). The number in parentheses is the source amplitude factor for M_0 at each station. The four numbers below each pair of waveforms are, from top to bottom, (1) the cross-correlation time-shift $\Delta T = T_{\mathrm{obs}} - T_{\mathrm{syn}}$ required for matching the synthetics $s(t)$ with the data $u(t)$ (a positive time-shift means that the synthetics arrive earlier than the data), (2) the maximum cross-correlation percentage between $u(t)$ and $s(t - \Delta T)$, (3) the percentage of the total misfit and (4) the amplitude ratio $\ln(A_{\mathrm{obs}}/A_{\mathrm{syn}})$. See Alvizuri (2015) for a description of the header lines.

Figure 5. Grid search for the best-fitting depth for the example event (Fig. 4). The red arrow marks the catalogue depth (0.6 km; 5.2 km below the surface), and the white arrow marks the depth obtained from our moment tensor inversion (−0.2 km; 4.4 km below the surface). The grey line with solid circles is the variance reduction VR for the moment tensor solution obtained at that particular depth (scale at right). The best solution occurs at the maximum in variance reduction $\mathrm{VR}_{\max} = 22.1$. The beachballs are plotted at the value of $\ln(\mathrm{VR}_{\max}/\mathrm{VR})$, which gives the variance reduction relative to the maximum (scale at left). The orientation and magnitude are free to change for each depth. The black dashed line is the best-fitting parabola, which is used for estimating the uncertainty in depth; here the best-fitting depth is -0.2 ± 0.5 km, which is 4.4 ± 0.5 km below the surface.

and amplitudes of the P waveforms—especially on the vertical component—and for this event we are also able to use the surface waves, which have large enough signal.

In Fig. 5, we show how the moment tensor solution varies as a function of event depth. The optimal depth is at 4.4 km below the surface elevation of 4.6 km, which differs by only 0.8 km from the traveltime-derived depth of 0.6 km. Our choice of optimal depth relies on the accuracy of the amplitude measurements. The depths listed in the catalogue are based on P and S traveltimes, which are more reliable (Keyson & West 2013). Therefore, for all other events in our study, we chose to use event depths listed in the catalogue.

The variation in the misfit function is represented by the plots in Fig. 6. The locations of the stations relative to the event are plotted in (a), with each station coloured according to the observed first-motion polarity. For each moment tensor M in our grid search, we calculate the number of misfitting polarity measurements $n(M)$ (eq. 5). We define $n(\mathbf{\Lambda})$ as the minimum number of misfitting polarity measurements for a given lune point $\mathbf{\Lambda}$:

$$n(\mathbf{\Lambda}) = \min\left(n([\mathbf{\Lambda}]_U) \,:\, U \in \mathbb{U}\right) \tag{6}$$

where $\mathbb{U}$ is the set of all orientations and where $[\mathbf{\Lambda}]_U$ and $n([\mathbf{\Lambda}]_U)$ are given by eqs (1) and (5). Fig. 6(b) is a plot of $n(\mathbf{\Lambda})$ for the example event. A blue point ($n(\mathbf{\Lambda}) = 0$) indicates that there is at least one orientation U for which the predicted polarities of $[\mathbf{\Lambda}]_U$ all match the observed polarities. A green point ($n(\mathbf{\Lambda}) = 1$) indicates that there is at least one orientation for which the predicted polarities match all but one of the observed polarities, but there is no orientation whose predicted polarities match all of the observed polarities. In Fig. 6(b) (see also Fig. 1), all points $\mathbf{\Lambda}$ above the arc $\lambda_3 = 0$ are red ($n(\mathbf{\Lambda}) = 4$); since $\lambda_1 \geq \lambda_2 \geq \lambda_3 > 0$, then all polarities of $[\mathbf{\Lambda}]_U$ are upward, regardless of U and $n(\mathbf{\Lambda})$ must then be the number of stations with downward polarity, which in this example is four. Similarly, if $\mathbf{\Lambda}$ is below the arc $\lambda_1 = 0$, then $n(\mathbf{\Lambda})$ is the number of stations with upward polarity, which in this example is seven.

The inclusion of polarities in the inversion restricts the number of moment tensor gridpoints for which we calculate the waveform misfit (eq. 2). As a result, the source-type gridpoints $\mathbf{\Lambda}$ are restricted to the region $n(\mathbf{\Lambda}) = 0$ of the lune (shaded in Fig. 6c and blue in Fig. 6b). At each such $\mathbf{\Lambda}$, a beachball is plotted in Fig. 6(c). The beachball is the 'best' moment tensor at $\mathbf{\Lambda}$, in the sense that it minimizes the misfit function for moment tensors M with source type $\mathbf{\Lambda}$ and $n(M) = 0$; the orientation and magnitude of M are allowed to vary, but the source type $\mathbf{\Lambda}$ is fixed. Each beachball in the figure is coloured by its misfit value (or rather variance reduction VR). Stated more formally: on the lune subset $n(\mathbf{\Lambda}) = 0$ we define a function $\Phi(\mathbf{\Lambda})$ in terms of $\Phi(M)$ (eq. 2) by

$$\Phi(\mathbf{\Lambda}) = \min\left\{\Phi(t[\mathbf{\Lambda}]_U) : U \in \mathbb{U},\ n([\mathbf{\Lambda}]_U) = 0,\ t_1 \leq t \leq t_2\right\}. \tag{7}$$

The variable t changes the magnitude of the moment tensor.

Figure 6. Full moment tensor misfit summary for the example event. For details, see Section 3. (a) Map of source location (red star) and stations used in the inversion for this event. The station is coloured blue if the observed first-motion polarity on the vertical component is up (compression) and white if it is down (dilatation). (b) Contour plot of the polarity misfit on the lune. Not to be confused with the waveform misfit, the polarity misfit $n(M)$ (eq. 5) for a moment tensor M is the number of stations where the observed first-motion polarity differs from the polarity predicted from M. The polarity misfit $n(\mathbf{\Lambda})$ (eq. 6) at a point $\mathbf{\Lambda}$ on the lune is then the minimum of $n(M)$ for moment tensors M having source type $\mathbf{\Lambda}$. At each point $\mathbf{\Lambda}$ in the region where $n(\mathbf{\Lambda}) = 0$ (blue), there is therefore a moment tensor M with source type $\mathbf{\Lambda}$ that has correct polarities, that is, polarities that match the observed polarities at all 11 stations. (c) Contour plot of the variance reduction VR($\mathbf{\Lambda}$). The variance reduction VR($\mathbf{\Lambda}$) at a point $\mathbf{\Lambda}$ is the maximum variance reduction VR(M) for moment tensors M that have source type $\mathbf{\Lambda}$ and that have correct polarities. (Compare eq. 7, which is the analogue of VR($\mathbf{\Lambda}$) for misfit.) Large values (blue) of VR represent better fit between observed and synthetic waveforms. Since M is required to have correct polarities, the plot of VR($\mathbf{\Lambda}$) is only defined on the region $n(\mathbf{\Lambda}) = 0$. The beachball plotted at each point $\mathbf{\Lambda}$ of this region is the moment tensor $M(\mathbf{\Lambda})$ that maximizes VR(M) with $\mathbf{\Lambda}$ fixed. Of the beachballs $M(\mathbf{\Lambda})$, our desired solution M_0 (green box) is the one with largest VR. The grey arcs on the lune are the great circle arcs $\lambda_1 = 0$, $\lambda_2 = 0$, and $\lambda_3 = 0$ (white, green and red in Fig. 1). Selected eigenvalue triples (black dots) on the boundary of the lune are indicated, with the understanding that the triples need to be normalized. The positive isotropic source (1, 1, 1) is at the top, the negative isotropic source (− 1, −1, −1) is at the bottom, and the double couple (1, 0, −1), not shown, would be at the centre of the lune. (d) The moment tensor M_0, the same as in (c) but plotted in a lower hemisphere projection. For this event, all ray paths travel upward from the source to the stations, so the stations to the east, having upward (compressional) first motions, are plotted on the left of the beachball at the antipode of the ray path direction.

