APPENDIX 2. ABSTRACTS OF TALKS GIVEN AT THE 2017 THOMPSON FIELD FORUM*

Rock fragmentation at high strain rate under compressive and tensile loading

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Several rock damage fabrics, including gouge in the principal slip zone of faults and highly fragmented rocks associated with dynamic events such as earthquakes and long runout landslides, have been attributed to brittle deformation at high strain rates. Rock fragmentation plays a critical role in these catastrophic events, yet the processes leading to brittle fragmentation remain enigmatic. Past experimental work suggests that there exists a critical threshold in stress-strain rate space through which rock failure transitions from failure along a few discrete fracture planes to intense fragmentation, yet the micromechanics of the brittle fracture process depend heavily on the associated loading configuration (e.g., compression vs. tension). During impulsive events such as earthquake rupture and long runout landslides, the stress tensor at any point in the surrounding rock body can be complex, in some cases cycling rapidly between compression and tension. We present new experimental results on Arkansas Novaculite and Westerly Granite in which we examine damage fabrics produced by dynamic fragmentation under simple loading configurations including uniaxial compression and isotropic tension and compare these results with theoretical models of rock fragmentation.

Large lurking landslides of California

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Very large (>10^6 m^3) deep-seated bedrock landslides (rock avalanches, complex slumps, etc.) are more abundant in California than indicated by previous mapping. They occur in a wide variety of settings including transpressional mountain ranges, along low-angle normal faults, in volcanic complexes, and glaciated regions. Often the boundaries and internal structure of such deposits are correctly mapped by geologists but the deposit itself is not identified as a landslide due to untelling or ambiguous geomorphology. Exposures of the internal structure of the deposit revealing mass-wasting deformational textures and kinematics are often key to positive identification of the largest deposits (yet these textures are rarely taught to geologists in training). Misinterpretation of large landslide deposits can lead to critical misinterpretations of regional tectonics, fault activity, climate history, and landslide abundance and scaling relationships. Here I will highlight some new examples of very large landslides in California and their implications for the geologic history of the surrounding regions.

A photogrammetry-based structural characterization of the Markagunt gravity slide, southwest Utah

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Understanding the mechanics of long runout landslides such as the Markagunt gravity slide requires detailed three-dimensional structural characterization of the slide material, including shear-related structures near the basal plane and damage throughout the translated block. Three-dimensional surface reconstructions developed utilizing the principles of photogrammetry are a highly accurate and efficient method for mapping remote, inaccessible, or hazardous geologic exposures. Photogrammetry is a technique that captures 3D information of features from overlapping photographs of the same feature taken at various camera angles. The resulting high-resolution surface images can provide valuable information for the complete structural characterization of geologic exposures, allowing for the identification of cross-cutting relationships, fracture orientation, damage fabrics and grain size distribution. In this presentation, I will discuss the preliminary results of our Markagunt structural characterization obtained through the use of Agisoft PhotoScan software coupled with ground-based and unmanned aerial vehicle (UAV) based photography.

Investigating the roles of paleoclimate and pre-existing topography in triggering the Markagunt gravity slide

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My interest to the Markagunt gravity slide focuses on two aspects: 1) the roles of paleoclimate in making the Brian Head Formation the basal slip surface of this gravity slide; 2) the role of pre-existing topography in promoting slope failure. The Brian Head Formation was deposited during the late Eocene and early Oligocene. The deposition crossed the Eocene-Oligocene boundary (~34.0 Ma) when continental climate in the western U.S.A. experienced dramatic cooling and drying. I hypothesize that the wet Eocene climate caused alteration of voluminous volcaniclastics into clay minerals. The high water content of clay minerals not only mechanically weakened the Eocene strata, but also lubricated the fault and caused fault slip in the Brian Head Formation. Hypothesis testing requires two sets of data: 1) age determination and sedimentologic characterization of the Brian Head Formation at various distances along the slide; 2) hydrogen isotope compositions of clay minerals and hydrated volcanic glasses in the Brian Head Formation, and of pseudotachylyte in the fault zone. The North America Cordillera hinterland may have experienced uplift related to mantle upwelling after the Cretaceous-early Paleogene crustal shorten-

*First author was presenter

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ing. The topographic wave may have migrated southward and reached southern Utah and Nevada during the late Oligocene. I hypothesize that this part of the Cordillera hinterland reached critical elevation during the late Oligocene, and the topography became supercritical with the thermal uplift associated with the Marysvale volcanic activities. Hypothesis testing requires paleoelevation reconstructions by applying volcanic glass hydrogen isotope composition and carbonate clumped isotope temperature along a transect between southern Utah and low-elevation region in southern California.

