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Could the coseismic fractures of a lake ice reflect the earthquake mechanism? (Afyon earthquakes of 2 March 2002, Central Anatolia, Turkey)

Tekin Yürür [a,*], Onur Köse [b], Hünkar Demirbağ [a], Çağlar Özkaymak [b], Levent Selçuk [b]

[a] *Department of Geological Engineering, Hacettepe University, 06532 Beytepe, Ankara, Turkey*
[b] *Department of Geological Engineering, Yüzüncü Yıl University, 65080 Zeve, Van, Turkey*

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Abstract

Eyewitness reports that the two moderate earthquakes (3 February 2002) in Afyon, Central Anatolia, Turkey, produced fractures at the icy surface of a partially frozen lake near the reactivated fault scarp. In places along the shoreline, the ice thrusted towards the land. Far from the shoreline, several fractures developed on the approximately 15 cm-thick ice of the lake. Among them, geometric features of two fracture junctions suggest that fractures accommodated lateral movements. Almost no coupling should exist between the ice and the shaking ground because of the water beneath the ice, these fractures cannot be directly associated to ground ruptures. Alternatively, we propose that the great inertia of the ice mass caused the collision of the ice layer with the shore land when the ground beneath this layer moved towards the lake. As a result, the ice-ground interface deformed and the icy "hinterland" fractured. The orientations of the stress axes deduced from fracturation fit with those suggested by focal mechanism solutions and ground rupturing. Consequently, the ice of the lake surface seems to indirectly record the mechanism of the Afyon earthquakes.

Keywords: Earthquake; Lake ice cover; Coseismic fracturation; Afyon; Turkey

1. Introduction

The Çay and Çobanlar (Afyon) earthquakes (Fig. 1) (3 February 2002, 07:11:29.18 GMT, Mw = 6.2, and 09:26:43.71 GMT, Mw = 6.0, [1]) caused human life losses and material damage [2]. The location of the epicenter varies according to different sources (Fig. 1B). Ground ruptures observed in the field are orientated approximately E-W and N35°E [2], and show similarities with the trends of the fault movements suggested by focal mechanisms (Fig. 1B). The E-trending fractures are associated with a downward slip of the northern blocks, and one of the N35°E-trending fractures is associated with the downward slip of the NW block. In a visit we did to the region 3 d after the earthquake, we observed fractures over the surface of a partially frozen lake formed in the hanging-wall part of a north-facing normal fault, possibly reactivated during the earthquakes [2,3]. Our fieldwork is near a place named Bataklıçayır (at about 5 km east of the Değirmendere town) (Fig. 1C). The study area is located near the second epicenter, but farmhouses are reported to be damaged during both quakes. The internal parts of the lake surface comprise an approximately 15 cm thick ice layer, and water below. The ice fractured during the earthquake according to a farm-keeper, Kadir Acun, who also reported to have observed, in the ground, the advancing waves, which at their passage damaged a farm house 100 m far from him. In this paper, we report our observations about the nature and geometry of some of these fractures, and discuss on the possibility of their formation during the earthquake.

2. Nature and geometry of the fracturation

The fractures developed on the ice are several centimeters wide, several hundreds meters long, spaced for several meters, and are all closed. In some localities near the shoreline locally trending E-W, the compacted snowy ice thrusts towards the ground for several decimeters (Fig. 2). The sense of the transport is from north to south. Far from the shoreline and more inwards, two junctions of fractures display interesting characteristics. In one case, the junction forms be-

* Corresponding author.
E-mail address: tyurur@hacettepe.edu.tr (T. Yürür).

