Rupture pattern of the Oct 23, 2011 Van-Merkez, Eastern Turkey earthquake

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Abstract High-frequency rupture process of the Oct 23, 2011 Van-Merkez earthquake is imaged by back-projection method using high-quality teleseismic P wave data from the US Array, and prestack Kirchhoff migration using P wave data from a subarray of global seismic networks. The rupture model with two asperities is confirmed by previous two methods. In low-frequency imaging, a large asperity derived from the migration method corresponds to the second one from the high-frequency P waves. The consistency of the locations of asperities from datasets with different frequency bands indicates that there is possible insignificance of the frequency-dependent feature for the earthquake. The resultant images illustrate the spatial and temporal evolution of the rupture, which mainly propagated WSW over a length of 33 km during the first 18 s, accompanying with bursts of two asperities at 3 and 11–13 s. The rupture direction is confirmed by the S wave corner frequency variations of strong ground accelerations. The rupture fronts are mainly located at the updip of the causative fault. Based on polarities of the P waveforms and focal mechanisms of the mainshock and aftershocks, the failure of these two asperities is determined to have occurred on a reverse fault with a dip angle of 47° . Hence, the rupture pattern of the 2011 Van-Merkez earthquake

was dominated by a unilateral rupture toward the west-southwest direction.

Keywords 2011 Van-Merkez earthquake · Rupture pattern · Back-projection · Kirchhoff migration

1 Introduction

On Oct 23rd 2011, a catastrophic earthquake struck the vicinity of the Lake Van, eastern Turkish Plateau with an average elevation of about 2 km, which was generated by the intra-continental collision of the Arabian and Eurasian plates under a tectonic regime characterized by NNW-SSE compression and WSW-ENE extension (Koçyiğit et al. 2001). Figure 1 shows different epicenters and focal mechanisms. The epicenters are relocated by the Disaster and Emergency Management Presidency, Earthquake Department Ankara, Turkey (AFAD, www.deprem.gov.tr), the European Mediterranean Seismological Centre (EMSC, www.emsc-csem.org), and the United States Geological Survey (USGS, www.usgs.gov), and the focal mechanisms are obtained by the GeoForschungsZentrum Potsdam, Germany (GFZ, www.gfz-potsdam.de), the global centroid moment tensor (GCMT), and the USGS. The discrepancies among these source parameters mainly result from the different datasets and velocity models being used. Moreover, there is a trade-off between origin time and hypocentral location. Although no obvious surface faulting was observed after the earthquake, the segmented morphological trace (Fig. 1) of the buried fault ($N60^\circ\text{degE}$, $N70^\circ\text{degE}$) inducing the earthquake is implied from the field studies on destruction and deformation of the man-made structures (AFAD 2011). The strike of the implied causal fault is very consistent with that (255°) constrained by body waves from

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Fig. 1 The epicenters determined by the AFAD (diamond), EMSC (hexagon), and USGS (star) and focal mechanisms obtained by the GFZ, GCMT, and USGS (using body waves) for the 2011 Van-Merkez earthquake in the vicinity of the lake Van, eastern Turkey. Five strong motion stations (triangle), respectively, labeled with 4902, 0401, 1302, 5601, and 4901 are those of the TR-KYH near the epicenter. The solid white region is the Lake Van. The black line depicts the surface trace of the causative fault, whereas the dashed line represents a subparallel fault. The inset illustrates the station distribution of the US Array (black triangle) and the global seismic network (gray triangle). The contours indicate the iso-epidistance lines with an interval of 30°

the USGS, but slightly deviates from that (268°) given by the GFZ. Considering the consistency among the location and depth of the hypocenter, focal mechanisms, and inferred surface trace of the causal fault, the epicenter and focal depth (38.69°N, 43.50°E, 16 km) from USGS are adopted in this study.

