edges. Although the shape of an isolated non-wetting fluid-filled pore is not affected by deformation, the geometry of an initially random distribution of pores is substantially changed. To explore this phenomenon, deformation experiments were performed in a Paterson gas-medium apparatus on samples of olivine + aqueous fluid and diopside + aqueous fluid. In sheared samples, pore fluid is segregated into planar regions of high fluid fraction, which in 2D we refer to as 'bands of pore fluid. The bands form at an angle of 20° to the shear direction and in a sense antithetic to the shear. The degree of interconnection of pores within bands depends on the wetting behavior of the solid-fluid system and on the extent of deformation of the solid matrix. The permeability of the system to porous flow will be highly anisotropic under such conditions. Porous flow of fluid perpendicular to the length of the bands will be limited by flow in the relatively fluid-free regions between the bands. Porous flow parallel to the bands will be limited by grain size for non-wetting fluids and by channel dimensions for wetting fluids. In subduction zones, the subducting slab releases aqueous fluids upon devolatilization of hydrous minerals. Corner flow in the mantle wedge will focus the free aqueous fluid into linear bands. Thus, porous flow of the free aqueous fluid through the mantle wedge to the melting source region can take place along highly anisotropic, high-permeability paths.

**T31F-11 1120h**

### The Role of Flux Melting on U-series Systematics of Young Lavas from Costa Rica and Nicaragua

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We have acquired U, Th and Pa isotope data for young lavas that derive from source regions affected by slab fluid addition that ranges in magnitude from minor beneath Costa Rica to substantial beneath Nicaragua. Four of the five Costa Rican samples have ($^{231}$Pa/$^{235}$U) and ($^{230}$Th/$^{238}$U)>1; five out of six Nicaraguan lavas have ($^{230}$Th/$^{238}$U)<1 and ($^{231}$Pa/$^{235}$U)>1, but ($^{231}$Pa/$^{235}$U) ranges to lower values in Nicaragua. On a ($^{231}$Pa/$^{235}$U) vs. ($^{230}$Th/$^{238}$U) diagram, the data, though limited in number, seem to define two trends with decreasing ($^{230}$Th/$^{238}$U), one with a slope of ~2.5 and the other with a slope of ~0.7. Trace element ratios indicate that the latter were affected more by addition of hemipelagic sediment, suggesting a link between subduction-fluid source and Pa-Th-U systematics.

The combined $^{231}$Pa-$^{235}$U and $^{232}$Th-$^{238}$U-$^{230}$Th data provide constraints on the timing and mechanisms of fluid addition and partial melting beneath the Central American arc. Significant ($^{231}$Pa/$^{235}$U) excesses (>1.5) in both Costa Rica and Nicaragua require a melting process that allows for ingrowth, as simple batch or fractional melting cannot explain the excesses at melt fractions large enough to explain trace element abundances and ratios. We propose a flux-ingrowth melting model in which the mantle wedge flows downward with the subducting slab and partially melts as fluid is added to regions with suitably hot temperature. We assume critical melting at low porosity ($\sim 10^{-3}$) and that melt extraction and transport are rapid enough (< 8 kyr) to preserve observed $^{226}$Ra excesses. Because solid mantle may traverse the melting region over $10^5$-$10^6$ yrs., $^{231}$Pa and $^{230}$Th ingrow from U retained in the matrix. Magmas are aggregated instantaneously from all parts of the melting regime.

This flux-ingrowth model matches a wide range of U-series and trace element data from Costa Rican and Nicaraguan lavas, with required average extents of melting of ~1% and 8-10%, respectively. Integration of melts from regions that have experienced extensive fluid addition, partial melting and U-daughter ingrowth with those from incipiently fluxed and melted regions yields liquids with elevated ($^{231}$Pa/$^{235}$U) even after extensive fluid addition. The model produces linear arrays on Th isotope equiline plots which resemble isochrons, but which have no age significance. Upwelling and/or extensive melt-rock reaction is not required by U-series data from Central America or other arcs. Finally, the flux-ingrowth model is broadly consistent with substantial $^{226}$Ra excesses in Nicaragua without requiring the action of a distinct late slab fluid.

**T31F-12 1135h**

### New constraints on element transfer rates beneath the Tonga-Kermadec arc from combined U-Th-Ra, U-Pa and Be isotope data

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The intra-oceanic Tonga-Kermadec island arc has formed by westward subduction of Pacific oceanic lithosphere beneath the Australian plate. The arc volcanoes are located 110 km above the surface of the subducting plate and typically erupt basaltic-andesites and andesites with subordinate volumes of dacites and rhyolites. Active back arc spreading has formed the Lau Basin and Havre Trough behind the arc and resulted in the mantle wedge beneath the arc becoming highly depleted. This arc has been the focus of much interest because the depleted nature of the mantle wedge renders it highly sensitive to additions from the subducting plate. In common with many other island arcs, trace element and isotope data can be used to identify separate fluid and sediment contributions to the source of the erupted lavas and we have analysed U-Th-Ra, U-Pa and Be isotopes in order to place constraints on the time scales and physical processes involved in generating the Tonga-Kermadec lavas. Recognition of a Louisville volcaniclastic sediment contribution to the northern-most Tonga lavas has been used to estimate that addition of the sediment component may have occurred as long as 2-4 Myr ago. New Be isotope data show that Be isotope ratios range from 1-10 in the lavas but that the subducting sediments have quite low 10Be contents. Combined with the condensed sediment section this requires that almost the entire sediment section is subducted and that Be recycling into the arc lavas is 30% efficient. The largest Be isotope ratios are found in those lavas which also exhibit the largest U- and Ra-excesses which suggests that Be is stripped from the sediment pile and transported into the magma generation zone by fluids released from the underlying altered oceanic crust. This is consistent with recent fluid-mineral partitioning data and means that Be cannot be used to infer the sediment transfer time. Ra-Th activity ratios range from 1 up to 6.2, and the largest Ra-excesses occur in the most depleted rocks which also have the highest Ba/Th ratios indicating that the Ra-excesses also result from fluid addition. These disequilibria must have been formed within the last few 1000 years, however the U-Th and Pa-U data from Tonga both indicate U addition occurred 60 000 years ago. A simplified two-stage dehydration model has been developed to reconcile these data. Unlike U, Ra lost to the mantle wedge during initial dehydration is replenished in the subducting altered oceanic crust by in-growth from residual Th. Whereas the U budget was dominated by the first fluid flux, the Ra-excesses record the addition of fluid to the mantle wedge probably less than 1000 years ago. The large Ra-excesses in the primitive lavas place tight constraints on the time permitted for melt generation, segregation and ascent. However, Pa is enriched relative to U in the Kermadec lavas indicating that partial melting processes have over printed the fluid U addition in this section of the arc. This may require addition of small porous flow or dynamic melt fractions with large Pa-excesses to the rising magmas as they ascend through the hot centre of the mantle wedge. Finally, the Ra-excesses are negatively correlated with silica constraining the time scale for differentiation from basalt to dacite and rhyolite to be less than 6000 years.

