UDC 550.340

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https://doi.org/10.23939/jgd2023.01.070

FOCAL MECHANISM OF THE INDUCED EARTHQUAKE OF 2015-06-13 (Alberta, Canada) BASED ON WAVEFORM INVERSION

Understanding the source mechanisms of induced earthquakes is important to distinguish them from natural earthquakes. The main objective of our study consists in finding out which parameters of the source mechanism can be used most effectively to identify the induced earthquakes. A possibility is also being explored whether they can be retrieved from data of a limited number of stations or even just one. We calculate versions of the seismic moment tensor and the corresponding focal mechanisms of the induced event of 2015-06-13 (t_0 = 23:57:53.00 UTC, φ = 54.233˚N, λ = -116.627˚E, h_s = 4 km, ML4.4) near Fox Creek, Alberta, Canada, by inversion of only direct waves recorded at one, two, three and seven stations. The versions turned out to be practically identical, which indicates the advantage of using only direct waves and the very possibility of determining the focal mechanism from the records at the limited number of seismic stations, which may be especially valuable in areas with a sparse seismic network. The versions also turned out to be very similar to the one obtained in [Wang, 2018], which can be considered an additional proof of the reliability of our method. The source time function of the Alberta event had a longer duration (~4 s) than is typical for tectonic earthquakes of similar size. We assume that this very feature may be specific to induced earthquakes and used in combination with others to distinguish them from tectonic earthquakes.

Key words: induced earthquakes; natural earthquakes; seismic moment tensor; focal mechanism; source time function; waveform inversion.

Introduction

Understanding the source mechanisms of induced earthquakes is important to distinguish them from natural earthquakes and to estimate the time-dependent seismic hazard in areas of ongoing large-scale industrial activity that may cause destructive earthquakes. The main objective of our study consists in examining which parameters of the source mechanism can be used most effectively to identify the induced earthquakes. A possibility is also explored whether they can be retrieved from data of a limited number of stations or even just one, which could be particularly valuable in areas with low seismicity and a small number of seismic stations.

Induced Seismicity Monitoring and well-log-based velocity and density models in northeast British Columbia (Canada) are presented in [Mahani & Malytskyy et.al., 2021]. Seismicity of Alberta (Canada) and environs for the period from 1 January 2000 to 6 March 2015 were explained and used in Eaton & Mahani (2015). In this article, authors investigated the focal mechanisms of some earthquakes that have occurred in Alberta since December 2013 [Eaton & Mahani, 2015]. The focal mechanisms solutions of these events were obtained using the polarity of P-wave first motions registered on regional seismic network. Within Alberta, the majority of seismic activity is concentrated within clusters located near the Rocky Mountain deformation front (see Fig.1 in Eaton & Mahani, 2015).

In this paper, we present the results of determining the source time function (STF) and moment tensor of the induced event with a reported magnitude ML4.4 that occurred on 2015-06-13 (t_0 = 23:57:53.00 UTC, φ = 54.233˚N, λ = -116.627˚E, h_s = 4 km) about 30 km south of Fox Creek, Alberta, Canada [Wang, 2018]. Based on our results, we make an assumption that it is the longer duration of its STF(t) than typical for tectonic earthquakes of similar size that may be specific to induced earthquakes.

Currently, the moment tensors are calculated by several approaches: using amplitudes of seismic waves [Vavrychuk & Kuhn, 2012; Godano et al., 2011], S/P amplitude ratios [Hardebeck & Shearer, 2003], or full waveforms [Dziewonski & Woodhouse, 1983; Sipkin, 1986; Sileny et al., 1992; Mai et al., 2016; Weber, 2006, 2016].

Accuracy and reliability of all the moment tensor inversions depend on whether the two major assumptions hold. First, it is assumed that the point source approximation is valid and second, that the effect of the Earth’s structure on seismic waves is modelled correctly. If either of these assumptions does not hold, the resulting moment tensor may contain a large non double-couple component, even if the source mechanism is a double-couple.

To comply with the assumption of a point source, only seismic waves with wavelengths longer than the dimensions of the fault plane are used in the inversion method developed by us [Malytskyy, 2010, 2016; Mai et al., 2016; Malytskyy & Kozlovskyy, 2014; Malytskyy & D'Amico, 2015]. Addressing the problem of inexorable inaccuracy of seismic waves modelling we propose to invert only the direct P- and S-waves instead of the full field. An advantage of inverting only the direct waves consists in their much lesser distortion, if compared to reflected and converted waves, by inaccurate modelling of velocity contrasts, the direct waves carrying consequently much less distorted imprint by the source. An advantage, in this connection, of choosing the matrix method for calculation of the wave field consists in its ability to analytically isolate only the direct waves from the full field. Also, the analytical expressions are drawn out relating the moment tensor components to the components of displacements in the immediate vicinity of the source. As a result, our method enables us to calculate the seismic moment tensor **M**(t) by inverting the waves recorded only at a limited number of seismic stations.

