41cm of displacement using total station on 31st August 2002. In 1969, Ambrasys (1970) reported 24 cm displacement of the wall and Aytun(1995) measured 18cm. Between 1969 and 1972, Aytun(1995) also measured 0.6cm/yr average creeping rate using geodetic methods at the same site. Altay et al. (1991) observed 0.77cm/yr creeping rate using creep-meter between 1982 and 1990. These data provides us that cumulative displacement is 23cm and average creeping rate is approximately 0.7cm/yr between 1969 and 2002. In the early summer of 2002, we found the triggered surface slips of 3-6cm of right lateral probably associated with the 1999 Izmit earthquake of Ms7.4, at three sites along 3km-long strand of the Ismetpasa. The epicenter of the earthquake is located 225km, and the eastern tip of the surface rupture is 155km west of Ismetpasa. Those sites are 1) 2km west of the highway station, we observed 3cm displacement on the concrete garden wall of s gas station. The owner of the gas station explained that significant damage of the wall was realized right after the Izmit earthquake. 2) 200m west of the station we measured 6cm displacement on the railway road. 3) At Hamamli village, 1km east of the station, a few cm offset was founded on the brick-wall of house for livestock and on the paved road near the house a few days after the Izmit earthquake. We measured 6cm horizontal and 2cm vertical offset there. There is no information on a stable creeping at sites 1) and 2) since the 1999 earthquake.

It is not clear whether creeping on the section has been constant or consisted of episodic small slips like the 1999 event since 1990. In addition such a high creeping rate cant be neglected when we consider the recurrence of large earthquake events on NAFZ. From these points of view, we started the periodic geodetic measurements of the fault creep at Ismetpasa.

### S11B-1157 0830h POSTER

## Jog Structures at Both Ends of the Tepetarla Segment Ruptured as the First Subevent of the 1999 Izmit Earthquakes, Turkey, Revealed by Acoustic Surveys in the Izmit Bay and the Sapanca Lake

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Size and geometry of jogs among fault segments play important roles in rupture propagation during large earthquakes. We carried out a very detail acoustic survey around the both ends of the Tepetarla (Sapanca) segment, which ruptured as the first sub-event of the 1999 Izmit earthquakes of Mw7.4, in the Izmit Bay and the Sapanca Lake, using a very high-resolution, acoustic profiling system ?Sono-prob?(SP-3W; 3-8kH) and a sidescan sonar (DF1000). Survey lines were designed at 250 m interval to capture the details of fault geometry.

The Tepetarla segment on land is traceable for 19km almost straightly and continuously trending east to west with an average displacement of 2.8+-0.2 (one sigma) m. East of the segment continues in to the Sapanca Lake for about10km and makes a releasing double bends as the jog structure between Tepetarla and Arifiye segments. The double bends is 8 km-long and 2 km-wide consists of en-echelon faults with normal component of slip. East on the lake, the jog appeared on land for 2 km-long, as a 500 m-wide graben. Although South on the Arifiye segment there are several secondary faults making a hose tail structure, we couldn?t find any recent fault south of the tepetarla segment in the Sapanca Lake. West of the tepetarla segment continues into the Izmit Bay for 6 km making a releasing pull-apart structure between Golcuk and Tepetarla segments. The basin is 8 km-long , 3 km-wide and about 15 square km, surrounded by faults that have normal component. Subsidence of the large area of south coast of the Izmit Bay during the earthquake suggests that this pull-apart structure stretches at least several km deep. Those differentiations of geometry and size of jogs might strongly influence the rupture process of the 1999 Izmit earthquake.

# S11C MCC: Hall C Monday 0830h

## Volcano Seismology Posters *(joint with V)*

***Presiding:*** **B R Julian,** U.S. Geological Survey**; L House,** Los Alamos Seismic Research Center

### S11C-1158 0830h POSTER

## Using Accurate Hypocenter Locations to Understand Volcanic Earthquake Mechanisms

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Many well-determined moment-tensor focal mechanisms for earthquakes in volcanic and geothermal areas have significant non-double-couple components and involve volume changes. This observation rules out pure shear faulting, even on multiple faults, as the cause of such earthquakes, but is not in itself sufficient to uniquely resolve the source process. Radiated seismic waves depend only on the equivalent force system, which is not uniquely related to the source process. The geometry of seismic failure zones, as delineated by precise locations of earthquake hypocenters within clusters, offers a promising additional constraint.