Evaluating the role of active magmatism in generating landslide failure: Constraints on minimum rates of emplacement from paleomagnetic data, Henry Mountains, UT

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Rapid emplacement of magma into the shallow crust is a potential contributing factor to slope destabilization and catastrophic failure in volcanic systems. Testing of this hypothesis requires an understanding of the rate of magma emplacement on time scales commonly much shorter than is possible given the uncertainties associated with even the best radiometric geochronology. Here we present an example of using analysis of paleomagnetic secular variation to provide constraints on construction timing of a small-volume intrusion at timescales well below those available using standard dating techniques. The geologic archive of secular variation provides only a minimum estimate of the rate of pole motion, therefore a minimum rate of emplacement can be estimated. As a proof of concept, we analyze ^{14}C dated lava flows from Hawaii that also record changes in the position of the magnetic pole. Application of the maximum rate of secular variation from the Holocene to the Hawaiian flows reliably returns a minimum time elapsed between those flows. We apply the same approach to determine the minimum amount of time between the emplacement of sheets in the Trachyte Mesa, within the Henry Mountains of southern Utah. The Trachyte Mesa laccolith is a small (0.05 km^3) elliptical intrusion formed from numerous meter-scale-thickness pulses of magma emplaced on the eastern side of the much larger Mount Hillers intrusive center. Magnetizations measured in fifty cores collected for paleomagnetic analysis from ten different sheets display a high degree of internal consistency (α_{95} <5þ). Hysteresis data and thermo-susceptibility analysis together suggest all sheets are characterized by single domain titanomagnetite as a magnetic carrier. The sites record a minimum of 60° of secular variation, suggesting emplacement of Trachyte Mesa took at least 900 years. If rapid emplacement and inflation are key factors in the slope failure associated with the massive landslides investigated in this field forum, then the archive of secular variation stored in the associated shallow intrusive should suggest very short – i.e., century scale or less – time periods for emplacement.

The rock record of seismic slip with applications to long runout landslides

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Exhumed fault zones offer insights into deformation processes associated with earthquakes in unparalleled spatial resolution; however, it can be difficult to differentiate seismic slip from slow or aseismic slip based on evidence in the rock record. Likewise the exhumed basal slip surfaces of landslides provide similar insights, and recent advances in the study of earthquake rupture in exhumed faults can be extended to understand the rate of processes involved in long runout landslides. Previously, pseudotachylyte (quenched melt generated by frictional heat) was recognized as the only reliable indicator of rapid slip found in ancient faults. This assertion was based on models of frictional heat production providing evidence for fast slip. Significant progress in fault rock studies has revealed a range of reaction products that can be used to detect frictional heating at peak temperatures less than the melt temperature of the rock. In addition, features formed under extreme transient stress conditions can now be recognized in the rock record. Thus, pseudotachylyte is no longer the only indicator of fossilized earthquake ruptures. In this presentation I will discuss some of the established, and potential, signatures of earthquake rupture that may also be used to recognize catastrophic landslide transport in the Markagunt gravity slide. Many of these signatures are associated with a reduction of the friction coefficient and if present, have the potential to provide some explanation for the low effective frictional resistance associated with long runout landslides.

Investigating volcanic flank collapses and catastrophic sector collapse

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The flanks of volcanoes are constructed of superimposed layers of volcanic materials with varying characteristics (porosity, permeability, crystallinity, and glass content) which affect the strength and stability of the structure. This heterogeneity can promote flank failure if the volcano becomes destabilised; usually by flank overburden, magma emplacement, hydrothermal alteration, or anomalous geothermal gradients found in volcanic settings. Failure (either catastrophic or slow) can then be triggered by a range of internal and external phenomena such as seismicity, heavy rainfall, or the onset of eruptions.

