differ from the regional pollen zone (the expected model)- this could homoogenise or invert a trend in the pollen record (e.g. the 'European' ragweed rise). Similarly, resuspension could oxidise the pollen assemblage, selectively destroying the more susceptible species. Palynology can provide insights into the impact of stress release on the lake floor and constrain the age of the event. Palynological analysis of short cores (<20 cm) taken by a submersible near a set of intersecting pop-ups 2m high record recent disturbance of lake bottom sediment. These sediments, deposited since ~1840 A.D., have been resuspended and redeposited, resulting in a decline in the percentage of ragweed pollen upcore, contrary to the regional trend. This could imply the last significant motion on this bedrock feature was within the last 150 years. Probing by he submersible showed that over 50 cm of sediment existed at the core site, however, so it is possible that only the surface ~15 cm are disturbed, with the implication that other processes, such as storm-driven bottom currents, are selectively mixing the surface sediment in the pop-up field.

### 2:30 PM Blasco, Steve M.

DISTRIBUTION, AGE AND ORIGINS OF LAKEBED INSTABILITY FEATURES, GEORGIAN BAY, SOUTHERN ONTARIO

BLASCO, Steve M., Geological Survey of Canada, P.O. Box 1006, Dartmouth, N. S., Canada B2Y 4A2, blasco@agc.bio.ns.ca, HARRISON, Patricia H., C.M. GeoEnvironmental, 28 Mt. Edward Rd,. Dartmouth, N.S. B2W 3K4, KEYES, Darren, McQuest Marine Sciences Limited, 489 Enfield Road, Burlington, Ont., L7T 2X5, HARMES, Robert A. Geological Survey of Canada, P.O. Box 1006, Dartmouth, N. S., B2Y 4A2, FOLKES, Patrick, P.O. Box 51 , Tobermory, Ont. N0H 2R0.

Lakebed instability features have been mapped in Georgian Bay on high resolution bathymetric, sidescan sonar and subbottom profile data. These features include continuous and discontinuous linear acoustic backscatter anomalies (LABAs) in sediments, pockmarks (fluid vents in sediments), bedrock scarps and bedrock pop-ups.

Along a NW-SE acoustic profile transect across the Bay, LABAs trend from discontinuous to continuous and increase in frequency from east to west. They are more commonly associated with late Holocene sediments. Remotely operated vehicle camera observations and sediment coring across a LABA indicate some of these features, when found in middle to late Holocene age sediments, may occur a few centimetres below lakebed. A comparison of LABA distribution, morphology and orientation with historic steamship routes and ash disposal practices suggests LABAs are not of anthropogenic origin. Pockmarks and bedrock scarps also increase in frequency from east to west along the same transect. Pockmarks occur more frequently in early Holocene sediments. Bedrock scarps occur as both linear and curved features in map view and may be the product of erosional processes. An 1800m long, NW-SE trending pop-up feature observed along axis for a few hundred metres by a manned submersible significantly varied in sediment infill (from exposed bedrock to totally infilled) and morphology (from a single central fracture to a graben structure). The age of the pop-up remains poorly constrained but post dates deglaciation. With the exception of the scarps, the above features may result from neotectonic activity within the Paleozoic and Precambrian bedrock underlying Georgian Bay at the northern end of the Georgian Bay linear zone.

### 2:50 PM Onasch, Charles M.

THE BOWLING GREEN FAULT IN NORTHWEST OHIO: A MODEL FOR INTRACONTINENTAL FAULTS

ONASCH, Charles M., and KAHLE, Charles F., Department of Geology, Bowling Green State University, Bowling Green, OH 43403, conasch@bgnet.bgsu.edu

The Bowling Green fault in northwest Ohio is a major fault zone in the eastern midcontinent. The structure is typical of cratonic fault zones in that it has a long history of recurrent displacements, had a major effect on the stratigraphic development of the region, and is related to a major Precambrian basement structure (Grenville front).

