S11B MCC: 3011 Monday 0825h

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

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

S11B-01 0830h

The Susitna Glacier Thrust Fault-Characteristics of Ruptures That Initiated the Denali Fault Earthquake

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Seismograms show that the M_w 7.9 earthquake on the Denali fault began as a M_w 7.2 thrust-faulting event. Within days of the Nov. 3, 2002 mainshock, we discovered surface ruptures on a previously unknown thrust fault, which we named the Susitna Glacier fault (SGF). The SGF is a north- to northwest-dipping thrust fault that extends southwest from the upper part of the Susitna Glacier where it joins the Denali fault, downglacier to the southern margin of the Alaska Range, and west along the range front to the east edge of the Nenana River Valley. Field studies in 2003 verified that about 48 km of the SGF ruptured in 2002, of which 16-19 km were in glacial ice. Seasonal melting and ablation are rapidly destroying evidence of faulting in the ice. The westernmost 10 km of ruptures are small and discontinuous: they are difficult to trace because they are morphologically similar to abundant non-tectonic glacial and periglacial surficial geologic features. Primary motion on the SGF was south- to southeast-directed thrust faulting, but we found local minor lateral movement on zones that transfer slip between thrust faults. Data from 26 detailed topographic profiles show that the 2002 throw typically ranges between 1-3 m with a maximum of 4.3 m. We observed near-surface dips of 20°-40° in a few exposures. Combining typical throw and dip values suggests that the dip-slip movement was generally 3-6 m at the surface. Ground deformation on the SGF is complex in map view. The thrust-fault ruptures are typically comprised of multiple strands that have lobate morphologies and sinuous traces. Displacement on one strand is usually transferred to adjacent strands by ramps or tear faults. Locally, backthrusts form scarps as much as 2 m high. Folding and extensional grabens are common in the hanging wall; locally, downwarps in the footwall result in exaggerated scarp heights of 6-7 m. Empirical relations of earthquake magnitude versus surface-faulting parameters yield magnitude estimates of 6.8-7.2 for a 48-km-long surface rupture and a typical slip of 5-6 m. These values are consistent with seismological data for the initial thrust faulting.

S11B-02 0845h INVITED

Surface rupture and revised slip distribution on the Denali and Totschunda faults from the M 7.9 Denali fault earthquake

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We revised the preliminary slip distribution (Science, 2003, v. 300, p. 1037ff) along the Denali and Totschunda faults after additional fieldwork this summer. Features of the surface trace had degraded in places due to melting of snow, permafrost, and soil. However, without snow cover, offset of fine-scale features was much clearer at many new localities. We were also able to add additional measurements on glaciers, where offset snow-filled crevasses could be observed. As a result, the revised slip distribution provides considerably more detail and a higher level of confidence than that inferred solely from measurements collected immediately after the earthquake. The primary features of the revised slip distribution are: 1) a broad plateau of roughly 5-m offsets extending from 70 to 170 km east of the epicenter along the central part of the Denali fault, 2) high-slip values of 6.5-8+ m between 170 and 212 km east of the epicenter, 3) the step up from the 5 m plateau to the higher is sharp, occurring over a lateral distance of one kilometer, 4) there are three new, and anomalously high, measurements of 7.2-8.2 m along a 7-km length of the fault within the plateau of 5-m slip values, 5) there was a maximum 3-m offset on the Totschunda fault, which is 0.9-m higher than previously measured; 6) A previously inferred region of high slip in the vicinity of the Trans Alaska Pipeline is less obvious or absent. However, slip in that area is higher than the region to the west of the Delta River, 7) In contrast to geodetic and seismologic slip models that infer low slip and moment release in a zone 100-160 km east of the epicenter, we find continuous surface offsets of about 5 m; 8) A drop to zero slip, previously inferred at the Totschunda-Denali junction appears to be a result of slip values obtained from transfer structures. The smallest robust measurements of lateral slip in the transition zone were about a meter. Denali Fault Earthquake Geology Working Group : T. Dawson, P. Haeussler, J. Lienkaemper, A. Matmon, D. Schwartz, H.Stenner, B. Sherrod (USGS), F. Cinti, P. Montone (INGV, Rome)

S11B-03 0900h INVITED

Paleoearthquakes on the Denali-Totschunda Fault system: Preliminary Observations of Slip and Timing

