Program with Abstracts: Matawin 2007

27th Canadian Tectonics Group Workshop

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UQÀM
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CGC Québec

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Matawin, Quebec, Canada

Schedule of Events 27th CTG Workshop Matawin 2007

The program presents the schedule of talks, the list of poster presentations and the abstracts in alphabetical order. Oral presentations are 20 minutes long, with 5 minutes for questions.

Friday – October 12

20h00 – 23h00	**Welcome to the 2007 Canadian Tectonics Group Workshop. Registration, refreshments and poster set up**

Saturday – October 13

07h55	**Opening remarks**
08h00 – 08h25	**M. Duguet, S. Lin and D. Davis** New insights on the geology and the geodynamic of the Bird River Greenstone Belt, southeast Manitoba
08h25 – 08h50	**B. Lafrance, H. Gibson, M. DeWolfe and D. Lewis** Folding and thrusting in the Flin Flon mining camp, Manitoba
08h50 – 09h15	**W.M. Schwerdtner, K. Lu and D. Landa** Mesoscopic S-folds as indicators of a widely distributed, orogen-subparallel, late-stage shear in the Grenville Province of Ontario
09h15 – 09h40	**S. Lin** Synchronous Vertical and Horizontal Tectonism at the Late Stages of Archean Cratonization and Implications for Gold Mineralization
09h40	**Poster introductions and coffee break**
10h15 – 10h40	**M. Edwards and B. Grasemann** Was channel flow in the Grenville significant, and how could we know - A kinematic view from the Himalayas
10h40 – 11h05	**N. Austin, B. Evans, M. Herwegh and A. Ebert** Strain localization in the Morcles Nappe (Helvetic Alps, Switzerland)
11h05 – 11h30	**L. Godin, D.A. Kellet and K.P. Larson** Orogenic superstructure behaviour and mid-crustal plastic flow in the central Nepal Himalaya

11h30 – 12h00	**L. Nadeau** Field trip introduction : Arc magmatism, continental collision and exhumation : the Mesoproterozoic evolution of the south-central Grenville Province, Portneuf - St.Maurice region, Quebec
12h00 – 12h45	**Lunch**
12h45 - 16h30	**Load vehicles for 1st part of fieldtrip**
16h30 – 18h00	**Posters and refreshments**
18h00	**Gastronomic dinner at Auberge Le Campagnard**
20h00	**Annual GAC/SGTD meeting**

Sunday – October 14

08h00 – 08h25	**A.F. Baird, S.D. McKinnon and L. Godin** Stress channelling and partitioning of seismicity in the Charlevoix seismic zone, Canada
08h25 – 08h50	**E.A. Konstantinovskaya** Deformation of margin and fore-arc basin induced by arc–continent collision: Insights from Kamchatka, Taiwan and physical modeling data
08h50 – 09h15	**C. Studnicki-Gizbert, R.W. King, B.C. Burchfield and Z. Cheng** Geodetic and geological perspectives on the active tectonics of eastern Tibet and southern China: implications for the accommodation of strain in actively deforming crust
09h15 – 09h40	**J.C. White** The potential influence of "starting material" on rheology – The example of ultra-fine-grained (UFG) and nanostructured limestone
09h40	**Posters and coffee break**

10h00 – 10h25	**P.-Y. Robin** The Strain Probe: local two-dimensional Strain Determination from moving Points – Applications to analog experiments and to regional GPS Data
10h25 – 10h50	**J.W.F. Waldron** Fries with everything Fixing the ellipse in the Fry method of strain analysis
10h50 – 11h15	**R.M. Stesky and P. Budkewisch** Extracting Structural Data from Satellite Imagery: a Ground-truthing Exercise
11h15 – 12h15	**Lunch**
12h30 -	**Load vehicles for 2nd part of fieldtrip**
18h00	**Arrival in Montréal**

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Strain localization in the Morcles Nappe (Helvetic Alps, Switzerland)

Austin, Nicholas[1,*], Brian Evans[1], Marco Herwegh[2], Andreas Ebert[2]

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The Morcles Nappe (Swiss Helvetic Alps) is a recumbent fold structure (Escher et al., 1993; Masson et al., 1980; Pfiffner, 1993; Ramsay, 1981), consisting of marine carbonates and marls that were thrust about 12 km to the northwest over the siliciclastic cover sediments of the Aiguille Rouge Massif during the Alpine Orogeny (Goy-Eggenberger, 1998). Extensive work, by numerous researchers, on the Morcles Nappe has lead to well constrained strain rate estimates of 10^{-11} to 10^{-12} s^{-1} which are believed to be constant along the length of the thrust plane, and partitioned throughout ~50m perpendicular to the thrust plane (Ebert et al., 2007; Herwegh et al., 2005; Pfiffner and Ramsay, 1982). Peak metamorphic temperatures along the Morcles Nappe have been determined by a range of techniques (Burkhard and Goy-Eggenberger, 2001; Ebert et al., 2007; Frey et al., 1980; Goy-Eggenberger, 1998; Kirschner et al., 1995), and are constrained to be between 553 K at the northern end of the nappe and 668 K at the southern root zone. Ebert et al. (2007) observed a pronounced increase in calcite grain size with increasing temperature, and presumably decreasing stress along the thrust plane, in rocks where there is no evidence of additional phases pinning the calcite grain size. Based on these grain sizes, the paleowattmeter scaling relationship of Austin and Evans (2007) successfully predicts the geologically constrained strain rates. The presence of additional phases significantly reduces the calcite grain size. Distal to the thrust plane, it was found that CPO intensity decreased with increasing second phase content, or decreasing calcite grain size. TEM observations of these same rocks indicate that reduced CPO intensity is associated with elevated dislocation densities. On the other hand, analysis of variation in grain sizes and CPO perpendicular to the thrust plane, indicate that calcite grain size in monomineralic bands is dramatically reduced as the thrust plane is approached, and the calcite CPO intensity markedly increases. Again, applying the paleowattmeter scaling relationship of Austin and Evans (2007) to these microstructures leads to the interpretation of a dramatic increase in power dissipation proximal to the thrust plane. This analysis is complicated by the fact that the lowermost structural unit (Gault) consists of up to 50% quartz and dolomite, which are significantly stronger than the calcite at the deformation conditions (Barber and Wenk, 2001; Davis et al., 2005; Hirth et al., 2001; Rutter and Brodie, 2004; Stipp et al., 2006), however, calcite in these rocks exhibits the strongest CPO intensity; the structurally higher Urgonian (consisting of >90% calcite) has a coarser grain size (inferred to relate to lower power dissipation) and a weaker CPO. Initial localization within the Gault likely occurred due to geometric constraints, which in turn produced a strong CPO, leading to material softening and continued localized deformation along the base of the Morcles Nappe.