Calculation of seismic moment tensor and focal mechanism

The inversion scheme consists of two steps. The first one is forward modeling. We consider propagation of seismic waves in a horizontally layered medium and calculate synthetic seismograms on its upper surface. The point source is located inside a layer and is represented by seismic moment tensor **M**(t). The displacements on the upper surface **U** are presented in matrix form in frequency and wave number domain, separately for far-field and near-field [Malytskyy & Kozlovskyy, 2014]. Further, only the far-field displacements are considered and the wave-field from only direct P- and S-waves is isolated with application of eigenvector analysis reducing the problem to system of linear equations [Malytskyy, 2016].

Second step is inverse modeling. It consists in determining the parameters of the source under the condition that its location and velocity model are known in advance [Malytskyy, 2010, 2016; Mai et al., 2016]. Mathematically, the solution of the inverse problem reduces to the inversion of matrix **G** relating the source parameters **M**(t) to the observed field **U**. As a result, components of seismic tensor can be obtained using a solution of generalized inversion (Eq. 1) and transformed to time domain by applying the inverse Fourier transform [Malytskyy 2010, 2016; Malytskyy & Kozlovskyy, 2014; Malytskyy & D'Amico, 2015]:

$$\mathbf{M} = (\tilde{\mathbf{G}}^{*}\mathbf{G})^{-1}\tilde{\mathbf{G}}^{*}\mathbf{U}, \qquad (1)$$

where $\mathbf{U} = \left(U_x,\ U_y, U_z\right)^T$ contains displacement components of direct P- or S-waves, $\mathbf{M} = \left(M_{xz}, M_{yz}, M_{zz}, M_{xx}, M_{yy}, M_{xy}\right)^T$ consists of components of seismic moment tensor, **G** is a matrix relating the source parameters **M**(t) to the observed field **U** and $(\tilde{\mathbf{G}}^{*}\mathbf{G})^{-1}\tilde{\mathbf{G}}^{*}$ is the generalized inverse of **G**.

In the earlier version of our method, as well as in the most other moment tensor inversions, waveforms at several seismic stations are simultaneously inverted [Malytskyy, 2016]. Although much more information on the source should obviously be contained in the waveforms from several stations, it nevertheless can be shown that all the components of seismic tensor contribute to the waveforms at the limited number of seismic stations and, at least theoretically, can be retrieved from them, a possibility explored in a current version of the inversion.

We use our method to determine the seismic tensor and the focal mechanism for the induced event of 2015-06-13 (t_0 = 23:57:53.00 UTC, φ = 54.233°N, λ = –116.627°E, h_s=4 km, ML4.4) near Fox Creek, Alberta, Canada.

The location of the event and the stations and the focal mechanism obtained previously by [Wang 2018, http://www.eas.slu.edu/eqc/eqc_mt/MECH.NA/20150613235753/] are shown in Fig. 1. The waveforms (converted to displacements) recorded at the six stations (BRLDA, SWHSA, WTMTA, TD09A, TD002 and TD009) are shown in Fig. 2. After conversion to displacements the waveforms were band-pass filtered in the frequency range from 0.08 to 0.4 Hz. After that, we visually estimated the portions of records containing only direct P- and S-waves, also taking into account the phase delays at the stations and focal depth.

Table 1

1D crustal model used in the inversions (http://www.eas.slu.edu/eqc/eqc_mt/MECH.NA/20150613235753/).

h_s, km	V_P, km/s	V_S, km/s	r , g/cm^3
1.9	3.4065	2.0089	2.2150
6.1	5.5445	3.2953	2.6089
13.0	6.2708	3.7396	2.7812
19.0	6.4075	3.7680	2.8223
	7.9000	4.6200	3.2760