Figure 7. The influence of using first-motion polarities and surface waves on the full moment tensor solution, illustrated for the example event (Figs 4–6). Each two-part subplot is a distilled version of the full information represented in Fig. 6. The beachball is the solution M_0 (Fig. 6d); the lune plot shows VR($\mathbf{\Lambda}$), with dark blue colours representing preferred solutions. The cross is plotted at $\mathbf{\Lambda}(M_0)$, whose corresponding lune longitude γ and lune latitude δ are listed in the header. The value of VR(M_0) is listed, along with the range of VR that are plotted. See Table 3 for a comparison of inversion results for the example event. (a) Inversion using polarities, P waves, and surface waves. The expanded version of this figure is Fig. 6. (b) Inversion using P waves and surface waves. The difference between (a) and (b) are $\omega = 9°$, $\theta = 6°$, and $\Delta\text{VR} = -0.3$. (c) Inversion using polarities and P waves. (d) Inversion using P waves only. The difference between (c) and (d) are $\omega = 13°$, $\theta = 4°$, and $\Delta\text{VR} = -1.9$. For most of our events, we used polarities and P waves but not surface waves.

Figs 6(b) and (c) convey more information than does the minimum misfit solution M_0 alone, which is shown in Fig. 6(d) as well as in the green box in Fig. 6(c). We see that, based on polarities alone, many source types are possible, ranging from a tensional crack on the left boundary of the lune, to a double couple at the centre of the lune, to a variety of compressional cracks on the right boundary. We see, from the values of the waveform misfit function at the best beachballs, that there is a whole range of source types—dark blue in Fig. 6(c)—that are nearly as plausible as the source type for M_0.

We use the example event to explore the stability of the moment tensor solution when using different subsets of waveforms and different choices of weighting. We quantify the difference between two moment tensor solutions, M_1 and M_2, in terms of

(i) The difference ΔVR in variance reduction.

(ii) The angular difference $\omega = \angle(M_1, M_2)$ between moment tensors.

(iii) The angular difference $\theta = \angle(\mathbf{\Lambda}_1, \mathbf{\Lambda}_2)$ on the lune between two source types.

If the pair of moment tensors has the same U, then $\omega = \theta$; otherwise $\omega \geq \theta$ (Tape & Tape 2013).

3.1 Influence of first-motion polarities

Figs 7(a) and (b) show a comparison between the moment tensor solutions obtained with and without polarity measurements. The moment tensors in (a) and (b) are quite similar ($\omega = 9°$ and $\theta = 6°$), providing support for using all polarity measurements in the grid search. We see that the polarities at two stations (PLAR and PLLO) are upward and are not predicted by the moment tensor in (b). This is not too surprising, since the misfit function is a sum of waveform differences for all time windows, so the algorithm will tend to fit the largest waveforms, possibly at the expense of not

Figure 8. The influence of using different waveform components and different weights, illustrated for the example event. See Fig. 7 caption for a description of the subplots. Here, all inversions used first-motion polarities. See Table 3 for a comparison of inversion results for the example event. (a) Inversion using vertical-component *P* waves only. (b) Inversion using radial component *P* waves only. (c) Inversion using surface waves only. (d) Inversion using *P* waves and surface waves.

fitting the amplitudes or polarities of smaller waveforms. As discussed in Section 2.3, by using polarity measurements we ensure that all first-motion polarities are fit.

3.2 Influence of different waveform components

In Figs 7(c) and (d), we repeat the inversions of Figs 7(a) and (b), but without using surface waves. The comparison provides insights into how much the surface waves are influencing the solution. For example in Fig. 7, it appears that the surface waves have a tendency to pull the source type from the compressional cracks toward the double couple. For most of the 63 events, we could not identify any surface waves. Fig. 7 is a reminder that the inclusion of surfaces waves could influence the solutions.

We would also like to see stability of the solution when using different subsets of waveforms. Fig. 8 shows solutions for the case of (a) vertical-component *P* waves only, (b) radial-component *P* waves only, (c) surface waves only, and (d) all together. In all cases, we use first-motion polarity measurements. The solution with the worst misfit is for radial-component *P* waves only (Fig. 8b). We know from measurements of amplitude ratios (Fig. S4, Supporting Information) that the synthetic *P* radial component is too large and therefore we see that overfitting this component can lead to spurious results. This was discussed in Section 2.4.

The solutions using vertical-component *P* waves only (Fig. 8a), surface waves only (Fig. 8c), and both (Fig. 8d) are similar. We find that the inclusion of surface waves and radial waves both have the effect of producing worse (lower) VR, though the waveform differences are subtle to the eye. Our preference is to fit as much of the waveforms as possible, so we would like to fit more waveforms even if their inclusion leads to lower VR values.

4 CATALOGUE OF MOMENT TENSORS

We performed two sets of inversions for all 63 events in order to examine the influence of using first-motion polarities. Fig. 9 summarizes the differences between the two sets of inversions. For 40 out of 63 events, the difference between moment tensors is $\omega \leq 10^\circ$, the difference between source types is $\theta \leq 10^\circ$ and the difference in variance reductions is $\Delta\mathrm{VR} <= 2$ per cent, indicating that the inclusion of polarities does not produce substantially different solutions. In our final catalogue, we choose to fit all polarity measurements, recognizing that the waveform fits will be quantitatively slightly worse.

Figure 9. The influence of first-motion polarities on the moment tensor inversions for 63 events. Each of the 63 events is inverted twice, once with polarities (subscript 'p') and once without polarities (subscript 'np'). The two solutions are compared by (1) their moment tensors, quantified by the angle θ between source types $\mathbf{\Lambda}_{\mathrm{np}}$ and $\mathbf{\Lambda}_{\mathrm{p}}$, and (2) their fits to waveforms, quantified by the difference in variance reduction $\Delta\mathrm{VR} = \mathrm{VR}_{\mathrm{np}} - \mathrm{VR}_{\mathrm{p}}$. The figure shows that for the majority of the 63 events, inversions with or without first motions show differences in source types of $\theta \leq 5^\circ$ and differences in waveform fits of $\Delta\mathrm{VR} \leq 1$ per cent.

To illustrate these results, we select four events from Fig. 9 to display in Fig. 10. The events in (a)–(c) are representative in the sense that the differences between the solutions with and without using polarities are small. They show that by fitting waveform differences for P waves (but not using first-motion polarities), we are able to also predict the correct polarity of the P wave for almost all stations. The one exception is station PLLL in (b), and, for this moment tensor, PLLL is a nodal station. Fig. 10(d) shows an extreme case, where the inclusion of first-motion polarities leads to a very different solution. This event (20110823072700783) has the largest difference in VR among all 63 events: VR = 24 with polarities and VR = 36 without polarities. A visual inspection of the waveforms (Alvizuri 2015) indicates that the no-polarity-case moment tensor (with M_{w} 1.7) provides somewhat better fits than the polarity-case moment tensor (with M_{w} 1.5).