Soon after the 2011 Van-Merkez earthquake, the preliminary source models from the finite fault model (Hayes 2011; Shao and Ji 2011), InSAR (Atzori et al. 2011), and multiple-point-sources inversion (Zahradnik and Sokos 2014) were obtained. The common feature is that there is a major asperity near the epicenter. A fixed fault plane was given in these source models, which might be not very appropriate for earthquakes occurring in complex and segmented fault systems as the 2011 Van-Merkez earthquake. In recent years, a family of back-projecting approach without aforementioned strong constraints have

been employed in the study on rupture features of great earthquakes (Ishii et al. 2005; Krüger and Ohrnberger 2005; Xu et al. 2009; Zhang and Ge 2010). Especially, asperities or subevents can be resolved accurately (Zhang et al. 2011, 2012). This approach was first applied to a moderate size event, the April 6, 2009 L'Aquila, Italy earthquake, by D'Amico et al. 2010). To resolve the rupture of the 2011 M_w 7.1 Van-Merkez earthquake, a moderate size event, we first carry out the relative back-projection method (Zhang and Ge 2010) using high-frequency teleseismic P wave data from the US Array in the United States, and then P wave data from a subarray of the global seismic networks filtered with two frequency bands are employed to determine asperities in the rupture spreading using the prestack Kirchhoff migration (Baker et al. 2005; Zheng et al. 2007) with a similar stacking technique as the back-projection method.

Fig. 2 The vertical-component P waveforms from the US Array and the global subarray. The waveforms over a length of 60 s are aligned with the first trough from the epicenter at 0 s, where *dashed red lines* cross. **a** The P waveforms from 232 stations of the US Array are filtered with a high-frequency band of 0.2–2 Hz. **b** The P waveforms from 112 stations of the subarray of the global seismic networks are filled with a band of 0.1–1 Hz. **c** The P waveforms from the subarray are filled with a low-frequency band of 0.02–0.1 Hz

2 Rupture imaging

To image the rupture fronts of the 2011 Van-Merkez earthquake, P wave data from a regional seismic network in a limited azimuthal range and a global seismic network with full azimuth are utilized by the back-projection method (Zhang and Ge 2010) and the prestack Kirchhoff migration (Baker et al. 2005; Zheng et al. 2007), respectively. The regional seismic network (US Array) composed of more than 400 broadband stations is located northwest of the epicenter. The azimuth of the US Array to the earthquake promotes the determination of the westward rupture process, but suppresses the resolution to the southeast direction. Given the main period of the datasets being used, the imaging technique significantly depends on the differential arrival times between a source and the stations. For the US Array, only high-frequency P wave data are utilized. The epicentral distance and azimuthal coverage of the stations from the seismic network control the lateral resolution of approaches like the back-projection method (Kiser and Ishii 2012). To resolve more precise rupture process, both high- and low- frequency P wave data from a subarray of the global seismic networks which update data to the Incorporated Research Institutions for Seismology (IRIS, www.iris.edu) in full azimuth are utilized. A

reference station is needed in the relative back-projection method. This is appropriate for regional arrays due to their limited aperture, but is not suitable for the subarray of the global seismic network. Hence, the prestack Kirchhoff migration with a similar stacking process as the relative back-projection method is employed to handle the P wave datasets from the subarray of the global seismic network.

2.1 Rupture imaging from the US Array

The high-quality vertical-component P wave data (Fig. 2a) from the US Array which is composed of 232 stations (Fig. 1) filtered with a frequency band of 0.2–2 Hz were back projected to the source region. The source region over the latitude range of 38.19°–39.19°N and the longitude range of 43.00°–44.00°E is spatially gridded into 2,601 blocks of 0.02° by 0.02° fixed at the focal depth of 16 km. The centers of the blocks are considered as potential rupture fronts. Owing to the relative timing, the approach is insensitive to the velocity model. Hence, 1D earth standard velocity model AK135 (Kennett et al. 1995) is employed to calculate the theoretical travel time between a pair of potential rupture front and station. Virtually, the observed arrival time always differs from the theoretical time due to anisotropies and

Fig. 3 Rupture imaging derived from the US Array. **a** The spatial and temporal evolution of the rupture. The *rings* indicate the rupture fronts with *color* representing the rupture time (*color bar*) and area depicting the energy release. The *black points* denote the aftershocks with magnitudes equal or greater than 3.0 from Oct 23, 2011 to Nov 8, 2011. **b** The normalized energy of the rupture fronts varied with time. **c** The distance of the rupture fronts to the epicenter varied with time

heterogeneities along the ray paths. Calibrations to the deviations of the theoretical travel times are carried out by aligning the first 5 s of the P waveforms using cross correlation for all the stations with reference to the epicenter. Since the scales of the length and width of the source region are much smaller than those of the epicentral distances, the same calibrations are made to other potential rupture fronts. P wave Beams from the potential rupture fronts are formed by the 4th root stacking. Then, the energy of the potential rupture fronts at certain time is obtained by summing up the square of their corresponding beams within a time window of 6 s. Finally, the back-projected spatial and temporal evolution of the 2011 Van-Merkez is illustrated in Fig. 3a.