Investigation into the properties of these edifice building materials, especially frictional behaviour, allows for further understanding of the mechanisms for volcanic flank and sector collapse and the resulting motion of the detached blocks and material flow. Using a rotary shear apparatus to simulate natural fault slip conditions experienced at the base of the slide, a frictional property map can be developed as a function of velocity, normal stress and temperature. Frictional tests conducted on a range of rock types show a dynamic weakening behaviour at seismic slip velocities due to weakening mechanisms including gouge production and frictional melting among others. Recent studies on volcanic rocks suggest they may be susceptible to frictional melting at normal stresses and slip velocities well within the range of those which occur during flank collapse events.

The tendency for volcanic rock to have high glass content, which remobilises above the glass transition temperature, changes their reaction to frictional situations. Using synthetic glass samples (both sintered and solid (0% porosity)) and natural samples, the effects of glass content and porosity on the evolution of slip can be analysed. Synthetic samples allow for analysis without the complexities of variable chemistry or crystal content / size and may constrain the currently unknown mechanism for the failure of glass-rich specimens at relatively low frictional stresses. Investigation of these properties

may allow the better understanding of the relationship between stress buildup and subsequent deformation of volcanic flanks.

Observationally and geophysically constrained geodynamic models of Hawaiian volcanoes

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In recent decades, we have gained significant understanding about the present-day structure and dynamics of Hawaiian volcanoes. This knowledge stems from extensive onshore monitoring of volcanic and geodetic activity and seismicity, as well as a range of geophysical studies. Offshore studies, including bathymetric mapping, seismic surveys, and direct submersible observations and sampling, yielded constraints about the submarine flanks of the volcanoes. Onshore-offshore tomographic and gravity inversions provide additional insights into the internal structure of Hawaiian volcanoes. The integrated view arising from these studies has led to a new understanding of the long- and short-term dynamics of the Hawaiian volcanoes, and new hypotheses in need of rigorous testing.

Geodynamic models offer an efficient means to test hypotheses relating to the growth, internal structure, and dynamics of Hawaiian volcanoes. We conducted numerical simulations using the discrete element method (DEM), constrained by observations and interpretations. These studies explore the influences of basal decollement strength, a dense ductile cumulate core, and edifice interactions. The results demonstrate the fundamental role of gravitationally-driven processes in the long-term volcanotectonic evolution of Hawaii volcanoes, and also capture the intermittent nature of dynamic events, such as landsliding and deep flank earthquakes. A weak decollement proves to be key to generating the shallow volcanic slopes observed in Hawaii, and enables continuous outward displacement of Kilauea's south flank. The presence of a weak substrate and a weak ductile core (e.g., of cumulate mush) enables summit subsidence, consistent with present-day geodetic observations at Kilauea and near-summit normal faults that accommodate such subsidence. In addition, axial subsidence drives the outward displacement of the volcano flanks, and results in inward dipping strata and thrust faulting along the distal flanks, consistent with the frontal benches found at many Hawaiian volcanoes.

The interaction of active volcanoes also leads to complex evolution. Edifice overlap influences dynamic behavior significantly. The degree of volcanic buttressing depends on the relative positions of the two edifices. If a new edifice grows high upon the flanks of an older edifice, outward spreading of the underlying flank is enhanced. If the younger edifice is built low upon the pre-existing flanks, spreading of the underlying flank is prevented and possibly reversed. Furthermore, as the second edifice grows, it subsides into the underlying flank, partitioning it into a mobile downslope region entrained by spreading of the second edifice, and a comparatively stable upper flank region. These results suggest that much of the mass of Kilauea volcano may lie deeply buried within the underlying flank of Mauna Loa, while older Mauna Loa rocks may lie far from their source beneath the mobile flank of the younger volcano.