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Understanding the behavior of large strike-slip fault systems requires information about the amount of slip and timing of past earthquakes at different locations along a fault. A historical surface rupture adds a critically important baseline for calibration. During July 2003 we performed additional mapping of the 2002 Denali-Totschunda surface rupture with the goal of also measuring and dating slip during previous earthquakes. We were able to obtain slip values for prior events at a dozen locations along Denali-Totschunda strike-slip rupture. We focused on the penultimate event, which is easiest to distinguish (slip from individual older events can eventually be measured). On the Denali fault just west of the intersection with the Susitna Glacier thrust 2002 slip was low, 1.0 m to 1.5 m; cumulative slip from two events was 2.5-3.0, which is essentially double. On the 100-km-long section between Black Rapids Glacier and Gillett Pass, where 2002 slip averaged 5 m, three measurements indicate penultimate-event slip was about the same as 2002. The 7-8 m offset section east of Gillett Pass has the clearest paleoevent slip history. We measured three locations where 2002 slip was 7-8m and cumulative offset on channels was 14.5-16 m. Along this section previous workers noted gullies with 15 m offsets before the 2002 earthquake, suggesting the past three events here had similar slip. On the Totschunda fault paleo offsets appear to be similar in amount to 2002. At one locality we measured 2.8 m in 2002 and 5.4 m for two events. A second site had 1.0-1.4 m of offset in 2002 and 3.1 m for two events. A third location yielded 3.3 m in 2002 and 10.8 m on a paleochannel, which could represent three events with similar slip. A location in the Denali-Totschunda transition zone had a 5-6 m-high scarp and a well-developed sag pond, indicating that this complex part of the fault system has been active in previous events. The major observation is that the paleo offset measurements, though presently limited in number, indicate that penultimate event slip was very similar to the 2002 offset along the length of the ruptured Denali and Totschundafaults, and may have been similar for at least a third event back. For most of the it's length the 2002 rupture is expressed as a narrow mole track (typically 1m to 3m wide) but locally it has produced pull aparts and large fissures. These features contain a variety of organic deposits associated with the ground surface at the time of the penultimate earthquake(s) on the Denali and Totschunda faults. We sampled five of these, and recovered peat, pine needles, and trees that were toppled during the penultimate event(s). Including a test pit west of the Delta River, we have six sample sites that span the 5m and 7-8m rupture segments of the Denali, the Denali-Totschunda transition zone, and the Totschunda fault. Preliminary radiocarbon dates indicate that the timing of the penultimate event on the Denali fault is younger than 1400 to 1289 yr BP and may have occurred as recently as 520 to 310 yr BP. The penultimate event on the Totschunda fault occurred after 1340 to 1130 yr BP and most likely occurred shortly after 660 to 530 years BP. The Denali-Totschunda fault system is a remarkable laboratory, particularly in terms of preservation of fault geomorphology and organic material, for studying large strike-slip faults. These initial observations of paleoslip and event dates are the first steps in unraveling the behavior of this major strike-slip zone. Denali Fault Earthquake Geology Working Group: T. Dawson, P. Haeussler, J. Lienkaemper, A. Matmon, D. Schwartz, H.Stenner, B. Sherrod (USGS), F. Cinti, P. Montone (INGV, Rome), G. Carver. G.Plafker (Alyeska)

S11B-04 0915h INVITED

Change in Stress Directions Along the Central Denali Fault, Alaska, After the 2002 Earthquake Sequence

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On the basis of earthquake focal mechanisms, the state of stress along the central Denali fault, Alaska system changed after the 2002 earthquake sequence. Before the earthquake sequence, the maximum stress S1 was at a 60 degree angle with the Denali fault west of the point of its maximum curvature, fault-normal between the fault apex and the Totschunda strand, and at 50 degrees with respect to the Totschunda fault. In the epicentral region, the post-event S1 has rotated counter-clockwise. Along the rest of the rupture zone the sense of rotation is clockwise. The S1 direction became nearly fault-normal along the Totschunda strand. Along the central part of the rupture, S1 is over-rotated from the fault-normal direction by 10 to 35 degrees with the minimum stress S3 being nearly vertical, promoting reverse aftershocks. This could be an indication of dynamic overshoot.

S11B-05 0930h INVITED

The Denali Fault: Crustal deformation before and after the 2002, Mw=7.9, Denali Fault Earthquake

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The Mw 7.9 November 3, 2002 Denali fault earthquake ranks among the largest continental strike slip earthquakes in the last few decades, and is perhaps the best-recorded earthquake of its size from a geodetic point of view. EDM surveys across the Denali fault were carried out by the USGS in the 1980s, which showed low shear strain rates across the fault. We have carried out GPS measurements on two transects across the Denali fault since 1997. These data show 6-8 mm/yr of right-lateral strike slip motion across the Alaska Range. We explain these data using a model in which one or two faults of the Denali fault system slip with a total slip rate of 8 mm/yr. Because the Denali fault forms a small circle about a pole of rotation just offshore of the Kenai Peninsula, we interpret the Denali fault as forming the northern boundary of a block comprising much of southern Alaska that rotates counter-clockwise relative to North America. Following the earthquake, with the technical support of UNAVCO, we have installed 16 continuous GPS sites at a wide range of distances from the rupture, and carried out repeated campaign-style surveys of more than 50 additional sites. Horizontal postseismic displacement rates at continuous sites up to 200 km from the rupture reached 1-2 mm/day in the first month after the event. They gradually decayed to 0.2 mm/day 8 months after the event at the sites closest to the rupture. Displacement rates measured 8 months after the event were still 10 times larger than the pre-earthquake secular rates.