The rupture imaging as illustrated in Fig. 3b, c demonstrates that the rupture mainly propagated to the WSW direction over a length of 33 km at an average velocity of about 1.54 km/s in the first 18 s. The locations of the rupture fronts and direction of the rupture propagation are consistent with the strike of the causal fault. Most of the rupture fronts were located at the updip portion of the causal fault, where few aftershocks exist (Fig. 3a). Moreover, two asperities broke in the first 18 s (Fig. 3b). The first one broke near the epicenter at 3 s (Fig. 4b), and the energy stored in the second asperity which is about twice of that of the first one was released about 20 km west-southwest to the epicenter at about 11.2 s (Fig. 4c).

2.2 Rupture imaging from the subarray of the global seismic network

The complexity and segmentation of the earthquake make it difficult to recover the process and identify the locations of the asperities precisely, if only the data from the US Array with a limited azimuthal and epicentral distance coverage are utilized. The accumulated energy distribution (Fig. 4a) roughly indicates the resolution affected by the azimuth, epicentral distance, and configuration of the US Array. To overcome the limitation of the regional seismic network, P wave data from a subarray of the global seismic networks with an epicentral distance range of 40°–90° (Fig. 1) are employed by the prestack Kirchhoff migration. We employ P wave data filtered with two frequency bands of 0.1–1 and 0.02–0.1 Hz (Fig. 2b, c) to the source region gridded in the same way as the back-projection method.

For the high-frequency case, the normalized accumulated energy distribution (Fig. 4d) of the beams attests that there are two apparent asperities in the rupture process. The first one was initiated about 7 km north of the epicenter at 3 s (Fig. 4e), and the second one broke about 19 km west-southwest of the epicenter at about 12.8 s (Fig. 4f). The results are in good agreement with those derived from the US Array. Owing to non-sufficient magnitudes of peaks in the beams at other times, no more asperities could be discriminated definitely.

Fig. 4 The normalized accumulated energy distributions for high-frequency (h-f) of the US Array, h-f and low-frequency (l-f) of the subarray of the global seismic networks are shown in **a**, **d** **g**, respectively. The normalized energy distributions associated with two asperities for h-f of the US Array and the subarray of the global seismic networks are presented in **b**, **c**, **e**, and **f**, respectively. In addition, the distribution of the normalized energy of the second asperity for l-f of the subarray is shown in **i**. The *white star* denotes the epicenter and the *blue point* indicates the front with the maximum energy. **h** The obtained two asperities labeled *1* (red circle) and *2* (blue circle). The red and black star and triangle represent the first and second asperities obtained by the h-f of the US Array and the subarray of the global seismic networks, respectively. The yellow triangle indicates the asperity determined by the low-frequency of the subarray of the global seismic networks. The color bar indicates the normalized energy for the other figures in Fig. 4

For the low-frequency case with lower resolution, only one asperity is identified to west-southwest of the epicenter (Fig. 4i). Considering the trade-off between the rupture time and the location of the asperity, and the possible time discrepancy of the first motion associated with the epicenter for data with different frequency bands,

the asperity, which broke about 19.5 km west-southwest to the epicenter at 13.5 s (Fig. 4i), is actually the second one derived from the high-frequency datasets. The lack of the first high-frequency asperities indicates that the first asperity released less low-frequency energy relative to the second one.