Stress channelling and partitioning of seismicity in the Charlevoix seismic zone, Canada

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The Charlevoix seismic zone in the St. Lawrence valley of Québec is historically the most active in eastern Canada. The structurally complex region comprises rift faults formed during the opening of the Iapetus Ocean, superimposed by a 350 Ma meteorite impact structure, resulting in a circular highly fractured zone. Although seismicity is localized along two steeply dipping planar rift-parallel zones, previous work indicates that most of the large-scale rift faults appear to bound seismicity rather than generate earthquakes themselves.

In order to gain insight into the mechanics of the partitioning of this seismicity, a simple two-dimensional model of the Charlevoix seismic zone was built using the finite difference code FLAC. The rift-related faults are represented by discontinuities, which are assigned various frictional strength parameters. The heavily fractured impact structure is represented by an elastic continuum of reduced modulus. Boundary displacements are used to generate a regional stress field in the direction of tectonic loading. Given a high strength, the rift faults have little effect on the stress patterns. Stress trajectories naturally flow around the region of reduced elastic modulus, leaving the fractured area with lower stresses than the background level. However, when the rift faults have a low strength, they are unable to support stress trajectories inclined to them, due to the resolved shear stress exceeding their strength. This prevents trajectories from diverting out of the rift, effectively channelling higher magnitude stresses into the region of the impact structure between the faults than would naturally occur. Low-strength bounding faults can thus explain the localization of seismicity into linear bands, rather than distributed seismicity throughout the impact structure. It also explains how the rift faults act as boundaries to seismicity. These results indicate that the interplay between faults of varying strength and zones of differing elastic modulus can give rise to complicated stress patterns, and can explain many of the seismicity patterns observed in the Charlevoix seismic zone.

Contrôle structural des minéralisations uranifères, région du lac Minowean, Fosse du Labrador, Québec.

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Située dans la partie centrale de la Fosse du Labrador, la région du lac Minowean renferme des minéralisations uranifères connues depuis presque 30 ans. La récente campagne d'exploration, réalisée par Areva Québec inc., a permis d'éclaicir le modèle structural de mise en place de ces minéralisations. Cette région se trouve près de la limite ouest du domaine des nappes allochtones, délimitée à l'est, par la faille d'Argencourt. Les nouvelles observations de terrain laissent croire en l'existence d'un nouveau segment de nappe impliquant des roches volcaniques, d'âge Paléoprotérozoique, dans le secteur du lac Minowean. La compilation des données structurales et stratigraphiques suggère également que ce style tectonique ait grandement contribué à la genèse des minéralisations en U-Cu de la région.

Les roches du secteur appartiennent aux Groupes de Seward et de Pistolet, entités correspondant aux séquences fluviatiles et de plate-forme du premier des trois cycles volcanosédimentaires de la Fosse du Labrador (2,17-2,14 Ga). L'empilement est constitué, de la base au sommet, d'arkoses et de conglomérats rouges (Fm de Chakonipau et De Portage), surmontés par des siltites grises et rares dolomies (Fm de Lace Lake), puis de puissants grès quartzeux ou dolomitiques et de dolomies (Fm d'Alder). Les rives du lac Minowean et spécialement les hauts topographiques situés à l'est sont hôtes de roches basaltiques et/ou gabbroïques (Gr de Montagnais) et de sédiments argileux noirs à corrélation stratigraphique incertaine (Fm d'Uvé). La relation entre les roches de plate-forme continentale, des séquences volcanogéniques de milieu marin plus profond et des brèches associées démontre l'existence probable d'une nappe de charriage dans la région. Cette hypothèse s'exprime aujourd'hui par une klippe de volcanites et de siltites graphiteuses occupant le coeur du lac Minowean, avec un prolongement annexant possiblement les roches mafiques connues à plus de 30 km au nord.

Le cycle orogénique polyphasé trans-hudsonnien survenu à environ 1,84 Ga, à d'abord généré la mise en place d'une nappe de charriage (D1) impliquant les roches mafiques et les sédiments pélitiques associés sur les unités de plate-forme continentale selon un transport du NE vers le SW. Cette déformation s'exprime par une très forte schistosité, à faible pendage, limitée à ces roches (S1). Cet épisode a également occasionné un phénomène de bréchification sous la semelle (brèche tectonique) et la mise en place de brèches hydrauliques par l'injection de dolomie. La tectonique de nappe a de plus généré le développement de structures de chevauchements de second ordre au sein des roches de plate-forme, ayant possiblement contribué à un premier stade minéralisateur en U-Cu. La nappe est plissée en synforme et antiforme avec un léger déversement vers l'ouest des séquences du côté est du lac Minowean, soit à l'endroit des minéralisations en U-Cu. Il est possible que ce déversement ait été initialisé par l'imbrication d'une importante masse gabbroïque située à l'est des indices. L'accommodement de la déformation s'exprime ici par une schistosité secondaire (S2), NW-SE à NNW-SSE, dans les séries gréseuses et dolomitiques. Cet épisode de déformation s'accompagne d'une seconde mobilisation hydrothermale et d'une bréchification associée. On y retrouve donc de l'uranium associé à ces failles et une remobilisation probable de celui préalablement piégé dans les brèches syn-D1. Une déformation cassante tardive conjuguée, N40 et N 100, affecte la région et renferme à l'occasion des minéralisations de moindre envergure. Les minéralisations uranifères semblent donc étroitement associées aux processus de mise en place d'une nappe constituée essentiellement de roches volcaniques, apparentées à celles situées entre la faille d'Argencourt et la fenêtre de Mistamisk à l'est.