Our full catalogue is shown in Fig. 11(a) and is available in Alvizuri (2015). Event origin times, hypocentres and moment tensor results are listed in Table 4. Our 63 moment tensor solutions M_0 can be effectively represented by plotting them on the lune (Fig. 11a). The location of the beachball on the lune provides its source type. The proximity of each solution to 'end-member' moment tensors—such as the explosion source (at top), the double couple (at centre), or the CLVDs (left and right)—can be seen by inspection. The colour of the beachball provides the magnitude and the beachball itself conveys the orientation. What is not conveyed in Fig. 11(a) is the uncertainty associated with each solution; for this, we rely on source-specific plots showing the variation of misfit on the lune. In Section 5, we discuss the source types shown in our catalogue in the context of previous studies such as those in Fig. 11(b).

4.1 Subsets of the catalogue

We single out three subsets of events, in hopes of identifying different physical mechanisms that may be active at Uturuncu volcano.

Figure 10. Four examples of moment tensor solutions showing the influence of using first-motion polarities identified in Fig. 9. Each subplot contains a pair of beachball-and-lune plots. (a) Left: moment tensor solution M_0 and lune plot VR($\mathbf{\Lambda}$) using no first-motion polarities. Right: same, but using first-motion polarities. The blue circles on the beachball are upward first motions (compressions), and the white circles are downward first motions (dilatations). The difference between the two moment tensors is represented by their angular distance in matrix space ($\omega = 0^\circ$), their angular distance on the lune ($\theta = 0^\circ$), and their difference in variance reduction ($\Delta\mathrm{VR} = 0$). (b) Same as (a), but for a different event: $\omega = 10^\circ$, $\theta = 6^\circ$, and $\Delta\mathrm{VR} = -1.2$. (c) Same as (a), but for a different event: $\omega = 0^\circ$, $\theta = 0^\circ$, and $\Delta\mathrm{VR} = 0$. (d) Same as (a), but for a different event: $\omega = 65^\circ$, $\theta = 26^\circ$, and $\Delta\mathrm{VR} = -12.6$. The example in (d) was chosen to highlight an anomalous event with large values of θ and ΔVR; this is the bottom point plotted in Fig. 9.

Figure 11. Our catalogue of 63 moment tensor solutions, in comparison with previously published studies. (a) 63 moment tensor solutions from this study; beachballs are coloured by estimated magnitude. Solutions are tabulated in Table 4. A key component of our analysis—the permissible lune regions on the basis of polarities—is not represented here but can be seen in other figures (e.g. Fig. 6c and within Alvizuri (2015)). (b) Comparison between our solutions (red circles) and other published data sets for volcanic and geothermal regions (Table 1).

We refer to the subsets as isotropic, tensional crack, and double-couple events.

The isotropic events are shown in Fig. 12. We define an event to be 'isotropic' if (1) its first-motion polarities are upward at all stations and (2) $n(\mathbf{\Lambda}^{\mathrm{D}}) \neq 0$, where $\mathbf{\Lambda}^{\mathrm{D}} = (1, 0, -1)$ is the double-couple point at the centre of the lune. The second condition says that no double couple, regardless of orientation, can have the correct polarities, that is, polarities that match the observed polarities at all stations. For an isotropic event, any moment tensor with source type $\mathbf{\Lambda}$ in the region $\lambda_3 > 0$ of the lune will have correct polarities, but there may be many other moment tensors that also have correct polarities, since, as shown in Fig. 12, it may be possible to rotate a given beachball so that its white portions contain no stations. In fact, only one of the six events in Fig. 12 has a best-fitting moment tensor whose source type $\mathbf{\Lambda}$ is in the region $\lambda_3 > 0$, where all first motions are upward. The lune latitudes for the source types of the six moment tensors range from $\delta = 23^\circ$ to 46°; although the source types are not close to (1, 1, 1), they are far from being deviatoric.

The tensional crack events are shown in Fig. 13. We define an event to be a 'tensional crack' if (1) its best-fitting moment tensor has its source type $\mathbf{\Lambda}$ in the region $\gamma = -15^\circ$ of the lune and (2) $n(\mathbf{\Lambda}^{\mathrm{D}}) \neq 0$. Four of the events in Fig. 13 have best-fitting beachballs (moment tensors) that have thin white bands, and one might hope that the events would be associated with a single physical process. In that case, the orientations of the bands on the four balls should more or less agree, but they do not.

We define the 'double-couple events' by their location; they are all clustered in a single region about 15 km southeast of the volcano. All 14 of the events in this region are shown in Fig. 14. Most of these events occur within hours of each other and have similar moment tensor solutions. For all 14 events, a double-couple moment tensor is a possible solution on the basis of polarities ($n(\mathbf{\Lambda}^{\mathrm{D}}) = 0$). (However, note that with only six recording stations, the first-motion polarity measurements cannot exclude many source types.) Therefore, these events could arise from shear slip on a fault (i.e. with no opening).

Figs 15(a) and (b) show where our subsets of events are with respect to the volcanic centre and where they appear on the lune.

Table 4. Catalogue of full moment tensors computed in this study. The moment tensor parameters are magnitude M_w, lune longitude γ, lune latitude δ, strike κ, dip θ, and rake σ. Variance reduction is VR. The origin time, hypocentre and magnitude M_{KW} are from Keyson & West (2013). A text file for our catalogue is available as Table S2 in the Supporting Information.

