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November 19, 2009

MEMORANDUM TO: ACRS Members

FROM: Antonio F. Dias, Chief ***/RA/***
Nuclear Waste & Material Branch, ACRS

SUBJECT: TRANSMITTAL OF TRIP REPORT BY ACRS STAFF ON THE OCTOBER 2009 GEOLOGICAL SOCIETY OF AMERICA MEETING

Attached is the trip report by Senior Staff Scientist Neil Coleman regarding his attendance at the annual meeting of the Geological Society of America, where he co-chaired a hydrology session and also gave a presentation on catastrophic flooding. This trip represented training for Mr. Coleman to enhance his skills in supporting ACRS review of earth science issues (e.g., seismicity, hydrology) for new and existing nuclear facilities. The conference was held in Portland, OR from October 18-21, 2009. Mr. Coleman also participated in a pre-conference field trip that toured classic field sites in the Columbia Gorge and Channeled Scabland of Washington State. This region was extensively modified by megafloods spawned by catastrophic releases of water from glacial Lake Missoula, circa 15,000 years ago.

Enclosure: As stated

cc w/att:
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Trip Report - Attendance at the 2009 Geological Society of America (GSA) Annual Meeting, Portland, Oregon

Neil Coleman, ACRS Senior Staff Scientist

During October 18-21, 2009, I attended the GSA annual meeting in Portland, OR and participated in a pre-conference field trip to the Channeled Scabland of Washington State during October 12-17. Attendance at this GSA meeting provided training to enhance my skills in supporting ACRS review of earth science issues for new and existing nuclear facilities.

On Monday, October 19th I co-chaired a hydrology session, which was also a tribute session for the late Professor Roy Williams, who is credited, along with Dr. Dale Ralston, with initiating and directing the hydrogeology program at the University of Idaho (Moscow). Among his many accomplishments, Professor Williams was a founding member and Vice President of the International Mine Water Association and the author of four books and more than 124 papers. He served as a hydrology consultant to the NRC in the 1980's.

I gave an oral talk at GSA on the Johnstown Flood of 1889. This event caused the greatest loss of life (>2200 fatalities) from dam breach in U.S. history. The flood and its human consequences have been thoroughly described in the popular literature and cinema, but has received little scientific investigation. My talk provided a new estimate (>12,000 m^3/s) for the peak discharge that resulted from this dam breach, which was comparable to the average discharge of the Mississippi River. A companion talk on the Johnstown Flood was given by Dr. Carrie Davis Todd, who chairs the Department of Geology and Planetary Science at the University of Pittsburgh at Johnstown.

A number of abstracts submitted to this GSA meeting can provide insights relevant to siting studies for nuclear facilities. These relate to the topics of seismicity, catastrophic flooding, landslide/slope stability, climate change, and nuclear issues. Summaries of several abstracts are given below, along with a selection of meeting abstracts:

- Stein et al. - It now seems more useful to view mid-continent earthquakes as migrating, episodic, and clustered. Instead of occurring quasi-periodically along a single major fault system, they migrate over many faults in a large area. A fault will be active for several earthquake cycles, and then become dormant as others become active. Because deformation can be steady for a while then shift, the past earthquake history can be poor predictor of the future, and hazard assessment based on the recent earthquake record can overestimate risks in regions of recent large earthquakes and underestimate them where seismicity has been quiescent.

- Rittase et al. - The Garlock Fault in southern California may behave differently over varying timescales in terms of slip, strain and seismicity. It may be that the GF shares a genetic link between the San Andreas fault system and the eastern California shear zone, whereby transient strain gradients intermittently affect the three structures. The difference between late-Holocene geologic and geodetic slip-rates as well as the lack of geodetically documented strain may indicate the Garlock Fault is late in its earthquake cycle.

- Crone and Haller - The Borah Peak earthquake provided valuable insight into the 3-D fault geometry and the coseismic rupture on long Basin-and-Range normal faults. This insight shows us what we might expect when the next large earthquake ruptures a major range-front fault in the Intermountain West such as Utah's Wasatch fault.

- Iverson et al. - A new depth-averaged model of one-dimensional debris-flow motion seamlessly connects the quasi-static mechanics of initiation with the inertial dynamics of fully developed flow. Previous debris-flow models fail to make this connection because they employ initial conditions with unbalanced forces arbitrarily specified by the modeler. Natural debris flows, in contrast, commence when the balance of forces is tipped by an infinitesimal amount.

- Remo and Pinter - The use of river training structures to create a narrower and deeper river channel along the Middle Mississippi River has been linked to changes in flow conveyance and, in some places, to large-scale increases in flood levels (up to 4 - 6 m).