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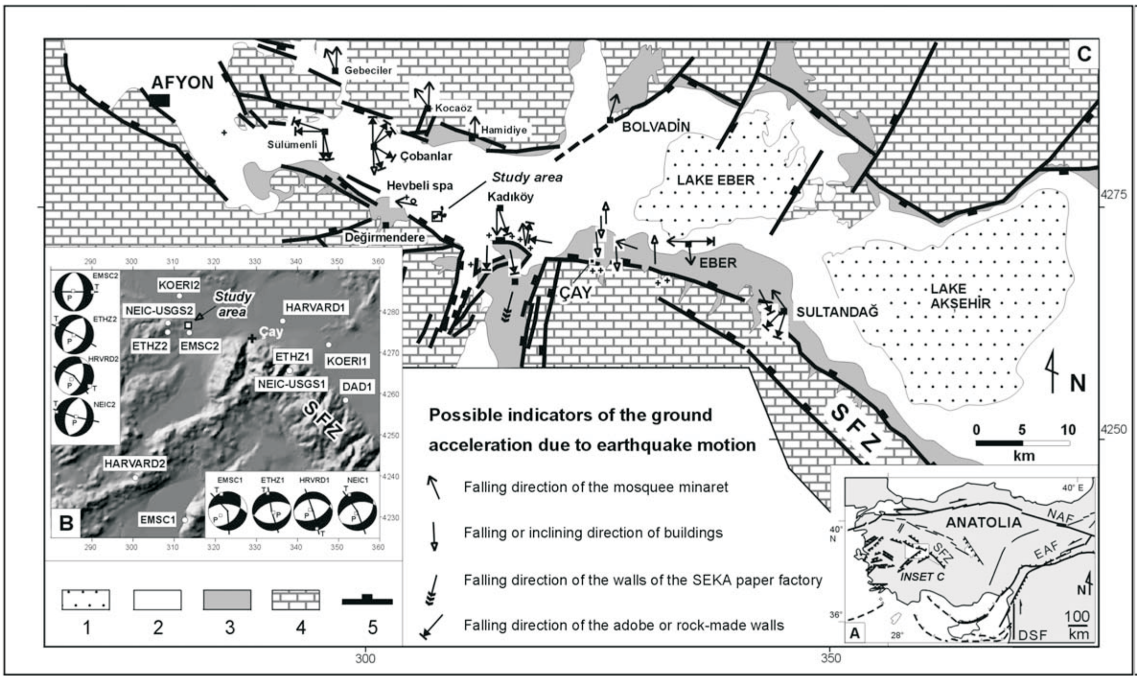

Fig. 1. (A) SimpliŞed tectonic map of Turkey. DSF: Dead Sea fault; EAF: East Anatolian fault; NAF: North Anatolian fault; SFZ: Sultandağlar fault zone; (B) location map of the study area shown on a Digital Elevation Model, prepared using 1/250 000 scale topographic maps. The map shows different epicenter locations of the two 3 February 2002 Afyon earthquakes, according to various sources [1,4—6,8,9] with parameters given at their Internet Sites. At the bottom and left side, there are the fault plane solutions of the Afyon earthquakes according to different sources [1,4—6] Lines radiating from the centers represent the slip vectors of the fault movements. SFZ: Sultandağlar fault zone. Coordinates are in UTM projection, and in km. (C) Geological map of the area considered, simpliŞed from Dirik [10]. SA stands for study area, and the small black surfaces just at the left of SA correspond to the small lakes on which ice fractures are observed. Slip vector data of objects that felt down or changed their original position during the earthquake are from Ulusay et al. [2]. Small black crosses denote where the surface ruptures are observed, according to Ulusay et al. [2]. Key to legend: 1, Quaternary (Lake deposits); 2, Quaternary (alluviums); 3, Plio-Quaternary (alluviums); 4, Basement rocks (Paleozoic-Mesozoic-Tertiary); 5, Normal fault.

tween an ESE-trending, several tens of meters long fracture (Fracture 1 in Fig. 3) and a shorter one (Fracture 2 in Fig. 3). In a close view (Fig. 4), the segment 1 of the fracture 1 jumps leftwards, and creates a relay where the ice uplifts. This reminds the compressional deformation seen in a restraining bend developing along a right-lateral strike-slip fault (Fig. 4b). Along the fracture 2, the ice is also broken (B in Fig. 4b) in a manner similar to a pop-up forming at the rightward jump of a fault segment experiencing left-lateral movements. The fracture 2 is orientated as an RÕRiedel fracture of the fracture 1.