## T32A MC: Hall D Wednesday 1330h

### Active Tectonics of Taiwan I *(joint with G, S)*

***Presiding:*** **C M Rubin,** Central Washington University**; Y Chen,** National Taiwan Univ.**; J Suppe,** Princeton University

**T32A-0861 1330h POSTER**

### Fault-Related Rocks From The Thrust Fault Zone in Miaoli Area, West Taiwan

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Taiwan is located in the orogenic belt, which the fault-related earthquakes were very common and severe in last few myrs. However, there are no any fault-related rocks have been reported until now. This research is the first article to report an unambiguous occurrence of pseudotachylyte and cataclasite in Taiwan. The fault-related rocks, including the pseudotachylyte and cataclasite have been found in the drilled core, about 600 meters in depth below the surface in the western foothill sedimentary sequences of Miaoli area, Taiwan. The pseudotachylytes are thin, submillimeter to centimeter in thickness and distribute intercalated in thick fault zone. They dominantly occur as injection veins, which contact sharply with host rocks, the sandstones and siltstones, and normal or cut with the major shearing zone. Petrogaphically, the pseudotachylytes consist of a black or dark brown, fine-grained to glassy aphanitic matrix with microlites, rounded or embayed clasts and numerous rock and mineral fragments. The presence of pseudotachylytes indicates that the fault zone has suffered the rapid seismic displacements. The cataclastic rocks include non-foliated clast-supported to matrix-supported cataclasites and foliated clastic-supported cataclasites. The former form either thin dark films underlining isolated shear plane or accumulating as thick lens or pods. The later have large varieties in structures, such as thin dark films displaying S-C fabrics silimar to those of mylonites, injected veins and well-polished slickensided surface. Under the microscope, the muscovite fragments show the structures of brittle-plastic shearing processes, such as fish, cleavage-steps, bending and folding. Those characteristics of cataclasites infer that the cataclasites may form under either the slow seismic movement or aseismic creep. From the occurrence, location and regional geology, this fault zone with abundant fault-related rocks may be correlated to the Shenchoshan thrust fault, which is a seismic fault moved in 1935. The coeval formation of pseudotachylyte and foliated cataclasite infers that the seismic displacement and aseismic creep occurred in the same shear zone.

**T32A-0862 1330h POSTER**

### A High Vp/Vs Zone Along the Subducted Slab Edge of the Philippine Sea Plate Beneath Northeast Taiwan: Insights for Slab Dehydration and Thermal Activity

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The Philippine Sea Plate subducts northwards beneath the Ryukyu Arc and terminates in northeast Taiwan. The associated back-arc basin, the Okinawa Trough, is also propagating westward till the Ilan Plain of the northeast Taiwan. Because of the westward motion of the northwestward subduction of the Philippine Sea Plate, the northeast Taiwan is generally considered as a post-collisional and extensional region. To investigate the subduction-related magmatism, we have performed a seismic tomography in northern Taiwan area. The tomographic results show a high Vp/Vs ratio zone along the subducted slab near East Longitude 121.7.

The anomalous Vp/Vs zone is generally caused by the decrease of the Vs velocity; consequently, we suggested that the anomaly could be associated with the dehydration of the subducted slab. The earthquakes in this area seem to occur along the bottom of the high Vp/Vs zone. However, the anomalous zone is not extending eastward along the whole subducted Philippine Sea slab but only concentrate near the edge of the subducted slab. It implies that the strong decrease of the Vs velocity could be partly caused by the asthenospheric material flowing eastward through slab widow created by the existence of the subducted slab edge.

### T32A-0863 1330h POSTER

## Imaging the Main Detachment under Taiwan: Implications for the Critical-Taper Mechanics and Large-Scale Topography

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Active deformation in the upper crust beneath central Taiwan is illuminated by over 100,000 small earthquakes that allow us to image in 3-D many of the important active faults of this region, in particular the Main Detachment of the Taiwan orogen. Most of these earthquakes are small (M=1 to M=4), and they include both background seismicity and aftershock swarms from larger events. We developed new techniques to constrain fault geometries in 3-D by combining earthquake hypocenter locations and focal mechanisms with geologic and petroleum data. We can fit fault surfaces to the data, with fitting errors on the order of $\pm$1km for most faults. The Main Detachment dominates the tectonics of the Taiwan orogen. It is subhorizontal, at a depth of about 10 km, from the Western Foothills to the Central Mountains, and then dives down into the mantle under eastern Taiwan. Faults above and below the detachment abut against it, showing that it is indeed a through-going tectonic feature. Some of the most dangerous faults that break the surface, like the Chelungpu thrust, are connected to the Main Detachment at depth. The reversal of topography at the crest of the mountain belt corresponds to the inflection of the Main Detachment under eastern Taiwan. This geometry is consistent with critical-taper wedge mechanics, and in particular with homogeneous mechanical properties of the wedge.

### T32A-0864 1330h POSTER

## A Preliminary Neotectonic Map of Taiwan, and its Implications for Future Destructive Earthquakes

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The disastrous effects of the 1999 Chi-Chi earthquake in Taiwan demonstrated an urgent need for better knowledge of potential earthquake sources of the island. Toward this end, we have prepared a neotectonic map of Taiwan. The map and supplementary materials are based upon structural and geomorphic expression of active faults and folds both in the field and on shade-relief maps prepared from a 40-meter resolution DEM, augmented by geodetic and seismologic data.