Seismicity

INTRAPLATE SEISMICITY IN NORTH AMERICA: A NEW VIEW

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Our hypothesis is that higher integrative lithospheric strength correlates with lower rates of continental crustal seismicity and with lower earthquake magnitudes, also known as Mmax. Integrative lithospheric strength is controlled by lithospheric composition and the geotherm. Mantle S-wave velocity anomalies are indicative of lithospheric composition and temperature, and are available on a global scale from seismic surface-wave tomography. In contrast, heat flow measurements, which also reflect the mantle geotherm, are lacking in many continental intraplate regions. We have created new global maps of lithospheric S-wave velocity anomalies (delta Vs) at a depth of 175 km and quantitatively compared the values of these mantle anomalies with the locations and moment magnitudes of earthquakes in the overlying crust. These S-wave anomalies are with respect to a global average velocity model. As is well known, positive delta Vs anomalies correlate with Precambrian cratonic lithosphere, and we have selected a depth of 175 km to ensure we are within the deep cratonic lithospheric root. We seek to demonstrate a correlation of cold, strong mantle lithosphere with lower seismicity rates and lower moment magnitudes. Our earthquake catalog is described by Schulte and Mooney (Geophy. J. Int., 2005) and contains about 1,300 crustal events. This catalog contains 740 continental intraplate earthquakes with moment magnitude in the range 4 to 5. We find only 7% (50) crustal earthquakes occur above mantle lithosphere with delta Vs greater than 4.5. The number of earthquakes is nearly constsant for values of delta Vs between 0.5 to 4.5. There are 460 continental intraplate earthquakes with moment magnitude in the range 5 to 6. We find that only 10% of all earthquakes occur above mantle lithosphere with delta Vs greater than 3.5. Most earthquakes occur above mantle lithosphere with delta Vs values between 0.5 and 3.5. There are 110 earthquakes with moment magnitude in the range 6 to 7. We find that 14% (16) earthquakes occur above mantle lithosphere with values of delta Vs > 3.5%. There are no earthquakes above mantle lithosphere with delta Vs greater than 4.5%. No earthquakes with moment magnitude > 7 occur above mantle lithosphere with delta Vs values > 3.5%.

HOW STEADY IS THE GARLOCK FAULT?

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Geologic, geomorphic, paleoseismic and geodetic data reveal significant temporal and spatial variability in slip rates and strain on the Garlock fault (GF) in southern California. With the aim of better understanding its mechanical role in facilitating active strain and slip on the North American-Pacific plate margin, we synthesize: (1) existing long- and short-term slip rate data, with new data herein; (2) mapped strain patterns; (3) existing paleoseismic data; and (4) geodetic data for the GF.

The 250-km-long GF cuts orthogonally across the Eastern California shear zone and is the second-largest active fault in California. New geologic mapping of a 50-km section of the GF in Searles Valley (SV) and Pilot Knob Valley (PKV) give intriguing spatial and temporal complexities to the post-5 Ma mechanical history of this fault. New geologic slip-rate data include estimated 30-20 k.y. and 4-3 k.y. terraces with incised drainages offset ~230 and 47 m, respectively. Known slip-rate estimates of 4-7 mm/yr were derived from 13.8-10 k.y. (^{14}C-age) offset shorelines in SE SV. Modern seismicity on the GF includes a Mw 4.4 (January 2009) at Goler Canyon in NW Fremont Valley and a Mw 3.2 (Spring 2008) in SE PKV. Pre-historical seismicity over a ~7000 k.y. period is highly irregular with 4 of 6 dated events within the past 2 k.y.¶ Significant N-S shortening, uplift and inversion of the Plio-Pleistocene Christmas Canyon basin adjacent to the Slate Range, and potentially uplift of the Slate Range too, suggests the loci of strain and deformation is not constant in space and time. Geodetic data does not discern sinistral slip on the GF and suggests the structure is locked or currently inactive.

A synthesis of these seemingly conflicting data may be reasoned if the GF is to behave differently over varying timescales in terms of slip, strain and seismicity. It may be that the GF shares a genetic link between the San Andreas fault system and the eastern California shear zone, whereby transient strain gradients intermittently affect the three structures. The difference between late-Holocene geologic and geodetic slip-rate estimates as well as the lack of geodetically documented strain may indicate that the GF is late in its earthquake cycle.