In another junction with similar fracture orientations, the ice was broken, with an ice block thrown away, and remained obliquely within the ice cover (A in Fig. 5b). The gap (B in Fig. 5b) left by the block is evident in the presence of a relatively thinner ice. The ice was broken and ejected possibly by contraction rising at the contact of laterally converging ice parcels (Fig. 5b).

Fig. 2. Photograph of the area where the lake ice thrusts (T) onto the ground.

3. Ice fracturation vs. earthquake parameters

Stress patterns that appear to create the observed fractures are plotted in Fig. 6. They are the N-S convergence for the thrusting, and NW-SE to WNW-ESE convergence for the strike-slip faulting. These directions are consistent with the

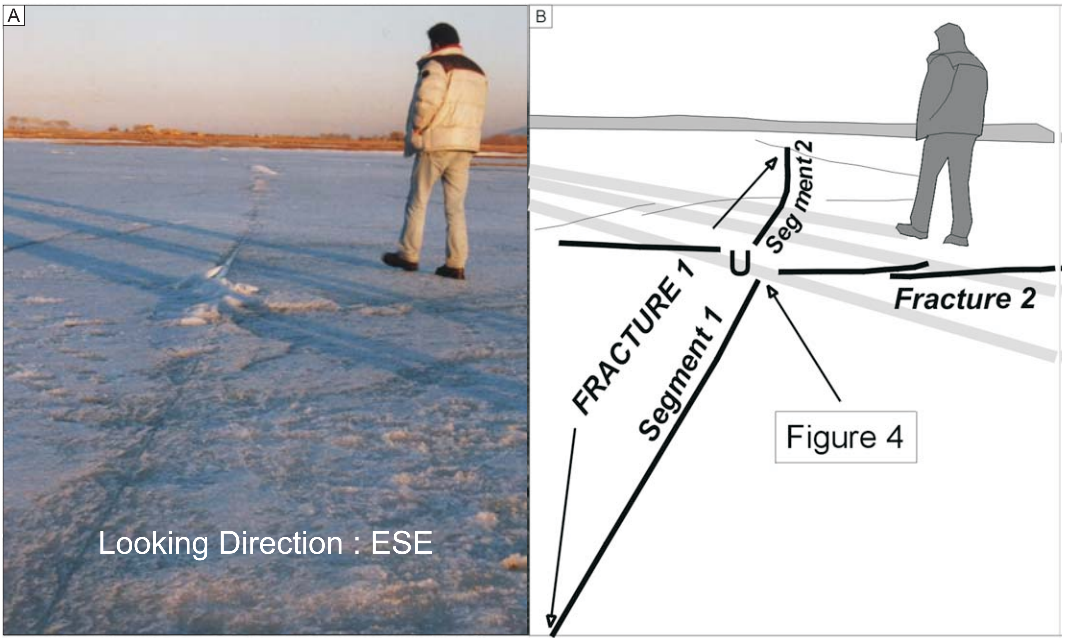

Fig. 3. Ice fracture and the uplift (U) developed along the fracture, suggesting transcurrent movements between the jumping segments (segment 1 and 2) of the same fracture.