We divide Taiwan into 10 distinct neotectonic domains. Each contains characteristic active structures. Extension dominates only two domains – the Ilan and Taipei domains, at the northern end of the island, above the subducting Philippine Sea plate. Despite modest geodetic rates, the Taipei Domain is of particular relevance to seismic safety, because the capital, Taipei City, sits on the hanging wall block of the principal structure, the Shanchiao normal fault. Immediately south is the Hsinchu Domain. Reverse and dextral faults there accumulate strain at modest rates. The concentration of high-tech industry in this region is proceeding without much consideration of the earthquake or rupture potential of these structures. Further south, the Chelungpu fault (source of the 1999 earthquake) and its western neighbor, the Changhua fault, are the principal components of the Taichung Domain. These structures die out to the north through a complex 20-km-wide transition belt into the Miaoli Domain, which consists of closely spaced folds and reverse faults. The destructive 1935 earthquake was caused by ruptures of a dextral accommodation structure in this transition zone and a back thrust in the Miaoli Domain. Blind thrust faulting characterizes the Chiayi Domain, south of the Taichung Domain. Although an abrupt GPS velocity gradient exists across the trace of the principal surface fault in this domain, that gradient most likely reflects the underlying ductile-brittle transition of the blind thrust, rather than the potential for future rupture of the exposed, inactive Chukou fault. At the southern end of Taiwan, accretion of forearc-basin and volcanic-arc rocks is beginning across two domains separated by the Central Range. On the west is the Kaohsiung Domain, across which strike-slip and reverse faults are accommodating E-W shortening and southward extrusion at rapid rates. In the western half of the domain, a complex belt of strike-slip and reverse faults associates with the climbing of the Manila Trench up the continental slope and onto the shelf. In the eastern half of the domain, rapid sinking of the Pingtung Plain between two left-lateral reverse faults may reflect the foundering oceanic crust of the forearc. Active accretion of the Coastal Range in eastern Taiwan occurs in distinct southern (Taitung) and northern (Hualien) domains. Rapid accretion in the Taitung Domain manifests itself as folding, faulting, and geodetic gradients on both sides of the arc-forearc suture, the Longitudinal Valley. The oblique component of accretion appears as large components of both sinistral and dip-slip motion on the Longitudinal Valley fault. To the north, accretion has nearly ceased; structures and geodetic measurements there suggest the predominance of sinistal deformation.

Our neotectonic map of Taiwan is our initial attempt to define the fundamental kinematic context of active deformation there. We hope that this will assist in ongoing attempts to design geodetic, geophysical, paleoseismic and other research projects.

### T32A-0865 1330h POSTER

## A Morpho-Neotectonic Map of western Taiwan Based on Fractal Analysis of DEM

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The Taiwan orogenic belt is a curved range belt formed by late Cenozoic oblique convergence, indentation and rotation tectonics between the Eurasian plate and the Philippine Sea plate. This study applies the fractal analysis of DEM to help delineate morphotectonic features and compiles a morpho-neotectonic map of western Taiwan. This map gives a more detailed picture on the kinematics of oblique convergence and indentation tectonics, especially in the low hills and coastal plains.

The angled variogram method was applied in a moving window fashion to extract the fractal vector from a 40-meter resolution DEM. The fractal vector can readily disclose anisotropic nature of a landscape surface which is known to be related to geologic structures. Morphotectonic features manifested by the fractal vector are are mainly distributed in the low hills and coastal plains over which Quarternary sediments cover.

There are five morphotectonic domains divided in the frontal thrust belt and coastal plains of western Taiwan. The Changhua-Yenlin Domain (III) is bounded by the Changhua Fault to the north and the B Fault to the south. It is situated upon the Peikang indenting block and is essentially aseimic and gently folded. To the north, the Taichung-Miali Domain (II) is subjected to transpressional tectonics and characterized by oblique slip thrusts and left-lateral simple shear deformation. The Tuntzuchiao Fault of 1935 earthquake is a right-lateral antithetic shear to accommodate crustal deformation. To the south, the Chiayi Domain (IV) is subjected to transtensional tectonics and characterized by inferred strike-slip faults and right-lateral simple shear deformation. The associated north-south trending fold system had been mapped by. The east-west trending normal faults had been mapped by CPC. The Meishan Fault of 1906 earthquake and the Shinhua Fault of 1946 earthquake can be deemed as right-lateral synthetic shear in this simple shear model. In spite of the extensional Taipei Basin, the Hsinchu-Taipei Domain (I) in northern Taiwan is not only in contractional tectonics, but also in divergent strike-slip component and block rotation. Local occurrences of extension roughly parallel to the trend of major structures. In southern Taiwan, the Tainan-Kaohsiung Domain (V) is less affected by the Peikang Indenting Block, yet the SW escape tectonics still plays some role. This Domain is characterized by northeast trending folds and thrusts with dextral slip component. Both synthetic and antithetic shears are also recognized in this Domain.

Based upon the contrasting pattern of the fractal vector and the seismic distribution, the morpho-neotectonic map may also provide a criteria to evaluate the relative tectonic activity of the five Domains in western Taiwan.