Table 1 Corner frequencies of horizontal components of S waves of five strong ground motion records and their means

Label	Epicentral distance (km)	Azimuth (deg)	f_c (Hz)		
			E-W	N-S	Mean
4902	95.5	302	0.5818	0.6212	0.6015
1302	116.3	259	0.8773	0.8182	0.8478
0401	120.8	341	0.4045	0.4439	0.4242
5601	159.6	238	0.3258	0.3258	0.3258
4901	170.8	273	0.3848	0.4242	0.4045

3 Rupture direction derived from strong ground motion

The corner frequency of near-field strong ground acceleration data can be applied to distinguish the direction of propagation for an orientation-preferred rupture. Since a segment of the onset of P waves is missed and the amplitudes of S waves are larger, we utilize S wave data from five near-source strong motion stations (labeled 4902, 1302, 0401, 5601, and 4901, Fig. 1) of the National Strong Motion Network of Turkey (TR-KYH, kyh.deprem.gov.tr) to constrain the main rupture direction for the 2011 Van-Merkez earthquake. The epicentral distances and azimuths of the five stations are listed in Table 1. The corner frequencies of the two horizontal components (N-S and E-W) of the strong ground accelerations are calculated by employing the spectrum scaling laws (Aki and Richards 2002) with roots of 2–4 to fit the amplitude spectrums. The best fittings to the amplitude spectrums are shown in S1–S5, which imply that the rupture might spread in a complicated way. As listed in Table 1, records at the station 1302 have higher corner frequencies relative to station 4902 with a shorter epicentral distance and station 0401 with an almost equal epicentral distance. In addition, compared with those from the station 5601 with a shorter epicentral distance, records from the station 4901 have higher corner frequencies. These observations imply an apparent rupture to the west-southwest direction for 2011 Van-Merkez earthquake. The consistency between rupture directions derived from strong motion and P wave data strongly supports results of the preceding rupture images.

4 Discussion and conclusions

In this study, high-quality teleseismic P wave data from the US Array are used to image the high-frequency rupture of the Oct 23, 2011 Van-Merkez earthquake utilizing the relative back-projection method. To overcome the azimuthal limitation of the US Array, P wave data from a subarray of the global seismic networks are employed to

image the asperities by the prestack Kirchhoff migration. Two asperities obtained from the high-frequency data of the subarray of the global seismic networks confirm those derived from the high-pass filtered data of the subarray as shown in Fig. 4h. For low-frequency P wave data from the subarray, the only asperity is the second one obtained by the high-frequency datasets. The fact that the locations of the same asperity are determined to be in the vicinity of each other indicates that there is no significance of the frequency-dependent feature for the earthquake. The final images demonstrate that spatial and temporal evolution of the rupture spreads to the west-southwest direction at the updip portion of the causal fault, where there are few aftershocks, resulting from most of the elastic strain energy at the updip has been released by the mainshock. The rupture propagated west-southwestwards over a length of 33 km during the first 18 s, accompanying with bursts of two asperities at 3 and 11–13 s, respectively. The first asperity is located in the vicinity of the epicenter, and the other one is about 19.5 km away from the epicenter. The direction of the rupture spreading is confirmed by the corner frequency distribution of S waves of strong ground accelerations. The fact that polarities of high-frequency P waveforms from the subarray of the global seismic networks with full azimuth associated with the two asperities are the same implies that both asperities broke with reverse focal mechanisms. The dip angle of the fault plane can be determined to be 47° by averaging dip angles of the aftershocks with reverse focal mechanisms (AFAD 2011). This indicates that the failure of the asperities occurred on a reverse fault with a dip angle of 47° . Thus, the 2011 Van-Merkez, eastern Turkey earthquake was dominated by the unilateral rupture to the west-southwest direction.

The rupture inversion on a fault plane derived from the finite fault model (Hayes 2011) presents a major asperity with the largest slip located in the vicinity of the epicenter within the initial 10 s. This asperity virtually is the first one (Fig. 4h) near the epicenter derived from high-frequency P wave data. The second peak at 11 s of the source time function from finite fault model is much lower than the first one. This is in contrary to our results (Fig. 3b), which results from the energy released by the asperity directly stems from the waveforms using imaging approaches, while that from the finite fault model is inverted under some constraints such as a given focal mechanism, the location of the hypocenter, and the rupture velocity (Lay et al. 2010). A rupture model which includes two or three major asperities following each other southwestwards and a less certain asperity located northeast of the epicenter, is obtained on a given fault plane by the multiple-point source moment tensor under the assumption that multiple-point sources have a fixed focal mechanism (Zahradnik and Sokos 2014). The two asperities in the southwest branch of

the rupture correspond with those in this study (Fig. 4h). Due to the dependency factors mentioned in finite fault model and the assumption of fixed focal mechanism in the study of Zahradnik and Sokos (2014), locations and magnitudes of the inverted asperities differ from those in this study. In addition, the preliminary source model from InSAR (Atzori et al. 2011) presents large slip to west of the epicenter on a north dip fault plane, owing to the lack of geodetic data. The slip distribution of the InSAR model projected on the surface is similar to that of the accumulated normalized energy (Fig. 4g) from low-frequency P wave data. The source time function inverted by Vallée (2011) is consistent with the normalized energy varied with time (Fig. 3b), such as the rupture duration time of 18 s and the two peaks of the moment rate.