Origin time	Longitude	Latitude	Depth	M_{KW}	M_w	γ	δ	κ	θ	σ	Npol	VR
2010-05-16 06:34:54.464	−67.18560	−22.26000	0.6	2.44	2.80	10	−10	150	76	−75	11	22
2010-05-16 08:56:11.725	−67.18490	−22.26290	5.1	2.21	2.60	−20	23	355	73	70	11	21
2010-06-01 07:36:04.690	−67.14330	−22.40580	1.1	1.14	1.80	5	−3	35	20	10	10	48
2010-06-01 22:13:52.679	−67.15120	−22.41310	4.8	1.28	2.00	10	−10	25	20	−5	11	38
2010-09-30 09:52:32.848	−67.09720	−22.46800	4.5	1.02	1.60	−15	30	15	73	90	5	43
2010-09-30 09:54:13.030	−67.09670	−22.46630	4.6	1.18	1.90	20	−10	30	20	−35	6	66
2010-09-30 09:56:12.039	−67.09730	−22.46450	4.5	1.48	2.10	20	−6	40	20	−30	6	67
2010-09-30 10:25:01.621	−67.10100	−22.45460	4.9	1.31	1.90	15	−3	50	20	−15	6	54
2010-09-30 11:45:31.523	−67.09330	−22.45600	4.2	1.12	1.80	15	−3	50	20	−20	6	66
2010-09-30 15:57:02.647	−67.09750	−22.45440	4.4	2.17	2.50	10	3	45	20	−40	6	53
2010-09-30 16:39:13.172	−67.11020	−22.48550	4.8	1.18	2.00	15	−10	45	40	−55	5	71
2010-09-30 17:23:33.129	−67.10050	−22.46470	4.7	1.69	2.20	5	6	75	28	−35	6	56
2010-09-30 18:35:17.772	−67.09560	−22.45960	4.5	1.36	1.80	5	23	40	5	−75	6	65
2010-09-30 21:59:12.435	−67.11050	−22.46970	5.4	1.99	2.40	5	10	75	20	−35	6	51
2010-10-01 11:10:55.009	−67.10680	−22.45200	4.6	1.98	2.40	25	−3	25	20	−40	6	54
2010-10-01 11:12:42.832	−67.11030	−22.45780	5.4	1.58	2.20	25	−6	45	28	−30	6	60
2010-10-05 03:21:24.419	−67.10110	−22.47510	4.1	1.45	2.00	5	−16	15	20	−40	7	50
2011-01-27 03:09:47.813	−67.20520	−22.41470	4.4	1.02	1.80	−15	30	95	76	90	12	57
2011-04-25 03:50:05.648	−67.15960	−22.30250	3.8	0.16	1.00	−15	30	255	45	80	11	38
2011-04-25 04:47:54.697	−67.15750	−22.30580	4.2	0.16	0.70	10	38	165	28	−90	19	20
2011-04-29 19:15:51.352	−67.20790	−22.25480	4.2	0.96	1.50	−30	34	150	81	−0	23	25
2011-04-30 15:56:47.801	−67.26760	−22.27770	4.2	0.48	1.30	−15	46	160	62	60	16	32
2011-05-01 12:59:10.539	−67.22360	−22.32290	4.6	0.34	1.10	−10	38	200	40	−40	18	28
2011-05-07 02:36:04.488	−67.09170	−22.53560	4.2	0.23	1.10	−10	16	5	66	−60	6	46
2011-05-28 02:37:26.768	−67.16800	−22.34170	9.8	0.29	0.50	−15	13	30	69	−35	11	33
2011-05-28 02:42:24.281	−67.16780	−22.34500	4.8	0.01	0.50	−15	13	5	58	−70	6	49
2011-05-28 02:52:38.269	−67.16060	−22.33740	4.7	0.07	0.90	−0	23	15	50	−90	15	34
2011-05-28 02:53:39.982	−67.16600	−22.34130	5.0	0.03	0.70	−5	34	10	62	−90	17	33
2011-05-28 03:35:23.921	−67.17050	−22.34610	6.2	0.01	0.60	5	26	210	87	10	16	29
2011-05-28 06:18:23.523	−67.18730	−22.23570	4.0	0.16	1.20	25	−19	30	70	90	6	55
2011-05-31 12:48:24.834	−67.25680	−22.19370	4.9	0.28	0.60	10	23	255	54	85	7	15
2011-06-06 07:02:01.270	−67.30960	−22.27640	2.5	0.19	1.20	−20	38	260	28	30	7	14
2011-06-22 02:33:24.299	−67.23240	−22.33870	4.2	0.18	0.60	10	38	15	83	−0	18	17
2011-06-30 10:42:59.611	−67.00150	−22.49720	4.1	−0.00	1.00	−10	19	45	28	−25	7	25
2011-07-08 14:58:21.435	−67.16500	−22.29920	3.9	0.00	0.90	−15	19	90	40	75	11	34
2011-08-02 03:00:42.673	−67.24990	−22.16650	12.0	0.17	1.10	−0	3	60	87	20	6	50
2011-08-08 10:38:42.458	−67.16720	−22.23130	13.3	0.25	0.70	−10	38	55	35	85	16	30
2011-08-09 03:21:09.852	−67.16970	−22.23770	5.8	0.02	0.70	−5	34	50	35	70	11	36
2011-08-10 03:18:14.398	−67.20560	−22.28700	4.8	0.22	0.90	5	3	225	50	−85	15	22
2011-08-10 03:18:38.705	−67.20610	−22.28890	4.5	0.15	1.00	20	10	105	58	−85	9	35
2011-08-17 00:43:17.677	−67.24330	−22.12260	4.5	0.15	0.90	−20	16	185	76	75	10	28
2011-08-23 07:26:42.794	−67.16570	−22.30830	4.3	0.10	0.80	−10	46	240	62	80	15	30
2011-08-23 07:27:00.783	−67.16980	−22.30720	4.2	0.87	1.50	−25	30	205	50	−30	21	24
2011-08-23 20:21:12.670	−67.19860	−22.26820	4.9	0.53	1.30	0	−13	110	45	−60	8	38
2011-08-29 07:14:01.139	−67.13580	−22.26970	4.2	0.01	0.80	15	19	350	28	45	7	55
2011-09-27 18:14:40.559	−67.23870	−22.19590	4.5	0.13	0.90	25	34	15	50	25	11	30
2011-09-27 21:10:49.558	−67.23990	−22.19600	4.8	0.29	1.00	5	3	20	90	5	12	36
2011-10-25 03:07:50.754	−67.13140	−22.28540	5.0	0.13	0.70	−10	34	0	76	10	7	46
2011-10-28 07:25:30.002	−67.12560	−22.50580	5.0	0.43	0.60	5	13	205	69	−55	10	37
2011-11-11 11:02:21.636	−67.24970	−22.51810	4.5	0.29	0.90	20	−13	225	87	85	7	58
2011-12-09 14:34:54.837	−67.16660	−22.29270	3.8	0.20	1.20	−15	26	60	58	65	7	48
2011-12-22 23:16:21.860	−67.17870	−22.29980	4.3	0.33	0.70	−20	23	270	40	−10	11	14
2011-12-22 23:17:08.220	−67.18440	−22.29550	4.5	0.43	0.80	−10	26	350	80	−85	11	7
2011-12-24 03:53:32.713	−67.25020	−22.37750	4.9	0.07	0.90	15	30	60	40	85	13	39
2011-12-24 06:41:28.067	−67.17930	−22.24090	4.7	0.47	1.00	5	30	330	54	−60	20	14
2011-12-24 06:43:11.431	−67.17250	−22.23990	4.8	−0.00	0.80	−30	34	162	80	−30	9	18
2011-12-24 06:49:06.473	−67.17940	−22.23940	4.7	0.11	0.80	0	42	30	40	65	15	23
2011-12-24 17:29:41.331	−67.17490	−22.23270	5.5	0.29	1.00	−5	23	85	32	90	6	37
2012-01-07 13:38:00.237	−67.16120	−22.29760	4.5	0.27	1.20	−20	10	105	40	75	7	46
2012-01-08 08:27:20.474	−67.16020	−22.29910	4.5	0.14	0.70	15	6	335	66	−80	17	31
2012-01-26 20:19:37.383	−67.22030	−22.27800	4.6	0.05	0.70	−0	16	120	40	−15	10	32
2012-02-02 12:58:16.847	−67.02280	−22.38860	8.0	0.42	0.70	−20	10	15	50	−50	8	53
2012-02-04 02:58:00.727	−67.06570	−22.40470	10.1	0.06	0.80	5	16	180	76	20	11	44

Figure 12. Solutions for isotropic events. We define an 'isotropic event' formally as having polarities (1) that are upward at all stations and (2) that exclude the possibility of a double-couple moment tensor. The locations of these events are shown in Fig. 15.

Figure 13. Solutions for tensional crack events. We define a 'tensional crack' event formally as having its best-fitting solution on the region of the lune with $\gamma \leq -15°$ and as having polarities that exclude the possibility of a double-couple moment tensor. The locations of these events are shown in Fig. 15.

Figure 14. Subset of events that occur in a region southeast of the volcanic centre, between longitudes −67.15° and −67.05° and between latitudes −22.53° and −22.43°. The events are sorted by origin time, with the first 12 occurring within a time period of 25 hr. For most of the events, a double-couple moment tensor provides a decent fit to the observed waveforms.; that is, the colour at the double couple (centre of lune) is dark blue. The locations of these events are shown in Fig. 15.

Figure 15. Summary of three subsets of events featured in Figs 12–14. The subsets are indicated by beachball colour: isotropic (blue: 6 events), tensional crack (green: 5 events), and double couple (red: 14 events). (a) Map of the subset events. Uturuncu volcano is marked by the crossline at longitude −67.19°, latitude −22.26°. As shown in the inset map, all three subsets are inside the array of stations (Fig. 2a). Most of the isotropic events and tensional crack events are distributed within 10 km of Uturuncu volcano. The cluster of double-couple events is about 25 km southeast of Uturuncu. (b) Lune plot of the subset events. Our selection criteria for the subsets are based on the source type; hence there is clustering on the lune.