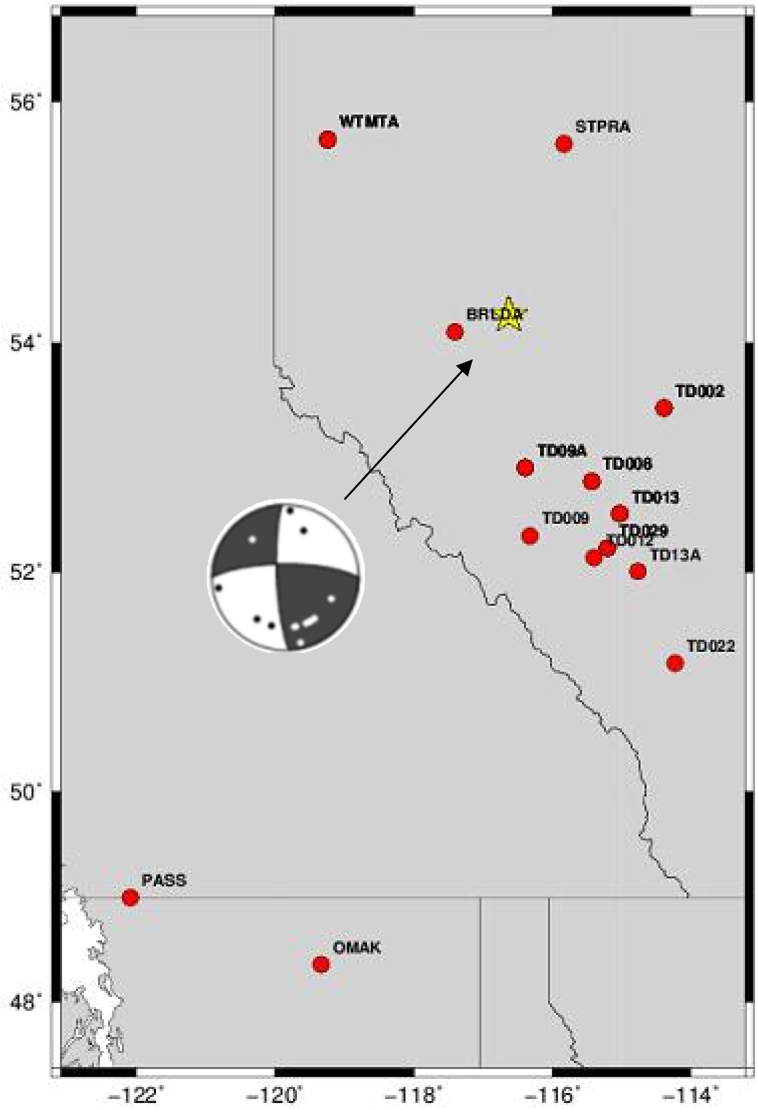


Fig. 1. The location of the Alberta event (yellow star) and the stations (red circles) and the focal mechanism of the event by [Wang, 2018], http://www.eas.slu.edu/eqc/eqc_mt/MECH.NA/20150613235753/.

Components of the seismic moment tensor **M**(t) and versions of the focal mechanism, calculated for a source depth (h_s) of 4 km by inversion of waveforms recorded at different configurations of stations, are shown in Fig. 3, Fig. 4, Fig. 5 and Fig. 6. The 1D crustal model used in the inversions is listed in Table 1.

Discussion and conclusion

The assumption of a horizontally layered half-space, as well as the distribution of seismic velocities in it, may turn out grossly incorrect in fact. Combined with inaccurate knowledge of source location and source time, as well as with a number of the other uncertainties, such as introduced by seismic noise in the observed seismograms etc., it may almost completely obscure the source imprint in the seismograms, and especially in those originating from only one station, turn the moment inversion ill-defined and lead to an intractable solution.

Addressing the problem, we've chosen to invert only the direct P- and S-waves instead of the full field. An advantage of the direct waves consists in their much lesser distortion, if compared to reflected and converted waves, by inaccurate modeling of velocity contrasts. Therefore, the direct waves carry a much less obscured imprint of the source. An advantage, in this connection, of the matrix method used by us for calculation of the wave field consists in its ability to analytically isolate only the direct waves from the full field.