We determined high-resolution earthquake hypocenters from Long Valley caldera, California, by applying the "HYPODD" algorithm (Waldhauser and Ellsworth, 2000) to data from 64 3-component digital seismometers deployed in the summer of 1997. This network also provides a rich set of P- and SH-wave polarities and amplitude ratios that are well distributed over the focal spheres of earthquakes in the south moat of the caldera, and which tightly constrain their focal mechanisms.

The hypocenters clearly resolve numerous planar failure zones with sizes ranging from a few hundred meters to 2 km. In many cases these planes pass through the middle of the dilatational P-wave polarity field, a situation compatible with the planes representing tensile faults, but not shear faults. The hypocenter locations thus support the conclusion drawn from moment tensors derived from amplitude ratios. The simplest interpretation of the focal mechanisms plus the hypocentral distributions is that the seismic source processes involve simultaneous tensile and shear failure, with the volume change reduced by some compensating process, probably related to rapid fluid flow.

### S11C-1159 0830h POSTER

## Waveform inversion of oscillatory signatures in long-period events beneath volcanoes

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The source mechanism of long-period (LP) events is examined using synthetic waveforms generated by the acoustic resonance of a fluid-filled crack. We perform a series of numerical tests in which the oscillatory signatures of synthetic LP waveforms are used to determine the source-time functions of the six moment tensor components from waveform inversions assuming a point source. The results indicate that the moment tensor representation is valid for the odd modes of crack resonance with wavelengths 2L/n,2W/n, n=3,5,7,..., where L and W are the crack length and width, respectively. For the even modes with wavelengths 2L/n, 2W/n, n=2,4,6,..., a generalized source representation using higher order tensors is required. In light of the small excitation efficiency of seismic waves in the even modes, the moment tensor inversion may be generally applicable to LP events. Our numerical tests also suggest that more than four, and ideally ten to fifteen, three-component stations surrounding an LP source are required for an accurate description of the moment tensor. We apply the moment tensor inversion to the oscillatory signatures of an LP event observed at Kusatsu-Shirane Volcano, central Japan. Our results point to the resonance of a sub-horizontal crack located a few hundred meters beneath the summit crater lakes. This finding may be regarded as the first direct and solid evidence supporting the idea that LP events originate in the resonance of a crack. The present approach may be useful to quantify the source location, geometry, and force system of LP events, and opens the way for moment tensor inversions of tremor.

### S11C-1160 0830h POSTER

## Seismicity at Great Sitkin Volcano, Andreanof Islands, Alaska

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In 1999, the Alaska Volcano Observatory (AVO) installed 6 telemetered, short-period seismic stations around Great Sitkin (GS) volcano as part of a 14-station volcano-monitoring network in the Andreanof Islands of Alaska. Since that time, AVO has located over 890 earthquakes within 10 km of GS, the third-highest seismicity rate of the 23 volcanoes monitored by AVO over the period 1999-present. GS has arguably the most diverse background seismicity of all 23 volcanoes. Recorded seismicity includes several minutes-to-hour-long tremor episodes, shallow and deep (> 10 km) long-period events, swarms of distal volcano-tectonic earthquakes, and two of the largest earthquakes ($M_L$ 4.3) ever recorded by AVO near a monitored volcano. The rate and character of seismicity suggests that magma may be moving in the GS system.

Of particular interest are two earthquake swarms that occurred in March-April and May-July of 2002. The first began March 17, consisted of more than 320 events located 15-20 km west of GS at depths of 10-25 km, and lasted for over 5 weeks. The mainshock ($M_L$ 4.3) occurred ~20 hours after the swarm's onset. The second swarm began May 28, consisted of over 460 events located 5-8 km southeast of GS at depths of 5-15 km, and lasted for over two months. The mainshock (also $M_L$ 4.3) occurred ~9 hours after the swarm's onset. This second swarm was preceded by two tremor episodes on May 27, one lasting for 20 minutes, the second lasting for an hour. Although the spatial relationship between the tremor episodes and the second swarm is unclear, the close temporal relationship suggests a common seismogenic process that could be magmatic in origin. We use cross-correlation and relative relocation techniques to more precisely determine the location and depth extent of the swarms, and calculate Coulomb stress changes to investigate whether static stress adjustments associated with magma intrusion beneath GS could have caused the two swarms.