Structural analysis of Pelagonian nappes of the Gjegjane and Korabi zones, NE Albania – preliminary results and possible implications for the obduction of the Mirdita ophiolite

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The Albanides are part of the Dinaro-Hellenides alpine collisionnal belt which has experienced a multiphase geodynamic evolution. The internal zones consist of imbricated Pelagonian nappes that show a mid-Jurassic episode of deformation related to ophiolite obduction, followed by the development of an Alpine fold-and-thrust belt in the external zones during the Cenozoic. In NE Albania, there is a series of Pelagonian nappes, making up the Korabi Zone which consists of a Paleozoic basement unconformably overlained by a Permo-Triassic to Jurassic cover sequence of rift-related siliciclastic and volcanic rocks that grade upward into a sequence of platform carbonates. The Korabi Zone occurs structurally below the Mirdita ophiolite, a 10- to 15 km-thick slab of Jurassic oceanic lithosphere which has escaped major Alpine deformation/metamorphism and represents the largest European ophiolitic complex. A major problem of Balkan geology regards the original site of formation of the Mirdita ophiolite: is it the remnant of a small oceanic basin obducted eastward and slightly thrusted over the Korabi Zone from the West? Or is it rooted into the Vardar Zone (a major intracratonic suture of former Yugoslavia), in which case the ophiolite was obducted westward and thrusted over the Korabi Zone from the East? In order to better understand the kinematics of obduction, detailed structural and metamorphic mapping of the overthrusted continental margin (i.e. the Korabi Zone) have been initiated in the Kukes area. The Korabi zone can be divided into two sub-zones: the Korabi (*sensu stricto*) and the Gjegjane sub-zones both consisting of a rift related volcano-sedimentary sequence. In both zones, a D1 penetrative event trending NE-SW create large-scale inclined NW-verging folds related to thin-skin tectonics during which the Paleozoic basement overthrusts its cover sequence. D2 folds with NE-trending, west-dipping axial-planar cleavages crenulate older structures. The Korabi and Gjegjane sub-zones are separated by a young (~10 Ma.) but major normal-sense fault zone presumably related to the exhumation of the Korabi sub-zone. Recently-acquired structural data are in agreement with a west-directed emplacement of the Mirdita ophiolite over the Pelagonian continental margin.

Offshore Paleozoic Bedrock Geology in the St. Lawrence River Estuary and Northern Gulf of St. Lawrence, Eastern Canada

Dietrich, J.R., A.C. Grant and A.V. Okulitch

Geological Survey of Canada

Studies of high resolution and multifold marine seismic reflection data are providing new information on offshore bedrock geology in the Paleozoic Anticosti and northern Magdalen basins. The major offshore structural trend mapped in this region is a curvilinear belt of anticlines, synclines and thrust faults in lower Paleozoic strata in the St Lawrence River Estuary, parallel to the northern coastline of Gaspe Peninsula. This submarine fold-belt is part of the external Humber Zone of the Appalachian Orogen, with the northern fold-belt edge marking the offshore Appalachian structural front. The fold-belt is up to 50 km wide between Gaspe and Anticosti Island. Structures in the outer part of the fold-belt encompass Silurian strata, indicating probable Acadian deformation. In this compilation, structures and strata mapped onshore have been extrapolated into the Estuary and integrated with elements interpreted from seismic data.

Most of the fold-belt structures terminate along-strike to the east, offshore of the northeastern end of Gaspe Peninsula. North and east of the fold-belt margin undeformed Silurian and Ordovician strata of Anticosti Basin dip gently basinward, with progressively younger units forming the bedrock surface toward the south. Lower Silurian platform carbonates on Anticosti Island dip offshore beneath a southward thickening wedge of undeformed (?)Siluro-Devonian clastic strata correlated to the Lower Devonian Clam Bank Formation of west Newfoundland. This interpretation is based on reprocessed seismic lines south of Anticosti Island that show a southward thickening (pre-Carboniferous) clastic wedge overlying Silurian carbonates, and recently published papers and seismic lines from southwestern Newfoundland that describe and show a thick section of Clam Bank strata extending westward from the Acadian structural front into the Gulf of St Lawrence.

With the inclusion of this widespread clastic unit, the bedrock map remains similar to the previously published map of Sanford and Grant (1990), with the notable exception that the clastic unit in the northern Gulf and Estuary is now depicted as pre-Carboniferous and all structures are interpreted as contractional features, not salt diapirs. Approximately 80 km south of Anticosti Island, folds and thrust faults occur in this lower Paleozoic section, delineating the Appalachian structural front in the north-central Gulf of St. Lawrence. The southern contact of the (Lower Devonian) clastic unit with older Ordovician rocks north and east of Gaspe Peninsula is placed at an interpreted thrust fault.

There is a significant change in trend and character of Paleozoic structures east of Gaspe Peninsula. In this area the Ordovician-Devonian contact is shown as a SSE trending fault (of uncertain displacement, but possible southwest-verging) parallel to a southeast to east trending synform in the Devonian unit. These structures (synform and fault) extend eastward beneath Carboniferous cover. Tentative interpretations suggest the fault and synform are part of a triangle zone at the (Acadian) structural front. Southeast of Forillon Peninsula, several (strike-slip?) faults are indicated.

The northern erosional edge of the Carboniferous Magdalen Basin extends along an east-west trend from eastern Gaspe across the northern Gulf of St. Lawrence. There is no seismic-data evidence of Carboniferous strata in the St. Lawrence River Estuary area.

New insights on the geology and the geodynamic of the Bird River Greenstone Belt, southeast Manitoba

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The Bird River Greenstone Belt of the Superior Craton is located between the North Carribou Superterrane and the English River subprovince to the north and the Winnipeg River subprovince to the south. The major tectonic event is dated at ca. 2695 Ma and corresponds to the closure of the oceanic domain that existed between the North Carribou Superterrane and the Winnipeg River subprovince.

