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 is the largest earthquake recorded on the Denali fault system. The Denali Fault earthquake was preceded by the 23 October 2002 M6.7 Nenana Mountain earthquake that ruptured a segment of the Denali fault about 20 km to the west of the M7.9 epicenter. Following the Nenana Mountain event, the Alaska Earthquake Information Center (AEIC) began the deployment of a temporary network of broadband and strong motion seismometers to supplement the 350 existing stations of the Alaska Seismic Network in recording aftershocks. This network was distributed along the Alaska, Glenn, Richardson and Denali highways and several instruments along the Nebesna Road. Six of these instruments were installed prior to the M7.9 event and 20 more in the week following. In the first month following the Denali Fault earthquake over 8 000 aftershocks were recorded. Here we present the double difference relocation results for aftershocks of the Nenana Mountain and Denali Fault events. The distribution of aftershocks indicated complex faulting along the rupture zone. Near the M7.9 epicenter, the aftershock distribution is bounded to the south by the Susitna Glacier fault but is not constrained by the Denali fault to the north. Many of the aftershocks north of the M7.9 epicenter have thrust mechanisms which may indicate that a series of small thrusts was activated by the earthquake north of the Denali fault. Additionally, heightened seismicity is observed on many smaller faults adjoining the Denali fault following the M7.9 event. From these observations, it is evident that the Denali Fault earthquake activated a significant portion of the Denali fault system in Central Alaska.

S12A-0366 1330h POSTER

Broadband Modeling of the 2002 Denali, Alaska, Earthquake on the Earth Simulator

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We use a Spectral-Element Method implemented on the Earth Simulator in Japan, to simulate broadband seismic waves generated by the November 3, 2002, Denali, Alaska, earthquake. The source model is constrained by teleseismic body waves and observed surface offsets. The earthquake was initiated by a small thrust event, and is well characterized by a 5-segment fault geometry dominated by right-lateral rupture along 220 km of the Denali fault. To use the finite fault model in our numerical simulations we approximate it by a set of 475 sub-events of size 4 km X 5 km; these sub-events represent the distribution of the moment-density tensor. We perform the three-dimensional numerical simulations, which incorporate 3D variations in compressional wave speed, shear-wave speed and density, attenuation, anisotropy, ellipticity, topography and bathymetry, and crustal thickness. We use model S20RTS of the mantle (Ritsema et al., 1999), model CRUST2.0 of the crust (Basin et al., 2000), and topography and bathymetry model ETOPO5. The simulations are performed on 1944 processors, which require 243 out of 640 nodes of the Earth Simulator. We use a mesh with 82 million spectral-elements, for a total of 5467 million global integration grid points (i.e., almost 15 billion degrees of freedom). This translates into an approximate grid spacing of 2.9 km along the Earth's surface. On this number of nodes, a simulation of 60 minutes of wave propagation accurate at periods of 5 seconds and longer requires about 15 hours of CPU time. The results of the simulation reveal significantly enhanced ground motions toward the conterminous United States for both body and surface waves. For reference, the same data are compared against SEM synthetics for 1D model PREM. The results show that the transverse component of SEM synthetics fit significantly better by the 3D model.

S12A-0367 1330h POSTER

Ground Motion Characteristics and Source Process of the 2002 Denali Earthquake Inferred from the Strong Motion Records

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The 2002 Denali earthquake, which occurred at the Denali Fault System in Alaska on 3 November, 2003, was one of the largest inland earthquakes all over the world. The Denali Fault System extends for more than 2000 km across south-central Alaska, Yukon Territory, northern British Columbia and southeastern Alaska (Lanphere, 1978). In this time the rupture started on the Susitna Glacier Fault with thrust motion, propagated eastward along the Denali Fault with right-lateral movement, and terminated on the Totschunda Fault (Fuis and Wald, 2003). From the particle motion at a strong motion site PS10 (pump station #10 of Trans Alaska Pipeline), which is located at about 3 km distance from the fault, we could recognize a significant phase with fault-parallel movement before fault-normal motions. This motion shows the fault displacement in front of PS10. We have also checked the orientation of seismometer at PS10 with visiting the place in this summer. Therefore, the sense of ground motion at PS10 is reliable. Comparing the observed and calculated travel time of this phase, the average rupture propagation velocity between the rupture starting point and a sub-fault in front of PS10 was estimated to be 2700 m/s. However, it does not deny the possibility of supershear rupture on a certain portion of source area, so that we need to examine carefully the rupture velocity during the rupture. Whole source process was investigated with the multi-time window kinematic waveform inversion (Hartzell and Heaton, 1983; Sekiguchi et al., 2000). A 1-D laterally homogeneous underground structure model was assumed based on the result of refraction and wide-angle reflection survey by Beaudoin et al. (1992). Green's functions were calculated using the discrete wavenumber method (Bouchon, 1981) together with the reflection transmission matrix method (Kennett and Kerry, 1979). Spatio-time smoothing and slip constraints as pure-dip to right-lateral slip for Susitna Glacier fault, right-lateral $\pm 45^\circ$ slip for other faults, were included (Sekiguchi et al., 2000). The appropriate strength of smoothing constraint was evaluated using Akaike's Bayesian Information Criterion (Akaike, 1980). Three components of velocity waveforms obtained at 10 strong motion stations including PS10 were inverted. We tried to include the detailed information of the surface displacement distributions compiled by Eberhart-Phillips et al. (2003) as constraint information in our analysis to make up the insufficiency of strong motion data. We could reproduce observed ground motion in low-frequency range (0.1-0.5 Hz for Alyeska stations, 0.05-0.5 Hz for others) based on the source model obtained by the inversion analysis. The inversion result showed that the ground motion at PS10 was mainly controlled by the nearest asperity. Large slips on the fault from the inversion result were observed at about 90 km east and about 170 km east from the epicenter. We are grateful to United States Geological Survey, University of Alaska, and Alyeska Pipeline Service Company for releasing digital strong motion records and to Alaska Earthquake Information Center for which we retrieved hypocentral information.