### T32A-0866 1330h POSTER

## Geomorphic Expressions of Subsurface Structures: A Case Study on Hanging Wall of a Thrust Fault

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Geomorphic features are re-evaluated along the Chelungpu fault (CLPF), the source of 1999 Chi-Chi earthquake terraces. In fact, numerous geomorphic features including river terraces have been documented in literatures; however, none of them was interpreted as related to active structure. The post 1999 earthquake investigation demonstrates that the surface ruptures coincide with a number of scarps along these previously reported terraces, representing their tectonic origin. Some of them, distributed away from main fault trace, are believed being related to fault-bend. At Tsao-Tun such a scarp has developed on a terrace surface across the dip change of the bedrock exposure along the riverbank, where is the surface expression of a fault-bend beneath. To track the extensions of this fault-bend on the surface, we established 9 cross-sections of bedrock based on field observations of the dipping angles as well as the corresponding altitudes on the hanging wall of the CLPF. A substantial change exists in all these cross-sections. To the south, the dipping angles change from 50X to 10 20X mountainward, whereas in the north it becomes less abrupt, from 50X to 30X. However, all cross-sections show that the altitude in the west is generally higher than that in the east. At Hsin-She area, E-W cross-sections show that the CLPF plane flattens to the east and becomes shallower to the north. The abrupt bending and flattening of the fault plane at depth also results in a monoclinal kink-shape in the hanging wall and produces a large scarp on the terrace. Furthermore, higher terraces show larger deformation than the lower ones, indicating that these structures have been active for a long time. Across this major scarp there is another minor scarp-line being clearly identified based on the offset of a terrace flight. To the east of the Hsin-She on the west bank of the Ta-Chia River the west-dipping terraces indicate that another active structure exists at depth probably along the modern riverbed. Future detailed subsurface geologic study can further help us to explain more geomorphic features that we have no idea on the mechanism so far. Before that to identify topographic anomalies is the best method to discover active subsurface structures and to mitigate earthquake hazards.

### T32A-0867 1330h POSTER

## Origin of the West Taiwan Basin by Orogenic Loading and Flexure of a Rifted Continental Margin

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Seismic and well data suggest that the West Taiwan basin developed by orogenic loading and flexure of a rift-type continental margin. The most likely source of the loading is Taiwan where oblique convergence between the Eurasian and Philippine Sea plates has produced an orogenic belt up to 300 km in length, 100 km in width and, 4 km in height. Flexure modeling shows that surface loading is unable to explain the depth of the West Taiwan basin. Other, subsurface or buried loads are required. Combined surface and buried loading explains the depth and width of the basin. It also accounts for a Bouguer gravity anomaly "high" and flanking "low" over the orogenic belt, a lateral offset of

20-30 km between the peak topography and the maximum depth to the seismic Moho and, evidence for tectonic uplift in the Penghu Islands. The "best fit" to the depth of the base of the foreland sequence in the northern part of the West Taiwan basin is for an elastic plate model with an elastic thickness, $T_e$, in the range 11-13 km. While these values are low when compared to most other foreland basins, they are similar to values derived from rifted continental margins. The northern part of the West Taiwan basin unconformably overlies a passive margin sequence and therefore appears to have inherited the long-term (> 1 Myr) flexural properties of the margin. In the southern part of the basin, however, the depth to the base of the foreland sequence dips too steeply to be explained by elastic plate models. This part of the basin therefore appears to be yielding rather than flexing. Differences in the flexural behaviour along-strike of the West Taiwan foreland basin lithosphere are reflected in seismicity patterns. The northern part of the basin is associated with a low level of seismic activity while the south correlates with an abundance of earthquakes, especially at shallow (< 25 km) depths. There is a cluster of earthquakes along two extensional faults that were active during rifting of the underlying margin. Therefore, lithospheric flexure and fault re-activation may be important contributors to the seismicity of the Taiwan region.

## T32A-0868 1330h POSTER

### Evidence for Prehistoric Coeseismic Folding Along the Tsaotun and Chushan Segments of the Chelungpu Fault Near Nan-Tou, Taiwan

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Although five large earthquakes in Taiwan have produced surface rupture during the last century, little is known about fault slip rates, recurrence intervals and spatial variations of fault displacement in Taiwan. The Mw7.6 1999 Chi-chi earthquake ruptured along previously unrecognized traces of the Chelungpu fault and has raised questions about potential sources of large earthquakes in Taiwan. The Chelungpu surface rupture is over 80 km long. It trends N-S along the western foothills of Taiwan, and is the westernmost active thrust fault with continuous surface expression resulting from east-west Philippine-Eurasian convergence. Vertical offset across the Chelungpu fault averaged 2 or 3 meters along the principal trace, but values as high as 5 and 6 meters were common along the northern 10 km. In order to characterize the prior rupture history along the Chelungpu fault, we are beginning paleoseismic studies along the Chelungpu fault. Paleoseismic and geomorphic studies along the southern Tsaotun and Chushan segments will determine spatial and temporal records of faulting on the Chelungpu fault. Two promising paleoseismic sites, near Nan-Tou, were chosen after examining aerial photographs that suggest prior fault scarps closely match the 1999 surface rupture. Here, vertical offsets average 1.5 2 meters along the principal trace of the fault. We report preliminary results of paleoseismic investigations across the 1999 surface rupture on the Tsaotun segment near Nan-Tou, Taiwan. Stratigraphic relations suggest folding is the predominant form of deformation in this region. Difference in the degree of tilt between buried paleosols across the fold scarp suggests prior coseismic folding. Termination of sandy units against continuous folded paleosols also supports prior displacement. Age constraints will be determined by AMS radiocarbon dating of detrital charcoal fragments that bracket the proposed event horizon. Coseismic folding and discrete fold scarp development along the Chelungpu surface rupture may well be analogous to future ruptures along the Sierra Madre fault, a range bounding thrust fault on the southern flank of the San Gabriel Mountians, or along reverse faults in Puget Sound, Washington. Such deformation pose substantial seismic hazards in these regions.

## T32A-0869 1330h POSTER

### Distribution and Structural Details of the Aftershocks of the 1999 Chi-Chi, Taiwan Earthquake

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Taiwan is the collision zone between the Eurasian Plate and the Philippine Sea Plate chacterized by a well-developed fold-and-thrust belt. The characteristics of the 1999 Chi-Chi, Taiwan Earthquake were very similar to those of subduction zone earthquakes (e.g. Kikuchi et al., 2000). Aftershock observations of the 1999 event were conducted for two months from 15 days after the main shock (Hirata et al., 2000). Over 8,000 aftershocks were recorded by the observation. To image a fine-scale aftershock distribution and structural details, we applied the Double-Difference Earthquake Location Algorithm (Waldhauser and Ellsworth, 2000) to the aftershocks data. As a preliminary analysis, we relocated about 1,000 aftershocks that occurred for 7 days by the algorithm. Aftershock hypocenters after relocated were more concentrated than those before relocated. Three 30-degree east-dipping planes were clarified, especially in the northern part of the rupture zone of the main shock. The dipping angle agreed with that of the main shock fault. About 30 km east of the main shock fault zone, a highly active seismicity occurred at a depth of 10 km. We suggest that the activity was triggered by the changes of the stress caused by the main shock and large aftershocks. A detailed study of the spatial and temporal distribution of the aftershocks will clarify generation mechanism, triggered earthquakes, and inhomogeneity of the crust in the collision zone.