### S11C-1161 0830h POSTER

## Relocation of Seismicity at Mauna Loa, Hawaii and Hengill, Iceland: Improved Delineation of Seismogenic Structures.

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Waveform cross-correlation based refinement of P arrival times and subsequent relocation of earthquakes was determined for events that occurred near the summit of Mauna Loa, Hawaii prior to the March, 1984 eruption and at the Hengill volcano, Iceland during a

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two-month survey in 1991. Hengill and Mauna Loa volcanoes have a similar rift structure and are hot-spot related volcanoes.

The relocated events at Mauna Loa illuminated a previously obscured structure beneath the northwestern flank. Simultaneous inversion for hypocenters and velocity model parameters using the refined arrival times resulted in well-constrained relative earthquake locations with very low arrival time misfits (average RMS 0.03 s). Pre-eruption seismicity from this time period occurred in two groups: a shallow group located near the Mauna Loa summit region, at depths of 1-3 km, and a deeper group located 4-6 km northwest of the summit, at depths of 5-10 km. After relocation, we found that most of the northwest flank earthquakes occurred along a 1 km planar feature striking about 60$^o$ E of North in a thin band about 500 m thick. This feature we interpret to be related to a rift zone that was stunted by the buttressing of the adjacent volcanoes Hualalai and Mauna Kea. Previous gravity and magnetic studies provide supporting evidence for the existence of a failed rift zone. Northwest flank focal mechanisms reveal a change in faulting from strike-slip in the southwest to a mix of strike-slip and normal faulting in the northeast.

The near summit seismicity that was previously diffuse (4.5 km in width) is reduced to a 6 km long feature (0.5 km in width) extending from depth (6 km) toward the summit. The focal mechanisms analyzed from the summit events showed a mix of faulting without a consistent pattern.

Previous studies at Hengill yielded locations of seismic activity that extend from 2-6 km in depth and no apparent correlation with surface features. The existence of non-double-couple focal mechanisms has been confirmed and attributed to high fluid pressures arising from geothermal activity. With the application of these relocation techniques, we hope to improve the resolution of any existing hypocenter clusters and/or fine scale subsurface structures.

## S11C-1162 0830h POSTER

### Seismic Monitoring of Volcanic Hazards in Valles Caldera, NM

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Valles Caldera, in north central New Mexico, was formed by major eruptions at about 1.2 and 1.6 Ma. Less intense volcanism has continued since then, with the most recent activity dated at about 60Ka. Since the caldera lies only about 20 km west of Los Alamos, any new volcanic activity within it could endanger Los Alamos (as well as other communities nearby). To help monitor any new activity, a seismic station (PER) was installed near the southern edge of the caldera, about 6 km SE of the El Cajete vent, the source of the most recent activity. Proximity to El Cajete was the major siting criteria, though the exact placement of the station also depended on factors such as quality of rock outcrop, solar exposure, radio telemetry (limited by mountains), and accessibility. There have been no earthquakes within the caldera during nearly 30 years of operation of the Los Alamos Seismograph Network (LASN). Several earthquakes were located to the south of the caldera and within about 10 km of it; the largest was about magnitude 1.5, the smallest, about magnitude 0. Thus, it appears that the interior of the caldera is non-seismic, perhaps down to magnitude 0.5 or 0. The data from the new PER station improves the sensitivity of the monitoring, and can provide hypocenters of earthquakes too small to be located by the network. PER initially had short-period, high-gain, three-component instrumentation, and recently was upgraded with broad-band equipment. Data from PER are recorded as part of the full network, which requires several station triggers for an event trigger, and as a single-station network, which event triggers with just a single trace. The single-station recording resulted in many thousands of spurious triggers. We chose to study microearthquakes whose S-P times were 2 s or less at PER. These were very small, with magnitudes of about -1 or less. To locate them, we used P-wave particle motions, which can have large uncertainties, because of relatively low signal to noise ratios. Nevertheless, because the PER station is so close to the El Cajete vent, even with a large uncertainty in azimuth, epicenters near the station can still be located within a km or so. An accompanying talk (Frostenson and House) discusses these earthquakes further.