The structures of the Bird River Greenstone Belt (BRBG) reflect a long-lived transpressive regime. At least, two kinematic events can be distinguished in the BRGB. A D1 event is characterized by a N-side-up shearing coeval with some backthrusting. This event is coeval with an amphibolite-facies metamorphism reaching the peak conditions (550°C-5kbars) after a pressure increase. A D2 event corresponds with a reworking of previous structures. It is characterized by a S-side-up shearing with a dextral strike-slip component in the east part of the belt. The D2 event occurred during the emplacement of pegmatitic granites and Marijane granite dated at 2645 Ma. Further investigations in the English River Sub-Province have allowed us to highlight the kinematic pattern of a major shear zone separating the English River Subprovince (ERSP) from the BRGB. This 3-4 km wide shear zone trending NW-SE on the north edge of the Maskwa batholith displays conspicuous dextral shear sense coeval with a magmatic event in the metasedimentary rocks of the ERSP. This dextral event is similar to the dextral shearing taking place eastward of the BRGB ca 2645 Ma. New geochronological data on Maskwa Batholith at 2830 Ma (U/Pb on zircon) highlights the role of the Maskwa granite in the collision between the North Carribou terrane and the Winnipeg sub-province. The Maskwa Batholith split from a continental margin during a back-arc spreading acted as a small rigid microcontinent during the collision and has to be seen as a distinct subprovince between the ERSP and the BRGB.

Was channel flow in the Grenville significant, and how could we know. A kinematic view from the Himalayas

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The increasing evidence (e.g. deep geophysical models, active and history surface displacement data, exhumed mid-lower regions of ancient orogens) and interest for coherent flow processes in the middle and lower crust in active orogens has been galvanised by, above all, the composite picture from the Himalaya via Project INDEPTH (International Deep Profiling of Tibet and the Himalaya) and others. Sub-surface imaging indicates that a km-scale wedge (or slab) of partial-melt-bearing, up to sillimanite facies, mid-crustal rocks dips gently towards the interior of the Himalaya orogen (Nelson et al 1996). Most now agree that this was extruded/exhumed over several m.yr. more or less always in this orientation; the gently-dipping (orogenward) upper and lower boundaries of this slab are horizons whose displacements of 10's to 100's km are associated with crustal scale shear zones. Critically, the coeval timing and reciprocal shear sense of displacement on and near these horizons is (being) well constrained by a plethora of P, T, t, d data, requiring some simple thermo-mechanical model of extrusion-fostering flow form the mid-crust. Various models have explored mid-/lower crustal flow and extrusion for the Himalaya / Tibet region (e.g. Zhao & Morgan 1987; Royden 1996; Beaumont et al. 2002, Vannay & Grasemann 2001, Grasemann & Edwards 2007). We develop a 2D kinematic model to explore the role of volume change (area increase) in slab extrusion to explore how melt input from deeper levels to a mid-crustal setting can influence material translation rates. We use a dilatancy term in the velocity gradient tensor that is dependent on the stretching rate factor, kinematic dilatancy and vorticity number. We discover significant enhancement in extrusion efficiency with a few percent of melt. We are testing our model can via measurement of rotations of material lines (veins, palaeo - geotherm, and -barometer horizons, etc). Further testing is a larger undertaking measuring 3D flow parameters at both slab boundaries at many places along and into the exposed slab. Such 3D flow measurements on BOTH boundaries is crucial however to examine if extrusion arises through channel (or some other type of) flow. Orogens lacking comprehensive preservation of both boundaries to the flown crustal portions (e.g. the Grenville orogen) therefore elude any definitive identification of flow type.

Orogenic superstructure behaviour and mid-crustal plastic flow in the central Nepal Himalaya

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In the central Nepal Himalaya, the Tethyan sedimentary sequence (TSS) forms the superstructure to mid-crustal infrastructure rocks of the Greater Himalayan sequence (GHS); the top-to-the-north South Tibetan detachment system (STDS) defines their contact. North-verging folds, opposite to the main orogenic vergence, structurally dominate the TSS. Although the absolute age of this folding is unknown, structural observations and ^{40}Ar/^{39}Ar thermochronology indicate that it formed between 50-23 Ma, predating the dominant Miocene motion on the STDS.

The GHS records a two-stage post-collisional history, marked by ca. 35 Ma burial metamorphism, followed by high-T, low-P, ca. 22 Ma metamorphism. Dominant top-to-the-south shear fabrics developed at peak temperatures at ca. 22 Ma pervasively transpose linear and planar features within the GHS. Vorticity analyses yield kinematic vorticity numbers between 0.29 and 0.80 (81–41\% pure shear), with a significant amount of stretch parallel to the flow plane (34-53\%). ^{40}Ar/^{39}Ar thermochronological data indicate that southward extrusion of the GHS terminated with cessation of movement on the STDS at 19 Ma.

Our data suggest that the orogenic superstructure actively influenced the behaviour of the infrastructure in the early stages of orogenesis through fold-thrust belt formation leading to prograde 35 Ma metamorphism in the GHS. Associated melt weakening in the infrastructure allowed the initiation of southward plastic flow of the GHS, locally modifying the vergence of superstructural folds towards the north. As melt weakening in the middle crust intensified and the rheological contrast between superstructure and infrastructure increased, the upper crust decoupled from the middle crust and deformation in the upper crust temporarily ceased. By 17 Ma the extruded mid-crustal rocks cooled sufficiently to require the upper, brittle component of the STDS to become active. As cooling continued (17-14 Ma), the superstructure and underlying infrastructure (i.e., the upper crust, STDS and exhumed mid-crust) re-coupled and was subjected to localized large-scale buckling. This marked a transient stage of out-of-sequence deformation before the activation of new thrusts structurally below the GHS in late Miocene.