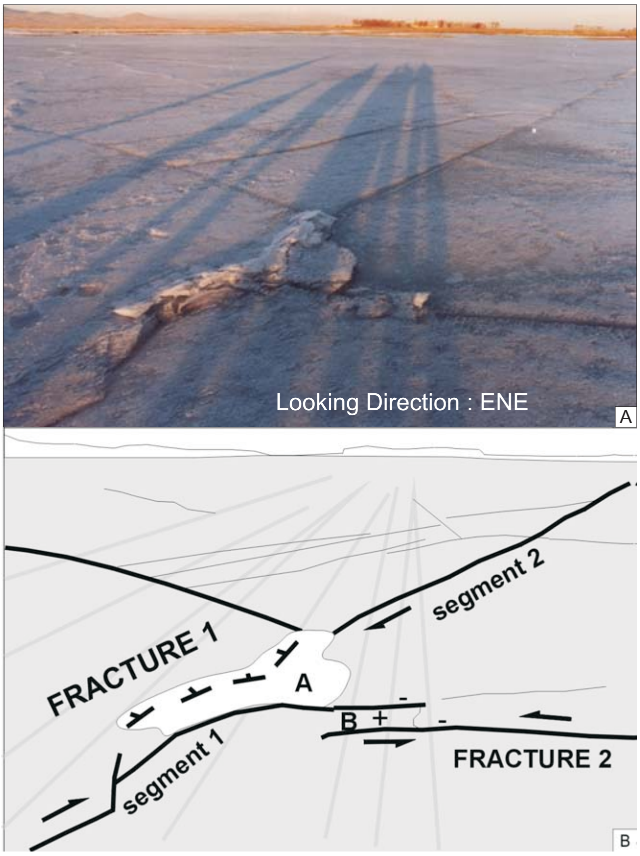

Fig. 4. Detail of the uplift shown in Fig. 3. A (photograph) and B (interpretive map). Dip and strike symbols represent the local tiltings of the ice surface. A and B are the two uplift areas discussed in text.

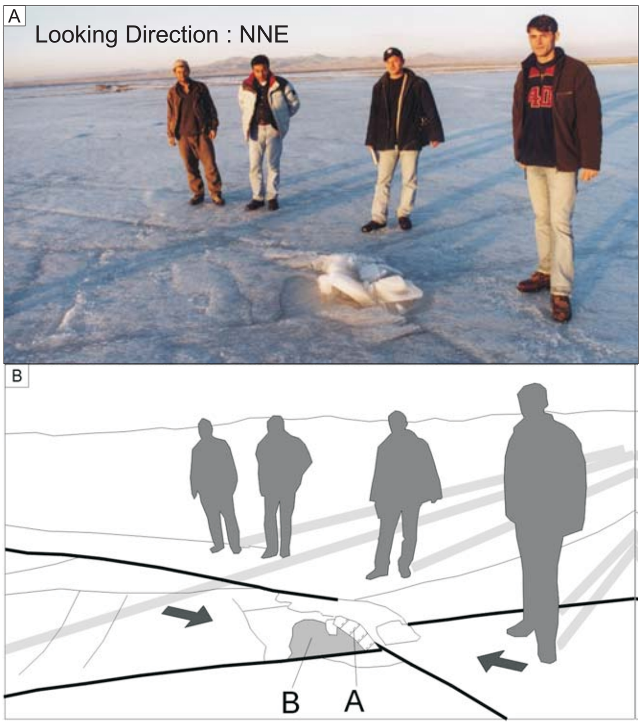

Fig. 5. View of another fracture junction in the ice cover. A. Photograph. B. Interpretive map. An obliquely lying ice fragment (A) was possibly thrown away from the breakpoint (B), fell into the water and later solidiŞed in nighttime. The ice may have fractured by stresses rising due to the convergence between the ice parcels as shown by arrows.