S12A-0368 1330h POSTER

Calibration of Alyeska Seismographs for the Denali Fault Earthquake of 3 November 2002

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Several of the most important records yet obtained of a large continental strike slip earthquake were produced by some of the 11 strong-motion seismographs operated by the Alyeska Pipeline Service Company, six of which recorded the event along the 800-mile Trans-Alaska Pipeline System corridor. These 200 sample/s instruments were designed for detecting strong shaking and generating alarms for the Pipeline Control System, evaluating the potential for damage to the pipeline and supporting facilities, and guiding shutdown, inspection, and other emergency responses in the event of strong shaking. While these instruments, particularly the one at Pump Station 10 (PS10), less than 3 km from the Denali fault, were very well placed to record the **Mw**7.9 event of 03 November 2002 and its rare examples of high-velocity, low-acceleration records from likely supershear rupture in a large event, they were not intended for seismological and engineering use at very low frequencies and require retrospective calibration for optimal application at these periods. In particular, they require calibration for the accurate recovery of permanent displacements and computing the responses of structures affected by long-period motions. Calibration of the 0.1- to 40-Hz 4-pole Butterworth bandpass filters and Honeywell Sundstrand Q-Flex™ QA1100™ and QA1200™ accelerometers from a nearly identical spare Alyeska instrument demonstrated that the low-cut corner frequency differed by 10 to 16% from the nominal value which can cause as much as 20% variation in the recovery of displacement signals from acceleration records. Therefore, we are retrieving the PS10 instrument and both of the neighboring Alyeska instruments in September, 2003, and calibrating their filters, amplifiers, and accelerometers in an effort to recover the most accurate ground motions to about 0.05 Hz, and possibly below. We will verify instrument orientations in the field, test instrument and site noise levels and baseline stability, test their ability to recover known displacements and displacement waveforms, measure their sensitivities, measure their static and dynamic linearity, measure filter corner frequencies and the filters' (fairly significant) sensitivities to temperature, and measure the vault and recording-room temperature responses during the Autumn of 2003 as a surrogate for the Autumn for 2002.

S12A-0369 1330h POSTER

Modeling teleseismic P and SH static offsets for Great strike-slip earthquakes

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Most body-wave modeling of earthquakes involves P and SH waves observed between 30° to 90°. Traditionally, only the "far field" contributions, whose waveforms are related to the moment-rate function ($\dot{M}(t)$), are considered. The "near field" contribution, whose waveform is determined by the moment release function ($M(t)$), has generally been neglected. According to the "far field" approach, the displacements should ultimately become zero. However, in broadband records of recent large strike-slip events, such as the 2001 Kunlun and 2002 Denali earthquakes, displacement offsets of up to two thirds of the peaks of the P and SH phases are maintained until they are disturbed by the later arriving PP or SS phases. Hence, "near field" contributions must be included when we study the source processes of such events. We investigate complete synthetic seismograms generated by three basic double-couple fault types: 90° strike-slip, 90° dip-slip, and 45° dip-slip using several numerical solutions. We find that for a shallow earthquake, a 90° strike-slip fault can excite large P and SH near field terms, while the other two fault types generate negligible amplitudes. Our theoretical analysis indicates that this observation is entirely controlled by the source excitation characteristics. More importantly, the amplitude ratio of the "far field" to the "near field" is roughly proportional to the reciprocal of the shear velocity at the hypocenter. Hence considering "near-field" contributions provides unique constraints not only on the entire strike-slip component of fault-slip, but also on the down-dip extension of the rupture. While the "near field" terms are important, it is computationally difficult to generate high-frequency Green's functions at teleseismic distances using normal-mode or spectral-element (SEM) methods. The reflectivity method also fails to produce the near field term of the P waves due to the inaccurate earth-flatten approximation. Therefore, we develop a ray-based algorithm using "near-field" source excitation coefficients and correcting for the geometrical spreading in the spherical earth with normal-mode synthetics. Broadband synthetics generated based upon this new method compare favorably with SEM simulation. The new approach is used to study the source process of the 2002 Denali earthquake along with local strong motion and GPS observations.