Evangelidis and Kao (2013) back-project strong motion to the source region of the 2011 Van earthquake. Overall, we identify two asperities as they do. Since the epicentral distances of the strong motion stations are closer to the source than those in this study, their results provide more detailed rupture feature for each asperity. Particularly, they found that the first one ruptures another N-S trending fault. However, the near-source strong motion waveforms typically contaminated by the scattering from the near-surface heterogeneities in the shallow crust would be imaged to generate more artifacts than the teleseismic data. Moreover, near-source imaging quality depends on the accuracy of the velocity model, which is typically not constrained well; this leads to mislocate the subevents of earthquakes.

The frequency-dependent feature is discovered in the rupture of giant earthquakes ($M_W > 8.5$), such as the 2010 Chilean (Kiser and Ishii 2011; Wang and Mori 2011) and 2011 Tohoku earthquakes (Koper et al. 2011; Roten et al. 2012; Wang and Mori 2011; Yao et al. 2011). However, the locations of the same asperity from different frequency-band datasets are determined to be close with each other (Fig. 4h). This implies that there is no significance of the frequency-dependent feature during the rupture of the earthquake. Therefore, to accurately resolve the asperities of a moderate size event, the high- and low- frequency datasets should be utilized simultaneously.

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References

Aki K, Richards PG (2002) Quantitative Seismology, 2nd edn. University Science, Sausalito