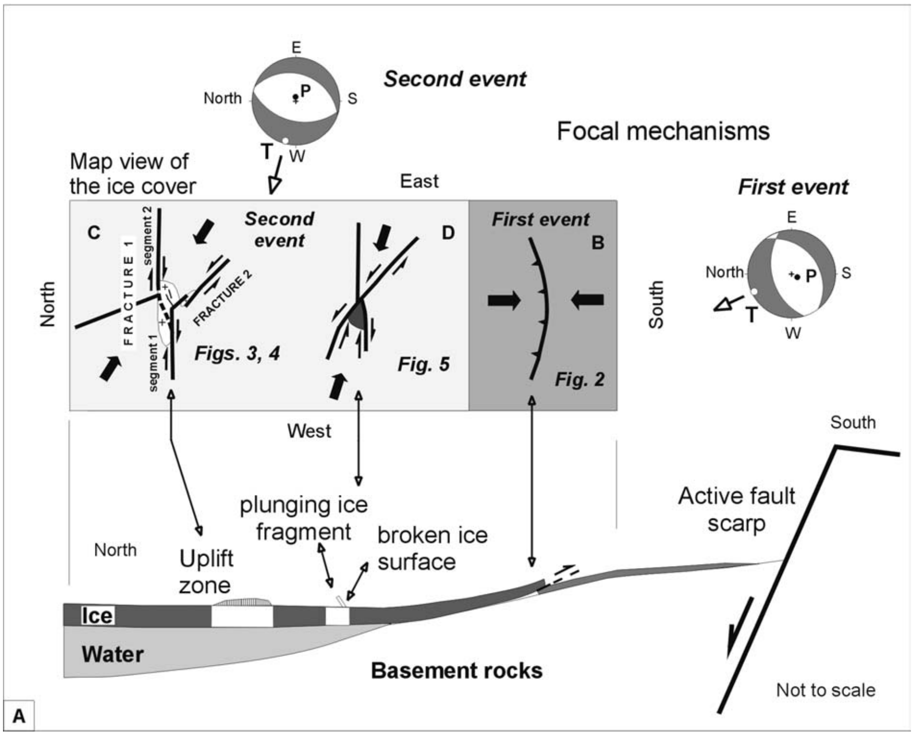

Fig. 6. (A) Schematized cross-section of the study area, showing the structural position of the fractures observed in the ice layer. (B, C and D) Map view indicates the fractures and types of movements deduced from their geometry. The two different stress patterns deduced from the ice fracturation seem to be in good agreement with those determined by the two focal mechanisms occurred in the study area.

fault movement slip vectors determined by the fault plane solutions of the two earthquakes [1,4–6]. On the other hand, these directions show similarities with the ground motion directions estimated by the field observations of the movements of several objects like buildings, walls that felt down, or changed their position during the earthquake (Fig. 1). However, the fault plane solutions suggest normal faulting, and we find rather contractional fractures in the ice cover. How to reconcile these two different phenomena? We try to answer this question in the next section.

4. Possible explanation of the ice fracturation

The passage of seismic waves beneath the ice cover cannot directly fracture the ice since the S shear waves do not pass through the water layer. In other words, frictional forces cannot exist between the ground and the lake ice in the presence of the water layer. Therefore, the fractures in the ice cannot be directly associated to ground rupturing. Alternatively, the passage of seismic waves, as seen by the farm keeper, may create waves in the ground, and much likely in the water confined between the ice and the ground. The passage of the seismic waves might have created wave-front parallel fractures, in the ice. These fractures can be of extensional or contractional type, or possibly of both type after successive wave passages. It is, however, hard to think that they may cause lateral movements as suggested by the nature of some fractures we observed in the ice layer. We alternatively propose a model (Fig. 7) in which the earthquake