S12A-0370 1330h POSTER

Ionospheric Remote Sensing of the Denali Earthquake Rayleigh Surface Waves

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Using the Global Positioning System, we detected ionospheric disturbances associated to the long-period Rayleigh waves of the 2002 Denali earthquake (Ms = 7.9). This is the ionospheric signature of the acoustic wave produced by the surface seismic vertical displacement. The dense California GPS networks allowed us to characterize the propagation properties of the wave and to determine a group velocity map with a high spatial resolution above the Western Unite States and Pacific coasts. This work demonstrates that bistatic remote sensing measurements of seismic waves with space/ground GPS Networks can be performed. Possibly, monostatic measurements with a dedicated satellite can be envisaged for the recording in the ionosphere of surface waves for large earthquakes. Such a space remote sensing of the local group velocity of Rayleigh surface waves might complement the seismic Networks effectively for high resolution global tomography of the earth's lithosphere.

S12A-0371 1330h POSTER

Crustal Deformation Associated With the 2002 Denali Fault Earthquake Sequence Observed by SAR Interferometry

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On October 23, 2002, the Mw 6.7 Nenana Mountain earthquake ruptured a 45-kilometer-long segment of the Denali fault. Eleven days later, November 3, interior Alaska experienced its largest earthquake in recorded history. The Mw 7.9 Denali fault earthquake began 10 kilometers east of the end of the Mw 6.7 rupture and propagated eastward along the Susitna Glacier , Denali, and Totschunda faults. Along the trace of the Nenana Mountain earthquake, aerial surveys found no evidence of surface slip. In contrast, the Denali fault event resulted in a 340-kilometer-long surface rupture and horizontal offsets that reached a maximum of nearly nine meters about 190 kilometers east of the epicenter. Synthetic aperture radar (SAR) interferometry provides an important tool for the study of crustal displacements and fault dynamics. Here we present interferograms for the Nenana Mountain and Denali fault earthquakes constructed from RADARSAT-1 satellite images acquired along the trace of the ruptures. In general, the interferograms show small, discontinuous patches of coherent fringes. Areas within 25 kilometers of the Mw 7.9 earthquake epicenter display no coherence. In the interferograms spanning the Mw 6.7 earthquake, coherent fringes are limited to regions more than 1.5 kilometers away from the fault. Right-lateral motion dominates the deformation signal in all of the interferograms. We compare the displacements revealed by the fringes with those measured at GPS sites located along several transects of the rupture zone. These comparisons allow us to refine slip models for the earthquakes derived from GPS and seismic data.

S12A-0372 1330h POSTER

Postseismic Transient After the 2002 Denali Fault Earthquake From VLBI Measurements at Fairbanks

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The VLBI antenna at Fairbanks observes in networks routinely twice a week and on additional days with other networks on a more uneven basis. The Fairbanks antenna position is about 150 km north of the Denali fault and from the earthquake epicenter. Time series of the VLBI horizontal position at Fairbanks show that over the first 6 months after the earthquake, the rate of change of position primarily in the northerly direction was about 30-40 mm/yr less than the long-term rate prior to the earthquake. We examine the transient behavior during the year following the earthquake to determine how the rate of change of postseismic deformation has decreased. We compare the VLBI time series with the GPS time series, which also shows a similar transient after the earthquake. We also compare the rate of transient decay from Fairbanks with decay from other examples of transient behavior following earthquakes that have been monitored by continuous GPS measurements.

S12A-0373 1330h POSTER

Intensity Distribution and Isoseismal Maps for the Denali, Alaska, Earthquake of 2002 November 3