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Dynamic centrifuge modelling of folding in extensional regimes – Applications to the interpretation of structures during exploration in sedimentary basins and gneiss and greenstone belts

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Through investigating the behaviour of rheologically and dynamically similar systems, simulations using the high-acceleration centrifuge in new INRS-ETE laboratory provide innovative insights into the temporal and spatial evolution of geological structures. Centrifuge models are especially suited to study dynamic systems where body forces (such as due to density differences) are important. A better understanding of the progressive development of complex structural geometries through physical modelling aids the interpretation of field, seismic, aeromagnetic and other remote-sensing data in sedimentary basins and gneiss and greenstone belts. Centrifuge models illustrate how folds may develop during rifting or post-orogenic collapse that otherwise may have been interpreted as forming during regional shortening. Reinterpretations of tectonic regime have important repercussions in exploration, opening the way to apply different exploration models and changing exploration strategy in targeting dilatant zones, etc.

Models illustrate a broad range of structural styles formed during layer-parallel extension. Upright open to tight folds locally folding isoclinal folds develop during boudinage of competent dense horizons. Such folds may develop in high-grade gneisses, such as between boudinaged mafic layers. Simple open folds develop in the footwall to extensional shear zones. Tighter, more complex folds develop in layers with strong mechanical anisotropy when competent dense horizons are displaced. Folds develop with axes both perpendicular and parallel to the transport direction during displacement between convergent lateral ramps. Similar structures develop in both sedimentary basins and metamorphic terrains. Diapirs fold the cover sequence on their margins. Diapirs emplaced along normal and transfer faults may produce folds with axial traces perpendicular and parallel to the bulk extension direction. Such folds may develop in Archaean greenstone belts and associated with salt diapirs in sedimentary basins. Their geometry may indicate the location of early extensional faults and transfer zones with implications for base metal and gold mineralization.

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Deformation of margin and fore-arc basin induced by arc–continent collision: Insights from Kamchatka, Taiwan and physical modeling data

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Both the analysis of the geological data and the results from 2D and 3D experimental modeling of arc-continent collision in Kamchatka and Taiwan reveal tectonic thickening of continental margin and shortening of fore-arc basin as important features of the collision evolution. Upper Cretaceous-Early Paleocene island arc collided obliquely with the Asian margin at 60-50 Ma in the south and at 48-38 Ma in the north of Kamchatka. Incipient eastward subduction of continental margin initiated tectonic delamination and accretion of continental crust in the margin at the beginning of the collision. The westward thrusting and thickening affected the basement in the south of Western Kamchatka. The conglomerate deposits accumulated at the base of the growing basement highs in Late Paleocene. The zircons of 47–53 Ma (U–Pb SHRIMP) were newly formed in tectonic slices of gneisses buried during the incipient margin subduction. The syn-collisional exhumation of basement rocks (Sredinny metamorphic massif) occurred along the west-vergent thrusts and the vertical faults at its western and eastern edges, respectively. The exhumation of the basement metamorphic rocks affected sedimentation and facies distribution in the adjacent basins both within the margin and the arc area. Failure of the overriding plate, fore-arc lithosphere subduction, and westward arc obduction occurred during the following stages of the collision. Fore-arc lithosphere subduction induced intense shortening and deformation in the forearc domain. The volcanic activity of the arc was ceased, the arc structures rapidly subsided and were conformably covered by continental-derived turbidites. Olistostrom deposits at the base of the turbidite series indicate the unstable sedimentary environments during the arc subsidence. The abundant detrital metamorphic minerals in the turbidites were likely supplied from the margin basement rocks exhumed in front of the collided arc. Collision of the Luzon arc with the Asian margin started 5 Ma resulting in tectonic thickening and syncollisional exhumation of the basement rocks (Central Range) in Taiwan. This event preceded deformation of the fore-arc basin and rapid uplift of the Coastal Range (collided arc) started 1 Ma. In southeastern Taiwan, a slice of forearc basement is suspected to subduct under the Luzon arc as a consequence of the transition from oceanic to incipient continental subduction. A syn-collisional orogenic basin develops during the progressive shortening of the forearc domain. Sediments of the basin compressed and thrust over the arc basement and the deformed accretionary wedge. Experiments of physical modeling suggest early deformation of subducting margin during arc-continent collision depends on strength of the margin crust relative to the strength of the overriding plate in the arc. The weak continental margin may suffer failure and thickening at the very early stages of arc-continent collision. Tectonic delamination of the crust, detachment of crustal blocks from the mantle basement, and their accretion at the front of the overriding plate result in significant thickening of the continental crust as it is observed in the examples of Kamchatka and Taiwan. The forearc lithosphere subduction initiates deformation of forearc basin and accretionary wedge.

Folding and thrusting in the Flin Flon mining camp, Manitoba

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The Flin Flon mining camp hosts several large Cu-Zn volcanic massive sulfide deposits, including the past-producer Flin Flon and Callinan deposits and the present-producer 777 and Trout Lake deposits. The structural architecture of the camp and the geometry of the deposits have been shaped by thrusting, regional folding, and later faulting. Volcanic rocks including the mine horizon are folded around a regional NW-trending fold, the Hidden Lake syncline, which predates the deposition of sedimentary cover rocks of the Missi Group. Later thrusting repeated the stratigraphy of the volcanic rocks, tightly folded the Missi rocks, and transported the volcanic rocks northward above their Missi cover rocks. The limbs of the Hidden Lake syncline were subsequently overprinted by dextral high strain zones, which were later reactivated as sinistral shear zones during the development of a regional NE-striking cleavage that cuts across both limbs of the Hidden Lake syncline. Stretching and slip during thrusting and folding resulted in the present cigar shape of the deposits and their possible offset and repetition.