The Limerock Canyon Formation, Markagunt Plateau, southwest Utah: Implications for paleogeography and relative chronologies in the Early Miocene

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Understanding the nature and context of Early Miocene sedimentation in southwest Utah is complicated by contemporaneous contractional and extensional deformation, widespread volcanism, and large-scale gravity-sliding. However, cross-cutting relationships and sedimentological studies in the Lower Miocene Limerock Canyon Formation (LCF) can provide insight to the relative chronologies and paleogeographic settings associated with enigmatic structures along the incipient Basin and Range–Colorado Plateau transition zone. Facies associations in the tuffaceous LCF suggest subaerial and subaqueous fan deposition and nearshore lacustrine deposition. Subaerial fan facies associations indicate environments dominated by plastic to pseudoplastic debris flows, hyperconcentrated flows, sheet floods, and lesser alluvial channel filling. The sub-aqueous fan facies associations are dominated by plastic to pseudoplastic debris flows, hyperconcentrated flows, and turbidity currents. Dewatering structures in subaqueous fan environments suggest rapid deposition of ~10-100 cm sediment gravity flows over saturated substrates. Nearshore lacustrine facies associations document the interaction of quiet water sedimentation (thinly-laminated muds / carbonate / water-lain ash) with higher energy, rippled beach deposits and sediment gravity flows. These data suggest the LCF represents deposition of a lacustrine fan-delta in the Early Miocene.

In contrast to other Lower Miocene units preserved across the breadth of the Markagunt Plateau, the LCF sits exclusively on the late Eocene–early Oligocene Brian Head Formation (BHF) in apparent disconformity (~10 million years). This relationship may represent a localized zone of positive topography prior to LCF deposition. Mesoscopic structures (~N-S vergent coulomb wedge-faults) produced by deformation in the footwall Ruby's Inn thrust are preserved in the BHF but are entirely absent in similar lithologies of the LCF. This implies that significant deformation of the Ruby's Inn thrust may have been complete by ~22 Ma. Finally, clast compositions and variations in grain maturity in the LCF record catastrophic emplacement and subsequent erosional unroofing of the Markagunt gravity slide.

Edifice-scale volcano collapse deposits: Where they come from and what they look like

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Gravitational failure of volcanoes is a relatively common phase in the growth and evolution of volcanoes. Failures dominate at steep-sided stratocones, but also occur at low-angle shield volcanoes, smaller lava-dome complexes, from both syn- and post-eruption collapse of caldera walls, or failure of solidified lava flows. Summit collapse incorporating the central conduit is most common, but large collapses can originate on volcano flanks. Edifice failures at continental and island arc volcanoes range to >10 km^3 in volume, but collapse of oceanic shield volcanoes can exceed 1000 km^3 and are of comparable size to the volcanic-field-scale failures that are the focus of this field forum. Collapse frequency is inversely related to collapse volume, with those >0.1 km^3 in size occurring globally during the past half-millennium at a rate of about four per century, those at oceanic shield volcanoes having a frequency several orders of magnitude longer and the miniscule sample of recognized volcanic field failures lying at the far end of the continuum. Edifice collapse during this same (0.5 ka) interval has been the most common destructive morphological phenomenon at volcanoes, with a frequency exceeding that of caldera collapse resulting from explosive magma chamber evacuation. Multiple failures at individual volcanoes are not uncommon, with ten or more collapse events each at volcanoes such as the Colima volcanic complex in Mexico, Taranaki (Egmont) in New Zealand, and Augustine in Alaska. Collapse scarps typically have steep headwalls that can obtain a depth of a km or more, with relatively low-angle basal failure planes. Often described as horseshoe-shaped in plan view, they more often have subparallel side walls breached widely in the failure direction, and structural influences can result in a wide variation in morphology. Scarps at stratocones can obtain caldera-sized dimensions typically around a km to >5 km in width and in some cases >10 km in length. Collapse is often retrogressive, with initial failures prompting subsequent collapse of over-steepened headwalls. Failures can occur in association with magmatic eruptions, phreatic eruptions, or in the absence of eruptive activity. Resulting highly mobile debris avalanches from edifice collapse events can travel from a few to many tens of km, covering in some cases >1000 km^2. Bulking from substrate entrainment may enhance volume and distribution, and in some cases near-proximal rheological transformation to lahar (debris-flow) facies may occur.