S11B-06 0945h

Early Postseismic Deformation Following the Mw 7.9 Denali Earthquake, 2002, From GPS Measurements.

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The rapid deployment of GPS receivers following the 3 Nov 2002 Mw 7.9 Denali Fault Earthquake occurred in two phases, with immediate campaign style deployment preceding the installation of new permanent stations. The initial deployment included multi-day to multi-week GPS measurements on existing campaign monuments, as well as on newly established monuments close to where the permanent sites were built. At all of the permanent stations, campaign style measurements from these very nearby points (within 10-20 meters) overlap the start of the permanent station data. Using these survey ties, we can connect the position time-series of these campaign data with the time-series of the associated permanent stations. The resulting records are a unique window into the earliest stages of post-seismic response of a large magnitude strike-slip event. Several stations close to the rupture show initial post-seismic velocities in excess of 2 mm/day. The data allow us to test models of afterslip and poroelastic and/or viscoelastic deformation operating on timescales of days to a month or two following the event.

S11C MCC: Level 1 Monday 0830h

Crustal Seismic Anisotropy as a Measure of Tectonic Deformation Posters *(joint with T, V)*

Presiding: **D Okaya,** University of Southern California**; N Christensen,** University of Wisconsin

S11C-0292 0830h POSTER

Field Observations of Crustal Seismic Anisotropy: Implications for Mapping Tectonic Structure in Metamorphic Terranes

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The study of seismic anisotropy within continental tectonic provinces provides earth scientists with a powerful tool for measuring and quantifying deformation within the crust. Preferred mineral alignment observed in metamorphic terranes produced by recrystallization during metamorphism is associated with planar structures such as slaty cleavage, schistosity, and gneissic layering. These structures are often pervasive for tens to hundreds of kilometers and produce significant compressional wave seismic anisotropy as well as shear wave splitting. Observations of crustal anisotropy within (1) slates of the chlorite subzone of the Haast schist terrane of South Island, New Zealand, (2) lower greenschist facies phyllites and metagraywackes of the Valdez Group Chugach terrane in southern Alaska, (3) amphibolite facies mica schists within the Yukon-Tanana terrane in the eastern Alaska range and (4) amphibolite facies quartzofeldspathic gneisses, approaching granulite grade, within the Nanga Parbat-Haramosh massif demonstrate that crustal anisotropy is not limited to rocks of any particular metamorphic grade and thus can be present at all crustal levels. Two refraction lines at approximately right angles shown up to 10% compressional wave anisotropy in relatively low grade metapelites of the Haast schist terrane. Fast velocities parallel the strike of the upturned slaty cleavage. Measured field velocities in the Chugach terrane, obtained from observed first arrival travel times, demonstrate significant compressional wave anisotropy (9%) with fastest directions oriented approximately east-west and parallel to foliations observed in outcrops. Within the Alaskan Yukon-Tanana terrane variations in seismic velocities of the first arrivals correlate with field observations of regional dips of foliated schists. A northward shallowing of foliation dips produces an observed northward increasing seismic velocity. The core of the Nanga-Parbat massif forms a large-scale antiformal structure with an axial orientation of N10 degrees E with near vertical lineations. Observations of local seismicity show shear wave splitting which originates within the high-grade granitic and metasedimentary gneisses of the massif. Laboratory velocity measurements on rocks collected from surface exposures within these four regions are consistent with the magnitudes and directions of the observed anisotropies. We conclude that future field investigations designed specifically to study crustal seismic anisotropy, combined with laboratory measurements, will provide valuable information on the structure, magnitude and extent of crustal tectonic deformation.