Synchronous Vertical and Horizontal Tectonism at the Late Stages of Archean Cratonization and Implications for Gold Mineralization

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"Vertical tectonism" and "horizontal tectonism" are two contrasting processes that have been proposed for Archean tectonics. Vertical tectonism, in this context, is due to density inversion (Rayleigh-Taylor-type instabilities), inherent between denser volcanic sequences (greenstones) and underlying less dense sialic material (granitoids), and is characterized by buoyant rising of granitoids (diapirism) and sinking of greenstones (sagduction). Horizontal tectonism, in the context of Archean tectonics, is similar (but probably not identical) to the present-day plate tectonics and is characterized by regional scale horizontal motion (drift) of "plates" or "microplates" and the resulting interactions (e.g. collision) among them. The two processes should not be mutually exclusive, and it is not necessary to downplay the significance of one to validate the other. Recent results show that both processes played an important role in Archean tectonic evolution. Furthermore, in the Superior Province, there is convincing evidence that the two processes occurred synchronously (and potentially interactively) at the late stages of Archean cratonization, and horizontal shearing (a result of horizontal tectonism) is concentrated in synclinal keels (a result of vertical tectonism). The Timiskaming-type sedimentary rocks were interpreted to have been deposited in the keels during the process. Results of dating ~400 detrital zircon grains from samples collected at various stratigraphic positions of such a sedimentary sequence indicate an unroofing pattern in the flanking domes that is consistent with such an interpretation. The synclinal keel-shear zone association provided a link between the upper crust and the lower crust or mantle, and might have served as a conduit for mineralizing fluids and magma that were generated in the crust and/or mantle during the process. Such a process at the late stages of Archean cratonization can readily explain the common association of gold deposits with greenstone belts in synclinal keels, shear zones, late felsic to intermediate intrusions and Timiskaming-type sedimentary rocks, as exemplified by the geology of the Hemlo gold deposit, a world-class deposit containing ~20 million oz. of gold. Evidence for synchronous vertical and horizontal tectonism reported here makes it necessary that both processes (as opposed to either one or the other) and their potential interactions are considered in interpretations of Archean terrains. It is suggested that synchronous vertical and horizontal tectonism was a common process in the Neoarchean and represents a transition from dominant vertical tectonism in the Mesoarchean (and Paleoarchean?) to dominant horizontal tectonism in the Proterozoic and Phanerozoic. It is further suggested that the process and the associated gold mineralization were both related to some fundamental process at the late stages of Archean cratonization, possibly slab break off following collision.

Clast-matrix Deformation Mechanism with Application to the Microstructural Analysis of Mylonites

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Porphyroclasts in mylonites commonly define a shape fabric which may hold important information on rheology and kinematics of the deformation. Understanding the development of this fabric may improve our ability to extract rheological and kinematic information from natural high strain shear zones.The clast-matrix deformation mechanism where the clasts are rigid is well understood because the problem has been investigated theoretically, by experiments, and by numerical modeling. However, the clast-matrix deformation mechanism where the clasts are deformable has not been well studied, although it is far more applicable to rock deformation. The theory for clast-matrix deformation where the clasts are deformable is based on Eshelby (1957, 1959). Solutions for 2D cases of simple shear and pure shear were given by Bilby & Kolbuszewski (1977). They recognized three distinct regimes of clast deformation path for simple shear. Numerical solutions to general 3D flow cases can be investigated using the numerical method of Jiang (2007b).

We have applied the solution of Bilby & Kolbuszewski's study (1977) to general 2D flows using the algorithm developed by Jiang (2007b). For a kinematic vorticity between 0 and 1, four regimes of clast deformation path are distinguished: In regime one ($0<r<6.5$, where r is the viscosity ratio of the clast to the matrix), clast deformation path is like that of the first regime for simple shear flow case (Bilby & Kolbuszewski, 1977) except that there is a shift of $-\frac{1}{2}\cos^{-1}W_k$ (W_k =0.866 in this study is the vorticity number of applied flow) for all the path curves from the $\varphi=0$ position(φ is the angle between the long semi-axis and x axis) for simple shear. Within this regime, we recognize 2 different clast deformation paths. Type 1 clast rotates with vorticity when R (aspect ratio) increases monotonically. Type 2 clast roates against vorticity, and its R may decrease first and then increase, or its R increases to $\varphi=0$ position directly depending on its initial position. In regime two ($6.5\le r<8.4$), there are 3 distinct clast deformation paths. Type 1 and 2 clasts rotate in almost the same way of the two types clasts in regime 1. But type 3 clasts oscillate there with little changes in their shapes and orientations. In regime three ($8.4\le r$), there are four different clast deformation paths. Similarly, type 1 and 2 clasts rotate in almost the same way of the two types clasts in regime 1. However, type 3 clasts oscillate with little changes of their shapes ($R\approx1$) and orientations, and type 4 clasts rotate periodically within the range of $-\pi/2\le \varphi \le\pi/2$ and without large changes in shapes. In regime four, when r increases to an extremely large value, all clasts behave as rigid clasts.

Our investigation shows that in the process of mylonitization, deformable grains may have different deformation-rotation path as opposed to a monotonic one. Identification of the various clasts may place constraints on deformation kinematics and rock rheology.

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Buckle folding of Grenville gneisses under orogen-subparallel shear on the kilometre scale: progress report after two field seasons in central and southeastern Ontario

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Mesoscopic buckle folds with S/Z style and elongation lineations parallel to the hinge lines abound in two subdivisions of the Grenville Orogen, Ontario: (i) the southwestern Central Gneiss Belt, and (ii) the basal (northwestern) contact zone of the Composite Arc Belt. At many localities, S/Z buckle folds have been bent about a transverse axis, without greatly affecting the cross-sectional fold geometry. Prior to bending, the buckle folds seem to have been cylindrical and their straight axis parallel to a principal direction (X or Y) of folding strain. Despite their slight distortion, therefore, the S/Z buckle folds may serve as indicators of a shear component normal to the hinge lines.

The geometry of 612 folds was studied in 2006 and 2007, and the attitude of numerous elongation lineations was measured in the field. Except in one sub-area, over 80% of all folds examined proved to have S-style if viewed in an easterly or southeasterly or southerly direction. This attests to a component of distributed, NE- to ENE-directed shear postdating the main foliation and associated regional strain. Quartzo-feldspathic pods and veinlets, however, transect the hinge zones of many folds, and reveal that veining and migmatization outlasted the buckle folding. The tectonic significance of the orogen-subparallel shear component remains to be established.