## S11C-1163 0830h POSTER

### Seismicity Located by a Station Near Valles Caldera, NM

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Four years of seismicity data from a new station located near the Valles Caldera of north-central New Mexico were analyzed to locate earthquakes within and near the caldera. The new station (called PER) was installed to study seismicity and volcanic hazards associated with the caldera. A previous talk (House and Frostenson) described the setting of this station. The station is located about 6 km from the El Cajete vent, which was the source of the most recent (about 60Ka) volcanic activity in the caldera. We were particularly interested in studying microearthquakes too small to be detected by the stations of the nearby Los Alamos Seismograph Network (LASN). Nearly four years of data from this station were scanned to identify microearthquakes with S-P times of 2 s or less at PER. A total of 18 microearthquakes were selected for study from many thousands of single-station event triggers. Most were so small that they could not be located by the network. We located them using particle motion directions (hodograms) and S-P times at station PER. The largest had a magnitude of about -1.5. Particle motions of several were indeterminate, and a total of 14 could be located. Initially we assumed the earthquakes occurred at the surface. Four epicenters are within five km of the El Cajete vent, and three of these occurred within a day of each other. Most of the remaining events were located south of the caldera, in an area with a moderate number of earthquakes located by the network. Many of the events have large vertical particle motions relative to horizontals, so they presumably occurred at some depth beneath station PER. Determining their depths (from particle motions) will be important for better understanding of how the earthquakes relate to other processes going on in the caldera. Ten of the 14 events occurred in three one-day-long miniswarms. Data from additional stations would provide better constraint on these hypocenters. Nevertheless, monitoring by this one station may be enough to obtain an indication of any new volcanic activity associated with this recently active vent.

## S11C-1164 0830h POSTER

### Seismotectonics of the Cerro Prieto Geothermal Field, Baja California, Mexico.

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We studied the background seismic activity in the Cerro Prieto geothermal field (CPGF) using a network of 21 digital stations. Earthquakes are located below the exploitation area of the CPGF, between 3 and 12 km depth, within the basement. Earthquakes follow roughly a N30$^o$E trend perpendicular to the Cerro Prieto fault. This activity is located on a horst-like structure below the geothermal field and coincides with the zone of maximum subsidence in the CPGF. Two earthquake swarms occurred along the SE-NW strike of the Cerro Prieto fault and in the neighborhood of the Cerro Prieto volcano. Magnitudes range from -0.3 to 2.5. A Vp/Vs=1.91 ratio of the activity below the volcano suggests a water-saturated medium and/or a partial-melt medium. We calculated 76 focal mechanisms of individual events. On June 1 and September 10, 1999, two earthquakes of Mw 5.2 and 5.3 occurred in the basement at depths of 7.4 and 3.8 km below the CPGF. Maximum peak accelerations above the hypocenter ranged from 128.0 to 432.0 cm/s$^2$. Waveform modeling results in a fault geometries given by strike=236$^o$, dip=60$^o$, rake=-58$^o$(normal) and strike=10$^o$, dip=90$^o$, rake=159$^o$(right lateral strike-slip) for the June and September events. Observed triangular source time function of 0.7 seconds and a double source with a total duration of 1.9 seconds for the June and September events were used to calculate the synthetics seismograms. Static stress drops and seismic moments for the June and September events are: $\Delta\sigma = 82.5MPa(825bars)$, $Mo = 7.65x10^{16}$ Nm (7.65x10$^{23}$ dyne-cm) and $\Delta\sigma = 31.3MPa(313bars) and Mo = 1.27x10^{17}$ Nm (1.27x10$^{24}$ dyne-cm). These stress drops are typical of continental events rather than stress drops of events originated in spreading centers. We concluded from the focal mechanisms of the background seismicity and June and September 1999 events, that a complex stress environment exits in the CPGF due to the continual thinning of the crust in the Cerro Prieto basin.