We see that the subsets of isotropic and tensional crack events occur near the volcanic centre. We also see that the swarm of possible double-couple events are slightly skewed toward the compressional CLVD (Fig. 15b).

It is important to realize that our definitions of 'isotropic,' 'tensional crack,' and 'double couple' here are rather formal and may not say much physically about the nature of the actual source processes. Our tensional crack events, for example, are approximately tensional cracks in the traditional sense if the classical moment tensor model (Aki & Richards 1980) is applicable. The moment tensors inferred in our study, however, give little, if any, support for the classical model, since many of them, if interpreted in the classical model, would require unreasonable values for the Poisson parameter.

5 DISCUSSION

5.1 The quality of waveform fits

The moment tensor literature includes solutions with higher values of VR and better-looking waveform fits than those displayed in Fig. 4 or in Alvizuri (2015). The perceived lower quality of our waveform fits arises because we are dealing with small events. Such events give clear *P*-wave signals only at high frequencies ($f \geq 1$ Hz), while the lower frequencies, which would normally be more reliable, are unavailable. From our perspective, by considering waveforms, rather than only the sign (or amplitude) of the first-motion polarities, we take a step forward in improving the estimation of moment tensors for small events.

The value of VR is calculated from amplitude differences and provides a useful comparison with other studies only when the misfit functions (including the chosen bandpass filters) are similar. For example, if the signal-to-noise ratios are adequate, then filtering seismograms at longer periods will result in better waveform fits and larger VR. This is because the assumption of a simple (e.g. layered) structure will be more appropriate for longer period waves. In general, we are interested in fitting the broadest possible band of frequencies, even if it results in lower VR. Also, at higher frequencies, the influence of 'site effects'—seismic velocity variations near each station—become more significant and contribute toward lower VR. (We discuss site effects in Section S2, Supporting Information.)

5.2 Toward uncertainty estimation for full moment tensors

Our waveform misfit function (eq. 2) is evaluated over a 6-D space of moment tensors. Moment tensor source types make up the lune, which is one-sixth of the unit sphere. Using plots such as Fig. 6, we emphasize the importance of showing the variations of the misfit function $\Phi(\mathbf{\Lambda})$ (eq. 7) over the space of source types, something that was first done by Ford *et al.* (2010, 2012; Table 1).

We acknowledge that we have not considered all sources of uncertainties, namely, the effects of 3-D structural variations (elastic or anelastic), the effects of topography, and uncertainties associated with different earthquake source parameters. The influence of

3-D structural variations has been considered in some studies (Liu *et al.* 2004; Chen *et al.* 2005; Covellone & Savage 2012; Zhu & Zhou 2016). The effects of topography have been considered for longer period waveforms (Chouet *et al.* 2003; Liu *et al.* 2004). See Stähler & Sigloch (2014) for a study that inverted for hypocentral coordinates, origin time and source time function in addition to the moment tensor parameters.

It is difficult constrain the source type for events as small as those in our study ($M_w = 0.3$–2.8). This makes uncertainty estimation important. We have recently introduced a confidence parameter for moment tensors and have applied it to a set of 21 earthquakes that we assumed to be double-couple moment tensors (Silwal & Tape 2016; Tape & Tape 2016). Our current plan is to adapt our full moment tensor approach to estimate confidence parameters.

5.3 Influence of first-motion polarities

Some of our rationale for using first-motion polarities was discussed in Section 2.3. Here, we review some results and discuss possible shortcomings. Fig. 9 showed that by fitting P waveforms (and surface waves, when available), we obtained moment tensor solutions whose first-motion polarities matched most or all of the observed polarities ($n(M_0) \approx 0$). In our study, we chose to constrain the waveform-fitting moment tensor solutions to also fit all first-motion polarities. This choice has the effect of increasing the influence of small-amplitude P waves that nevertheless have a discernible first-motion polarity. Without the inclusion of first-motion polarities, the direct waveform difference will be biased toward the highest amplitude P waves.

First-motion polarities alone determine a subset of allowable moment tensors, which in turn can be represented on a source-type plot such as the lune in Fig. 6(b). The shape of the region $n(\mathbf{\Lambda}) = 0$ depends on the signs of the first-motion polarities, the source–station geometry, and the ray take-off angles, which in turn are influenced by the seismic velocity model. Using a different velocity model will change the positions of piercing points on the focal sphere and will therefore change the set of allowable moment tensor solutions. Also, having more stations and uniformly distributed stations (with respect to the source) will result in a smaller allowable region of moment tensor source types.

In this study, our approach has been to first carefully identify all first-motion polarity measurements. We then only consider moment tensors whose predicted first-motion polarities all match the observations ($n(M) = 0$, eq. 5). A more flexible approach would allow for a weight (or uncertainty) to be assigned to each first-motion polarity measurement, and then the misfit function would balance two terms, one for waveform misfit and one for polarity misfit.

There are two things that first-motion polarities alone cannot provide: (1) magnitude and (2) a unique minimum of a misfit function. These can be obtained using amplitude measurements or waveform differences. We use waveform differences to obtain a moment tensor solution M_0 with minimum waveform misfit and with magnitude M_w. Plots of the misfit function on the lune reveal the region of plausible moment tensor solutions about the global minimum solution M_0.

5.4 Physical models for moment tensors

Our moment tensor catalogue in Fig. 11(b) provides a starting point for interpreting physical source models for the full moment tensors. We discuss our moment tensor solutions in the context of the classical model introduced by Aki & Richards (1980) and discussed in Dufumier & Rivera (1997), Minson *et al.* (2007) and Tape & Tape (2013).

Tape & Tape (2013) reviewed two perspectives on the classical model: (1) a single-process model as an oblique crack and (2) a two-process model involving the sum of a crack and a double couple. We refer to (1) as the classical model, following Dufumier & Rivera (1997), and (2) as the crack-plus-double-couple (CDC) model, following Minson *et al.* (2007). Each model has a pair of variables that is used to characterize the source type (Tape & Tape 2013).

Our moment tensor catalogue represented by the classical model is presented in Figs 16(a) and (b). The two parameters representing the source type in the classical model are the Poisson ratio ν and the angle $\alpha = \angle(\mathbf{N}, \mathbf{S})$ between the normal vector and slip vector. The angle α is a function of lune longitude, with $\alpha = 90^\circ$ corresponding to $\gamma = 0^\circ$. For our 63 events, α is centred on 90° and ranges from 30° to 150°, with a couple events near the tensional crack end-member of $\alpha = 0^\circ$ (Fig. 16b).

Mathematically, any value of ν is possible, but the physically permissible range is $-1 \leq \nu < 0.5$, which is plotted in Fig. 16(a). Previous studies have found that Poisson ratios for orogenic belts range between 0.18 and 0.35 (Zandt & Ammon 1995) and for the crust beneath the Altiplano they average 0.25 (Zandt *et al.* 1996). A small portion of our events (8/63) have Poisson ratios within a reasonable range of $\nu = 0.15$–0.35. Results from other published studies imply Poisson ratios with similar wide spreads—both outside a reasonable range and outside the permissible range. This prompted Tape & Tape (2013) to conclude that either (1) the classical model did not apply to the situation at hand or (2) the published moment tensors (and predicted Poisson ratios) had large uncertainties.

The CDC model characterizes any moment tensor as a sum of a crack moment tensor and a double-couple moment tensor whose fault plane is the same as that of the crack. Two points are worth mentioning. First, the crack tensor and double-couple tensor do not have the same eigenframe, so one cannot discuss the 'decomposition' in terms of eigenvalues alone. Second, two sums are possible for each moment tensor (e.g. Tape & Tape 2012). Our moment tensor catalogue represented by the CDC model is presented in Figs 16(c) and (d). The two coordinates describing the source type for the CDC model are the azimuth ϕ on the lune and the crack fraction ζ (Tape & Tape 2013).