S11C-0293 0830h POSTER

Intrinsic Anisotropy of Textured Rocks

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The seismic anisotropy of crustal terrains has been detected in numerous passive and active source seismic experiments and confirmed by the ultrasonic laboratory measurements on textured samples of the metamorphosed rock formations. This observed anisotropy might be produced by variety of causes, including developed texture (lattice preferred orientation (LPO) of constituent minerals), structural layering and aligned fracturing of the formations of interest. In the case of the deformed metamorphic rocks with highly developed texture, LPO is generally accepted to be the main cause of anisotropy and this type of anisotropy is called here intrinsic anisotropy. Forward modelling of the intrinsic anisotropy is based on the theory of elasticity of polycrystalline aggregates and takes into account information about the texture of the rock and elasticity of constituent minerals. Elastic constants of a textured mica aggregate, which is one of the sources of anisotropy in metamorphosed rocks, were calculated on the basis of the widely used Voigt, Reuss and Hill assumptions. Taking into account significant anisotropy of the single mica mineral and the consequent wide separation of the Voigt and Reuss (upper and lower) bounds of some of the elastic constants of the anisotropic aggregate, the Geometric mean method was employed to further refine the elasticity. The Geometric mean method is based on simple and physically meaningful assumption of the invertibility of the elastic constants into the elastic compliances and yields unique set of elastic constants that are independent of the averaging domain and usually lie within the Voigt-Reuss bounds. Limits of the seismic anisotropy of the mica aggregate have been estimated. Intrinsic anisotropy depends primarily on the level of anisotropy of constituent minerals and their alignment (strength of texture). Similar technique could be applied to investigate elasticity of multiphase polycrystalline aggregates as more realistic model for anisotropic metamorphic rocks.

S11C-0294 0830h POSTER

P-wave Velocity Anisotropy and Shear-wave Splitting of Sheared Metasediments from the Flin-Flon Belt, Trans-Hudson Orogen

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Metasediments of the upper greenschist - lower amphibolite facies of metamorphism from two ductile shear zones of Flin-Flon Belt (FFB) of Trans-Hudson Orogen (THO) were used to carried out laboratory measurements of compressional wave (Vp), shear-wave (Vs) velocities and shear-wave splitting. The investigated metasediments vary in composition from felsic to mafic. Test sites with outcrops of sheared metasediments were correlated with a series of inclined seismic reflectors possibly extending from the midcrust and intersecting a well mapped shear zone at the surface. Determination of lithological and physical properties of highly deformed metasediments is essential for proper interpretation of the nature of observed seismic reflectors. To investigate anisotropic properties of the rocks compressional velocity was measured to confining pressures of 300 MPa in three mutually orthogonal directions with respect to the visible textural properties. In addition, on nine selected samples shear-wave velocity was measured at two orthogonal polarizations for each of three propagation directions to determine shear-wave splitting and correlate it with P-wave anisotropy. For most of the hand specimens seismic heterogeneity was investigated by measuring P- and S-wave velocities on several cores cut in the same direction. Elastic velocities were measured on the 147 core samples in total. Observed Vp anisotropy varied from quasi-isotropic to highly anisotropic (Ap=24%). Maximum observed shear wave splitting reaches the value of 0.77 km/sec at confining pressure of 300 MPa. An estimated splitting of the SKS wave propagating through the ten kilometres thick crustal slab of metasediments, characterized by the averaged value of laboratory observed shear-wave splitting, may reach value of 0.2 sec. Pressure invariance of observed P-wave anisotropy and shear-wave splitting indicates that lattice preferred orientation (LPO) of highly anisotropic minerals such as mica and hornblende is mainly responsible for measured seismic anisotropy.

S11C-0295 0830h POSTER

P- and S-Wave Velocities in Crustal Rocks: Evidence from Measurements and Calculations

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Elastic anisotropy is an important property of most rocks constituting the Earth crust, and it has various sources. Most important is lattice (crystallographic) preferred orientation (LPO) due to the anisotropic properties of most rock-forming minerals and the LPO of the polycrystalline aggregates. In addition, oriented microcracks and grain shape preferred orientation (SPO) may also be of importance. Because elastic wave propagation is sensitive to cracks, elastic wave velocities travelling through a rock are higher parallel to the fractures than across them. With increasing pressure microfractures close and their contribution to elastic anisotropy diminishes. The remaining part of velocity anisotropy is nearly pressure-independent and largely caused by the LPO of the constituent minerals, such as mica and hornblende. In order to evaluate the respective contribution of the various parameters, on needs to discriminate between the two effects. This poster reports results obtained from the simultaneous measurement of P- and S-wave velocities in three orthogonal directions (up to 600 MPa and 600°C) on cube-shaped samples of metamorphic crustal rocks (amphibolites, gneisses) and investigates the relationship between crystallographic fabric, oriented cracks, shear wave splitting and shear wave polarisation. The laboratory measurements are complemented by 3D velocity calculations based on the LPOs of the rock-forming minerals (hornblende, mica). The measurements and calculations show that velocity anisotropy, shear wave splitting and shear wave polarisation are interrelated to the structural frame of the rocks (foliation, lineation). This information provides a powerful tool for the understanding and interpretation of seismic data.

S11C-0296 0830h POSTER

3D Strain Geometry and Crystallographic Fabric in Experimental HT Deformation of Solnhofen Limestone

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