## T32A-0870 1330h POSTER

### Coseismic Deformation and Static Stress Changes Following by the Chi-Chi Earthquake in Taiwan

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The destructive Chichi earthquake (ML=7.3) occurred on September 21, 1999, in Central Taiwan. It produced a rupture trace more than 100 km long following the Chelungpu Fault. Many geodetic measurements have been taken to this area for detecting the coseismic deformation following by the Chi-Chi earthquake. Both the seismological records and the GPS measurements indicated significant coseismic slip varying from a few metres to nearly 10 metres. The coseismic deformation and static stress changes caused by the Chi-Chi Earthquake were carried out by an elastic dislocation model in a homogenous half-space. This study adopted the rupture model of the Chi-Chi Earthquake (Ma et al., 2001) using high-quality 21 three components near-source strong motion records, 22 P-wave broadband teleseismic displacement waveforms, and 131 well-distributed GPS data. Our results show that the coseismic slip distribution cannot fit by a single planar fault, but rather two-segment fault with a northeast striking section near the northern end. The static stress change induced by the Chi-Chi Earthquake mainshock infer that most aftershocks in the fold-and-thrust belt were triggered by the mainshock. The strike-slip fault near the terminations of the Chelungpu fault might enhance the static stress changes. Our study also shows the regional stress state play a crucial role of the static stress transfer.

## T32A-0871 1330h POSTER

### Slip Distribution of the 21 September 1999 Earthquake in Taiwan From Inversion of GPS, SPOT Images and Strong Motion Data

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The Chi-Chi earthquake, Taiwan 1999, broke the Chelungpu Thrust Fault, a thrust ramp within the Taiwanese accretionary wedge. This event highlights the subduction process of the South China margin beneath the Philippine Sea Plate. As this ramp emerges on the island, near-field surface displacements related to the rupture are exceptionally well documented by GPS, SPOT images and strong motion measurements. This wide set of data provides an opportunity to derive an elastic model of coseismic slip distribution along a splay fault rupture plane. Our inversion method is based on a 3D point source dislocation solution of Okada (1985). This approach allows any fault geometry including curvature and variable dip angle. Our rupture plane, consistent with the fault trace and structural cross-sections, is meshed with 23100 triangular elements. In order to limit the number of model parameters, triangles grid are grouped into sets. For each of these groups, the strike- and dip-slip on the point sources components are constant. Consequently, the inversion leads us to discuss the way in which the triangles are joined together to obtain a reasonable model resolution for the best adjustment of the data. The repartition of these sets depends on the number of data and their distribution around the fault. It also has to take into account the diminishing resolution with depth. We present here the different results for the Chi-Chi earthquake, coseismic slip models and their resolution, depending on the data sets included in the inversion. We finally discuss the geodynamical implications for the seismic cycle in this area.

## T32A-0872 1330h POSTER

### Deformation mechanism of the northern ending surface raptures of the Chi-chi earthquake

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The 1999 Chi-Chi earthquake (ML=7.3) produced a ca. 100 km-long surface rupture. The striking of the surface fault roughly showed a N-S striking south of the Pifeng Bridge; however, it changed to the EW direction, and the deformation zone became to 1-2 km in wide in the northern segment. This paper identifies the surface rupture deformation mechanism and proposes a north-ending model of the Chenungpu fault as explained in the following: 1. The total net slip in the northern segment was 8-11 m but this dispersed into 2-3 faults. 2. The horizontal slip direction was in the NW direction along the Chelungpu fault, but it changed to the N-S direction in the Shihkang to Jofangchu areas. 3. Most of the surface ruptures were controlled by preexisting weak zones that took on two different styles: one was an E-W striking fault, and the other was a fold axial plane. 4. In the Nanwei area, the surface ruptures were governed by the Nanwei anticline, which showed southeast-verging faulting in the southeastern limb and folding in the northwestern limb and the vertical slip reach to 8-9 m high. 5. In the Shihkang to Chaolipu area, the surface ruptures showed different verging thrusting and in the Chiaolipu area, the vertical displacement reached to 12 to 15 m, which was the highest uplifting area along the Chelungpu fault. 6. The detachment fault under the northern ending is around 600-1500 m in depth. 7. The shape of the foreland basin, which showed a south dipping ramp structure in the Tungshih area, governed the northern ending of the Chelungpu fault.

## T32A-0873 1330h POSTER

### Tectonic Analysis of Contractional Structures Within the Southern Taiwan Orogen using GPS

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We have collected GPS data from the southern portion of the Taiwan fold and thrust belt in order to assess the kinematics of this fold and thrust belt on a structure-by-structure basis. Our data set includes over 1500 site-sessions at 130 sites in campaign mode and 14 local permanent sites.

The magnitude of the horizontal component of velocity (Vh) systematically decreases from east to west with respect to cratonic Eurasia. As has been found by others, the azimuth of Vh rotates counterclockwise in going toward the southwest. Not all variations in velocity are associated with mapped major faults. The vertical component of velocity (Vv) follows a different pattern. To the east of the Slate Belt-Western Foothills

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boundary, the orogen appears to be uplifting at a uniform rate, although not rigidly. To the west, Vv values appear to be controlled by local fault dip. Nearby thrust fault dip is a good predictor of surface velocity inclination. Within he Western Foothills Vv is highly variable in contrast to the slow spatial variation in horizontal velocity. Except for the plate boundary (Longitudinal Valley), strain rates are highest in the frontal fold and thrust belt. Significantly, to the level of detail available at present, all structures in the fold and thrust belt appear to be active, although some more than others. Strain rates are modest over the central range and extensional in nature. In addition, some strain nets straddling the Slate Belt Western Foothills boundary indicate extension.

