S11H MCC: 3011 Monday 1020h

The 2002 Denali Fault Earthquake: Observations and Implications II

(joint with G)

Presiding: **A Frankel,** U.S. Geological Survey**;** **W L Ellsworth,** U. S. Geological Survey

S11H-01 1020h

The Common Phenomenon of Transient-Triggered Seismicity

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The 2002 M7.9 Denali, Alaska earthquake triggered seismicity rate increases at many sites throughout British Columbia and into the US through northern Utah and Nevada. Denali triggered rate increases occurred in areas not clearly tectonically active, implying that even in areas where ambient stressing rates may be low, the crust may still be critically stressed. These observations demonstrate that remote earthquake triggering caused by the 1992 M7.4 Landers, California, earthquake did not reflect some peculiarity of the region or earthquake. Rather, earthquakes may be triggered by transient deformations nearly anywhere. Rate increases are not clearly apparent in seismicity catalogs, and we observe them in high-pass filtered, broadband seismic data recorded continuously at seismographs operated by the Geological Survey of Canada and various U.S. networks. Seismicity rates increase nearly concurrently with the arrival of the Denali earthquake seismic waves and at sites in the direction of theoretically expected maximum seismic wave radiation from the Denali mainshock. We verify the latter using on-scale seismic data supplemented with 1 Hz GPS data recorded in British Columbia and the US at distances where seismographs went off-scale. Based on the temporal coincidence we infer a causal relation between the transient deformations associated with Denali earthquake surface waves and the seismicity rate increases. Therefore, measurements of the time between the passage of seismic waves and rate increase onsets can provide constraint on underlying physical triggering mechanisms. Noting that rate increases are not observed at sites where recorded peak wave velocities exceed those at more distant triggered sites, we hypothesize that wave frequency matters and attempt to identify the spectral band of seismic waves for which the wave amplitudes best correlate with the rate changes.

S11H-02 1035h

Ground Motions in the Near Field of the November 3, 2002 Denali Fault, Alaska, Earthquake

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A free-field strong-motion recording of the Denali Fault, Alaska, Earthquake was obtained by Alyeska Pipeline Service Company just 3 km from where the Denali Fault slipped over 5 m horizontally and 1 m vertically in the earthquake. The instrument was part of the monitoring and control system for the Trans-Alaska Pipeline and was located at Pump Station 10, approximately 84 km east of the epicenter. After correction for a 0.1 Hz high-pass filter, we recover a fault-parallel permanent displacement of the instrument of 2.3 m. Dynamic ground motions during the earthquake have relatively low acceleration (0.39 g) and very high velocity (1.86 m/s). The most intense motions occurred during a 1.5 s interval generated by the propagation of the rupture front past the site. Growth of the fault-parallel displacement is nearly monotonic, with over half of the permanent displacement occurring during this 1.5 s interval. Preliminary modeling suggests that the rupture velocity exceeded the shear wave velocity near the instrument, and that the peak slip velocity on the fault exceeds several m/s. The low accelerations and high velocities observed near the fault in this earthquake agree with observations from other recent large-magnitude earthquakes. Following the earthquake, the permanent displacement of the support structure for the pipeline and other geodetic reference points was determined by GPS survey along more than 50 miles of the pipeline route. These permanent displacement data display a clear signature of elastic rebound, with displacement amplitudes decreasing with increasing distance from the fault trace. The best-fitting model consisting of a uniform dislocation in an elastic half-space has 6 m of right-lateral fault slip from the surface to a depth of 11 km. This model predicts 2.4 m of displacement at Pump Station 10, in good agreement with the strong motion displacement measurement. At the fault crossing, additional displacements were determined from orthographically corrected aerial photographs of slider beams that were part of the system that successfully accommodated the movement of the Denali Fault beneath the pipeline. The principal surface trace of the rupture cuts through glacial fluvial outwash sands and gravels. Survey data show that the total right-lateral displacement across the 500 m-wide deformation zone is 5.8 m. About 4.5 m of the displacement occurs within a 100 m-wide zone, and the maximum displacement between survey marks spaced 15 m apart is slightly more than 2.4 m. The distributed slip zone at the pipeline crossing most likely reflects the local surficial geology, as nearby offsets of up to 5.5 m on single traces were observed. Collectively, the dynamic and static ground motions in the near-field of the Denali Fault paint a simple picture of a rupture that lasted but a few seconds at any point on the fault and displaced the fault with relatively uniform slip amplitude of about 6 m from the surface to a depth of 11 km.