At least seven episodes of displacement spanning much of the Paleozoic can be documented from surface and subsurface structural and stratigraphic relations. Episodes during the Cambrian and Early Ordovician probably involved strike-slip displacement. Later episodes during the Ordovician and Silurian involved predominantly dip-slip displacement, including both east-down and west-down senses. The youngest episode, southwest-verging thrusting, is consistent with the contemporary stress field and may be post-Paleozoic. Throughout its history, the fault has influenced the stratigraphic evolution of the region in terms of thickness changes, facies changes, amount of dolomitization, and local unconformities that can be spatially related to the fault.

Recently, we have discovered numerous, laterally-extensive stratabound breccias and spectacular bed-normal breccia pipes in the Middle Silurian Bass Islands Gp. near the fault. We interpret such features to be seismically-induced dewatering structures (seismites). These, along with soft sediment deformation structures and down-to-the-basin listric normal faults indicate that the fault was active during deposition of Middle Silurian rock units.

The location of the fault is controlled by the underlying Grenville front. Episodic reactivation of this suture by far-field stresses associated with plate margin orogenic activity or lithospheric flow was responsible for the displacement episodes in the overlying Paleozoic rocks.

### 3:10 PM Marshak, S.

FAULT REACTIVATION IN THE ILLINOIS BASIN REGION, CENTRAL UNITED STATES

MARSHAK, S., Dept. of Geol., Univ. of Illinois, 1301 W. Green Street, Urbana IL 61801, smarshak@uiuc.edu; McBRIDE, J. H., and NELSON, W.J., Illinois State Geological Survey, 615 E. Peabody Drive, Champaign IL 61820; JOHNSON, J.E., Dept. of Geol., Univ. of Illinois, 1301 W. Green Street, Urbana, IL 61801

Recent analysis of subsurface and seismic reflection data along with ongoing surface mapping in the Illinois Basin, Midcontinent USA, including new mapping in Cenozoic cover, permit construction of a Phanerozoic record of fault reactivation. 3-D subsurface models, based on analysis of drilling data and reprocessed recently released industry seismic reflection profiles, document that faults in the southern Illinois Basin and surrounding region are basement-penetrating, disrupt the surface of the basement, and underlie fault-propagation (forced) monoclinal folds in the Paleozoic cover strata. Stratigraphic analysis demonstrates the existence of Ordovician, Devonian, Pennsylvanian, and Permian pulses of fault reactivation. Most displacement accumulated during Late Mississippian to Mid-Carboniferous time (i.e., during the Alleghanian and/or Ancestral Rockies orogenies). In general, the structures resemble 'Laramide-style' structures of the Colorado Plateau and Rocky Mountain foreland, although they have smaller amplitudes. Their geometry, as well as the geometry of subsidiary structures, indicates Paleozoic movements are dominantly reverse to transpressional. Known normal faults (such as the Centralia Fault Zone) are post-Pennsylvanian extensional features, some of which reactivated older reverse faults and appear to influence contemporary seismicity. Recent geologic mapping in southernmost Illinois documents that recurrent movement continued in some cases into the Quaternary. Upper crustal fault structure could provide a fabric capable of contemporary reactivation. In a few instances, earthquake hypocentral locations and focal-mechanism solutions of modern earthquakes correlate with deep crustal reflectors.

## SESSION 129, 01:30 PM

## WEDNESDAY, OCTOBER 28, 1998

## S20. ROLE OF PARTIAL MELTING DURING EVOLUTION OF CONVERGENT OROGENIC BELTS - GSA STRUCTURAL GEOLOGY TECTONICS DIVISION

## MTCC 714AB

### 1:30 PM Silver, Paul G.

THE THERMAL AND DEFORMATIONAL PROPERTIES OF OROGENIC MANTLE.