The variation of ζ (Fig. 16d) reveals that most of our events—if interpreted as a sum of a double couple and a crack—have significant crack fraction (Fig. 16d). It is useful to consider the end-members of the CDC model. If all events clustered near $\zeta = 0^\circ$, then we would likely invoke a single-process model of shear faulting (with no opening or closing); if all events clustered near $\zeta = 90^\circ$, then we might invoke a single-process model of tensional (or compressional) cracks. In the context of the CDC model, our events imply that contributions from the double couple and the crack are comparable in size.

Instead of interpreting M_0 in terms of the classical model or CDC model, one might choose to find the minimum misfit for an 'end-member' source type (Chiang *et al.* 2014). Fig. S24 in the Supporting Information summarizes results for the example event if we constrain the solution to be a double couple (Fig. S24b, Supporting Information), a tensional crack (Fig. S24c, Supporting Information), or a compressional crack (Fig. S24d, Supporting Information). For this event, there is at least one moment tensor for each of these subsets that satisfies $n(M) = 0$ (eq. 5). This shows that, for source–station geometries such as ours, something more than polarities alone—for example, measurements of waveform differences—is

Figure 16. Source types of our 63 moment tensors represented (a) and (b) by the classical model and (c) and (d) by the crack-plus-double-couple model. In the classical model each moment tensor source type is represented by a Poisson ratio ν and by the angle α between the fault normal and the slip direction. In the crack-plus-double-couple model, each source type is represented by its azimuth ϕ on the lune and by the crack fraction ζ. These four quantities are calculated directly from the eigenvalues of the moment tensors. (a) Poisson values ν, plotted for the physically permissible range $-1 \leq \nu \leq 0.5$. 18 events fall outside the permissible range. (b) Angle between slip vector and normal vector: $\alpha = \angle(\mathbf{N}, \mathbf{S})$. For a tensional crack $\alpha = 0°$, for a compressional crack $\alpha = 180°$, and for a double couple $\alpha = 90°$, where the slip vector is in the fault plane. (c) Azimuthal angle on the lune ϕ, measured from the double couple at ($\gamma = 0°$, $\delta = 0°$). Values increase in a counterclockwise sense from $\phi = 0°$ at the isotropic point. (d) Crack fraction ζ. For a double-couple moment tensor, $\zeta = 0°$. For a tensional or compressional crack, $\zeta = 90°$.

needed to constrain the source type. If considering the full moment tensor space, the minimum of the waveform misfit function occurs at M_0, which has a source type at ($\gamma = 5°$, $\delta = -13°$). However, it is possible that one could have additional information that would warrant constraining the moment tensor inversion to a specific source type. For example, one might have microseismicity at depth or GPS measurements at the surface that are consistent with pure opening at depth.

6 CONCLUSIONS

(i) We present a compilation of 63 full moment tensors for events at Uturuncu volcano, Bolivia, for the time period of the PLUTONS array (2010 April 12–2012 March 9). Our catalogue represents the complete set of events for which we could obtain reliable moment tensor solutions. For each event, we used as many waveform measurements (both P waves and surface waves) and first-motion measurements as possible.

In the context of the published literature (Table 1), our catalogue of moment tensors is large, the events we analyse are small (M_w = 0.3–2.8), the waveforms are high frequency. We present the variations in misfit function over the space of source types for each event.

(ii) We characterize three subsets of moment tensors within our catalogue. One subset, located close to the volcano, contains six events with isotropic components whose first-motion polarities exclude the possibility of a double-couple mechanism.

(iii) Our findings of positively isotropic events are in agreement with other studies of full moment tensors in volcanic and geothermal settings (Fig. 11b). As noted in Tape & Tape (2013), the large spread in source types of previously published events could be explained by a multiple-process model. Alternatively, they could be explained by the classical model, whereby the full moment tensor solutions have large uncertainties is the space of source types (i.e. on the lune). Most previous studies did not provide uncertainty estimates, making interpretation challenging.

Our plots of misfit $\Phi(\mathbf{\Lambda})$ on the lune (Fig. 6) are a step toward uncertainty estimation. They show the range of permissible source types. Considering this range, we conclude that the classical model remains a possibility (Section 5.4).

(iv) Full moment tensor inversion of P waveforms at the frequencies used in this study (2–10 Hz) is a delicate procedure, especially when the velocity structure is not well known. We would expect more reliable solutions in a setting with larger magnitudes (say, up to M_w 4). In that case, lower frequency waves, including surface waves, could be used within full moment tensor inversions. Solutions for larger events could help determine the reliability of the solutions for smaller events, for which fewer waveforms are available.

ACKNOWLEDGEMENTS

We thank the PLUTONS team for acquiring and archiving seismic waveforms used in this project. Seismic waveforms are available from the IRIS Data Management Center. CA acknowledges the Observatorio San Calixto in La Paz, Bolivia, for their logistical support during deployment and data collection. We thank Vipul Silwal for support with the moment tensor inversion code and for participating in the effort to pick consensus first-motion polarities. We acknowledge support from the National Science Foundation under grants EAR-1215959 and EAR-0909254. We thank editor Eiichi Fukuyama, reviewer Sean Ford and an anonymous reviewer who suggested the scattering analysis in Section S1 (Supporting Information).

REFERENCES

Aki, K. & Richards, P.G., 1980. *Quantitative Seismology, Theory and Methods,* W.H. Freeman.

Alvizuri, C., 2015. *Seismic moment tensor catalog for Uturuncu volcano*, Bolivia, ScholarWorks@UA. Available at: http://hdl.handle.net/11122/6266 (last accessed 2016 January 22): descriptor file, text file of catalog, and composite figures of waveform fits and misfit analyses.

Aso, N. & Ide, S., 2014. Focal mechanisms of deep low-frequency earthquakes in Eastern Shimane in Western Japan, *J. geophys. Res.,* **119,** 364–377.

Baig, A. & Urbancic, T., 2010. Microseismic moment tensors: a path to understanding frac growth, *Leading Edge,* **29,** 320–324.

Boyd, O.S., Dreger, D.S., Lai, V.H. & Gritto, R., 2015. A systematic analysis of seismic moment tensor at The Geysers geothermal field, California, *Bull. seism. Soc. Am.,* **105**(6), 2969–2986.

Chen, P., Jordan, T.H. & Zhao, L., 2005. Finite-moment tensor of the 3 September 2002 Yorba Linda earthquake, *Bull. seism. Soc. Am.,* **95**(3), 1170–1180.

Chiang, A., Dreger, D.S., Ford, S.R. & Walter, W.R., 2014. Source characterization of underground explosions from combined regional moment tensor and first-motion analysis, *Bull. seism. Soc. Am.,* **104**(4), 1587–1600.

Chinn, D.S. & Isacks, B.L., 1983. Accurate source depths and focal mechanisms of shallow earthquakes in western South America and in the New Hebrides Island Arc, *Tectonics,* **2**(6), 529–563.

Chmielowski, J., Zandt, G. & Haberland, C., 1999. The central Andean Altiplano-Puna magma body, *Geophys. Res. Lett.,* **26**(6), 783–786.

Chouet, B. *et al.*, 2003. Source mechanisms of explosions at Stromboli Volcano, Italy, determined from moment-tensor inversions of very-long-period data, *J. geophys. Res.,* **108**(B1), 2019, doi:10.1029/2002JB001919.