S11H-03 1050h

Source Process of the M7.9 Denali Fault, Alaska, Earthquake: Sub-Events, Directivity, and Scaling of High-Frequency Ground Motion

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Analysis of strong-motion recordings of the Nov. 3, 2002 M7.9 Denali Fault earthquake from distances of 3-300 km shows the complexity of this large event and the scaling of high-frequency ground motion. Waveform modeling indicates that the earthquake started with an approximately east-west striking thrust subevent, corresponding to the surface rupture observed along the Susitna Glacier fault. I inverted the strong-motion waveforms after the first sub-event to determine the slip as a function of space and time along the Denali and Totschunda faults. The inversion result contains two strike slip sub-events along the Denali fault centered about 80 and 190 km east of the hypocenter. The first strike-slip sub-event was centered on the Denali fault across from the instrument at Pump Station 10 and occurred near a releasing bend in the fault. The second strike-slip sub-event occurred just to the west of the junction of the Denali and Totschunda faults and had the largest moment release. These areas of high slip correspond to locations of large slip found from geodetic data and surface offsets. The preferred inversion solution entails a fast rupture velocity of about 3.5 km/sec between the two strike-slip sub-events, which is close to the shear-wave velocity at depth. Rupture directivity caused large differences in waveforms for stations at varying azimuths. I compared acceleration spectra of the strike-slip portion of the M7.9 Denali Fault earthquake with those of the adjacent M6.7 Nenana Mountain earthquake recorded at the same sites. The high-frequency spectral amplitude ($>$ 0.5 Hz) of the M7.9 earthquake is somewhat less than expected from a scaling relation where the energy radiated at any given frequency is proportional to the fault area, which is the high-frequency scaling relation typically observed for smaller earthquakes.

S11H-04 1105h

Source models for the 2003 Denali Fault Earthquakes from InSAR and GPS.

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The November 3 2002, M7.9 Denali Earthquake is the largest continental strike-slip earthquake to have occurred since the development of InSAR. It was preceded by a M6.7 "preshock" on 23 October – the Nenana Mountain Earthquake. We have used coseismic range changes from InSAR, and displacements from GPS where available, to find source models for the earthquakes, and to investigate the relationship between the two events. To determine the coseismic surface deformation and a source model for the Nenana Mountain Earthquake, we used 6 interferograms, constructed using radar images from the Canadian Radarsat-1 and European ERS-2 satellites. Modeling the event as dislocations in an elastic half space suggests that there was nearly 0.9 m of right-lateral strike-slip motion at depth, on a near-vertical fault, but that the maximum slip in the top 4 km of crust was less than 0.2 m. We currently have just 3 coherent Radarsat-1 interferograms that contain the coseismic deformation of the 3 November 2002, Denali Earthquake and covered the western part of the rupture. However, the spatial coverage is poor for the eastern half of the rupture, where we only have one interferogram with relatively poor coherence. The Denali Earthquake began at the western end of the rupture with thrusting on the previously unidentified Susitna Glacier Fault (SGF). The combination of ascending and descending interferograms in this area enables the fault geometry at depth to be determined reliably: inversions for fault geometry suggest that the fault had an average strike of 251° and dipped 40° to the north. We also carried out a joint inversion of the InSAR data with 40 GPS displacements, provided by the University of Alaska and UC Berkeley. Initial results suggest that the maximum slip was $\sim$12 m, around 60–70 km east of the Trans-Alaska pipeline crossing. Using our model for the Nenana Mountain Earthquake, and our geometry of the Susitna Glacier Fault, we found that the Nenana Mountain Earthquake increased the Coulomb stress at the future hypocenter of the Denali Earthquake by 30–60 kPa, encouraging the subsequent failure.

S11H-05 1120h INVITED

Kinematic and Dynamic Rupture Models of the November 3, 2002 Mw7.9 Denali, Alaska, Earthquake

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Regional seismic waveforms, continuous and campaign-mode GPS data, and surface slip measurements were used to obtain a kinematic model of the rupture process of the November 3, 2002 Mw7.9 Denali, Alaska, earthquake. The event initiated as a Mw7.0 reverse slip event on the north-dipping Susitna Glacier fault with subsequent right-lateral slip distributed over approximately 300 km of the Denali fault system. Near-shear rupture velocity was inferred from direct measurement of S-wave arrival time and the kinematic modeling. The average and maximum slips were found to be 2.14 m and 9.94 m. Static stress drop varies from 1 to 5.2 MPa over the 5-segment fault model. Dynamic modeling shows the rupture propagated along the Susitna Glacier and Denali faults then transferred to the Totschunda fault, before stopping. The transfer from the Denali to the Totschunda faults is due to the Totschunda's more favorable orientation with respect to the regional stress field.