SILVER, Paul G., Carnegie Inst. of Washington, DTM, 5241 Broad Branch Rd. NW, Washington DC 20015, silver@dtm.ciw.edu and KINCAID, Chris, Graduate School of Oceanography, U. Rhode Island, Narragansett, RI, 02882.

The recognition that mountain building can usually be attributed to the collision and deformation of tectonic plates, has revolutionized geology over the last 30 years. Although the model of a shortened, thickened plate accounts for the elevation of mountains and the thick crustal roots usually associated with orogenies, it has difficulty explaining the thermal properties of the mantle, namely the absence of a corresponding thickened and cool subcontinental mantle lithosphere (SCML). One popular explanation for the excess heat within the orogenic mantle is delamination1, where the cool lithosphere is removed and replaced by warm asthenosphere. The delamination hypothesis can be tested using constraints on mantle deformation from seismic anisotropy. A shortened, thickened plate is expected to produce vertically coherent deformation throughout the crust and SCML, while a delaminated SCML is not. Examination of the existing data set for mantle anisotropy reveals that for compressional orogenies (both former and present-day), the crust and top 100-200km of the mantle generally deform coherently, implying that orogenically thickened mantle lithosphere is not removed during mountain building. Northern Tibet, for example, was formed by intense shortening and is characterized by high elevation and thickened crust. Although the upper mantle beneath this zone is anomalously hot, there is, nevertheless, a striking correspondence between crustal deformation (inferred from faults) and mantle deformation, which is not consistent with the delamination hypothesis. We propose an alternative model in which heat is produced by the orogeny itself. Distributed shear heating in the SCML is treated as an energy source. Numerical experiments show that the uppermost SCML is rapidly heated during orogeny, resulting in elevated heat transfer between the SCML and overlying crust, but without removal of the deformed SCML. This model thus successfully accounts for both the mechanical and thermal properties of the orogenic mantle. It requires, however, that orogenic stresses are somewhat higher (over 2 kbar) than usually assumed.

### 1:45 PM Brown, Larry D.

DEEP SEISMIC BRIGHT SPOTS, MAGMATISM AND THE ORIGIN OF THE TIBET PLATEAU

BROWN, Larry D., and ROSS, Andrew R., Institute for the Study of the Continents, Snee Hall, Cornell University, Ithaca, NY, 14853, brown@geology.cornell.edu; NELSON, K.D., Syracuse University, Syracuse, NY.

One of the most pronounced observations from deep seismic reflection profiling world-wide is the occurrence of unusually strong reflections at mid-crustal depths, usually in areas of lithospheric extension. The first of these was encountered during COCORP profiling of the Rio Grande Rift in the mid-70's and correlated with an anomalous shear wave reflector previously identified from microearthquake recordings. Several lines of evidence suggested that the Socorro Bright Spot marks liquid magma, a conclusion consistent with recently observed P-S conversion of teleseismic waves. Tectonic setting (Cenozoic extension) and depth of emplacement (ca 20 km) led interpreters to suggest that such magma is basaltic, ponding at a level of neutral buoyancy. The Socorro magma 'layer' has influenced the interpretation of similar bright spots around the world, although corollary evidence confirming the role fluid is often lacking. The value of mid-crustal bright spots as a tectonic marker is emphasized by recent INDEPTH profiling in southern Tibet. The Tibet bright spots correspond to strong shear wave reflectors/teleseismic converters and the top of a mid-crustal low velocity/high conductivity zone. A fluid origin is all but certain, and geophysical data appear to rule out a mantle origin. Although there is a suggestion from seismic AVO analysis that hydrothermal brines are involved, synthesis of all the data is consistent with these bright spots marking the onset of partial melting induced by crustal thickening. Their presumed granitic composition rules out density-controlled emplacement; a rheologic barrier is likely, with the bright spots serving as a proxy for the brittle-ductile transition. Together with the other INDEPTH geophysical observations, the Tibet bright spots strengthen the case for low ductility in the deep crust and corollary models of hydraulic uplift of the Tibetan Plateau.