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Macroseismic data for the 2002 Nov 3 Denali, Alaska, earthquake were obtained from three sources: (1) the Did You Feel It? Internet intensity questionnaire, which yielded automatically computed Community Internet Intensities (CII) from over 3400 respondents in 182 zip codes; (2) a postal canvass yielding traditional Modified Mercalli intensities (MMI) assigned by an analyst to returned canvass cards for 86 zip codes; (3) additional data from the Geological Survey of Canada, the West Coast and Alaska Tsunami Warning Center, press and engineering reports. The purposes of this study were to present a carefully evaluated distribution of intensities for the Denali earthquake and to compare intensities derived by methods (1) and (2) above in order to calibrate the new Internet method against the results of the older postal canvass method. Thus each of the two data sets ((1) plus (3); (2) plus (3)) was evaluated independently of the other and the results compared before a final isoseismal map, based on all three, was created. To facilitate investigating these types of intensity-related phenomena, we have developed a relational database for displaying all the data for each zip code, searching for anomalous responses, locating sites, finding and marking all reports of specific effects such as seiching, reading and searching observers' comments, assigning MMIs and comparing CII, RCII (reviewed CII), MMI, etc. With the aid of this database, RCII were found for each community by including consideration of observers' written comments plus data from sources listed in (3). One problem so far unique to the Denali earthquake arose from observers on seiche-rocked boats who often responded as if experiencing the earthquake on land, resulting in high CIIs requiring revision. Other problems resulted from Alaska's low population density: huge zip code areas that had to be subdivided and too few towns to clearly define the near-fault intensities and the periphery of the felt area. Although both CII and MMI intensities are based on intensity questionnaires, the CII and MMI data are derived quite differently. A traditional MMI is often assigned to a single observation from a community based on a detailed questionnaire. The CII for a zip code is automatically calculated based on a statistical formula using data from multiple observers in that zip code responding via a short Internet questionnaire. This new CII method has many obvious advantages including having an initial map quickly available for disaster responders, obtaining far more data than was previously possible, obtaining better intensities from places with multiple respondents than from a single observer, and automating some tedious tasks. The three resulting Denali isoseismal maps are in very good agreement within the damage-level intensities (MMI 6 and above). The outer isoseismals, mostly extending across regions of low population, varied depending on locations of available information; most notably, an outlying low-intensity felt area in Washington State appears on the final and RCII-only maps but not on the MMI-only map because it lies beyond the limits of the postal canvass. This study demonstrates the need for analyst review of the CII for important earthquakes and the advantage of the new CII method over the old postal canvass in acquiring data from sparsely inhabited places and in locating unanticipated felt regions.

S12A-0374 1330h POSTER

Changes in hydrothermal activity and remotely triggered seismicity in Yellowstone National Park following the M7.9 Denali fault earthquake, Alaska

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The 2002 M7.9 Denali fault earthquake (DFE), Alaska, had a profound impact on the Yellowstone volcanic system despite the large distance of 3100 km. In this paper, we will report on changes in hydrothermal activity and triggered seismicity in Yellowstone following the DFE. We will also discuss possible mechanisms causing the observed changes and elaborate on a possible relationship between changes in hydrothermal activity and triggered seismicity. Following the DFE pronounced changes in the eruption behavior of several geysers in Yellowstone National Park were observed. For example, eruption intervals of Daisy Geyser located at Upper Geyser Basin dropped from 2.5 h prior to the Denali fault earthquake to 1.5 h after the Denali fault earthquake. In addition and coincident with the arrival of the large amplitude surface waves, intense earthquake swarms were remotely triggered throughout Yellowstone's major geyser basins. These observations can, in general, be explained by the interaction of large dynamic strains accompanying the DFE surface waves with hydrothermal fluids. Geyser eruption intervals are sensitive to conduit permeability and depth extent of the conduit suggesting that alteration of these two parameters caused the observed changes. A possible mechanism to increase the permeability of the geyser's conduit would be the removal of mineral seals due to dynamic stress changes associated with large amplitude surface waves. Opening of existing or new fractures at depth by intense earthquake swarm activity could increase conduit length, thus changing geyser eruption intervals. A number of mechanisms involving the interaction of hydrothermal fluids with large amplitude surface waves may have caused remote triggering of intense earthquake swarms close to Yellowstone's major geyser basins. These include rupturing of isolated compartments in which super-hydrostatic fluid pressure prevailed, the release of gas bubbles within hydrothermal fluids producing advective gas overpressure, and oscillation of gas bubbles within a saturated hydrothermal fluid increasing local pore pressure through rectified diffusion. The coincident occurrence of changes in hydrothermal activity and remotely triggered seismicity may suggest a causal relationship between the two. Unfortunately, the existing data is limited and we are not able to resolve whether there is a causal relationship between the two or changes in hydrothermal activity and triggered seismicity are just unrelated responses of a hydrothermal system to large amplitude surface waves.