We interpret these results to indicate that the depth of involvement of the deformation in the orogen deepens to the east (as would be expected) but changes character and perhaps deformation mechanism across the Slate Belt Western Foothills boundary. Rocks moving by both folding and motion on thrust faults have a larger influence on surface motions in the west. The Slate Belt Western Foothills boundary appears to mark a fundamental transition in present surface motions across Taiwan.

### T32A-0874 1330h POSTER

## The Present-Day Tectonic Setting of Taiwan Based on an Analysis of GPS and Seismological Data.

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We inverted 143 GPS velocity vectors at Taiwan for strain and rotation rates and relative motion on faults. By a joint interpretaion of the crustal deformation field and other geophysical data and models (e.g. seismicity, tomography) we derived a model for the tectonic setting of Taiwan.

We determined significant lateral extrusion in both northern (to the NE) and southern Taiwan (to the S), separated from the central area by two major seismogenic transfer fault zones. The rapid uplift and NE-SW extension in the Central Range are inferred to result from exhumation of the forearc block. At Hualien, a southward propagating tear fault has develloped along the outer boundary of the Luzon arc and incipient subduction of the Phillipine Sea Plate to the WNW has commenced at its northern tip. Thus a new trench is develloping southward along the eastern coast of Taiwan.

URL: http://www.geo.uu.nl/∼bos

### T32A-0875 1330h POSTER

## Structure, Kinematics, and Thermal/Erosion History of the eastern Central Range, Taiwan

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Analyses of structure, incremental strain histories, and thermochronometry in the eastern Central Range of Taiwan provide insights into the kinematics within the metamorphic core of the Taiwan arc-continent collision. The results of these analyses are consistent with a three-dimensional displacement field that is fixed relative to the geometry of a thin-skinned double-sided wedge. The obliquity between the Luzon arc and the Asian passive margin results in a collision that propagates southward through time, and this time-space equivalence allows north to south variations in structural and thermal history to be evaluated in the context of mountain belt evolution. There are three general structural events in the eastern Central Range of Taiwan. D1 involves west-vergent folding and development of a slaty cleavage/schistosity with growth of fibrous overgrowths and ellipsoidal chlorite-mica aggregates. D2 is represented by east-vergent folds that deform the earlier fabrics and are associated with crenulation cleavages. D3 is defined by brittle normal faults that crosscut all the earlier fabrics.

Strain analyses indicate 270 to 880 percentages of extension parallel to the mountain belt during D1. D1 strain histories, after restoring the rotations associated with D2 east-vergent folding, depict west-vergent thrusting followed by left-lateral shearing. This temporal variation in extension direction and shear direction from down-dip to along-strike is similar to the observed west-to-east variation in the orientation of the D1 stretching lineation across the Central Range. This observation, coupled with the reversal in vergence of structures from west-vergent during D1 to east-vergent during D2, indicates that the rocks of the Asian passive margin have advected from west to east relative to a displacement field that is fixed relative to the mountain belt topography. The consistency in D1 strain histories from south to north indicates that all the rocks of the eastern Central Range have moved through this same displacement field. The left lateral shear is indicative of strain partitioning, with the margin-parallel component of the relative plate motion vector accommodated in the eastern portion of the ductile core of the mountain belt.

The erosion history of the eastern Central Range can be observed from the early stages of emergence above sea level in southern Taiwan to a mature steady state in central and northern Taiwan. We document this evolution with low temperature thermochronometers, including new apatite fission track ages and previously published zircon fission track ages. Fission track ages from Miocene and Eocene meta-sandstones are consistently unreset (ages older than deposition) in southernmost Taiwan and consistently reset (ages less than stratigraphic age) at distances of 60 km (apatite) and 100 km (zircon) north of the southern tip of Taiwan. We interpret this as reflecting progressive erosion towards the north. The fission track results north of the boundary between reset and unreset values depict constant ages at varying distances north of the boundary, suggesting that thermochronometers in the northern, more mature areas of the orogen record a balance between uplift and erosion.

### T32A-0876 1330h POSTER

## Thermo-Mechanical Modeling of Exhumation and Erosion in the Taiwan Orogen

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We investigate the evolution of the Taiwan orogen by constructing a thermo-mechanical, finite element model simulating the growth of an orogenic wedge through subduction and accretion, modified by erosion. Our goal is to predict observed surface patterns in apatite and zircon fission track ages throughout the orogen and thus estimate residence time, uplift and exhumation rates of material presently at the surface. We present modifications to an existing thermo-mechanical finite element model to describe the mechanics of deformation and heat transfer in the orogen explicitly parameterizing deep structural underplating as a flux of material to the base of the orogenic wedge. The mechanical model dynamically solves for crustal deformation by temperature-dependent, non-linear viscous and plastic deformation mechanisms. A thermal component to the model solves the advective-conductive heat transfer equation with radiogenic heat production in the crust for all of the lithosphere given the velocity solution in the crust and prescribed kinematics for the remaining lithosphere.

The oblique orientation of the colliding Eurasian margin and Luzon arc implies a southward propagation of the collision so that the transient evolution of erosion is observed from the first sub-aerial exposure of the orogen in the south to a prolonged steady-state region in central and northern Taiwan. This pattern is observed in both apatite and zircon fission track ages where Miocene and Eocene rocks are unreset in the south and reset to near constant values in the north as one progresses north (at 60 and 100 km for apatite and zircon respectively). The geometry of the orogenic wedge (mean elevation, width, asymmetry, crustal thickness) also follows the general pattern of the southern sections evolving to resemble the mature steady-state central and northern island.

These data provide constraints on the time evolution of the wedge model. Given the N-S propagation of collision and erosion, we calibrate the model by comparing early stages of the model (predicted ages and geometry) with the southern sections of the island and later stages with the north. The orogen dimensions are largely calibrated by adjusting the material strength properties of the model. We calculate predicted ages using temperature histories of tracked material in conjunction with annealing models for apatite and zircon. The kinematic pattern, and thus temperature histories and predicted ages of particles traveling through the orogenic wedge, is largely controlled by the relative degree of underplating and the temporal and spatial distribution of erosion. Initial work shows that in order to obtain the surface pattern of fission track ages, high erosion rates and moderate degrees of underplating are needed.