### 2:00 PM Park, Stephen K.

THE INFLUENCE OF FLUIDS ON PARTIAL MELTING BENEATH NANGA PARBAT, PAKISTAN HIMALAYA

PARK, Stephen K., IGPP, 1432 Geology, University of California, Riverside, CA 92521, magneto@ucrmt.ucr.edu; and NSF-CD Nanga Parbat Group

Rapid exhumation of the Nanga Parbat-Haramosh Massif (NPHM) in the past 3 Ma has exposed rocks from the middle crust. Thin leucogranite dikes, migmatites and small bodies of granite with ages as young as 1 Ma are common. Clearly, partial melting is occurring beneath Nanga Parbat. An interdisciplinary study of the NPHM yields new constraints on the extent of partial melting and the conditions under which that melt forms. Abundant microseismicity ceases abruptly at a depth of 5 km below sea level (9-12 km below the surface) and at depths of 8 km on the flanks, which is inferred to be the brittle-ductile (b-d) transition. Fluid inclusion and oxygen isotopic studies indicate that meteoric waters circulate to shallow crustal depths (above the b-d transition) and are then heated to a dry steam phase before returning to the surface. Most surprising is the lack of evidence for widespread magma below the b-d transition. Prominent S wave arrivals and electrically resistive crust are arguments against widespread magma. Average fluid contents from rock resistivity are less than 0.01% in the crust to depths of at least 40 km. Such resistivities above the b-d transition are consistent with evidence of dry steam from the fluid inclusions and the harmonic nature of some local seismic events. Below the transition, we infer from the finite resistivity and NaCl content of the brines (5% from fluid inclusions) that these fluids are interconnected. Fluids generated from metamorphism and partial melting may instead be concentrated in isolated, rapidly deforming regions. The young igneous bodies observed at the surface are due presumably to dry decompression partial melting caused by the rapid exhumation at Nanga Parbat. Generation of granitic melts under dry conditions would lead to electrically resistive magma bodies, which would be consistent with the high resistivity. The passage of S waves through this region precludes the presence of large magma bodies, but small pockets of granitic magma are permitted by the MT data, plausible sources of scattering seen in the seismic data, and consistent with the occurrence of only small and scattered young granitic bodies.

## 2:15 PM Royden, Leigh H.

CRUSTAL MELTING WITHIN THE HIMALAYAN-TIBETAN OROGENIC SYSTEM: WHY DOES IT HAPPEN AND WHAT DOES IT DO?

ROYDEN, Leigh H., HUERTA, A.D., HODGES, K.V. and BURCHFIEL, B.C., Dept. Earth Atmos. Planet. Sci., M.I.T., Cambridge, MA 02138, wiki@goodwin.mit.edu.

Within the Himalayan orogen, deformation has altered temperatures by advection of heat within elements of deforming crust. However, the largest effect of deformation on the thermal structure of the Himalayas is achieved via the rearrangement of heat producing elements within the crust. Within the Himalaya, the excess heat that controls crustal metamorphism appears to be generated internally by crustal radiogenesis and can explain the location, timing and degree of their metamorphism. Heating has also resulted in the generation of in situ crustal melts and appears to control the nature and locus of extensional and compressional deformation along the Himalayan orogen. Within the Tibetan plateau proper, the rearrangement of crustal heat-producing elements during crustal thickening has probably also exerted a major control on the thermal structure of the crust, and is likely to have resulted in partial melting, or pronounced thermal softening, of the deep crust. Evidence for this is mainly indirect because mid-crustal rocks of the appropriate age are generally not exposed in most parts of the plateau. Circumstantial evidence for weakening (melting?) of deep Tibetan crust comes from the low topographic relief that obtains across most of the plateau (despite a 15 km difference in crustal thickness from north to south), from the presence of margin-perpendicular extension around much of the plateau, and from the lack of shorting structures along the eastern and southeastern plateau margins. Along the southeastern plateau margin, uplift of the plateau appears to have occurred with only minor accommodation structures, such as steep normal and reverse faults. In places even these accommodation features are missing and an older landscape surface is warped gently over the plateau edge without significant structural interruption. Modeling results suggest that this structural style occurs only when a very weak mid to lower crust is present, and emphasizes the importance of crustal heat production in controlling the temperature, rheology and deformation style of the Himalayan-Tibetan orogenic system