GEORGE P. WOOLLARD TECHNICAL LECTURE: NEW VIEW OF NEW MADRID: LITTLE MOTION, COMPLEX FAULTS, SMALL HAZARD

STEIN, Seth, Earth & Planetary Sciences, Northwestern University, 1850 Campus Drive, Evanston, IL 60208-2150, CALAIS, Eric, Earth & Atmospheric Sciences, Purdue University, West Lafayette, IN 47906, LIU, Mian, Dept. of Geological Sciences, Univ of Missouri-Columbia, Columbia, MO 65211, and LI, Qingsong, Lunar & Planetary Institute, Houston, TX 77058

GPS studies over 18 years within the New Madrid Seismic Zone (NMSZ) show no detectable motion to steadily increasing precision - currently 0.2 mm/yr. The NMSZ is thus deforming too slowly - if at all - to account for large earthquakes in the area over the past ~5,000 years. Hence the recent cluster of large magnitude events does not reflect long-term fault behavior. The GPS data together with increasing evidence for temporal clustering and spatial migration of earthquake sequences in continental interiors indicate the need for a different view on

midcontinental earthquakes. Traditionally, intraplate seismic zones have been treated like slowly deforming (< 2 mm/yr) plate boundaries. We expected steady deformation in narrow zones, such that the past rates and locations shown by geology and the earthquake record would be consistent with present deformation shown by geodesy, and predict future seismicity. It now seems more useful to view mid-continent earthquakes as migrating, episodic, and clustered. Instead of occurring quasi-periodically along a single major fault system, they migrate over many faults in a large area. A fault will be active for several earthquake cycles, and then become dormant as others become active. Because deformation can be steady for a while then shift, the past earthquake history can be a poor predictor of the future, and hazard assessment based on the recent earthquake record can overestimate risks in regions of recent large earthquakes and underestimate them where seismicity has been quiescent. In this scenario the currently active parts of the NMSZ are the presently most active of many faults, the recent seismic events are primarily aftershocks of large past events, and the lack of present deformation suggests that the recent cluster of earthquakes has ended. It is useful to view midcontinent earthquakes as a classic complex system controlled by interactions between faults. Although an individual fault taken in isolation acts quasi-periodically, the network of interacting faults gives complex variability in space and time. Initial numerical modeling shows that fault interactions can give rise to such variability without local or time-variable loading, either of which can provide further variability. A complex system view seems likely to improve understanding of mid-continent tectonics, the resulting earthquakes, and their hazards.

THE 1983 BORAH PEAK, IDAHO EARTHQUAKE—A MODEL FOR SURFACE-RUPTURING EVENTS IN THE WESTERN U.S

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The Mw 6.9, 1983 Borah Peak, Idaho, earthquake is the most recent normal-faulting earthquake to produce large scarps in the western U.S. It produced about 36 km of surface rupture on the central part of the 127-km-long Lost River fault (LRF), which can be divided into six segments based on the geometry of the range front and the distribution and characteristics of late Quaternary fault scarps. The earthquake nucleated at about 16 km depth, downdip from a prominent range-front salient that marks the boundary between the 24-km-long Thousand Springs segment (TSS) and the 23-km-long Mackay segment (MS) to the southeast. The rupture propagated unilaterally to the northwest and produced the biggest scarps (maximum throw of 2.7 m) and zones of complex ruptures on the TSS. Near the northwestern end of the TSS, the rupture bifurcates and forms a 14-km-long west-trending splay of small, simple scarps across the Willow Creek Hills (WCH). The WCH is an intra-valley bedrock ridge that separates TSS from the Warm Springs segment (WSS) to the northwest. Along the range-front fault, simple scarps, less than or equal to 1 m high, formed along 8 km of the WSS.

The LRF and surrounding area was largely aseismic in the decades prior to 1983, so precursory seismicity did not signal the impending event. The earthquake ruptured a 45°–50°-dipping, planar fault that extends through the entire seismogenic crust. Virtually no aftershocks occurred on the MS, suggesting that the structure at the MS–TSS boundary allowed the two parts of the fault to act with complete independence. In contrast, the northwestward propagating rupture on the TSS was able to trigger a small amount of slip on the WSS and create ruptures on western splay in the WCH. The steep range front suggests that the LRF has a history of sustained late Cenozoic slip, and limited paleoseismic studies indicate that the Holocene recurrence for surface-faulting earthquakes is several thousand years. The Borah Peak earthquake provided valuable insight into the 3-D fault geometry and the coseismic rupture on long Basin-and-Range normal faults. This insight shows us what we might expect when the next large earthquake ruptures a major range-front fault in the Intermountain West such as Utah's Wasatch fault.

Catastrophic Flooding

USE OF HYDROGEOMORPHIC AND SEDIMENTARY EVIDENCE TO REFINE CONVECTIVE RAINFALL ANALYSES AND FLASH-FLOOD CHARACTERISTICS

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There is a critical need to improve rainfall analyses for extreme rainstorms and resultant streamflows. Such advancements will enhance emerging technologies designed to improve rainfall estimates, hydrologic modeling, and flash-flood forecasting. Convective rainfall amounts and intensities can vary substantially over temporal scales (minutes) and spatial scales (a few kilometers), particularly for watersheds in semi-arid and arid regions in the west-central United States. In many areas, precipitation and streamflow gages are sparse to nonexistent, particularly in remote areas. Limited resources often preclude extensive data collection, and flood-producing rainstorms often do not occur in instrumented basins. Even in instrumented basins, observational networks may not work properly because of storm or flood damage.