- Atzori S., C. Tolomei, S. Salvi, and S. Zoffoli (2011) SIGRIS report on Co-seismic ground displacement and preliminary source models. [Available at <http://supersites.earthobservations.org>]. Accessed 25 Oct 2011
- Baker T, Granat R, Clayton RW (2005) Real-time earthquake location using Kirchhoff reconstruction. *Bull Seismol Soc Am* 95(2):699–707. doi:10.1785/0120040123
- D'Amico S, Koper KD, Herrmann RB, Akinci A, Malagnini L (2010) Imaging the rupture of the M_W 6.3 April 6, 2009 L'Aquila, Italy earthquake using back-projection of teleseismic P-waves. *Geophys Res Lett*. doi:10.1029/2009GL042156
- Disaster and Emergency Management Presidency, Earthquake Department Ankara, Turkey (AFAD) (2011) Report on the Van earthquake. [Available at <http://www.deprem.gov.tr>]. Accessed 10 Oct 2011
- Evangelidis CP, Kao H (2013) High-frequency source imaging of the 2011 October 23 Van (Eastern Turkey) earthquake by backprojection of strong motion waveforms. *Geophys J Int* 184:699–718. doi:10.1093/gji/ggt437
- Hayes G. (2011) Finite fault model: Updated result of the Oct 23, 2011 M_W 7.1 eastern Turkey earthquake. [Available at <http://www.usgs.gov>]. Accessed 23 Oct 2011
- Ishii M, Shearer PM, Houston H, Vidale JE (2005) Extent, duration and speed of the 2004 Sumatra-Andaman earthquake imaged by the Hi-Net array. *Nature* 435:933–936. doi:10.1038/nature03675
- Kennett BLN, Engdahl ER, Buland R (1995) Constraints on seismic velocities in the earth from travel times. *Geophys J Int* 122:108–124. doi:10.1111/j.1365-246X.1995.tb03540.x
- Kiser E, Ishii M (2011) The 2010 M_W 8.8 Chile earthquake: triggering on multiple segments and frequency-dependent rupture behavior. *Geophys Res Lett* 38:L07301. doi:10.1029/2011GL047140
- Kiser E, Ishii M (2012) Combining seismic arrays to image the high-frequency characteristics of large earthquakes. *Geophys J Int* 188:1117–1128. doi:10.1111/j.1365-246X.2011.05299.x
- Koçyiğit A, Yılmaz A, Adamia S, Kuloshvili S (2001) Neotectonics of east Anatolian Plateau (Turkey) and Lesser Caucasus: implication for transition from thrusting to strike-slip faulting. *Geodin Acta* 14:177–195. doi:10.1016/S0985-3111(00)01064-0
- Koper KD, Hutko AR, Lay T, Ammon CJ, Kanamori H (2011) Frequency-dependent rupture process of the 2011 M_W 9.0 Tohoku earthquake: comparison of short-period P wave back-projection images and broadband seismic rupture models. *Earth Planets Space* 63:599–602. doi:10.5047/eps.2011.05.026
- Krüger F, Ohrnberger M (2005) Tracking the rupture of the $M_W = 9.3$ Sumatra earthquake over 1,150 km at teleseismic distance. *Nature* 435:937–939. doi:10.1038/nature03696
- Lay T, Ammon CJ, Hutko AR, Kanamori H (2010) Effects of kinematic constraints on teleseismic finite-source rupture inversions: great Peruvian earthquakes of 23 June 2001 and 15 August 2007. *Bull Seismol Soc Am* 100(3):969–994. doi:10.1785/0120090274
- Roten D, Miyake H, Koketsu K (2012) A Rayleigh wave back-projection method applied to the 2011 Tohoku earthquake. *Geophys Res Lett* 39:L02302. doi:10.1029/2011GL050183
- Shao GF, Ji C (2011) Preliminary result of the Oct 23, 2011 M_W 7.13 Turkey earthquake. [Available at www.geol.ucsb.edu]. Accessed 7 July 2011
- Vallée M (2011) Focal mechanism and source time function. [Available at www.emsc-csem.org]. Accessed 1 Aug 2011
- Wang D, Mori J (2011) Frequency-dependent energy radiation and fault coupling for the 2010 M_W 8.8 Maule, Chile, and 2011 M_W 9.0 Tohoku, Japan, earthquakes. *Geophys Res Lett* 38:L22308. doi:10.1029/2011GL049652
- Xu Y, Koper KD, Sufri O, Zhu L, Hutko AR (2009) Rupture imaging of the M_W 7.9 12 May 2008 Wenchuan earthquake from back projection of teleseismic P waves. *Geochem Geophys Geosyst* 10(4):1525–2027. doi:10.1029/2008GC002335

- Yao HJ, Gerstoft P, Shearer PM, Mecklenbräuker C (2011) Compressive sensing of the Tohoku-Oki M_W 9.0 earthquake: frequency-dependent rupture modes. *Geophys Res Lett* 38:L20310. doi:[10.1029/2011GL049223](https://doi.org/10.1029/2011GL049223)
- Zahradnik J, Sokos E (2014) The M_W 7.1 Van, Eastern Turkey, earthquake 2011: two-point source modelling by iterative deconvolution and non-negative least squares. *Geophys J Int* 196:522–538. doi:[10.1093/gji/ggt386](https://doi.org/10.1093/gji/ggt386)
- Zhang H, Ge ZX (2010) Tracking the rupture of the 2008 Wenchuan earthquake by using the relative back-projection method. *Bull Seismol Soc Am* 100(5):2551–5560. doi:[10.1785/0120090243](https://doi.org/10.1785/0120090243)
- Zhang H, Ge ZX, Ding LY (2011) Three sub-events composing the 2011 off the Pacific coast of Tohoku earthquake (M_W 9.0) inferred from rupture imaging by back-projecting teleseismic P waves. *Earth Planets Space* 63:595–598. doi:[10.5047/eps.2011.06.021](https://doi.org/10.5047/eps.2011.06.021)
- Zhang H, Chen J, Ge Z (2012) Multi-fault rupture and successive triggering during the 2012 M_W 8.6 Sumatra offshore earthquake. *Geophys Res Lett* 39:327–423. doi:[10.1029/2012GL053805](https://doi.org/10.1029/2012GL053805)
- Zheng YC, Lay T, Flanagan MP, Williams Q (2007) Pervasive seismic wave reflectivity and metasomatism of the Tonga mantle wedge. *Science* 316(5826):855–859. doi:[10.1126/science.1138074](https://doi.org/10.1126/science.1138074)