## 2:45 PM Liu, Mian

GEODYNAMICS OF POSTOROGENIC EXTENSION IN THE NORTH AMERICAN CORDILLERA

LIU, Mian., Dept. of Geological Sciences, University of Missouri, Columbia, MO 65211, mian@geosc.missouri.edu

Cenozoic tectonics in the North American Cordillera has been dominated by postorogenic extension and volcanism. While gravitational collapse has been suggested as the major cause of extension, the geodynamics are not well understood. We examine the effects of gravitational collapse using numerical modeling that is constrained by geological and geophysical date from the Cordillera. Our results indicate the diachronic inception of postorogenic extension along the Cordillera may reflect the nonuniform synorogenic shear heating and mantle upwelling. Both burial heating and viscous relaxation within the ductile crust tend to amplify deviatoric stresses within the brittle crust and thus facilitate crustal collapse. Postorogenic extension tend to occur in the direction orthogonal to the trend of orogenic belts, and some detachment faulting may have occurred along preexisting thrust faults. Crustal collapse of the Cordillera orogen may have been largely decoupled from the mantle lithosphere because of the stratified continental rheology; crustal partial melting and magma intrusion may allow decoupling between finer rheological layers so that localized extension can occur at much lower stress levels than that required by overcoming the integrated yield strength of the entire lithosphere. Crustal collapse may have played a major role in mid-Tertiary extension in the Cordillera, including formation of many core complexes. However, it is unlikely to have been the major cause of basin-and-range extension. We suggest that a strong pulse of mantle upwelling in the mid-Tertiary, as indicated by the 'ignimbrite flare-up,' may have triggered basin-and-range extension. Convective instability of thickened lithosphere may be a viable mechanism to produce the mid-Tertiary mantle thermal perturbation. In any case, an active mantle upwelling with internal convective heating under the Basin and Range province seems needed to account for the continued extension and volcanism since mid-Miocene. Such a mantle upwelling may have also contributed to late Cenozoic uplift of the Sierra Nevada and probably part of the Colorado plateau.

## 3:00 PM Foster, David A.

MAGMATISM, OROGENY, AND METAMORPHIC CORE COMPLEX FORMATION IN THE CORDILLERAN HINTERLAND: NORTHERN IDAHO BATHOLITH REGION, U.S.A.

FOSTER, David A., Dept. of Geology, University of Florida, Gainesville, Florida 32611, and Dept. of Earth Sciences, La Trobe University, Melbourne, Australia, dfoster@geology.ufl.edu; FANNING, C. Mark, Research School of Earth Sciences, Australian National University, Canberra, Australia