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S11H-06 1135h

Slip Transfer from the Denali to Totschunda Faults During the 3 November 2002 M_w 7.9 Denali, Alaska, Earthquake

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We analyze dynamic slip transfer from the Denali to the Totschunda faults. This adopts methodology from earlier studies (Poliakov et al., 2002; Kame et al., 2003) in which it was shown that the propensity of the rupture path to follow a fault branch is determined by the preexisting stress state, branch angle and incoming rupture velocity at the branch location. Even though the studies rely on 2D numerical simulations, we think that they describe correctly the first order of phenomena associated with dynamic branching along geological fault systems. Here we check that theory on the Denali-Totschunda rupture process. This is a more complete analysis than Bhat et al. (2002). The M_w 7.9 Denali earthquake, which was mainly a right lateral strike-slip event, occurred on 3 November 2002 and ruptured for about 340 km, with the last 76 km being on the Totschunda Fault which branches off from the Denali Fault at an angle of about 15° to the extensional side. The rupture path chose Totschunda, exclusively, beyond the Denali-Totschunda branching point. We have no evidence on prestress directions very near the branch, but Ratchkovski and Hansen (2002, 2003) have recently evaluated stress directions for interior Alaska including near the Denali fault. The principal stress closest to the branch is almost fault-normal with the local direction of the Denali fault (Ratchkovski, 2003). Earlier works on the stress field in central Alaska suggest that the prestress inclination with Denali was around 70° in the area of branching. Thus we use the values of 70° and 80° in our numerical simulations. The average rupture velocity seems to be about 0.8 c_s (Kikuchi and Yamanaka, 2002), although the velocity as the branch was approached is not yet constrained. As it is not yet clear what was the rupture velocity at the branching point, other than that it was rather high (Eberhart-Phillips et. al., 2003), we use 0.6 c_s, 0.8 c_s, 0.9 c_s and even 1.4 c_s as parameters in our simulations. We numerically simulated slip transfer from Denali to Totschunda by the methodology of Kame et al. (2003) which uses a 2D elastodynamic boundary integral equation model of mode II rupture with self-chosen path along a branched fault system. The strength of the faults is assumed to follow a Coulomb law with friction coefficient which slip-weakens from its static to dynamic value. All our simulations for sub-Rayleigh rupture velocities, except one, predict that the rupture path branches off along Totschunda without continuation along Denali. For the case when the prestress inclination is 70° and incoming rupture speed at branching is 0.9 c_s, there is also a continuation of rupture along Denali beyond the branching point, at a speed slower than that along Totschunda. However when the prestress inclination is steeper, at 80°, the rupture chooses Totschunda exclusively when its velocity near the branching point is around 0.9 c_s. We also see exclusive continuation of rupture on Totschunda when the rupture is super-shear, 1.4 c_s.

S11H-07 1150h

Coseismic Slip Distribution of the Denali Fault Earthquake as Estimated From GPS Measurements.

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On 3 November 2002 an Mw 7.9 earthquake occurred in central Alaska, rupturing portions of the Susitna Glacier, Denali and Totschunda faults. 38 existing GPS points in the interior and south central Alaska were measured within two weeks of the earthquake. In addition 12 permanent GPS sites were operating within 500 km of the epicenter at the time of the earthquake. Inversion of the displacement field indicates that the event was dominated by a complex, right-lateral strike-slip rupture along the Denali fault, with relatively low slip on the western part of the rupture and high slip from about 60 km east of the hypocenter extending to the junction of the Denali and Totschunda faults. In the summer of 2003 many additional sites were surveyed to better estimate the coseismic slip distribution of the earthquake. We will present the new and improved coseismic displacement field and resulting slip distribution. We also investigate the impact of half space versus layered space models on the slip distribution.

S11H-08 1205h

Could a Complex Earthquake like the 2002 Denali Fault Event hit the Los Angeles area?

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The Denali Fault earthquake sequence began with the 23 October 2002 Mw6.7 Nenana Mountain foreshock, followed on 3 November 2002 by the Mw7.9 Denali Fault mainshock. The mainshock demonstrated that rupture of secondary thrust faults can trigger nearby strike-slip faults, highlighting the possibility that such dangerous earthquakes could occur in more densely populated regions with similar tectonics. For example, previous workers [Eberhart-Phillips *et al., Science,* 2003] have suggested that an earthquake similar to the Denali Fault mainshock could occur in the Los Angeles metropolitan region, home to more than 13 million people. We have tested this proposal by modeling static and dynamic stress interactions between the Sierra Madre-Cucamonga thrust and San Andreas/San Jacinto strike-slip fault systems near Los Angeles. We find that the comparison with the Denali Fault mainshock breaks down due to differences in background stress and fault geometry. In particular, rupture of the Sierra Madre-Cucamonga system is unlikely to trigger rupture of either the San Andreas or San Jacinto fault, as the Susitna Glacier fault triggered the Denali fault during the 2002 event. However, our modeling suggests that under rare circumstances, a large earthquake on the northern San Jacinto fault could trigger a cascading rupture of the Sierra Madre-Cucamonga system, potentially growing into a dangerous Mw7.5–7.8 earthquake on the edge of the heavily populated Los Angeles metropolitan region.