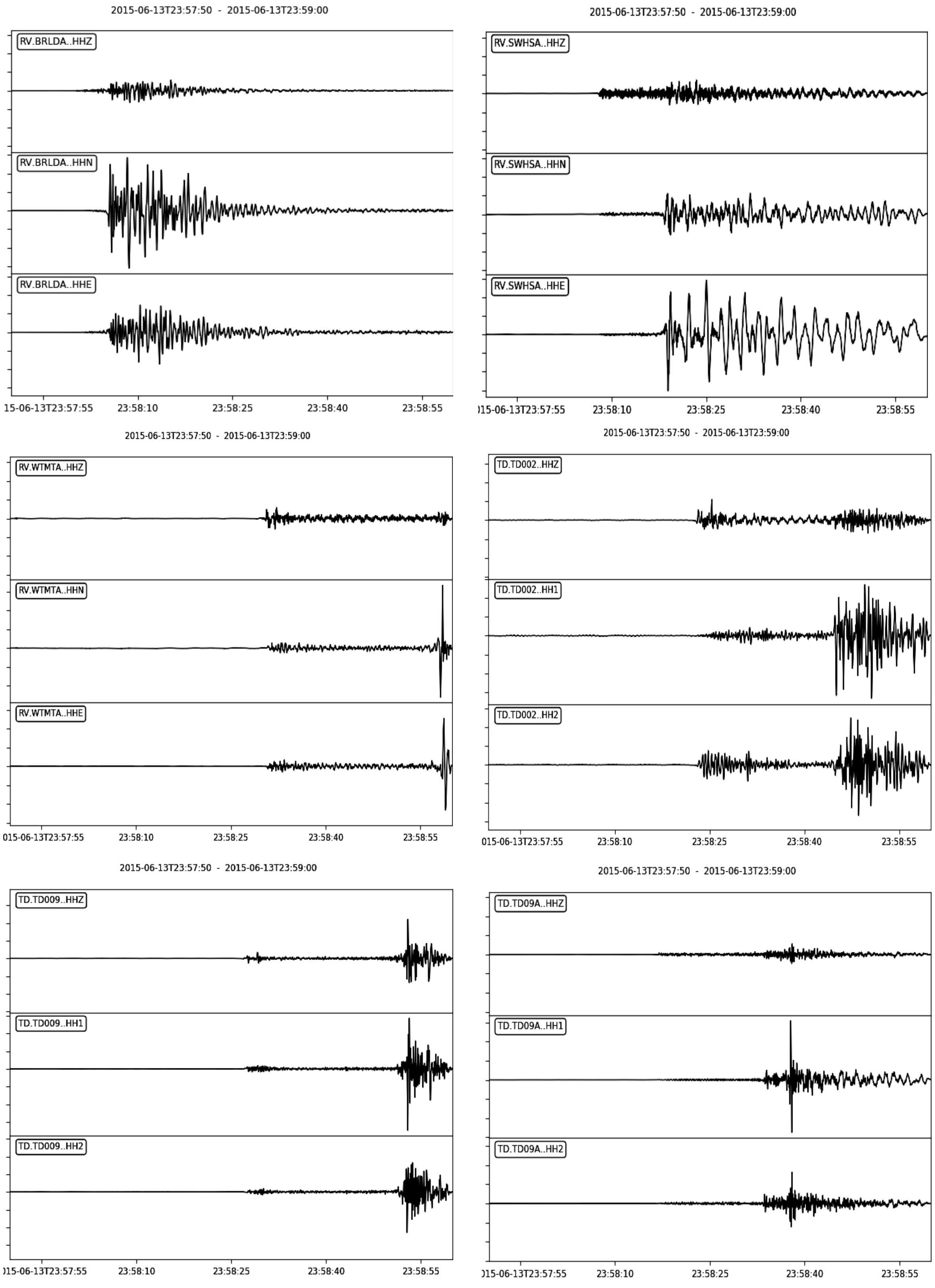
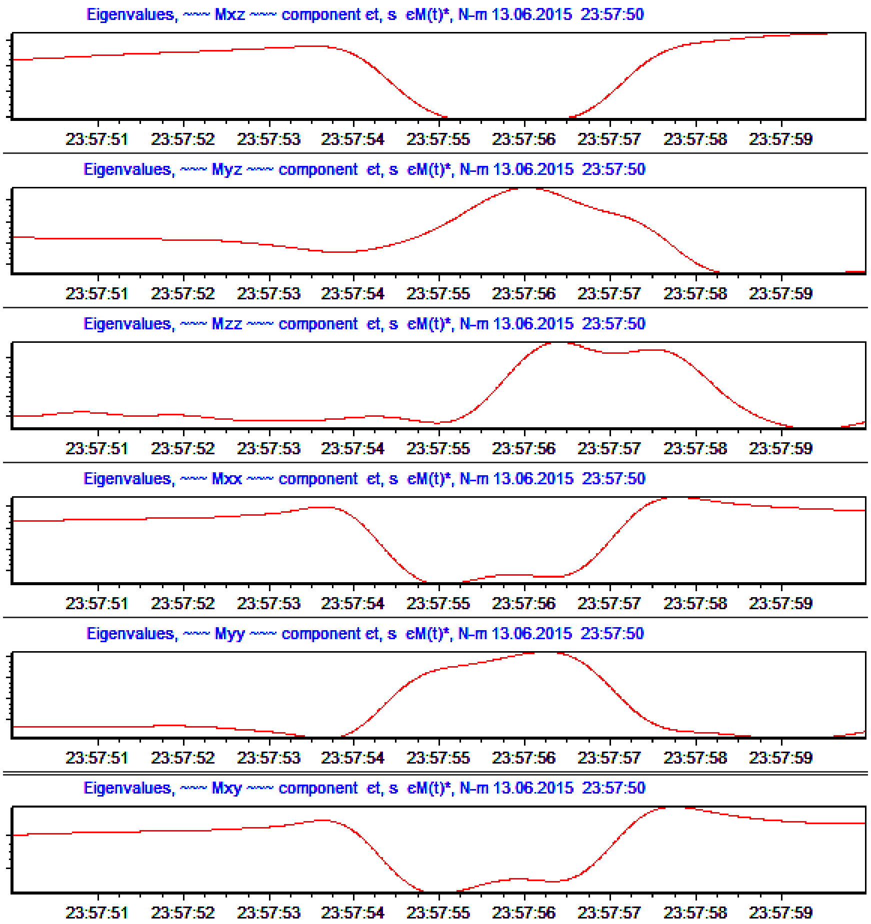
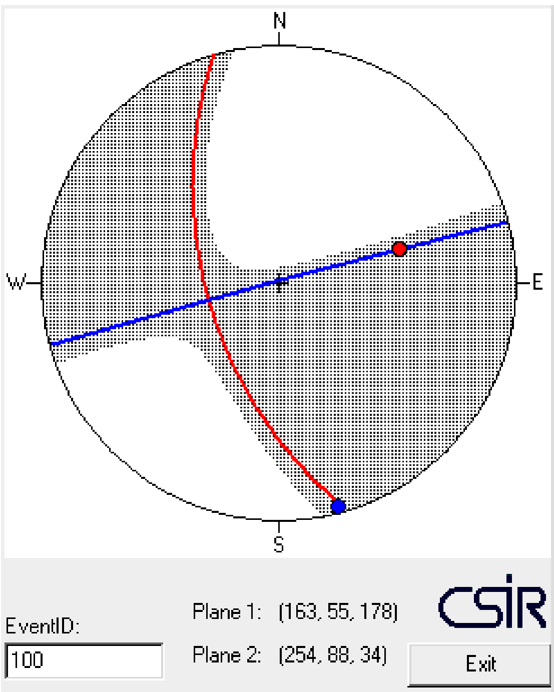