### T32A-0877 1330h POSTER

## Fault Architecture and Local Structure at the Northern end of the Chelungpu Fault, Taiwan, and Their Relationship to Surface Displacement From the 9-21-99 Earthquake

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Rupture of the Chelungpu fault (CLF) during the September 21, 1999, 7.6 Mw earthquake produced an 85-km long trace with net surface displacements of up to 11.5 m. Maximum displacement occurred at the northern end of the fault, despite maximum ground shaking that occurred ∼60 km south of this location in the south-central region of the fault trace near the epicenter. On site field logging of the core from a 450 m-long inclined hole drilled through the fault zone, combined with local geologic mapping, indicates that the fault dips 50-60$^\circ$east within 300 m of the surface at the northern end of the fault. This analysis reveals that the CLF is parallel to bedding in the hanging wall, and slip was confined to a narrow, <20 cm wide gouge zone within the Chinsui Shale Formation. Structural analysis of the core concludes that the fault caused an asymmetric damage zone confined primarily to the hanging wall of the slip surface. The 1999 primary slip surface was determined by its location within the core, parallel to bedding when aligned with the surface outcrop, associated damage zone, and striations corresponding to surface slip vectors. 3-5 subsidiary faults in the hanging wall and footwall of the CLF show localized, asymmetric damage zones similar to that seen near the active slip-surface.

We propose that the fault displacements at the northern end were extremely large, and maximum ground acceleration relatively low, due to rupture and slip localization on a very narrow slip surface parallel to local bedding attitudes.

### T32A-0878 1330h POSTER

## Erosion-Induced Backstepping and Reactivation of the Chelungpu Thrust: Implications for patterns of modern strain release in west-central Taiwan.

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Restoration of fault-related folds and the geomorphology of the Taiwan thrust belt suggests the Chelungpu thrust was reactivated in late Quaternary time, perhaps as recently as ca. 145 ka. Evidence for reactivation includes: the morphology of young drainage channel networks uplifted between the Chelungpu and Shuangtung thrusts; folding of late Quaternary river terraces, geodetic data and erosion of a large fault-related fold in the hangingwall of the thrust. Previous work argued that reactivation of the Chelungpu thrust is caused by indentation of the thrust belt against the Peikang basement high, which is located in the foreland of the orogen southwest of the Pakuashan anticline. We argue, however, that reactivation of the thrust is due to erosional removal of material in its hangingwall where regional topography is 500-2000 m lower in elevation than further north and south. High sediment yields of suspended load in rivers incised in the fold belt hindward of the Chelungpu thrust support the idea of more rapid removal of material from the central highlands to the foreland in this region. To provide an initial test of this hypothesis, we undertook simple calculations of the orogens response to erosion using critical taper theory based on the previous work of Dahlen. We calculated the change in width of the orogen by increasing the rate of erosion by 1.0 mm/yr to 6.5 mm/yr from an ambient rate of 5.5 mm/yr and used a 7 km thickness for the foreland basin and a shortening rate of 70 mm/yr. Our results suggest the orogen would step hindward 14 km with an increase in erosion of 1 mm/yr. The distance between the Pakuashan and Tatuashan anticlines that mark the leading edge of the belt and the surface trace of the reactivated Chelungpu thrust is about 14 to 25 km. Differences between our results and the measured distance between the Chelungpu thrust and the frontal anticlines may be due to an underestimate of the erosion rate, or by our simple model of wedge geometry for this part of the Taiwanese mountain belt.

## T32A-0879 1330h POSTER

### A Growing Anticline in Tainan City, Taiwan

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Tainan City has been known as an earthquake prone town since the early immigration of the Han people from Mainland China about four hundred years ago. For the purpose of clarifying tectonic activity and paleo-earthquakes in the Tainan City area, we have finished the excavation of three trenches and the drilling of four holes at the so-called Houchiali Fault on the eastern margin of the Tainan tableland. We carefully observed the cores and exposures in the trenches, performed a detailed mapping, and took samples for C-14 dating and other types of analysis. The results show the trench sites are located at a flexure scarp without direct evidence of faulting. But, from the fact of tilting of Holocene sediments to about 50 degrees and the development of a fracture system in the sediments, one may realize that this is without doubt an active structure. We have tested many different models to interpret the observed geologic evidence in the trenches and outcrops, finally determined a growing fault-propagation fold model to be the best interpretation for the Tainan Anticline, while the Houchiali fault is a back-kink or a blind back-thrust type. A diapiric fold had been discussed as possible for a long time by many researchers, but a fault-propagation fold in origin does not contradict with a mud diapiric feature, which was formed during the folding.

Field evidence shows that the main active phase of the Houchiali Fault and the Tainan Anticline would have been after the deposition of the Tainan Formation about two to three thousand years ago. During the active deformation phase, the Tawan Formation onlaped the Tainan Formation, as well as tilted during the folding, thus, beds on higher stratigraphic horizon show lower dip-angle. Estimated from a detailed geologic profile, the horizontal shortening of the anticline is estimated to be 30 meters. The vertical uplift of the Tainan Formation is also about 30 meters. This indicates that the deformation rate has been about 1cm/year both horizontally and vertically over the last three thousand years.

About three hundred years ago, a major uplift event occurred at the trench site area, the ground surface was then subjected to erosion and scouring, and formed an angular uncomformity. After this erosion surface was formed, a major faulting occurred. This event caused ground cracking and the tilting of a tomb (estimated to be 150 300 years old) by about 7 degrees. After this paleo-earthquake event, a fault sag pond was formed, and the lake started to accumulate lacustrine sediments. It was then filled up and subjected to weathering and soil formation. Finally, the trench site was covered by recent fill about ten to twenty years ago.

After reviewing the historic earthquake documents, we suggest that the fissure filling phenomenon on the angular unconformity surface and the tilted tomb may be related to the 1862 Tainan earthquake, which killed more than 300 people in the City and more than 1000 died during the whole event. If we could accept the fault-propagation fold model, we may also suggest that the ramp of the decollement surface underneath the Tainan City could be the initiation point of an earthquake. Therefore, the earthquake hazard potential of the Tainan City should not be ignored. Lacustrine mud and sand deposits above the angular uncomformity have suffered gentle folding and tilting by about 1-2 degrees. This phenomenon should be very recent, and we should pay more attention to monitor it in the future study.