Arc magmatism, continental collision and exhumation : the Mesoproterozoic evolution of the south-central Grenville Province, Portneuf - St.Maurice region, Quebec

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From arc magmatism to continental collision and exhumation, grenvillian terrains of the St.Maurice region provide a window to mid- to deep-crustal geological processes as they apply to a wide variety of studies ranging from tectonics to regional metamorphism, metallogeny to mineral exploration, mantle dynamics to crustal growth.

The region is located at the juncture between the geologically and tectonically contrasting northeast and southwest segments of the Grenville Province. Four contrasting lithotectonic domains are recognized. On the north-west, the structurally lowest *Mékinac-Taureau domain (1)* makes up a broad crustal-scale dome composed mainly of transposed and granoblastic intermediate and felsic granulitic orthogneisses. One of the orthogneiss body has yielded an U-Pb zircon crystallisation age at 1.37 Ga. This dome is structurally overlain on its south and east flanks by the allochthonous monocyclic *Morin Terrane (2)*, and to the east, by the allochthonous polycyclic *Portneuf-Mauricie domain (3)*. These domains were intruded at 1.07 Ga by a number of small gabbronorite intrusions and by large masses of porphyritic granite and monzonite ca. 1.06 Ga, which underly most of the *Parc des Laurentides domain (4)* farther east. *Morin terrane* comprises the anorthosite-mangerite-charnockite-granite suite (AMCG) of the *Morin Complex* emplaced ca. 1.16 Ga, and stand out by the abundance of supracrustal rocks of the *Grenville Supergroup*, namely pelitic paragneiss with subordinate marble and quartzite, presumably deposited ca. 1.25 Ga. In addition, it may also comprise a younger metasedimentary sequence possibly deposited after ca. 1.18 Ga. The ca. 1.45 Ga volcano-sedimentary paragneisses of the *Montauban Group* and the ca. 1.4 Ga calc-alkaline metaplutonic rocks of *La Bostonnais Complex* constitute the distinctive lithological assemblages of *Portneuf-Mauricie domain*. In addition, the Montauban area, long known for its Au, Pb and Zn volcanic massive sulphide mineralisations, corresponds to a regional metamorphic low, with middle to upper amphibolite facies parageneses and local preservation of primary structures.

The planar fabric east of the *Mékinac-Taureau domain* dome is generally gently to moderately dipping southeasterly to easterly. Mineral and stretching lineations define two sub-orthogonal poles plunging gently SE and N-NE. The southeast pole corresponds to early lineations associated with northwest directed thrusting and peak metamorphism. Conversely, N-NE trending lineations locally mark late-Grenvillian oblique-senestral extensional ductile shear zones, possibly a consequence of the exhumation of the *Mékinac-Taureau domain* dome, responsible for the preservation of the Montauban metamorphic low.

The Strain Probe: local two-dimensional Strain Determination from moving Points – Applications to analog experiments and to regional GPS Data

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The strain probe' calculates a least-square fit to the two-dimensional strain recorded by the displacements of three or more points. By calculating a strain from the motion of any set of specifically selected points, the probe can detect and map sharp local strain gradients and discontinuities that may be associated with heterogeneities in underlying mechanical behaviour. The strain calculated can also be assessed statistically. The strain probe is easy to implement and to adapt to specific problems.

The method and its use are first demonstrated on analog deformation experiments with the Rotating Polarized Stage, experiments in which we want to examine and contrast strains within individual grains. Published GPS station velocity measurements in the South-Western United States demonstrate the use of the strain probe on regional tectonic problems.

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Mesoscopic S-folds as indicators of a widely distributed, orogen-subparallel, late-stage shear in the Grenville Province of Ontario

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The structural record of post-thrust, ductile deformation in the Grenville Province of Ontario remains to be fully documented and properly understood. During the summers of 2006 and 2007, we studied well-exposed, mesoscopic, open to close, S/Z folds and their axial mineral-shape lineations in two divisions of the Grenville Province, (1) the Central Gneiss Belt, in the Georgian Bay – Muskoka region, and (2) the basal (northwestern) contact zone of the Composite Arc Belt, in the Minden – Haliburton – Wilberforce – Maynooth – Barry's Bay region. Throughout both regions, the short limbs of typical S/Z folds are decorated by parasitic M-folds, whose origin can be explained on the basis of simple two-dimensional models. At many localities, originally cylindrical folds have been distorted by slight to moderately strong bending about a transverse, generally NE-SW axis. Moreover, the hinge zones of S/Z folds are commonly cut by quartzo-feldspathic pods or thin pegmatitic veins.

Over 80% of the 612 folds studied to date have S-style, in all but one sub-area, if viewed in an easterly, southeasterly or southerly direction. S-folds abound not only in the vicinity of litho-structural boundaries, but occur also within the Muskoka domain and at least as far as 30 km southeast of the basal contact of the Composite Arc Belt. Accordingly, one episode of the post-thrust ductile deformation included an orogen-subparallel component of distributed, sinistral or sinistral-normal shear. East-northeasterly shear prevails in the walls of the Allochthon Boundary Thrust and the basal contact (NW boundary) of the Composite Arc Belt. In the Muskoka domain and the Haliburton – Maynooth area, however, the shear direction is more nearly northeast. Judging from the shape of typical S-folds, the shear magnitude is not very large ($\gamma < 3$). But the common abundance and widespread occurrence of S-folds suggests that orogen-subparallel distributed shear played a significant role in the post-thrust deformation of well-foliated Grenville rocks, at least in the Gneiss Belt (Ontario) and adjacent parts of the Composite Arc Belt.

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Extracting Structural Data from Satellite Imagery: a Ground-truthing Exercise

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For structural geologists, documenting the large-scale internal geometry of geological bodies is often a challenging task. Various physical, environmental and financial factors can limit the ability to acquire the necessary information. Poor outcrop exposures, difficulties making magnetic compass measurements and remote or inaccessible locations are among them. Yet, having some prior knowledge of this large-scale geometry can help in the planning of field work, seismic surveys and other decisions to support efficient allocation of resources.