NEXRAD weather radar (WSR-88D) is increasingly being used to quantify rainfall, however, validation is fundamentally necessary to determine a storm's footprint and assess predicted rainfall estimates. NEXRAD data have limitations that can substantially affect the reliability of derived rainfall amounts. For example, hailstorms may result in overestimated rainfall amounts and extreme winds may change the location of the storm's footprint as reported by NEXRAD.

Hydrogeomorphic techniques have been developed to refine convective storm rainfall estimates in conjunction with flash-flood documentation efforts. The techniques use physical evidence remaining on hillslopes and in river channels, particularly in the documentation of sediment erosional and depositional features, to make inferences about the hydrometeorological conditions. These data are used to refine or validate NEXRAD rainfall estimates, the storm footprint, and rainfall-runoff footprint. This presentation includes discussions of several documented storms and floods with a focus on: 1) the approach, results, and benefits of documenting recent convective rainstorms and associated flood discharges; 2) coordination with the National Weather Service to determine rainfall thresholds that may produce hazardous flash floods for different land uses; 3) limitations and uncertainties of hydrometeorologic estimates, and; 4) transfer of the methodologies to other hydroclimatic regions.

JOHNSTOWN FLOOD OF 1889 – DESTRUCTION AND REBIRTH

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This year is the 120th anniversary of the flood that caused the greatest loss of life from dam breach in U.S. history. The Johnstown flood of 1889 is well-known for its devastation of Johnstown and surrounding mining and milling communities of the Conemaugh Valley. More than 2200 lives were lost. Although the catastrophe is well documented in the popular literature and cinema, little scientific work has been done on this flood. Based on new surveys at the site and along the Conemaugh River, and review of contemporary photographs and historical documents, we are reexamining this event to reconstruct the peak discharge and flood hydrograph. Our presentation includes 1889 images of the South Fork dam breach and flood damage, present-day views of dam remnants, and a hydrologic analysis of the reservoir geometry and dam breach. One of our efforts is to reconcile 1889 elevation data and flood levels with modern-day GIS and GPS reference frames. An early result of our research is that the peak discharge rate for the flood appears to be controlled less by the release rate from the South Fork Reservoir and more by the sudden collapse of the massive Conemaugh viaduct bridge, 6 km downstream from the dam. A debris dam blocked the arch beneath this stone masonry bridge, causing water to build up in a river meander gorge until the bridge was overtopped and collapsed, releasing a flood wave that obliterated almost everything in its path. The peak discharge likely exceeded 12,000 m^3/s. Economic and material assistance from across the nation soon reached the Conemaugh Valley. The survivors rebuilt the communities, which once again thrived given the region's importance in coal production.

CONTROLS OF HYDROGRAPH SHAPE ON FLOODPLAIN SEDIMENTATION DURING MAJOR FLOODS

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Paleoflood analyses associate intervals of floodplain deposition with a specific discharge, operating on the assumption that deposition depends alone on the flood peak. However, this neglects the importance of other flood characteristics—such as time-to-peak and drawdown time—on the amount of sedimentation. Recent research indicates that hydrograph shape controls entrainment of sediment fractionally, so it follows that aspects of the hydrograph would also affect floodplain sedimentation, especially considering the time integral of overbank flow. This paper investigates these relationships using a 2D hydrodynamic and suspended sediment transport model (Telemac) applied to a 70 km reach of the Feather-Yuba Rivers, CA where recent large floods have remobilized sediment produced in 19th century mining. Total sediment influx per unit channel width (m^3/m), and deposition (m^3) resulting from nine days of a rapid-rising, and receding flood (1986) were compared to 18 days of an event exhibiting a steady rise and decline in discharge (1997). Differences between hydrograph characteristics reflect antecedent conditions, reservoir operations, and storm centers. Upstream boundary conditions were defined by hourly discharge measurements and suspended sediment concentrations derived from rating curves. Sediment (d_{50} = 0.03 mm) was transported to, and deposited onto, the floodplain over both the rising and falling limbs of each flood. With only 27 hours to rise, 84% of the total modeled 1986 deposition occurred after the discharge peak. In contrast, 52% of the total 1997 modeled deposition preceded the discharge peak by 10 hours. Although the sediment influx was greater in 1997 compared to 1986, three orders of magnitude less sedimentation resulted (0.0017×10^8 m^3 and 5×10^8 m^3 respectively). Rapid floodplain filling early in the 1986 flood increased resistance, limiting further incursion, lowering flow velocities, and increasing inundation depths 0.5 m to 11.5 m over the 1997 flood. Deposition was encouraged by the prolonged inundation period early in the flood when suspended sediment concentrations were high. Results suggest that sedimentation hysteresis patterns, as well as the sediment supply and flood peak are relevant to understanding overbank accretion processes during large floods.