S12A MCC: Level 1 Monday 1330h

The 2002 Denali Fault Earthquake: Observations and Implications III Posters *(joint with G)*

Presiding: **P J Haeussler,** U.S. Geological Survey**; R Hansen,** University of Alaska, Fairbanks**; D Christensen,** University of Alaska, Fairbanks

S12A-0363 1330h POSTER

The 2002 Denali Fault, Alaska Earthquake Sequence Recorded on the Regional Network: Earthquake Locations, Magnitudes, and Focal Mechanisms

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The largest inland earthquake in North America in almost 150 years struck Alaska on November 3, 2002. It ruptured three different faults ending with a total rupture length of 330 km and maximum vertical and horizontal offsets of 4 m and 8.8 m, respectively. The M 7.9 Denali Fault event was preceded by M 6.7 Nenana Mountain event on October 23, 2002. In response to the magnitude 6.7 and 7.9 events, the Alaska Earthquake Information Center installed a network of temporary instruments for the aftershock monitoring. More than 16,000 aftershocks of both the magnitude 6.7 and 7.9 events have been recorded and located as of the end of December, 2002. The magnitude of completeness of the aftershock catalog varies along the rupture zone. While for the whole catalog the magnitude of completeness is 1.4, it is as low as 1.1 at the western end of the rupture and as high as 2.2 at the eastern end. Estimated b-value for the October-November sequence is 0.7. The aftershocks of the M 6.7 Nenana Mountain event extend 45 km along the Denali Fault pedominately to the west of the epicenter. The 7.9 event had a magnitude 4.4 foreshock which occurred 3.5 hours prior to the mainshock and had right-lateral strike-slip faulting mechanism. The largest aftershock (magnitude 5.8) occurred 20 min after the mainshock, 95 km to the east of the epicenter. Aftershocks of the M 7.9 event present a complex pattern along the rupture zone. In some places, they outline the vertically dipping faults along the main trace of the rupture. However, the cluster centered on the mainshock epicenter occupies a broad region. On its south side, it is outlined closely by the ground rupture along the Susitna Glacier fault, while on the other end it extends over onto the northern side of the Denali fault. In the area east of the Richardson Highway the aftershocks outline dipping structures on both sides of the Denali fault. At the eastern end of the rupture, the aftershocks form a diffuse band extending from the Totcshunda strand towards the main trace of the Denali fault. The majority of the aftershocks are located in the uppper 10 km of the crust. The P-wave first motion focal mechanisms indicate predominantly right-lateral strike-slip and reverse motions. This catalog of focal mechanisms has been used to calculate principal stress directions along the Denali fault trace.

S12A-0364 1330h POSTER

Aftershock Recordings of Nenana Mt. and Denali Fault Earthquakes of 2002

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Recent large earthquakes (M6.7, M7.9) in central Alaska ruptured the Denali Fault in late 2002. This rare opportunity to study this complex fault system required a substantial effort to obtain quality seismic data through the installation of a temporary seismic network. Less than one month after the M7.9 earthquake on November 3, 2002 twenty-six temporary sites were installed within 100 km of the Denali Fault. Of these 26 stations, 12 were Guralp 5-TD strong motion accelerometers recording triggered signals based on site-specific STA/LTA parameters to flash memory. The remaining 14 sites contained broadband seismometers (Guralp 40T or Guralp 3T) recording continuously to Reftek 72A-08 digital acquisition systems with 16- or 24-bit digitization and stored on Reftek 72A-05 hard drives. Stations were visited about every three weeks and remained in operation until the end of June 2003. The success of data recovery was inhibited by faulty power systems and inoperative equipment in harsh, remote Alaskan conditions. Installation and maintenance of this temporary network was performed by Alaska Earthquake Information Center (AEIC) personnel, with equipment provided by AEIC, PASSCAL, and the USGS. Data collected from the Denali Fault temporary network proved indispensable for the location of over 16,000 aftershocks between October 23 and the end of November 2002. Subsequently, we expanded the permanent broadband array along the Denali Fault westward of the 2002 rupture zone. In addition, one of the temporary sites (HARP) has become permanent. Data from this expanded network is recorded in real-time.

URL: http://www.aeic.alaska.edu

S12A-0365 1330h POSTER

The 3 November 2002 M7.9 Denali Fault, Alaska Earthquake: Double Difference Relocation of Aftershocks.

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The M7.9 Denali Fault earthquake occurred at approximately 1:12 PM AST on 3 November 2002, rupturing nearly 300 km of the Denali fault, a major right lateral strike-slip feature in central Alaska. This event