One available, yet little used, option is satellite imagery, when used with derived digital elevation data. The principle is based on the classic “three-point problem,” long used to teach geology students how to read structural maps. One can calculate the orientation of a structural plane from the spatial coordinates of at least three points on that planar surface. By measuring such sets of points at various locations within the image, the geologist can quickly construct a structural orientation map of the observed strata and use that map to estimate the internal geometry of the lithological units in the area. This map is incomplete, of course, since only planar measurements can be made, and it requires that lithological contacts be visible in the image. Nevertheless, much can be learned while still in the office to constrain the ideas about the region’s geology and to help plan the field work.

To aid in this procedure, we developed a computer program called Orion™ (© Pangaea Scientific) under contract with the Canada Centre for Remote Sensing and now available commercially. Orion™ accepts geocoded satellite imagery and an associated digital terrain model (DTM) defining the elevations within a grid of spatial points. Using the mouse pointer, the user clicks on the chosen sample points, while Orion™ computes the best-fit plane through those points and shows the calculated attitude and associated fitting and error statistics. Orion™ includes a number of tools to aid in measuring the planes, including a point editor, a trace of the fitted plane projected over the satellite image and a rotatable three-dimensional projection of the topographic surface with the image draped over it and including a projection of the fitted plane. Ultimately, though, the user makes the decision of when the fit is acceptable and bears the responsibility for that choice.

We will describe the methodology in more detail and give examples from Ellef Ringnes Island and Bathurst Island in the Canadian Arctic. Because both regions are of relatively low relief, these examples help to define the limits to the method. In both cases, the computed attitudes compare favourably with ground-based measurements.

Geodetic and geological perspectives on the active tectonics of eastern Tibet and southern China: implications for the accommodation of strain in actively deforming crust.

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We present a compilation of the active faults of the eastern margin of the Tibetan plateau, southwestern China and northern Myanmar based on a review of published literature, maps, seismicity records, remote sensing analyses and fieldwork. We have identified all major faults and summarized all available slip-rate estimates. This geological perspective of the active tectonics of the eastern Tibetan region is compared with the perspective from geodetic measurements. We combine updated GPS measurements from two separate networks and use the combined velocity field to constrain a deforming block model. We choose the model geometry such that it conforms as closely as possible to the mapped geology in order to highlight differences between the geologic and geodetic perspectives on the active tectonics. While we find that modeled slip rates on the block boundaries are generally consistent with geologic slip-rate estimates on major faults, discrepancies occur between a block model description and the mapped geology where strain is diffuse and poorly localized. Notable examples of these areas are the southern strands of the Xiaojiang fault system north of the Red River and within the Lanping-Simao fold belt. These broad zones of deformation are poorly described by narrow block boundaries, but block modeling remains a useful tool for identifying these regions and quantifying the strain they accommodate. We note with interest that these studies show that significant strain rates can be accommodated in areas with no active faults. This has major implications for attempting to reconstruct the kinematics of ancient geological terranes.

Fries with everything? Fixing the ellipse in the Fry method of strain analysis.

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Centre-to-centre measurements are used in the Fry method of estimating fabric ellipses for strain analysis. Despite the usefulness of the method, estimation of the elliptical shape of the central vacancy field in a Fry plot is typically subjective. Enhanced Fry plots, in which inter-object distances are adjusted for object size, reduce the level of uncertainty, but still require a subjective judgment of ellipse shape and orientation. In addition, the enhanced plotting method cannot be applied where object size is undefined, as in the case of dewatering pipes seen in turbidites of the Proterozoic Windermere Supergroup in the Omineca Belt of the western Cordillera. Two new methods can provide more objective estimates of the fabric ellipse by locating the elliptical locus of maximum point-density gradient. The point-count density method compares the number of points in a central elliptical area with the number in a surrounding annulus having the same area. By varying the dimensions of the ellipse it is possible to maximize the point-density contrast between the inner ellipse and the surrounding annulus, providing an estimate of the shape of the fabric ellipse. The continuous function method uses an exponential function to measure the fit of points in the Fry plot to a trial ellipse. By varying the dimensions of the trial ellipse, it is possible to maximize the value of this function, providing a second estimate of the shape of the fabric ellipse. Both methods use the image processing software ImageJ, although the search for the optimum ellipse in the continuous function method is more rapidly executed using the Solver program in Microsoft Excel.

The potential influence of "starting material" on rheology – The example of ultra-fine-grained (UFG) and nanostructured limestone

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Ultra-fine-grained rocks (grain size < 5 μm) are commonly associated with major displacement zones within Earth. In extreme cases, grain sizes can approach that of nanostructured materials (a few hundred nanometers) for which mechanical responses are not always as predicted by extrapolation from theory, or experimental and natural deformation of 'normal' microcrystalline material. Micritic (lithographic) limestone is commonly noted in association with major detachments (e.g. McConnell thrust, Glarus thrust) and the initial fine-grained nature has been presented as a fundamental factor controlling localization. Subsequent interpretation of deformation mechanisms from theoretical considerations and deformation experiments then proceeds from this assumption of ideal, small grains. Preservation of the syndeformational grain size in such units is moot unless homologous temperatures are sufficiently low or other textural or kinetic factors sufficiently suppress grain coarsening. The common occurrence of platformal carbonates in upper crustal deformation regimes allows microstructural characterization to be undertaken with the reasonable expectation that thermally induced adjustments of fabric are minimal. One question, among several, that immediately arises is how such an otherwise strong lithology serves to focus deformation. For sub-greenschist conditions at temperatures below 523K (250°C), deformation occurs below depths of 7-12 km at maximum lithostatic pressures of 180-300 MPa. Transitions in deformation modes under these conditions are abrupt in both space and time; under roughly the same conditions, micrite exhibits extreme fracture toughness and brittle response, distributed shearing and folding, and localized ductile flow. Refinement of the controls on these responses is a core motivation of this research. In aid of the latter, characterization of microstructures in ultra-fine-grained limestones, both protoliths and tectonites, by analytical transmission electron microscopy has established evidence for initial microstructural complexity in undeformed limestones that begins to explain some of the varied response seen in nature.

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