## S11C-1165 0830h POSTER

### Seismic Activity at Vailulu'u, Samoa's Youngest Volcano

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Submarine volcanic systems, as a product of the Earth's mantle, play an essential role in the Earth's heat budget and in the interaction between the solid Earth and the hydrosphere and biosphere. Their eruptive and intrusive activity exerts an important control on these hydrothermal systems.

In March 2000, we deployed an array of five ocean bottom hydrophones (OBH) on the summit region (625-995 m water depth) of Vailuluu Volcano (14$^o$12.9'S;169$^o$03.5'W); this volcano represents the active end of the Samoan hotspot chain and is one of only a few well-studied intra-plate submarine volcanoes. We monitored seismic activity for up to 12 months at low sample rate (25 Hz), and for shorter times at a higher sample rate (125 Hz).

We have begun to catalogue and locate a variety of acoustic events from this network. Ambient ocean noise was filtered out by a 4th-order Butterworth bandpass filter (2.3 - 10 Hz). We distinguish small local earthquakes from teleseismic activity, mostly identified by T- (acoustic) waves, by comparison with a nearby GSN station (AFI). Most of the detected events are T-phases from teleseismic earthquakes, characterized by their emergent coda and high frequency content (up to 30 Hz); the latter distinguishes them from low frequency emergent signals associated with the volcano (e.g. tremor). A second type of event is characterized by impulsive arrivals, with coda lasting a few seconds. The differences in arrival times between stations on the volcano are too small for these events to be T-waves; they are very likely to be local events, since the GSN station in Western Samoa (AFI) shows no arrivals close in time to these events. Preliminary locations show that these small events occur approximately once per day and are located within the volcano (the 95% confidence ellipse is similar to the size of the volcano, due to the small size of the OBH network). Several events are located relatively close to each other (within a km radius) just NW of the crater.

## S11C-1166 0830h POSTER

### Swarm Sequences in the Waiotapu and Waimangu Geothermal Areas, New Zealand, January-June 1995

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From January 1995 until June 1995, New Zealand's Institute of Geological and Nuclear Sciences, the University of Memphis, and the University of Leeds jointly conducted a large-scale seismic experiment in the Taupo Volcanic Zone (TVZ), New Zealand. Permanent New Zealand National Seismograph Network seismic stations in the central North Island were supplemented by the deployment of 64 short-period seismometers and 21 broadband sensors, covering an area of about 210 km$^2$ with an inter-station spacing of 5-15 km. The additional stations were sited so as to cover the most historically active sections of the central and northern TVZ, such as the Taupo Fault Belt, volcanic centers, and areas of surficial geothermal activity, as well as to extend profiles to basement rocks on either side of the TVZ.

During the deployment, preliminary earthquake locations showed that at least 12 shallow (depth < 10 km) swarm sequences comprising five or more small ($1.2 < M_L < 2.9$) events occurred in the vicinity of the Waiotapu and Waimangu geothermal areas, with several additional swarms occurring just to the northwest of these geothermal areas within the Taupo Fault Belt. Individual events were scattered throughout the eastern half of the Waiotapu thermal area, the northern two-thirds of the Waimangu thermal area, and the Taupo Fault belt in the vicinity of the geothermal areas.

More precise locations using a combination of waveform correlation techniques to align P-wave picks among events and relative location techniques to calculate event hypocenters show hypocenters to be more tightly clustered than the initial locations, with epicentral source regions for individual swarms ranging from

near-point sources to zones with a maximum dimension of about 5 km. Source regions for some of the swarm sequences overlap with those from other sequences, while others occur in spatially distinct regions, suggesting that there are a number of processes causing these events and that some of these processes are repetitive in time. Similarity of waveforms at individual seismic stations during several different swarm sequences further supports the existence of one or more repetitive, long-lived source processes.