Chouet, B.A. & Matoza, R.S., 2013. A multi-decadal view of seismic methods for detecting precursors of magma movement and eruption, *J. Volc. Geotherm. Res.,* **252,** 108–175.

Comeau, M.J., Unsworth, M.J., Ticona, F. & Sunagua, M., 2015. Magnetotelluric images of magma distribution beneath Volcán Uturuncu, Bolivia: implications for magma dynamics, *Geology,* **43**(3), 243–246.

Covellone, B.M. & Savage, B., 2012. A quantitative comparison between 1D and 3D source inversion methodologies: application to the Middle East, *Bull. seism. Soc. Am.,* **102**(5), 2189–2199.

Dahm, T. & Brandsdóttir, B., 1997. Moment tensors of microearthquakes from the Eyjafjallajökull volcano in South Iceland, *Geophys. J. Int.,* **130**(1), 183–192.

del Potro, R., Díez, M., Blundy, J., Camacho, A.G. & Gottsmann, J., 2013. Diapiric ascent of silicic magma beneath the Bolivian Altiplano, *Geophys. Res. Lett.,* **40**(10), 2044–2048.

de Silva, S.L., 1989. Altiplano-Puna volcanic complex of the central Andes, *Geology,* **17,** 1102–1106.

Devlin, S., Isacks, B.L., Pritchard, M.E., Bamhart, W.D. & Lohman, R.B., 2012. Depths and focal mechanisms of crustal earthquakes in the central Andes determined from teleseismic waveform analysis and InSAR, *Tectonics,* **31,** TC2002, doi:10.1029/2011TC002914.

Dufumier, H. & Rivera, L., 1997. On the resolution of the isotropic component in moment tensor inversion, *Geophys. J. Int.,* **131,** 595–606.

Eisner, L., Williams-Stroud, S., Hill, A., Duncan, P. & Thornton, M., 2010. Beyond the dots in the box: microseismicity-constrained fracture models for reservoir simulation, *Leading Edge,* **29**(3), 326–333.

Fialko, Y. & Pearse, J., 2012. Sombrero uplift above the Altiplano-Puna magma body: evidence of a ballooning mid-crustal diapir, *Science,* **338,** 250–252.

Ford, S.R., Dreger, D.S. & Walter, W.R., 2009. Identifying isotropic events using a regional moment tensor inversion, *J. geophys. Res.,* **114,** B01306, doi:10.1029/2008JB005743.

Ford, S.R., Dreger, D.S. & Walter, W.R., 2010. Network sensitivity solutions for regional moment-tensor inversions, *Bull. seism. Soc. Am.,* **100**(5A), 1962–1970.

Ford, S.R., Walter, W.R. & Dreger, D.S., 2012. Event discrimination using regional moment tensors with teleseismic-*P* constraints, *Bull. seism. Soc. Am.,* **102**(2), 867–872.

Foulger, G.R., Julian, B.R., Hill, D.P., Pitt, A.M., Malin, P.E. & Shalev, E., 2004. Non-double-couple microearthquakes at Long Valley caldera, California, provide evidence for hydraulic fracturing, *J. Volc. Geotherm. Res.,* **132,** 45–71.

Guilhem, A., Hutchings, L., Dreger, D.S. & Johnson, L.R., 2014. Moment tensor inversions of $M \sim 3$ earthquakes in the Geysers geothermal fields, California, *J. geophys. Res.,* **119**(3), 2121–2137.

Haberland, C., Rietbrock, A., Schurr, B. & Brasse, H., 2003. Coincident anomalies of seismic attenuation and electrical resistivity beneath the southern Bolivian Altiplano plateau, *Geophys. Res. Lett.,* **30**(18), 1923, doi:10.1029/2003GL017492.

Horálek, J., Šíený, J. & Fischer, T., 2002. Moment tensors of the January 1997 earthquake swarm in NW Bohemia (Czech Republic): double-couple vs. non-double-couple events, *Tectonophysics,* **356,** 65–85.

Isacks, B.L., 1988. Uplift of the central Andean plateau and bending of the Bolivian orocline, *J. geophys. Res.,* **93**(B4), 3211–3231.

Jay, J.A. *et al.*, 2011. Shallow seismicity, triggered seismicity, and ambient noise tomography at the long-dormant Uturuncu Volcano, Bolivia, *Bull. Volc.,* **74,** 817–837.

Julian, B.R., Miller, A.D. & Foulger, G.R., 1998. Non-double-couple earthquakes: 1. Theory, *Rev. Geophys.,* **36**(4), 525–549.

Julian, B.R., Foulger, G.R., Monastero, F.C. & Bjornstad, S., 2010. Imaging hydraulic fractures in a geothermal reservoir, *Geophys. Res. Lett.,* **37,** L07305, doi:10.1029/2009GL040933.

Keyson, L. & West, M.E., 2013. Earthquake sources near Uturuncu Volcano, *presented at 2013 Fall Meeting*, AGU, San Francisco, CA, December 9–13, Abstract V13B-2603.

Liu, Q., Polet, J., Komatitsch, D. & Tromp, J., 2004. Spectral-element moment tensor inversions for earthquakes in southern California, *Bull. seism. Soc. Am.,* **94**(5), 1748–1761.

Miller, A.D., 1996. Seismic structure and earthquake focal mechanisms of the Hengill Volcanic Complex, SW Iceland, *PhD thesis,* University of Durham, Durham, UK.

Miller, A.D., Foulger, G.R. & Julian, B.R., 1998a. Non-double-couple earthquakes: 2. Observations, *Rev. Geophys.,* **36**(4), 551–568.

Miller, A.D., Julian, B.R. & Foulger, G.R., 1998b. Three-dimensional seismic structure and moment tensors of non-double-couple earthquakes at the Hengill–Grensdalur volcanic complex, Iceland, *Geophys. J. Int.,* **133,** 309–325.

Minson, S.E. & Dreger, D.S., 2008. Stable inversions for complete moment tensors, *Geophys. J. Int.,* **174,** 585–592.

Minson, S.E., Dreger, D.S., Bürgmann, R., Kanamori, H. & Larson, K.M., 2007. Seismically and geodetically determined nondouble-couple source mechanisms from the 2000 Miyakejima volcanic earthquake swarm, *J. geophys. Res.,* **112,** B10308, doi:10.1029/2006JB004847.

Nayak, A. & Dreger, D.S., 2014. Moment tensor inversion of seismic events associated with the sinkhole at Napoleonville salt dome, Louisiana, *Bull. seism. Soc. Am.,* **104**(4), 1763–1776.

Pesicek, J.D., Sileny, J., Prejean, S.G. & Thurber, C.H., 2012. Determination and uncertainty of moment tensors for microearthquakes at Okmok Volcano, Alaska, *Geophys. J. Int.,* **190,** 1689–1709.

Pritchard, M.E. & Simons, M., 2002. A satellite geodetic survey of large-scale deformation of volcanic centres in the central Andes, *Nature,* **418,** 167–171.

Riedesel, M.A. & Jordan, T.H., 1989. Display and assessment of seismic moment tensors, *Bull. seism. Soc. Am.,* **79**(1), 85–100.

Ross, Z.E., Ben-Zion, Y. & Zhu, L., 2015. Isotropic source terms of San Jacinto fault zone earthquakes based on waveform inversions with a generalized CAP method, *Geophys. J. Int.,* **200,** 1267–1278.

Salisbury, M.J., Jicha, B.R., de Silva, S.L., Singer, B.S., Jiménez, N.C. & Ort, M.H., 2011. $^{40}Ar/^{39}Ar$ chronostratigraphy of Altiplano-Puna volcanic complex ignimbrites reveals the development of a major magmatic province, *Bull. geol. Soc. Am.,* **123**(5–6), 821–840.