The Idaho-Bitterroot batholith is an example of an exhumed, mid-crustal, plutonic-metamorphic complex that formed during maximum crustal thickening in the hinterland of the Cordilleran Orogen. The timing of magmatism, metamorphic, and deformation provide an analogue for magmatic and deformation processes active at mid-crustal depths in orgenic belts like Tibet and the Andes. SHRIMP U-Pb zircon dates indicate that high-grade metamorphism was coincident with the intrusion of syntectonic quartz diorite plutons at ca. 75-80 Ma. Large scale melting of the middle crust occurred between ca. 65-53 Ma, leading to the intrusion of the voluminous main-phase peraluminous plutons as thick sills. This was accompanied by further upper amphibolite facies metamorphism and migatization at the exposed crustal levels. The youngest deep-level granitic intrusions are about the same age as initial crustal collapse at ca. 50 Ma. Collapse occurred mainly on the Bitterroot shear zone which deforms these younger intrusive rocks. Therefore, wholesale crustal melting followed crustal thickening, in this part of the Cordillera, by as much as 15-20 m.y., but pre-dated crustal collapse and exhumation by only 1-3 m.y. Collapse in this sector of the Orogen appears to have been focussed where the plutonism was most intense and long-lived. Exhumation is revealed by the transition from amphibolite facies mylonitization, to greenschist facies shearing, to brittle faulting, to inactivity of the shear zone that progressed from west to east from ca. 50-44 Ma, based on U-Pb and Ar-Ar results. Alkali feldspar granites were emplaced contemporaneous with the onset of exhumation, but were intruded only into the shallowest Eocene crustal levels. Their generation may have been linked to decompression of the lithospheric column during crustal thinning, which may have been driven by a change in the regional stress regime due to plate rearrangements.

## 3:15 PM Vanderhaeghe, Olivier

CAMEMBERT TECTONICS: CRUSTAL FLOW AND INTRA-LITHOSPHERIC DECOUPLING DURING COLLAPSE OF OROGENIC BELTS

VANDERHAEGHE, Olivier, Oceanography, Dalhousie University, Halifax, Nova Scotia, B3H 4J1, Canada, olivier@adder.ocean.dal.ca; TEYSSIER, Christian, Dept. of Geol. and Geophysics, University of Minnesota, Minneapolis, MN 55455, USA

A major tenet of plate tectonics is that lithospheric plates are rigid and that their relative motion is accommodated locally at their boundaries. This is a useful assumption to compare relative plate motion and deformation at oceanic plate boundaries, but it breaks down when applied to the convergence of continental lithosphere. In this case the plate boundary is typically diffuse and, in general, the displacement field deduced from crustal deformation is not directly comparable to plate kinematics. A comparison of active orogenic belts such as the Himalaya-Tibet system recently investigated by INDEPTH profiling (Nelson et al., 1996) with older/eroded orogenic belts such as the North American Cordillera and the Western Variscan belt, provides critical insight into the evolution of upper and mid- to lower crustal behavior at different stages of orogeny, and a possible explanation of the discrepancy between plate-scale and crustal-scale behavior. These examples indicate (1) a dominantly vertical direction of maximum shortening; (2) tectonic transport commonly oblique to plate motion; (3) an arcuate shape of the thrust front at the edge of the thickened orogenic belts; (4) decoupling between a brittle upper crust affected by normal faulting and a ductile lower crust dominated by viscous flow; (5) a partially molten mid- to lower crust.

These features are consistent with radial flow controlled by gravitational collapse of the overthickened crust as exemplified by the collapse of a mature Camembert cheese. In the evolved stages of orogenic evolution, the dominant driving force for crustal deformation is not due to plate tectonics but to the buoyancy force related to lateral variations in crustal thicknesses. The presence of a partially molten crust might play a key role in allowing intra-lithospheric decoupling between the collapsing crust and the converging lithospheric mantle.

## 3:30 PM Jamieson, R. A.

PARTIAL MELTING IN CONVERGENT OROGENS: THERMAL CONSTRAINTS AND MECHANICAL CONSEQUENCES

JAMIESON, R.A., Dept. of Earth Sciences, Dalhousie University, Halifax, N.S., Canada, B3H 3J5, beckyj@is.dal.ca; BEAUMONT, C., Dept. of Oceanography, Dalhousie University, Halifax, N.S., Canada, B3H 4J1; ELLIS, S., Geologisches Institut, Universitaet Bern, Balzerstrasse 1, Bern 3012, Switzerland