### S11C-1167 0830h POSTER

### Relocating the Hypocenters of an Earthquake Swarm Near Waiouru, South East of Ruapehu, North Island, New Zealand

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Over the past ten years, there has been continuous lower-crustal seismicity in the magnitude range $1.7<=M_L>=4.2$ near Waiouru, 20km south east of Mount Ruapehu, New Zealand, averaging 13 events per month. This study uses the Double-Differencing algorithm of Waldhauser and Ellsworth (2000) to produce precise relative relocations of the hypocenters and thus analyze seismicity, testing whether the swarms origins are tectonic or volcanic. Data comes from a temporary seismic network deployment (CNIPSE) from January to June 2001, which significantly increased the number of stations recording the swarm.

The final relocation reveals earthquakes aligned on a fault-plane oriented 219°, dipping 6°NW, parallel with the surface fault break of the Snow Grass Fault. Composite focal mechanisms reveal normal faulting, oriented 216°, dipping 48°NW. These two fault-plane orientations are parallel, and indicate extension in the Waiouru area. An average b-value of 1.06 over ten years implies tectonic causes.

Activity increased to over 40 events per month in January and March of 1995, coinciding with heating phases in the Ruapehu Crater Lake before the eruption in September 1995. The b-value of the swarm over this period rose to b=1.71, and stayed high through activity in late 1996. Both this high b-value and the temporal correlation suggest the swarm was related to volcanic activity.

Results suggest a complicated relationship between a tectonic swarm associated with propagation of back-arc spreading of the Taupo Volcanic Zone, overprinted with volcanic associations at times of activity on Ruapehu.

### S11C-1168 0830h POSTER

### Seismic Velocity Structures of Larderello Geothermal System, Italy: Preliminary Results

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The steam-dominated geothermal system of Larderello is located in Tuscany and is the largest Italian area of electricity generation from geothermal resources. Enel Green Power, the main company of the ENEL Group involved in the renewable resources development, has drilled several wells down to maximum depth of about 4.0 km below see level in order to exploit deep and hot steam reservoirs. The explored area is about 400 $km^2$ with an installed running capacity of about 530 MW. Two steam-dominated reservoirs were found at different depth. The shallowest one at depth of about 1 km, with pressure between 0.2 and 1.5 MPa and temperatures ranging between 150°C and 260°C, is hosted in very permeable carbonate formations (limestone and anhydrite). The deepest reservoir is located in the metamorphic basement up to depth of 3-4 km b.s.l. and is characterized by pressure of about 7.0 MPa and temperature ranging between 300°C and 350°C. Water reinjection is operating in the shallow reservoir of the geothermal area with the aim of both sustaining and increasing reservoir pressures as well as steam production. A network of 26 seismic stations, three of which are three components, permanently records the seismic activity of the Larderello area. Data analysis showed that epicenters span over the whole exploited region even though clusters are visible in particular areas; hypocentral depths are mainly distributed up to 10 km. More detailed hypocenter re-localization might indicate linear features due to regional stress field regime and to the fluid propagation paths into the fracture systems that previously might have been obscured within the seismic clouds. However, precise hypocenter localization calls for high-resolution 3D-velocity model of subsurface structures that is lacking for this area. This study has been addressed to purse this goal and, as a consequence, images of the seismic velocity structures from earthquakes tomographic inversion have been computed. This area was chosen as a suitable test site since the availability of well data can provide a more constrained a priori velocity model. The analyzed data set consists of approximately 500 microearthquakes occurring from January 1994 through September 2000. The estimate duration magnitude ranges between 0-3. The good quality of recorded waveforms allowed us for high precision readings of P- and S- wave first arrivals. Results of a 3D velocity tomographic inversion contributed for a high-quality imaging of subsurface structures in term of Vp and Vp/Vs ratio that may be correlated to the main geological features of the geothermal system.

## S11D MCC: 133 Monday 0830h

### Forensic Seismology: Exotic Seismic Sources and Man-Made Events I *(joint with OS, PA)*

***Presiding:*** **K D Koper,** Saint Louis University**; T Wallace,** University of Arizona

### S11D-01 0835h INVITED

### Forensic Seismology and Nuclear Explosion Monitoring

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Forensic seismology was first termed by H.I.S. Thirlaway in the late 1950s to describe what is now known as verification seismology. In nuclear monitoring it is often the study of anomalous events that for some reason caused an operational system to break down. Examples of events that have elicited study include abnormal mining explosions, mine collapse and rockbursts, earthquakes near nuclear test sites and anomalous nuclear explosions. Analysis of these anomalous disturbances has been the key to understanding source physics. This information in turn, has improved our understanding of the physical basis of seismic event identification, yield estimation, and evasion scenarios. In this talk, we will review examples of anomalous disturbances from different types of sources and how the subsequent analysis led to an improved understanding the effect of source phenomenology on nuclear explosion monitoring.