Šilený, J. & Milev, A., 2006. Seismic moment tensor resolution on a local scale: simulated rockburst and mine-induced seismic events in the Kopanang gold mine, South Africa, *Pure appl. Geophys.,* **163,** 1495–1513.

Šilený, J. & Milev, A., 2008. Source mechanism of mining induced seismic events—resolution of double couple and non double couple models, *Tectonophysics,* **456,** 3–15.

Šilený, J., Hill, D.P., Eisner, L. & Cornet, F.H., 2009. Non-double-couple mechanisms of microearthquakes induced by hydraulic fracturing , *J. geophys. Res.,* **114**, B08307, doi:10.1029/2008JB005987.

Silwal, V. & Tape, C., 2016. Seismic moment tensors and estimated uncertainties in southern Alaska, *J. geophys. Res.,* **121,** 2772–2797.

Sparks, R. S.J., Folkes, C.B., Humphreys, M. C.S., Barfod, D.N., Clavero, J., Sunagua, M.C., McNutt, S.R. & Pritchard, M.E., 2008. Uturuncu volcano, Bolivia: volcanic unrest due to mid-crustal magma intrusion, *Am. J. Sci.,* **308,** 727–769.

Stähler, S.C. & Sigloch, K., 2014. Fully probabilistic seismic source inversion—Part 1: efficient parameterisation, *Solid Earth,* **5,** 1055–1069.

Stierle, E., Vavryčuk, V. & Bohnhoff, M., 2014. Resolution of non-double-couple components in the seismic moment tensor using regional networks—II: application to aftershocks of the 1999 M_w 7.4 Izmit earthquake, *Geophys. J. Int.,* **196,** 1878–1888.

Tan, Y., Song, A., Wei, S. & Helmberger, D., 2010. Surface wave path corrections and source inversions in southern California, *Bull. seism. Soc. Am.,* **100**(6), 2891–2904.

Tape, W. & Tape, C., 2012. A geometric setting for moment tensors, *Geophys. J. Int.,* **190,** 476–498.

Tape, W. & Tape, C., 2013. The classical model for moment tensors, *Geophys. J. Int.,* **195,** 1701–1720.

Tape, W. & Tape, C., 2016. A confidence parameter for seismic moment tensors, *Geophys. J. Int.,* **205,** 938–953.

Vavryčuk, V., 2001. Inversion for parameters of tensile earthquakes, *J. geophys. Res.,* **106**(B8), 16 339–16 355.

Vavryčuk, V., 2011. Tensile earthquakes: theory, modeling, and inversion, *J. geophys. Res.,* **116**, B12320, doi:10.1029/2011JB008770.

Walter, F., Clinton, J.F., Deichmann, N., Dreger, D.S., Minson, S.E. & Funk, M., 2009. Moment tensor inversions of icequakes on Gornergletscher, Switzerland, *Bull. seism. Soc. Am.,* **99**(2A), 852–870.

Walter, F., Dreger, D.S., Clinton, J.F., Deichmann, N. & Funk, M., 2010. Evidence for near-horizontal tensile faulting at the base of Gornergletscher, a Swiss Alpine Glacier, *Bull. seism. Soc. Am.,* **100**(2), 458–472.

Ward, K.M., Zandt, G., Beck, S.L., Christensen, D.H. & McFarlin, H., 2014. Seismic imaging of the magmatic underpinnings beneath the Altiplano-Puna volcanic complex from the joint inversion of surface wave dispersion and receiver functions, *Earth planet. Sci. Lett.,* **404,** 43–53.

West, M. & Christensen, D., 2010. *Investigating the Relationship Between Pluton Growth and Volcanism at Two Active Intrusions in the Central Andes,* International Federation of Digital Seismograph Networks. Other/Seismic Network, doi:10.7914/SN/XP_2010.

West, M.E., Kukarina, E. & Koulakov, I., 2013. Structure of Uturuncu volcano from seismic tomography, *presented at 2013 Fall Meeting*, AGU, San Francisco, California, December 9–13, Abstract V13B-2600.

Zandt, G. & Ammon, C.J., 1995. Continental crust composition constrained by measurements of crustal Poisson's ratio, *Nature,* **374,** 152–154.

Zandt, G., Beck, S.L., Ruppert, S.R., Ammon, C.J., Rock, D., Minaya, E., Wallace, T.C. & Silver, P.G., 1996. Anomalous crust of the Bolivian Altiplano, central Andes: constraints from broadband regional seismic waveforms, *Geophys. Res. Lett.,* **23**(10), 1159–1162.

Zandt, G., Leidig, M., Chmielowski, J., Baumont, D. & Yuan, X., 2003. Seismic detection and characterization of the Altiplano-Puna magma body, central Andes, *Pure appl. Geophys.,* **160,** 789–807.

Zhao, L.-S. & Helmberger, D.V., 1994. Source estimation from broadband regional seismograms, *Bull. seism. Soc. Am.,* **84**(1), 91–104.

Zhu, L. & Ben-Zion, Y., 2013. Parameterization of general seismic potency and moment tensors for source inversion of seismic waveform data, *Geophys. J. Int.,* **194,** 839–843.

Zhu, L. & Helmberger, D., 1996. Advancement in source estimation techniques using broadband regional seismograms, *Bull. seism. Soc. Am.,* **86**(5), 1634–1641.

Zhu, L. & Rivera, L.A., 2002. A note on the dynamic and static displacements from a point source in multilayered media, *Geophys. J. Int.,* **148,** 619–627.

Zhu, L. & Zhou, X., 2016. Seismic moment tensor inversion using 3D velocity model and its application to the 2013 Lushan earthquake sequence, *Phys. Chem. Earth,* in press, doi:10.1016/j.pce.2016.01.002.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this paper:

Contents

S1 Classification based on wavenumbers and assumed heterogeneity
S2 Influence of velocity structure on moment tensor inversions

List of Tables

S1 Wavenumber-distance (*kL*) values for our study
S2 Text file of moment tensor catalog
S3 Grid for full moment tensor grid search

List of Figures

S1 Classifying the influence of scattering with a *ka*-*kL* plot
S2 *P*-wave travel times vs hypocentral distance
S3 Stability of moment tensor inversions
S4 Observed and synthetic amplitude ratios
S5 Station amplitude ratios, weights V01 R01 S01
S6 Station amplitude ratios, weights V10 R01 S10
S7 Maps of station amplitude ratios
S8 Waveform fits for the example event. Absolute scale
S9 Waveform fits for the example event, weights V10 R01 S10, no polarities
S10 Waveform fits for the example event, weights V10 R01 S00
S11 Waveform fits for the example event, weights V10 R01 S00, no polarities
S12 Waveform fits for the example event, weights V10 R00 S00
S13 Waveform fits for the example event, weights V00 R01 S00
S14 Waveform fits for the example event, weights V00 R00 S10
S15 Misfit summary for the example event, weights V10 R01 S10, no polarities
S16 Misfit summary for the example event, weights V10 R01 S00, no polarities
S17 Misfit summary for the example event, weights V10 R01 S00
S18 Misfit summary for the example event, weights V10 R00 S00
S19 Misfit summary for the example event, weights V00 R01 S00

S20 Misfit summary for the example event, weights V00 R00 S10
S21 Waveform fits for the example event, weights V10 R01 S00, double couple
S22 Waveform fits for the example event, weights V10 R01 S00, tensile crack
S23 Waveform fits for the example event, weights V10 R01 S00, compression crack
S24 Inversions for different physical models

http://gji.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggw247/-/DC1.

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the paper.