S12A-0375 1330h POSTER

Intermediate-Term Declines in Seismicity at Mt. Wrangell and Mt. Veniaminof Volcanoes, Alaska, Following the November 3, 2002 Mw 7.9 Denali Fault Earthquake

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On November 3, 2002 a Mw 7.9 earthquake ruptured segments of the Denali Fault and adjacent faults in interior Alaska providing a unique opportunity to look for intermediate-term (days to weeks) responses of Alaskan volcanoes to shaking from a large regional earthquake. The Alaska Volcano Observatory (AVO) monitors 24 volcanoes with seismograph networks. We examined one station per volcano, generally the closest to the vent (typically within 5 km) unless noise, or other factors made the data unusable. Data were digitally filtered between 0.8 and 5 Hz to enhance the signal-to-noise ratio. Data for the period four weeks before to four weeks after the Mw 7.9 earthquake were then plotted at a standard scale used for AVO routine monitoring. Mt. Veniaminof volcano, which has had recent mild eruptions and a rate of ten earthquakes per day on station VNNF, suffered a drop in seismicity by a factor of two after the earthquake; this lasted

for 15 days. Wrangell, the closest volcano to the epicenter, had a background rate of about 16 earthquakes per day. Data from station WANC could not be measured for 3 days after the Mw 7.9 earthquake because the large number and size of aftershocks impeded identification of local earthquakes. For the following 30 days, however, its seismicity rate dropped by a factor of two. Seismicity then remained low for an additional 4 months at Wrangell, whereas that at Veniaminof returned to normal within weeks. The seismicity at both Mt. Veniaminof and Mt. Wrangell is dominated by low-frequency volcanic events. The detection thresholds for both seismograph networks are low and stations VNNF and WANC operated normally during the time of our study, thus we infer that the changes in seismicity may be related to the earthquake. It is known that Wrangell increased its heat output after the Mw 9.2 Alaska earthquake of 1964 and again after the Ms 7.1 St.Elias earthquake of 1979. The other volcanoes showed no changes in seismicity that can be attributable to the Mw 7.9 earthquake. We conclude that intermediate-term seismicity drops occurred at Mt. Wrangell and Mt. Veniaminof volcanoes, in strong contrast to cases of short-term seismicity increases observed at volcanic systems such as Katmai, Mount Rainier, Yellowstone, Mammoth Mountain, and the Geysers, Coso and Cerro Prieto (Mexico) geothermal fields. This suggests that fundamentally different mechanisms may be acting to modify seismicity at volcanoes.

S12A-0376 1330h POSTER

Spatial Based Integrated Assessment of Bedrock and Ground Motions, Fault Offsets, and Their Effects for the October-November 2002 Earthquake Sequence on the Denali Fault, Alaska

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A National Science Foundation (NSF) Small Grant Exploratory Research Grant was awarded to the University of Alaska Fairbanks to archive bedrock and ground motions and fault offsets and their effects for the October-November 2002 earthquake sequence on the Denali Fault, Alaska. The scope of work included the accumulation of all strong motion records, satellite imagery, satellite remote sensing data, aerial and ground photographs, and structural response (both measured and anecdotal) that would be useful to achieve the objective. Several interesting data sets were archived including ice cover, lateral movement of stream channels, landslides, avalanches, glacial fracturing, "felt" ground motions, and changes in water quantity and quality. The data sources may be spatially integrated to provide a comprehensive assessment of the bedrock and ground motions and fault offsets for the October-November 2002 earthquake sequence. In the aftermath of the October-November 2002 earthquake sequence on the Denali fault, the Alaskan engineering community expressed a strong interest to understand why their structures and infrastructure were not substantially damaged by the ground motions they experienced during the October-November 2002 Earthquake Sequence on the Denali Fault. The research work proposed under this NSF Grant is a necessary prerequisite to this understanding. Furthermore, the proposed work will facilitate a comparison of Denali events with the Loma Prieta and recent Kocelli and Dozce events in Turkey, all of which were associated with strike-slip faulting. Finally, the spatially integrated data will provide the basis for research work that is truly innovative. For example, is may be possible to predict the observed (1) landsliding and avalanches, (2) changes in water quantity and quality, (3) glacial fracturing, and (4) the widespread liquefaction and lateral spreading, which occurred along the Tok cutoff and Northway airport, with the bedrock and ground motions and fault offsets extrapolated from the product of the research. An integrated assessment of the composite effects may be performed to better understand the bedrock and ground motions and fault offset regime that existed during the earthquake sequence.

S12A-0377 1330h POSTER

Earthquake Induced Water Waves in Washington State

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The Mw 7.9 Denali earthquake of 3 November 2002 caused minor damage to at least 20 houseboats by initiating water waves in Lake Union, Seattle, Washington. Damage caused by unusual water activity is not uncommon in Washington State. Newspaper reports show that damage also has been caused by water waves in the Seattle area during local or distant earthquakes in 1899 (Yakutat Bay Alaska earthquake), 1949 (Olympia earthquake) and 1965 (Seattle-Tacoma earthquake). Analysis of Pacific Northwest Seismic Network (PNSN) recordings of the Denali earthquake demonstrates that large water waves are due in part to local amplification of seismic waves by the underlying Seattle sedimentary basin. Simple formulae predict water wave amplitudes only half or smaller than those reported for swimming pools and lakes. Resonance initiated by multiple cycles of surface waves, focusing, and near-shore effects could further amplify the water waves. To understand the type and origins of these water waves, we are examining the response of a water body of rectangular shape and rectangular cross-section subjected to hypothetical forcing functions, and to forcing functions derived from seismograph records of major earthquakes. The results provide estimates of the potential wave heights during future large earthquakes on the nearby subduction zone or on local faults.