Fig. 2. The records of the Alberta event (converted to displacements) at BRLDA, SWHSA, WTMTA, TD009, TD002 and TD009A stations. The records are band-pass filtered in the frequency range of 0.08–0.4 Hz.

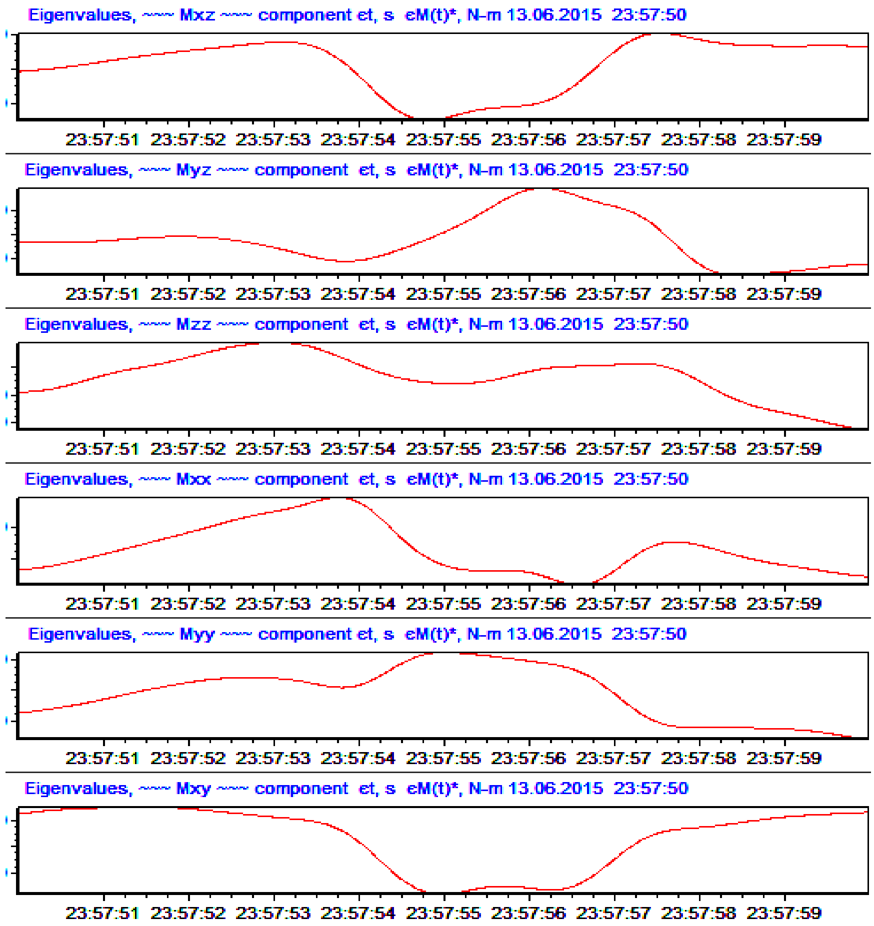


a

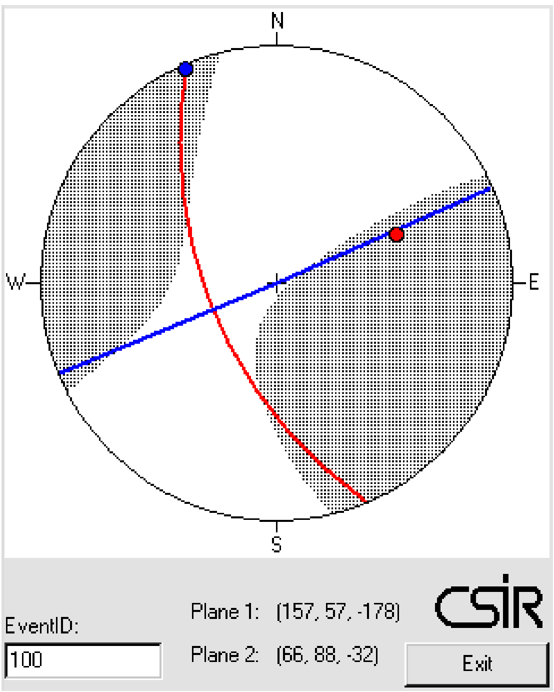


b

Fig. 3. Components of the seismic moment tensor **M**(t) calculated for the earthquake of 2015-06-13 by inversion of its waveforms only at the station BRLDA (a) and the corresponding version of the focal mechanism (b).