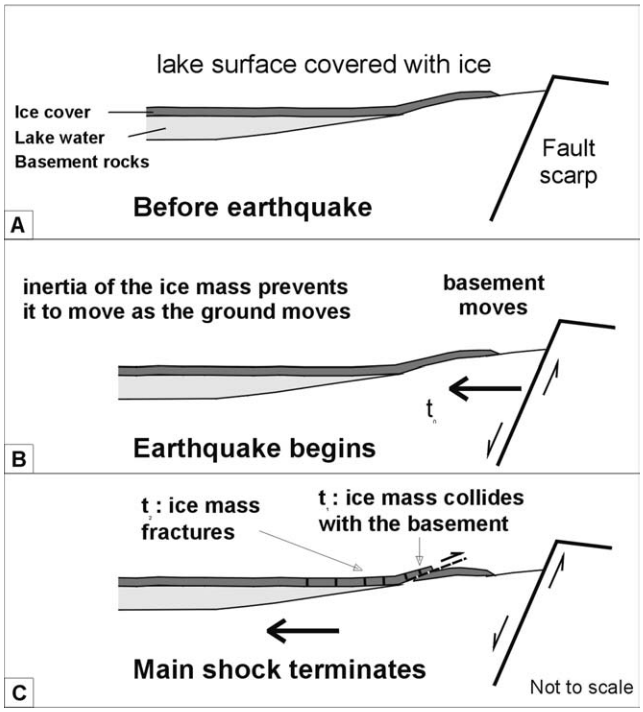

Fig. 7. (A, B and C) Schematic cross-sections to explain the fracturation of the ice cover during the earthquake.

induces stresses in the ice cover. In the southern parts of the lake, the horizontal component of the earthquake slip vector causes the ground to move laterally (Fig. 7B). The value of this component should be greater than $0.113 \times g$ (gravity acceleration), the greatest value recorded by a strong motion accelerometer installed in the Afyon city [8] about 70 km far from the epicenter, while the study area is about 30 km far from the epicenter. At the first moment, at time t_0, the ice mass will not move as the ground moves because of its great inertia due to the important mass of the ice. Immediately after, at time t_1, the convergence between the basement and the ice cover puts them into contact (Fig. 7C). This convergence creates stresses within the ice layer, which thrusts and fractures. The thrusting sense of the ice raft is towards the south. In our model, this requires a northerly motion of the ground rocks towards the stationary ice mass. Such a movement is consistent with the field data that show that during the first earthquake, the northern blocks of the approximately E-trending fractures slipped downwards. The falling directions of several objects also indicate this sense although there are also exceptions (for example in Sülümenli and Çobanlar) (Fig. 1C). Concerning the second earthquake, there is apparently one observation [2], made very near to the study area (the slip vector near the Heybeli spa, just at the west of the study area, Fig. 1C) and suggesting that the northwestern block of a N35°E-trending fracture slipped downwards. If this fracture reflects the fault attitude of the second quake, then we may suppose that the ground moved towards the WNW. This direction of the ground displacement is in agreement with the orientation of the slip vectors suggested by the fault plane solutions (solutions at the left of the Fig. 1B). Additionally, the WNW-ESE direction of the ground displacement during the earthquake is suggested by some of the falling directions of objects (near Sülümenli, Çobanlar and Çay). Therefore, NW-SE to WNW-ESE orientated second convergence, which we deduce from the fact that ice fracturation is consistent with a WNW-ESE orientated motion of the ground, as required in our model.

The proposed model is based on ice-basement collision, causing first the deformation of the ice-basement boundary, and later the internal deformation of the ice mass, similar to orogenic processes operating in collisional crustal zones (e.g. Dewey et al. [7]). In our case, the N-S convergence of the ice boundary and the WNW-ESE convergence in the ice "hinterland" do not support a simple collision and deformation of the ice layer. Possibly, the same deformational process affected the ice layer during the two successive but mechanically different earthquakes, for which we found partial deformational elements. If our explaining thesis is correct, this type of fracturation may be useful to understand the surficial processes of the ground deformation in seismically active areas.

5. Conclusion

We observed fractures developed on the ice cover of a lake during an earthquake. Their geometry suggests that the fractures have accommodated vertical and horizontal displacements. As the ice is not coupled with the ground since a water layer separates them, a direct mechanism between the ice and the ground cannot be envisaged to explain the ice fracturation. We propose that the ice cover of the lake experienced horizontal and vertical strain because of the collision with its basement rocks, during the first moments of the earthquake. This collision is the consequence of the convergence between the ice layer that tended to stay at rest due to its great inertia, and the basement that experienced displacements when the earthquake began. The directions of the movements between the ice mass and the ground that we deduce from the ice fracturation are consistent with those suggested by field observations of ground ruptures and co-seismic motions of several objects. We think that even indirectly, the ice cover recorded some characteristics of the ground displacements during the earthquake.

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