S12A-0378 1330h POSTER

Geophysical Investigation of the Denali Fault and Alaska Range Orogen Within the Aftershock Zone of the October-November, 2002, M=7.9 Denali Earthquake

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The aftershock zone of the November 3, 2002, M-7.9 earthquake that ruptured along the right-slip Denali Fault in south-central Alaska has been investigated using gravity, magnetic, magnetotelluric, and deep-crustal, seismic-reflection data as well as outcrop geology and earthquake seismology. Strong seismic reflections from within the Alaska Range orogen north of the Denali Fault dip as steeply as 25° north and extend to depths as great as 20 km. The most intriguing finding from geophysical data is that earthquake aftershocks occurred above a low-resistivity (less than about 10 ohm-m) rock body that lies mainly at depths greater than about 10 km. The low electrical resistivity might result from electrical conduction along carbon films in the Mesozoic flysch deposits that are truncated along the strike-slip Denali Fault. However, we prefer the interpretation that the low resistivity results from deep fluids, as suggested by the occurrence of the Denali bright spot, a strong and flat seismic reflection from midcrustal depths. Deep fluids may have weakened the middle and lower crust and helped localize seismicity. The Denali Fault developed during the Cenozoic along a Cretaceous suture zone that separates mainly Paleozoic continental rocks to the north from Mesozoic oceanic rocks to the south. Seismically reflective features within the Alaska Range orogen reveal relict, Cretaceous faults or shear zones that are essentially aseismic under today's stress regime. Faults that ruptured during the Denali earthquake are non-reflective, most likely because they dip steeply.

S12A-0379 1330h POSTER

Field-based Digital Mapping of the November 3, 2002 Susitna Glacier Fault Rupture - Integrating remotely sensed data, GIS, and photo-linking technologies

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In July 2003, the U.S. Geological Survey and the Alaska Division of Geological & Geophysical Surveys (DGGS) conducted field studies on the Susitna Glacier Fault (SGF), which ruptured on November 2002 during the M 7.9 Denali fault earthquake. The DGGS assumed responsibility for Geographic Information System (GIS) and data management, integrating remotely sensed imagery, GPS data, GIS, and photo-linking software to aid in planning and documentation of fieldwork. Pre-field preparation included acquisition of over 150, 1:6,000-scale true-color aerial photographs taken shortly after the SGF rupture, 1:63,360-scale color-infrared (CIR) 1980 aerial photographs, and digital geographic information including a 15-minute Digital Elevation Model (DEM), 1:63,360-scale Digital Raster Graphics (DRG), and LandSat 7 satellite imagery. Using Orthomapper software, we orthorectified and mosaiced seven CIRs, creating a georeferenced, digital photo base of the study area. We used this base to reference the 1:6,000-scale aerial photography, to view locations of field sites downloaded from GPS, and to locate linked digital photographs that were taken in the field. Photos were linked using GPS-Photo Link software which "links" digital photographs to GPS data by correlating time stamps from the GPS track log or waypoint file to those of the digital photos, using the correlated point data to create a photo location ESRI shape file. When this file is opened in ArcMap or ArcView with the GPS-Photo Link utility enabled, a thumbnail image of the linked photo appears when the cursor is over the photo location. Viewing photographed features and scarp-profile locations in GIS allowed us to evaluate data coverage of the rupture daily. Using remotely sensed imagery in the field with GIS gave us the versatility to display data on a variety of bases, including topographic maps, air photos, and satellite imagery, during fieldwork. In the field, we downloaded, processed, and reviewed data as it was collected, taking major steps toward final digital map production. Using the described techniques greatly enhanced our ability to analyze and interpret field data; the resulting digital data structure allows us to efficiently gather, disseminate, and archive critical field data.

S12A-0380 1330h POSTER

Active Structures in the Foothills of the North-Central Alaska Range

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The northern foothills of the Alaska Range are situated at the apex of the northward bend of the Denali Fault in central Alaska. Despite the proximity of the northern foothills to the Denali Fault and historic large-magnitude earthquakes, the tectonic framework of this region has not been well-studied. To assess the active structures of the region, I mapped the sequence of Quaternary fluvial terraces, performed differential GPS transects across a number of these terrace treads, analyzed landforms and drainage basins, and developed cross-sections along the Nenana River, which bisects the foothills belt. The mapping and GPS transects show evidence for displacement of terraces by both folds and faults. Geomorphic analyses indicate deformation and uplift over the entire foothills belt. A distinct pattern of east-trending folds and faults exists in both the bedrock and the younger geomorphic features. This corresponds with a northward decrease in relief to the abrupt mountain front that forms the boundary between the foothills and the Tanana basin to the north. These patterns indicate that the northern foothills is an active fold-and-thrust belt that is prograding northward into the Tanana basin. The basal detachment beneath this fold-and-thrust belt likely begins at the Denali fault in the south, and shallows northwards toward the mountain front. The faults that are recognized at the surface are backthrusts from south-dipping splays of the basal detachment. The activity of these structures implies that this region is a likely seismogenic source area with a significant potential impact on military facilities and important transportation corridors that are nearby.