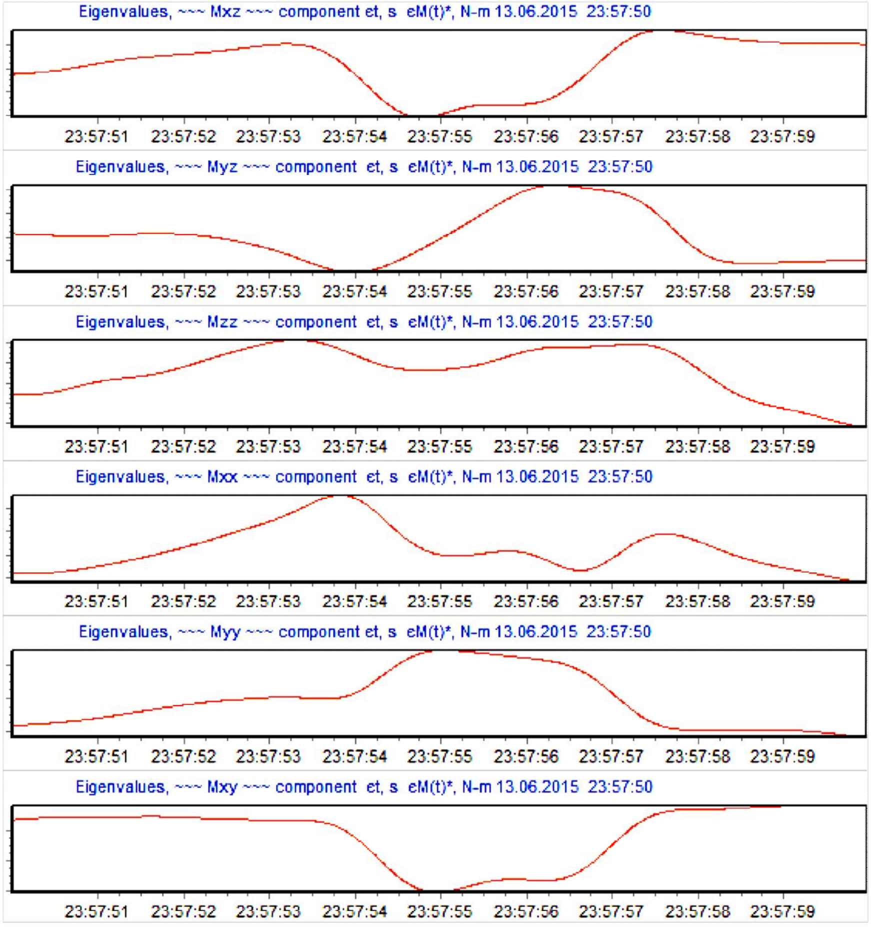


a

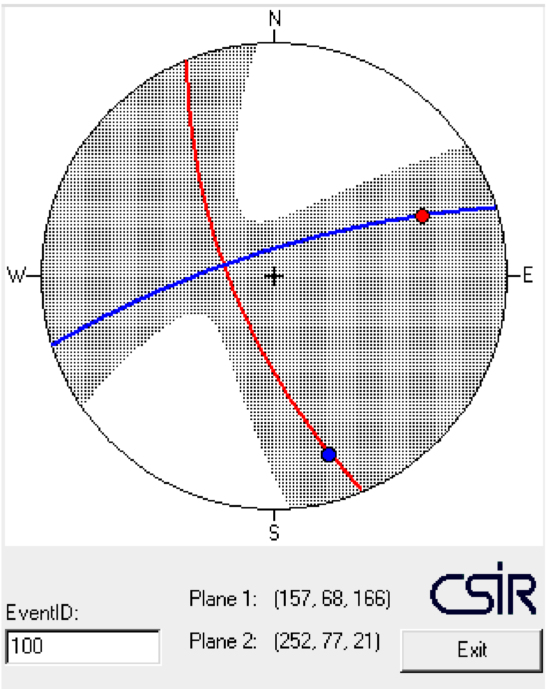


b

Fig. 4. Components of the seismic moment tensor **M**(t) calculated for the earthquake of 2015-06-13 by inversion of its waveforms at two stations, BRLDA and SWHSA (a), and the corresponding version of the focal mechanism (b).