RIVER TRAINING STRUCTURES: EFFECTS ON FLOW DYNAMICS, CHANNEL MORPHOLOGY, AND FLOOD LEVELS

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The use of river training structures to create a narrower and deeper river channel – including wing dikes, bendway weirs, and chevron dikes – along the Middle Mississippi River (MMR)has been linked to changes in flow conveyance and, in some locations, to large-scale increases in flood levels (up to 4 to 6 m). However, the mechanisms by which wing dikes impact flood conveyance are not fully understood. Previous research suggests river training structures may broadly affect flow conveyance: (1) through direct interaction with flow and/or (2) indirectly by their effects on channel geometry and bedforms.

Explicit assessment of training structure effects on flow conveyance was accomplished by constructing two 2-D hydrodynamic models: (1) a calibrated model of present river conditions (i.e., with wing dikes) and (2) a scenario model without training structures. Modeling results show that river training structures can locally create complex flow patterns, lengthening flow paths and thereby reducing flow velocities by up to -2.0 m/s (80% for a 40-year flow event). The reduction in flow velocity resulted in some losses of flow conveyance and corresponding increases in stage of up to 0.5 m. However, these results suggest that indirect effects are the primary driver of historic decreases in flood flow conveyance and large-scale increases in flood stages along the MMR.

Recent construction of new river training structures within St. Louis Harbor and the availability of pre-construction data provide a unique opportunity to test the impacts of these structures on flow dynamics, flood conveyance, and river channel morphology. Comparison of pre- and post-river-training structure construction bathymetry within St. Louis Harbor shows significant local aggradation (up to 3 m) within portions of the navigation channel instead of the desired incision (deepening). This unintended geomorphic response suggests current screening techniques (physical models) used in the design and placement for river training structure may be inadequate to accurately predict the complex geomorphic response created by the construction of such structures. We are currently testing numerical models to see if they have a better predicative capability.

GLACIAL MEGAFLOODS

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Megafloods (terrestrial water flows with discharges exceeding one million cubic meters per second) are the largest known freshwater floods, with flows comparable in scale to (though of shorter duration than) ocean currents. Although there are no modern examples of megafloods, such flows occurred during major periods of glaciation. A prominent example is the paleoflooding caused by late Pleistocene outbursts from Glacial Lake Missoula, which formed when the Purcell Lobe of the Cordilleran Ice Sheet extended south from British Columbia to the basin of modern Pend Oreille Lake in northern Idaho. The ice thereby impounded the Clark Fork River drainage to the east, forming a lake extending into western Montana with a water volume of about 2500 cubic kilometers and a depth of 600 m at the dam. The largest Lake Missoula

outbursts were in the range of 10 to 20 sverdrups (one sverdrup equals one million cubic meters per second) and involved flows that lasted several days. The Missoula Floods were responsible for generating the Channeled Scabland of east-central Washington state -- a complex of anastomosing rock-cut fluvial channels, cataracts, loess “islands,” rock basins, broad gravel deposits, and immense gravel bars. These flows deeply inundated the Columbia Gorge and the Willamette Valley before discharging into the Pacific Ocean. Other late-glacial megafloods occurred along the margins of the great ice sheets that formed during the Pleistocene in North America, Eurasia, and southern South America (Patagonia). River basins connected to these ice sheets were impacted by the flooding such that invasions of water changed drainage patterns, enlarged valleys, and delivered huge fluxes of water and sediment to the oceans. Numerous spillways were flood-integrated into temporary rivers in parts of North America (the St. Lawence, Mackenzie, Yukon, Mississippi, and Columbia Rivers) and Eurasia (the Ob, Irtysch, Yenesei, Volga, Dneiper Rivers). The late Pleistocene megafloods are associated with a broad range of hydrologic and climatic changes that are only now being fully understood.