S

S12A-0381 1330h POSTER

Geotechnical and Surface Wave Investigation of Liquefaction and Strong Motion Instrumentation sites of the Denali Fault, Mw 7.9, Earthquake

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Following the Mw 7.9 earthquake on the Denali and Totschunda faults on 3 November 2002, we conducted two investigations to map the regional extent and severity of liquefaction ground failures and assess the geotechnical properties of these sites, as well as profile the soil properties beneath three seismometers located at Alyeska Pump Stations 9, 10, and 11. The most noteworthy observations are that liquefaction damage was focused towards the eastern end of the rupture area. For example, liquefaction features in the river bars of the Tanana River, north of the fault-break, are sparsely located from Fairbanks to Delta, but are pervasive throughout the eastern area of the break to Northway Junction, the eastern limit of our survey. Likewise, for the four glacier-proximal rivers draining toward the north, little or no liquefaction was observed on the western Delta and Johnson Rivers, whereas the eastern Robertson River and non-glacial Tok River, and especially the Nabesna River, had observable-to-abundant fissures and sand vents. Several rivers systems were studied in detail. The Nabesna River emerges from its glacier, and drains and fines northward as it crosses the fault zone resulting in an asymmetrical liquefaction pattern. South of the fault, falling liquefaction resistance of soil (fining from sandy gravel to gravely sand) and rising loads from ground motions (approaching the fault) abruptly intersect such that there is a well defined, narrow, soil transition from undisturbed-to-fully liquefied approximately 5 kilometers from the fault. North of the fault, both liquefaction resistance (continued fining) and ground motions fall in tandem, leaving a much broader zone of liquefaction. The Delta River liquefaction occurrence is more complex, where side-entering glacial rivers form non-liquefiable gravel fans and alter the composition and compactness of the main-stem deposits. Immediately upstream of the gravelly Canwell glacier tributary, and immediately at the fault crossing, liquefaction features are abundant. To characterize soil properties, we used a portable continuous sine wave-spectral analysis of surface waves (CSS-SASW) apparatus to profile the shear wave velocity of the ground, and an auger to profile the corresponding texture of the river deposits. We occupied 25 liquefaction evaluation test sites along with the three Alyeska seismometer sites. On the Nabesna, Delta and other rivers, we only find liquefaction features in soil deposits where normalized shear wave velocities fall below 225 m/s. Severity of fissures and lateral spreads dramatically increase in soils as the velocities fall, especially below 170 m/s. In some cases, the most pronounced ground failures are far from the fault zone (60-100 km) in extremely loose, low velocity fine sands. Geotechnical testing performed on field samples revealed that liquefied soils ranged from well graded sandy gravels in close proximity to the fault (< 5km) to silty sands and low plasticity silts at greater distances. At the Alyeska pump station seismometer sites, we are able to invert profiles of shear wave velocity to depths of 140-200 meters. The averaged NEHRP (30 meter) velocities for pump stations 9, 10, and 11 are 376 m/s, 316 m/s, and 362 m/s, respectively.

S12B MCC: Level 1 Monday 1330h

Total Recall: Paleoseismology Posters

(joint with G, T, PA)

Presiding: **P Bodin,** Center for Earthquake Research and Information, University of Memphis**; A E Blythe,** University of Southern California

S12B-0382 1330h POSTER

Location and Shallow Structure of the Frijoles Strand of the San Gregorio Fault Zone, Pescadero, California