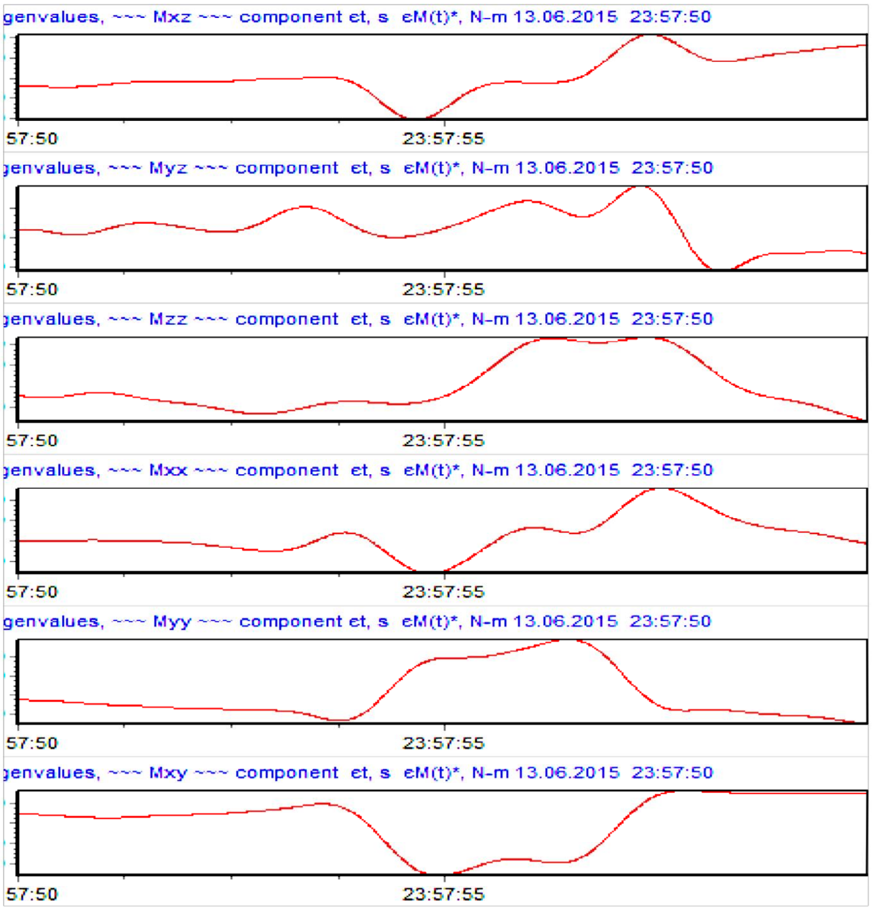


a

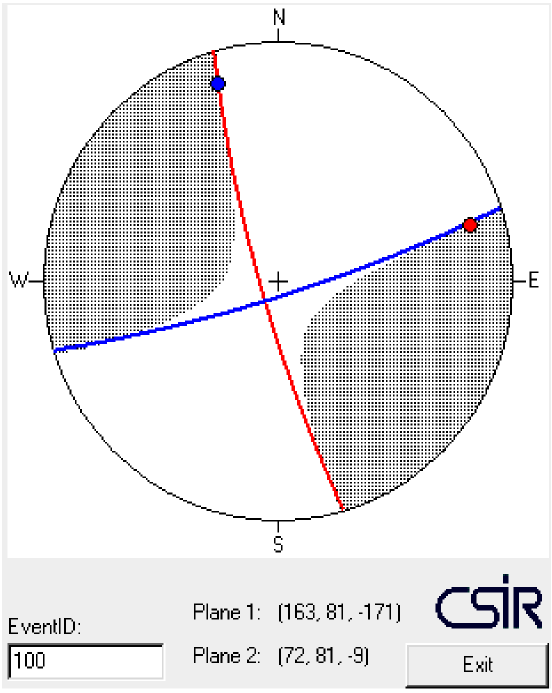


b

Fig. 5. Components of the seismic moment tensor **M**(t) calculated for the earthquake of 2015-06-13 by inversion of its waveforms at three stations, BRLDA, SWHSA ad STPRA (a), and the corresponding version of the focal mechanism (b).



a



b

Fig. 6. Components of the seismic moment tensor **M**(t) calculated for the earthquake of 2015-06-13 by inversion of its waveforms at seven stations, BRLDA, SWHSA, STPRA, WTMTA, TD09A,TD002 and TD009 (a), and the corresponding version of the focal mechanism (b).

Versions of the seismic moment tensor **M**(t) and the corresponding focal mechanisms calculated by us for the induced event of 2015-06-13 near Fox Creek, Alberta, Canada, by inversion of waves recorded at only one, two, three and seven stations turned out to be almost identical (Fig. 3–6), which indicates the correctness of our approach and the very possibility of determining the focal mechanism from waveforms recorded at only one station. The focal mechanism was almost vertical strike-slip with the fault planes oriented north-south and east-west. At the same time, our mechanism turned out to be very similar to the one obtained in [Wang, 2018], which can be considered an additional proof of its reliability.

It is also important to note that the source time function we obtained for our induced event has a longer duration (~4 s) (see Figs. 3–6) than is typical for tectonic earthquakes of similar size. We assume that this feature can be used combined with some others to distinguish tectonic earthquakes from induced ones.

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ФОКАЛЬНИЙ МЕХАНІЗМ ІНДУКОВАНОГО ЗЕМЛЕТРУСУ 2015-06-13 (Альберта, Канада), ВИЗНАЧЕНИЙ ЗА ДОПОМОГОЮ ОБЕРНЕННЯ ХВИЛЬОВИХ ФОРМ

Розуміння механізму вогнища індукованих землетрусів важливе, щоб уміти відрізняти їх від природних. Основною метою нашого дослідження було виявлення параметрів фокального механізму, які з найбільшою ефективністю можна використати для ототожнення індукованих землетрусів. Досліджено також можливість визначення цих параметрів за даними обмеженої кількості станцій, або й навіть однієї. Ми обчислюємо версії тензора сейсмічного моменту і відповідні фокальні механізми індукованої події 2015-06-13 (t_0 = 23:57:53.00 UTC, φ = 54.233˚N, λ = –116.627˚E, h_s = 4 km, ML4.4) поблизу Фокс Крік, Альберта, Канада, оберненням лише прямих хвиль, записаних на одній, двох, трьох і семи станціях. Усі версії виявилися практично однакові, що свідчить про перевагу використання лише прямих хвиль і про саму можливість визначення фокального механізму з використанням записів лише на одній станції, що може бути особливо актуально у регіонах з малою кількістю сейсмічних станцій. Ці версії виявилися також дуже схожими на отриману в [Wang, 2018], що можна вважати додатковим аргументом на користь надійності нашого методу. Часова функція вогнища події в Альберті виявилася довшою (~4 s), ніж це типово для тектонічних землетрусів такої самої сили. Є підстави припустити, що ця ознака може бути характерною саме для індукованих землетрусів і може бути використана разом з іншими для того, аби відрізняти їх від тектонічних.

Ключові слова: індуковані землетруси; природні землетруси; тензор сейсмічного моменту; фокальний механізм; часова функція вогнища; обернення хвильових форм.

Received 20.04.2023