## T32A-0880 1330h POSTER

### Transtensional tectonics along a major north-south trending fault in the active convergent Taiwan mountain belt

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The southwestern Taiwan is situated on a transition zone between collision (Chinese continental margin and Luzon arc) and subduction (South China sea and Luzon arc). It is mainly characterized by an extensive composite of alluvium plains (piggy back basin and foreland basin), which is bounded to the east by a geomorphically well-expressed N-S trending linear fault, the Chaochou fault. To the east of the fault, the mountains raise abruptly up to more than 2500 meters and are mainly composed of Eo-Miocene argillite, slate, metasandstone and marble. These mountains are the southern termination of the Central Range, the backbone of the Taiwan mountain belt. Former studies had shown that the Chaochou fault to be either a thrust dominated or a major left-lateral strike slip fault, which is within a transpressional tectonic environment because of the oblique convergence of the Eurasian and Philippine Sea plates.

We propose the Chaochou fault and its immediately adjacent areas recently experienced transtensional tectonic movements. A number of outcrop-scale faults, with both strike-slip and normal-slip components, show a predominant NNE to NE extension and/or ESE to SE compression in the eastern side of the Chaochou fault. Strain magnitude and orientation data from slates also show extension in the direction of NE-SW, which is basically perpendicular to the plate convergence vector (azimuth ca 310 degrees). In addition, GPS studies by the Central Geological Survey in the study area clearly show that the Central Range has a component of stretching parallel to the N-S trending Chaochou fault. Importantly, the motion vectors show transtension in the whole area of the southwest Taiwan across the Chaochou fault. The above kinematic data suggest that the major, possibly active Chaochou fault was recently experiencing left-lateral transtensional tectonic movement rather than a previously expected transpressional tectonic movement in the southwestern Taiwan.

The transition from tectonic regimes of transpressional deformation (thrust and strike-slip fault) to recent transtensional deformation (normal and strike-slip fault) in the region of the Chaochou fault may be attributed to the distinctive tectonic setting at the transition of collision and subduction, especially to the present southwestward extrusion of the study area.

## T32B MC: Hall D Wednesday 1330h

### What Makes a Craton a Craton? II *(joint with GP, S, V, MR)*

***Presiding:*** **L Moresi,** CSIRO, Exploration and Mining**; W Mooney,** USGS

## T32B-0881 1330h POSTER

### What Makes a Craton a Craton

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Cratonic lithosphere is unique in that it can remain tectonically stable and relatively thick over a time scale approaching a billion years. The physical factors that are key to explaining these observations remain to be fully elucidated. As a step toward this goal, we have undertaken a large suite of numerical simulations that explore the physical conditions required to both stabilize cratonic crust and provide longevity for deep, subcrustal cratonic lithosphere. Several potential factors are considered both alone and in unison. These include: 1) Chemical buoyancy of deep cratonic lithosphere, 2) Viscosity of deep cratonic lithosphere, 3) Viscosity of lower cratonic crust, 4) Brittle yield properties of cratonic crust and/or sub-crustal cratonic lithosphere, 5) Presence or absence of mobile belts surrounding cratons. Based on available data constraints, in terms of lithospheric buoyancy and rheology, the simulations do suggest that the buoyancy and/or viscosity of deep cratonic lithosphere in isolation are not the key factors to making a craton a craton. The simulations instead suggest a controlling role for the yield strength of cratonic lithosphere as a whole in providing stability and longevity.

## T32B-0882 1330h POSTER

### Global variations in density, composition, and thermal regime of continental roots

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We use gravity, thermal, and seismic data to examine how the density and composition of lithospheric roots vary beneath the cratons. Our interpretation is based on the gravity anomalies calculated by subtracting the gravitational effects of bathymetry, topography, and the crust from the observed gravity field, and the residual topography that characterizes the isostatic state of the lithosphere. We distinguish the effects of temperature and compositional variations in producing lithospheric density anomalies using two independent temperature constrains: based on interpretation of the surface heat flow data (Artemieva and Mooney, JGR, 2001) and estimated from global seismic tomography data (Ekstrm and Dziewonski, JGR, 1998). We find that in situ lithospheric density differs significantly between individual cratons, with the most dense values found beneath Eurasia and the least dense values beneath South Africa. This demonstrates that there is not a simple compensation of thermal and composition effects. We present a new gravity anomaly map that was corrected for crustal density structure and lithospheric temperatures. This map reveals differences in lithospheric composition, that are the result of the petrologic processes that have formed and modified the lithosphere. All significant negative gravity anomalies are found in cratonic regions. In contrast, positive gravity anomalies are found in two distinct regions: near ocean-continent and continent-continent subduction zones, and within some continental interiors. The origin of the latter positive anomalies is uncertain.

## T32B-0883 1330h POSTER

### On the relations between cratonic lithosphere thickness, plate motions, and basal drag

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Seismic and thermal estimates suggest a highly variable thickness of Precambrian lithosphere (140-350 km), with a bimodal distribution for Archean cratons ($\sim$ 220 km and $\sim$ 350 km). We discuss the origin of such large variations in lithospheric thickness and examine mechanisms of lithospheric erosion. Our analysis shows that the horizontal and vertical dimensions of Archean cratons are strongly correlated: larger cratons have thicker lithosphere. The basal drag model of lithosphere erosion (Sleep, 2001) is tested as a means of explaining the present-day bimodal distribution of lithospheric thicknesses of the Archean cratons. In agreement with theoretical predictions, we find that lithospheric thickness in Archean keels is proportional to the square root of the ratio of the craton length (along the direction of plate motion) to the plate velocity. These results show that the basal drag model provides a viable explanation for the variation in thickness of Archean cratonic roots. Basal drag may have varied in magnitude over the past 4 Ga. Higher mantle temperatures in the Archean would have resulted in lower mantle viscosity. This in turn would have reduced basal drag and basal erosion, and promoted the preservation of thick (>300 km) Archean keels, even if plate velocities were high during the Archean.

## T32B-0884 1330h POSTER

### Heat Flow in the Western Superior Province of the Canadian Shield

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