DURATION AND TIMING OF GLACIAL OUTBURST FLOODS FROM PLEISTOCENE LAKE MISSOULA

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Effects of catastrophic drainage of Pleistocene glacial Lake Missoula were simulated using a sophisticated model for flooding and inundation of rugged, three-dimensional terrain. We used a three-dimensional domain of square cells 250m on a side, covering much of the Pacific Northwest of the United States. We simulated the Columbia River blocked with ice near the Okanogan valley to force flow through Grand Coulee and simulated a dam near the northernmost extent of the Clark’s Fork of the Columbia River to create a model of glacial Lake Missoula with a stage of 1250m. Sudden removal of the dam holding Lake Missoula simulated a dambreak flood, and created high model flood stages that match nearly all field indicators of high stage attributed to the Missoula Floods. Catastrophic rupture of the ice dam produced rapid flooding of eastern Washington, rapid filling of Pasco, Yakima, and Umatilla Basins, and then slow drainage of these basins through the Columbia Gorge. Details of this flood scenario are significant for interpreting field exposures. Flow occurs across the Cheney-Palouse Scablands and empties into the Snake River and then Pasco Basin before floodwaters racing along the Columbia River enter Pasco Basin from the north. Maximum rate of filling of Pasco, Yakima, and Umatilla Basins occurs when the rate of influx from the Cheney Palouse Scablands and Snake River is comparable to the influx through the Columbia River system. This initial scenario is unsustainable for more than a few days, however, as dropping stage in the Rathdrum-Spokane valley starves the flow into the Cheney-Palouse. By the third day most flow is through the Columbia River drainage. After three days, Lake Missoula has almost completely drained and the lake volume has been transferred to Pasco, Yakima, and Umatilla basins, with a minor amount draining through the Columbia Gorge downstream. Drainage of these basins through the Gorge requires another 25 days.

Landslide/Slope Stability Issues

ELEMENTS OF AN IMPROVED MODEL OF DEBRIS-FLOW MOTION

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A new depth-averaged model of one-dimensional debris-flow motion seamlessly connects the quasi-static mechanics of initiation with the inertial dynamics of fully developed flow. Previous debris-flow models fail to make this connection because they employ initial conditions with unbalanced forces arbitrarily specified by the modeler. Natural debris flows, in contrast, commence when the balance of forces is tipped by an infinitesimal amount. Mechanical feedbacks involving coupled shear deformation, porosity change, and pore-pressure change can then cause dramatic evolution of the force balance in the course of a few seconds, enhancing or hindering subsequent motion and determining the potential for liquefaction and flow. To represent such feedbacks, our new model describes coupled evolution of the depth-averaged solid volume fraction, m, depth-averaged porosity, 1-m, depth-averaged flow velocity, v, flow depth, h, and the non-hydrostatic component of basal pore-fluid pressure, p_{bed}. This coupling can drive motion toward dynamic equilibrium (yielding a slow landslide) or runaway acceleration and liquefaction (yielding a debris flow), contingent on evolution of m. We derive an evolution equation for m by considering mass conservation during porosity change in conjunction with the effects of both classical soil consolidation (caused by changes in effective normal stress) and dilatancy (caused by shearing). The dilatancy is characterized by an angle, ψ, which expresses the depth-averaged ratio of the plastic volume strain rate and shear strain rate. The value of ψ is positive during dilative behavior and negative during contractive behavior, but it necessarily evolves toward zero as m evolves toward a value that equilibrates with the ambient state of stress and shear rate. Moreover, as m and ψ evolve, p_{bed} evolves in concert because fluid is drawn toward regions of dilation and expelled from regions of contraction. Analytical solutions of simplified versions of the model equations illustrate the basic physics and feedback mechanisms involved. Numerical solutions of the full set of coupled partial differential equations exhibit a wide variety of behaviors, consistent with the behaviors observed in experiments and in the field.

THE PERFECT DEBRIS FLOW: AGGREGATED RESULTS FROM 28 LARGE-SCALE EXPERIMENTS

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Data collected during 28 controlled experiments reveal robust patterns as well as sources of variability in debris-flow dynamics. In each experiment ~10 m^3 of unsorted, water-saturated sediment composed mostly of sand and gravel discharged from behind a gate, descended a steep, 82-m flume, and formed a deposit on a nearly horizontal runout surface. Experiment subsets were distinguished by differing basal boundary conditions (1 vs. 16 mm roughness heights) and sediment mud contents (1 vs. 7 percent dry weight). Aggregated sensor measurements of evolving flow thicknesses, basal normal stresses, and basal pore-fluid pressures demonstrate that debris flows in all subsets developed dilated, coarse-grained, high-friction snouts, followed by bodies of nearly liquefied, finer-grained debris. Mud increased flow mobility by maintaining high pore pressures in flow bodies, and bed roughness reduced flow speeds but not distances of flow runout. Roughness had this effect because it promoted flow agitation that enhanced grain-size segregation, thereby aiding growth of lateral levees that channelized flow. Grain-size segregation also contributed to development of ubiquitous roll waves, which had diverse amplitudes exhibiting fractal number-size distributions. Despite the

presence of these waves and other sources of variability, the aggregated data have well-defined patterns that constrain individual terms in a depth-averaged debris-flow model. The data imply that local flow resistance evolved together with global flow dynamics, contradicting the hypothesis that any consistent rheology applied. We conclude that new evolution equations, not new rheologies, are needed to model the emergence of archetypical debris-flow behavior from the interactions of debris constituents.