Migmatites in convergent orogens typically form relatively late in the metamorphic history at temperatures above 700°C and pressures of 5-10 kbar. The migmatites are commonly deformed by compressional and/or extensional structures, and leucosomes may show a variety of cross-cutting relationships with respect to host-rock fabrics. Because the presence of partial melt should substantially decrease the strength of the host rock, migmatite that forms during convergence is likely to influence the style of subsequent deformation within the orogen. Coupled thermal-mechanical models of convergent orogens offer some insight into heat sources and sinks, timescales of heating and cooling, exhumation mechanisms, and feedbacks between thermal and mechanical processes. Simple models involving subduction of sub-orogenic mantle beneath 'standard' crust, with heat production concentrated in the upper 20 km, produce model orogens that are too cool to undergo partial melting. Tectonic accretion of radioactive crustal material ('tarm') in the upper mantle immediately beneath the model orogen can produce high temperatures within the mantle tarm, but the formation of migmatite at mid-crustal depths is unlikely. Model experiments suggest that the most effective way to produce temperatures high enough for partial melting within the orogenic crust is by tectonically thickening the heat-producing layer at crustal levels. This can be done through accumulation of a large accretionary wedge, collision and thickening at a continental margin, or subduction of lower crust along with sub-orogenic mantle. Temperatures high enough for partial melting appear to require substantial amounts of convergence. Model results for small amounts of convergence show that even moderate heating of the lower orogenic crust leads to some decoupling and propagation of the orogen into its footwall. As the model orogenic crust weakens, exhumation of lower crust on the retro-side of the orogen may become focused by lateral strength contrasts. Where a very weak lower crustal layer is caught between two strong converging blocks, deformation is broadly distributed, crustal thickening is limited, and exhumation is localized against the bounding stronger blocks. In this case the style of deformation in the upper crust is not strongly dependent on the polarity of underlying subduction.

## 4:00 PM Bailey, R. C.

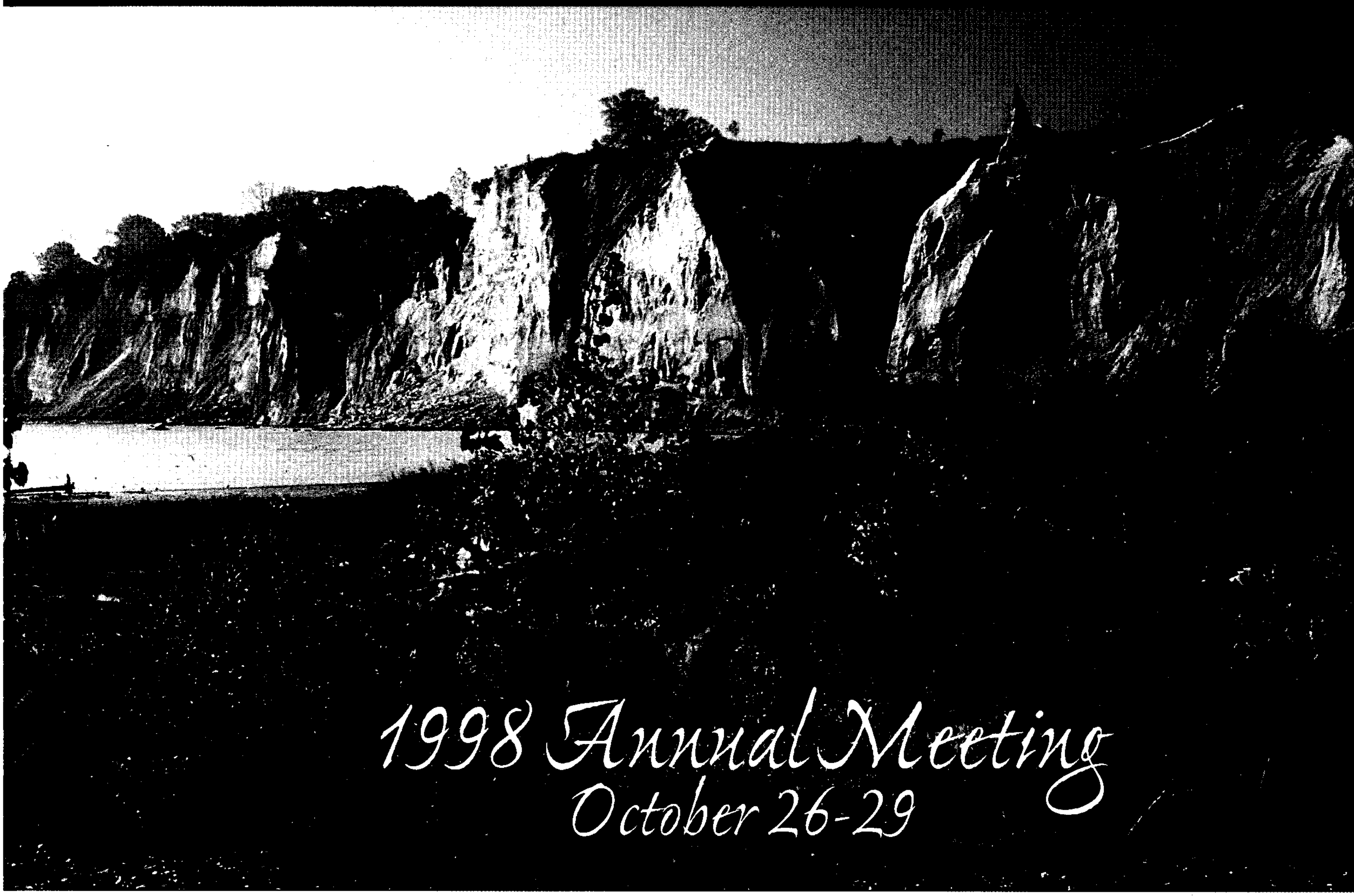
THRESHOLDS FOR GRAVITATIONALLY INDUCED THRUSTING BY ELEVATED TOPOGRAPHY OVER A DUCTILE CRUST