### S11D-02 0855h

### Seismology of Impacts

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Impacts of natural and artificial objects can generate significant seismic signals. Such impacts have been recorded by seismometers on a number of occasions. Aside from the public and media interest that such events generate, the signals can exhibit a wide variety of characteristics such that standard discrimination and source identification criteria may fail.

Impact events additionally have the interesting property that the kinetic energy of the impactor is known *a priori* or can be estimated using simple assumptions. This enables estimates of the maximum size and detectability of the seismic signal from any arbitrary impact scenario.

We have assembled a number of such events that have well-recorded on modern seismic systems, and have used the seismic data and information from other sources to develop a relation between the energy of impactor and the corresponding seismic signal. Modelling of the seismic signals has been shown to provide information about the source process. Examples are provided from artificial sources such as aircraft crashes on land and water, from various industrial accidents, and from a variety of natural sources.

### S11D-03 0915h INVITED

### Seismic Waves Generated by Aircraft Impacts and Building Collapses at World Trade Center, New York City and Shanksville, Pennsylvania on September 11, 2001.

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Seismologists sometimes do their work of data acquisition and analysis against a tragic background. Usually the context is fieldwork far from home, in an area subjected to the natural but sometimes devastating effects of an earthquake. As the appalling events of September 11, 2001 unfolded, we found that we had recorded numerous seismic signals of two plane impacts and building collapses, often at times different than those being reported elsewhere. Collapses of the two World Trade Center (WTC) towers generated the largest seismic waves, observed in five states and up to 428 km away. The North Tower collapse was the largest seismic source and had local magnitude ML 2.3. From this we infer that ground shaking of the WTC towers was not a major contributor to the collapse or damage to surrounding buildings.

The time of plane impact at the Pentagon on September 11, 2001 had often been reported with large scatter. We analyzed seismic records from five stations in the northeastern United States, ranging from 63 to 350 km from the Pentagon to examine whether we could obtain an accurate time of the Pentagon attack based upon our seismic network. Despite detailed analysis of the data, we could not find a clear seismic signal. Even the closest station ($\Delta$= 62.8 km) at Soldier's Delight, Baltimore County, Maryland (SDMD) did not record the impact. However, we positively identified seismic signals associated with United Airlines Flight 93 that crashed near Shanksville, Somerset County, Pennsylvania. The time of the plane crash was 10:06:05±5 (EDT). We recognized that information on accurate timing of earthquakes and other events is very desirable for emergency management agencies and government authorities handling mitigation efforts as well as for general public, and that the modern seismographic stations with accurate clocks can provide such reference time as long as there are discernable ground motion associate with such sources.

### S11D-04 0935h

### A Case Study in Forensic Seismology: The 1998 Natural Gas Pipeline Explosion Near Carlsbad, New Mexico

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On August 19, 2000 two seismometer networks in southeastern New Mexico recorded signals from a natural gas pipeline explosion. The explosion killed 12 members of an extended family that had been camping on the banks of a nearby river. Analysis of the particle motion, arrival times, and durations of the seismic signals indicate that three impulsive events occurred with origin times of 11:26:18.8 ± 1.9, 11:26:43.6 ± 2.1, and 11:27:01.7 ± 2.0 (GMT). Each event generated an $R_g$ wave with group velocity of 1.7-2.0 km/s and an air-coupled Rayleigh wave with a group velocity of about 345 m/s. The air-coupled Rayleigh waves had especially large amplitudes because of a geometric waveguide created by an atmospheric temperature inversion at the time of the accident. The first event was due to the explosive blowout of the buried, high-pressure pipeline while the second event was due to the ignition of the vented natural gas. The nature of the third event is unclear, however it was likely created by a secondary ignition. There were also two extended seismic events

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