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The San Gregorio fault is one of the principal faults of the San Andreas fault system in the San Francisco Bay area. Located west of the active trace of the San Andreas fault and near the coast, the San Gregorio fault zone consists of at least two northwest-southeast-trending strands, the Coastways and Frijoles faults. Little is known about the slip history on the San Gregorio, and information for the Frijoles fault is especially scarce, as it lies mostly offshore. To better understand the contribution of the San Gregorio fault zone to slip along the San Andreas fault system, we conducted a high-resolution, seismic imaging investigation of the Frijoles fault to locate near-surface, onshore, branches of the fault that may be suitable for paleoseismic trenching. Our seismic survey consisted of a 590-meter-long, east-west-trending, combined seismic reflection and refraction profile across Butano Creek Valley, in Pescadero, California. The profile included 107 shot points and 120 geophones spaced at 5-m increments. Seismic sources were generated by a Betsy Seisgun in 0.3-m-deep holes. Data were recorded on two Geometrics Strataview RX-60 seismographs at a sampling rate of 0.5 ms. Seismic p-wave velocities, determined by inverting first-arrival refractions using tomographic methods, ranged from 900 m/s in the shallow subsurface to 5000 m/s at 200 m depth, with higher velocities in the western half of the profile. Migrated seismic reflection images show clear, planar layering in the top 100-200 meters on the eastern and western ends of the seismic profile. However, to within the shallow subsurface, a 200-m-long zone near the center of the profile shows disturbed stratigraphic layers with several apparent fault strands approaching within a few meters of the surface. The near-surface locations of the imaged strands suggest that the Frijoles fault has been active in the recent past, although further paleoseismic study is needed to detail the slip history of the San Gregorio in this area.

S12B-0383 1330h POSTER

Integrated Seismic Imaging of the Carlsberg Fault in the Copenhagen City Center

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Images of the Carlsberg Fault in the area of the Copenhagen city center, Denmark, are obtained from normal incidence and refraction seismic data collected along a 3 km long E-W trending profile, which is oriented approximately perpendicular to the strike of the fault. The integrated seismic data set provides the most detailed images to 500 m depth so far obtained of this fault. The fault zone appears as a flower structure in the normal incidence section, and an abrupt change in the P-wave velocity structure across the fault zone further indicates that significant lateral movements have taken place along the fault. Vertical movements of up to 90 m are evident in the fault zone. Even the shallowest layers that can be imaged by the seismic data (approximately 30 m depth) are clearly vertically offset by the fault. In order to constrain the strike of the fault zone through the Copenhagen area we use shots detonated inside the fault zone, which are recorded by geophones distributed along arcs of circles situated up to 7 km away from the shots. Ground penetrating radar measurements are conducted to image the fault structures in the topmost 10 m. Geodetic measurements conducted in the Copenhagen area during the last 165 years indicate that the fault may still be active with horizontal displacements of about 5 cm over a 73-year period. Small cracks in walls and displacements of buildings may further indicate that the fault is still playing an active role in forming the Copenhagen area. However, no earthquakes are detected along the fault, and the seismicity of the study area is very weak. The formation of the Carlsberg Fault may be related to extensional stresses in a strike-slip system associated with the Sorgenfrei-Tornquist zone, which is situated only 40 km east of the study area. The Sorgenfrei-Tornquist zone is a major tectonic element in southern Scandinavia where it is situated close to the boarder between the Danish Basin to the southwest and the Baltic Shield to the northeast.

S12B-0384 1330h POSTER

Refined Slip History of the North Anatolian Fault at Gerede on the 1944 rupture

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We excavated four new fault crossing trenches and a complex of fault parallel trenches at Ardicli, 15 km east of Gerede on the 1944 Bolu-Gerede segment of the North Anatolian fault to resolve timing and slip in past earthquakes. A unique large gravel-filled channel (unit 10) was determined to be offset 17 to 20 m. Preliminary age control on the gravel shows it dates to the 6th or 7th century AD. Fault crossing trenches show evidence for 5 events after deposition of unit 10. Preliminary 14C dates place the earlier 3 of 5 events at AD 643-918 (EV5), AD 943-1298 (EV4), and AD 1171-1668 (EV3). These 3 events are recorded in 3 clayey units (8, 6, and 4). EV3 is the best represented with disruption into the base of unit 4 and on the main and subsidiary faults. The two most recent events are the 1944 (E1) and presumably the great 1668 earthquake (E2). Based on the offset of small channels cutting into the unit 4 surface at the site, slip in 1944 and 1668 was 5 +/- 1 m in each event. This suggests that the prior 3 events collectively produced 7 to 10 m slip, slightly less than that which occurred in the most recent events. EV4 may be correlated with 1050 earthquake, but no catalog has mentioned about EV5 and EV3, indicating that historic records of the large North Anatolian fault earthquakes are incomplete for this period. The finding of EV3 is important for the analysis of earthquake cycles. According to the catalogs, the interval of 618 years between 1050 and 1668 was much longer than the 1668-1944 interval and that around the Marmara Sea. With EV3, the recurrence may be much more periodic. Our detailed studies on the repeated slips along the 1944 segment indicate the slips during past 5 earthquakes are similar. The 1944 segment, especially in its central portion around Gerede is quite unique and straight. The refined slip history here will help to define regularity and irregularity of earthquake recurrence.

URL: http://www.home.hiroshima-u.ac.jp/kojiok

S12B-0385 1330h POSTER

Geophysical Investigation of a Slow Active Thrust Fault: the Trevaresse Fault, France

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