BAILEY, R.C., Geology and Physics Depts., University of Toronto, Toronto, ON, M5S 1A7, CANADA, bailey@physics.utoronto.ca

Overthickened crust over a region of enhanced ductility (produced by local heating or partial melting) in the deeper crust can undergo gravitational collapse by outward thrusting if the elastic thickness of the upper crust is small enough. Geodynamic analysis shows that for a given geometry of crustal thickening, the important diagnostic parameter is the ratio of excess elevation to elastic thickness. Above some critical value of this ratio, which depends on the geometry of the overthickening, hydrostatic uplift by the overpressured underlying ductile crust is sufficient to force thrust faulting at the lateral boundaries of the ductile zone. Values as low as a quarter for this critical ratio are quite possible even without assuming geopressured fluids in the thrust faults. With geopressured fluids or other lubrication, thrusting is even easier. The lowest thresholds are achieved only if the lateral extent of the overthickening and super-ductile zones exceed the flexural parameter (bending length) of the elastic upper crust. This type of gravitationally induced thrusting can only occur at a lateral contrast in the ductility of the lower crust; without such a boundary, overpressured deep ductile crust would be free to escape and depressurize by lateral flow in the lower crust as modeled by Bird and others, thus relieving the upper crustal stresses which would otherwise initiate thrusting. Thrusting, once initiated, will attempt to drive a scarp to an elevation which is in isostatic equilibrium with the hinterland excess topography; to the extent that erosion prevents such equilibrium, thrusting will continue. If the excess elevation exceeds a yet larger threshold, thrusting is not rate limited by erosion nor at a stationary front, but instead extrudes ductile middle crust upwards into a propagating overflow front behind which the upper crust rafts while extending and thinning.

ABSTRACTS WITH PROGRAMS VOL. 30, NO. 7 1998 GSA ANNUAL MEETING ISSN 0016-7592

# Abstracts *with* Programs



## 1998 Annual Meeting
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Photo of Scarborough Bluffs, Ontario by Peter Mvkusz

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