Nuclear Issues

UNDERGROUND NUCLEAR PARKS: A POTENTIAL NEW USE FOR UNDERGROUND SPACE

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Expanding nuclear power generation is viewed increasingly as a means to reduce carbon dioxide emissions and provide abundant, reliable electricity. Underground siting of nuclear power plants and nuclear fuel cycle facilities is an alternative to continued exclusive reliance on surface siting and is a potential new use for underground space. A promising approach is the underground nuclear park (UNP). UNPs would be highly secure underground facilities for generating multi-gigawatt levels of baseload electricity with options for peaking electricity, hydrogen and/or process heat. UNPs would include collocated, multiple nuclear power plants and nuclear fuel cycle facilities such as spent fuel storage, nuclear waste disposal (repository), and perhaps reprocessing, enrichment, and fuel fabrication facilities, assuming a closed fuel-cycle policy. UNPs would be sited in appropriate hydrological and geological settings, deep within bedrock units having properties suitable for construction of large underground openings needed to house the nuclear power plants and other underground facilities. Inherent advantages of the UNP approach--automatically realized by being deep underground--include enhanced radiation shielding provided by the rock mass, robust physical security against aircraft and missile attack, and an increased margin of containment safety against low-probability, high-consequence reactor accidents. Other advantages include preservation of surface aesthetics, less environmental impact, greater seismic resistance, greater public acceptance, and reduced nuclear waste transportation cost and controversy. In addition, recent work indicates the potential for the UNP approach to achieve lower capital and operating costs relative to conventional surface-sited nuclear power plants. For example, the rock mass surrounding UNP openings would be a preexisting natural structural material providing shelter for the nuclear reactors, equipment, and materials, thereby avoiding much of the commodity (concrete and steel) and labor cost required to construct the containment structure and other buildings at surface-sited nuclear power plants. Concepts for UNPs in bedded salt and granitic rock will be presented, along with ideas for UNP-based energy systems.

UNDERSTANDING THE IMPACT OF FUTURE GLACIATION ON THE PERFORMANCE OF A CANADIAN DEEP GEOLOGICAL REPOSITORY FOR USED NUCLEAR FUEL

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The Nuclear Waste Management Organization was established by the nuclear electricity generators in Canada and is responsible for implementing Adaptive Phased Management, the approach selected by the Government of Canada for long-term management of used nuclear fuel generated by Canadian nuclear reactors. In support of this objective, NWMO is pursuing an active technical research and development program in the area of used fuel storage and repository engineering, geoscience, safety assessment, and technical support to the development of a collaborative siting process.

The NWMO reference time frame for the safety assessment of a deep geological repository (DGR) is one million years, roughly equivalent to the time scale for the radioactivity in used fuel to decrease to that due to its natural uranium content. Given that the North American continent has been re-glaciated approximately every 100,000 years over the past million years, it is expected that a DGR site within the northern latitudes of North America will be subject to glaciation events associated with long-term climate change. Since glacial cycles are likely the most intense of plausible natural perturbations to a site, their potential impacts on the key safety functions of a DGR have been investigated within the Canadian program for several years. Work programs are being directed to improve the understanding of geosphere responses to past and future glaciation cycles, acquire insight into the resilience of the geosphere at repository depths and provide a reasoned basis to support the treatment of long-term climate change in a DGR safety case. Some of the elements of the multidisciplinary approach include:

•· Physical and temporal boundary conditions related to future glaciation by simulating the magnitude and time rate of change of ice sheet thickness, ground surface temperature and permafrost occurrence, amongst other attributes;

•· Impacts on redox stability based on numerical simulations and paleohydrogeological investigations;

•· Deep groundwater flow system evolution and impacts of Thermo-Hydro-Mechanical effects imposed by glacial cycles;

•· Seismicity and faulting induced by glacial rebound; and

•· Natural analogue studies to assess the impact of permafrost (eg Lupin Mine) and ice sheets (Greenland Project) on groundwater flow.

Climate Change, Policy, and the Public

THE ROLE OF EARTH SCIENTISTS AND THE PUBLIC IN COMPLEX CLIMATE AND ENERGY ISSUES

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Mitigating climate change impacts and transitioning to less climate-impacting energy systems involves successful local and national policies on low-carbon energy systems, management of energy waste products, and sustainability of key resources such as water. Climate, energy, and water are closely coupled, and earth scientists have long played a key role in resource development for energy and in the environmental protection and management of water resources. For example, scientists at the National Labs are currently assessing whether transportation fuel can be extracted from oil shale while managing carbon emissions and water use. Scientists' knowledge of the relationship between climate impacts and the hydrologic cycle is essential to informing the public about the value of water sustainability and conservation efforts, particularly when the benefits of such efforts may not be obvious on the time scale of a single generation. Scientists are also called upon to manage waste products from energy systems that impact climate or the environment, for example through geologic storage of carbon dioxide and radioactive waste. Waste disposal systems are often controversial and can depend on public acceptance for success.

The importance of public participation in the success of energy and environmental policy can be seen in the different fates of two geologic radioactive waste repositories in the western United States. Selection of a site for radioactive waste disposal at Yucca Mountain was the result of a top-down policy imposed by Congress. Lack of public acceptance and political opposition in Nevada had roots in the perception that the siting process was not fair or based on scientific merit. After years of pressure from Nevada lawmakers, Congress plans to terminate the project. In contrast, the Waste Isolation Pilot Plant near Carlsbad, New Mexico has accepted transuranic radioactive waste since 1999. City leaders in Carlsbad asked the federal government in the early 1970s to site the repository near Carlsbad and public acceptance has grown steadily in response to economic benefits and public confidence that the repository can operate safely. This demonstrates that controversial energy and environmental projects are more likely to succeed when policy makers, the public, and scientists work in partnership.

PRE-CONFERENCE FIELD TRIP TO THE CHANNELED SCABLAND

Prior to the GSA meeting I participated in pre-meeting trip #402, "The Great Missoula Floods and the Channeled Scabland." This trip was led by Richard Waitt, Roger Denlinger, and James O'Connor of the USGS–Cascades Volcano Observatory. This circuit of the Channeled Scabland, Columbia valley, the Cordilleran ice sheet margin, and other areas provided a comprehensive view of the erosional and depositional evidence of the Missoula floods. We explored evidence that there may have been 90 or more floods during the Late Wisconsinan glaciation and that their peak discharges ranged over two orders of magnitude. We also explored different routings of floods governed by changing configurations of the Cordilleran-ice margin and saw how two-dimensional hydraulic modeling consistent with all field evidence can explain that even the greatest floods originated solely from glacial Lake Missoula. Our huge S-route wound from Spokane, Washington to the Cheney-Palouse scabland to northern Quincy Basin, Grand Coulee, the ice sheet margin near Chelan, Columbia valley, to immense floodforms near Wenatchee and Moses Coulee, including the site of a Clovis cache. The route then led across the Quincy basin to Drumheller and Ephrata scablands, to great scablands and floodbars of Washtucna coulee, and into Snake valley, immense bars in the Snake River basin, to rhythmites near Walla Walla revealing scores of great floods, to the bottleneck of Wallula Gap, and down Columbia valley and its gorge through the Cascades past great bars and scabland, ending among the great fluvial gravel bars of Portland. Along the field trip route we visited spots familiar to J Harlen Bretz as he was developing the story of one great "Spokane Flood" in the 1920s. Subsequent work has shown that the fluvial features of the region were caused by many floods, although the number of true “megafloods” (i.e., floods with discharges >10^6 m^3/s) continues to be debated.

Participants in the field trip are shown below in a group photograph. Trip leader Richard Waitt is at left center wearing a dark broad-rimmed hat.

Additional information about the Channeled Scabland and its landforms is available in an interview with Professor Victor Baker, University of Arizona, who is a world expert on the physical processes of catastrophic flooding. The link to this interview by the Public Broadcasting Service is: http://www.pbs.org/wgbh/nova/megaflood/fantastic.html

Dry Falls cataract complex of the Great Cataract group. These now-dry waterfalls were carved in basalt bedrock by a succession of megafloods through the Grand Coulee.

Western Columbia Gorge – view is looking eastward (upstream).

Giant fluvial bars in upper Crab Creek valley near Wilson Creek. Four large bars consisting of gravel, cobbles, and boulders were visible on the valley floor. The large one in the background here (lighter colored zone across center) is bar #2 of J Harlan Bretz. A portion of bar #3 is visible at far left center. These large fluvial bars were deposited by waning high-energy Missoula floodwaters.

View of West Bar across the Columbia River. These asymmetric giant current dunes reveal downvalley flow of megaflood proportions.

Giant boulder transported by Okanogan glacial ice. This is a true glacial erratic, not transported by megaflooding. This 8-m high boulder, named "Yeager Rock," is located along SR172 on the Waterville Plateau, Washington state.

Richard Waitt (USGS) describing stratigraphic details of rhythmically-bedded deposits at Burlingame Ravine, in southern Washington due west of Walla Walla. This stratigraphic section reveals slackwater facies of the Missoula floods, and provides evidence that there were dozens of Missoula floods. As water ponded deeply behind the constrictions caused by Wallula Gap and the Columbia Gorge downriver, it backflooded 240 m deep (or more) up the Walla Walla and Yakima valleys. The deposits expose a stratigraphic section of 39 or 40 normally graded beds.