Deposit-scale morphologies include unusually thick (often >100 m) depositional units typically lacking primary stratification, hummocky terrain (formed in both extensional and compressional environments) with enclosed depressions often hosting small ponds or lakes, marginal levees and steep flow fronts. Outcrop-scale characteristics include polymictic compositions with block-facies material displaying pervasively fractured, unconsolidated to semi-consolidated segments of the former edifice transported relatively intact over long distances, abrupt color changes from neutral colors of heterolithologic mixed-facies material to more intensely colored, sometimes hydrothermally altered edifice segments. Jigsaw fracturing of clasts down to the size of sand grains and clustering of angular clasts is often present, along with shear zones and clastic dikes of variable orientation reflecting syn-emplacement deformation. Small blocks may be plastically deformed, with localized elongation, folding, and smearing. Basal contacts are often planar, and substrate material may variably be undeformed or truncated, striated, or display large-scale soft-sediment deformation of distal margin substrate.

Markagunt gravity slide deformational constraints on groundwater flow in the Panguitch municipal watershed, southwest Utah

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The Panguitch municipal watershed (PMW), located in the Dixie National Forest 10 km west of Panguitch, Utah, is underlain by part of the 5200 km^2 Miocene Markagunt gravity slide (Biek and others, 2015a). Panguitch relies on six springs in the PMW for the majority of its municipal water. Determining groundwater flow directions to these springs is complicated because of the combined effect of gravity slide structures and younger basin-range normal faults. Slide structures also change the properties of aquifers and confining units, most of which are volcanic rocks that predate the slide. Concern over potential groundwater contamination from livestock and forest fires prompted the Dixie National Forest to initiate a groundwater study to determine the origin and subsurface flow of the water that feeds the springs. Field mapping, 3-D fault modeling, and water quality monitoring were used to construct groundwater flow models for the watershed. A specialized model was created for ArcGIS products to create 3-D faults from new and existing 2-D geologic maps.

The study showed that groundwater within the PMW is localized within alluvial aquifers, volcanic and volcanic sandstone bedrock aquifers, and fault zones. Two creeks, Delong Creek and Indian Hollow, have eroded through the upper plate of the Markagunt gravity slide, directly above the slide's primary ramp fault. The bedrock, intensely deformed by the slide, shows increased permeability and total potential water yield. The six springs in the PMW are located along Basin and Range normal faults and gravity slide faults that crosscut the Markagunt Plateau, and their yields are clearly enhanced by the deformed slide rocks. Rock units south of the PMW springs dip north-northeast due to the ramp fault, allowing groundwater to be captured within the Butler Creek watershed to the south and from there to be guided northward to the PMW. Springs within the Indian Hollow area emerge from N 30° E trending vertical joints that are associated with gravity slide deformation.

House of cards: The role of load-bearing dyke networks in volcanic edifice instabilities

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The island of La Palma (Spain) is well known for large collapse events, the most recent of which removed a significant portion of the Cumbra Nueva edifice at ca. 550 ka. Erosion of this collapse scar has formed extensive cliffs within Caldera de Taburiente, exposing thousands of dykes in an approximately radial swarm. The role of these dykes in the edifice instability and eventual failure remains largely unexplored.

Using 21 UAV-based 3D virtual outcrop reconstructions to gain access to inaccessible exposures, we map the dyke networks in unprecedented detail over multiple areas of up to 1 km^2. These highlight frequent interactions between the dykes and the stratigraphy of interlayered basalts, pyroclastics and volcanic breccias, with dykes commonly terminating or developing complex geometries at contacts. Many dykes also form anastomosing networks as individual dykes join to form multiple-dykes. Significantly, we identify multiple ~1–5 m long faults that offset the dykes by 20–50 cm but do not propagate into the surrounding pyroclastics (Fig. 1). These faults initiate on irregularities in dyke geometry and terminate on the opposing dyke contact. Their offsets and geometries are consistent with gravitational loading. Hence, we suggest that dyke networks can form load-bearing frameworks in volcanic edifices. Such networks will initially support edifice load, allowing steeper slopes and larger edifice growth over time. However as the strength of the dykes is exceeded, progressive faulting will result in a strain-weakening effect, possibly allowing the edifice to reach a super-critical state prior to runaway failure. Although difficult to directly link to the 550 ka Cumbre Nueva collapse, it is clear that dyke networks influence edifice strength, and that much needs to be done to understand their role in catastrophic failures.

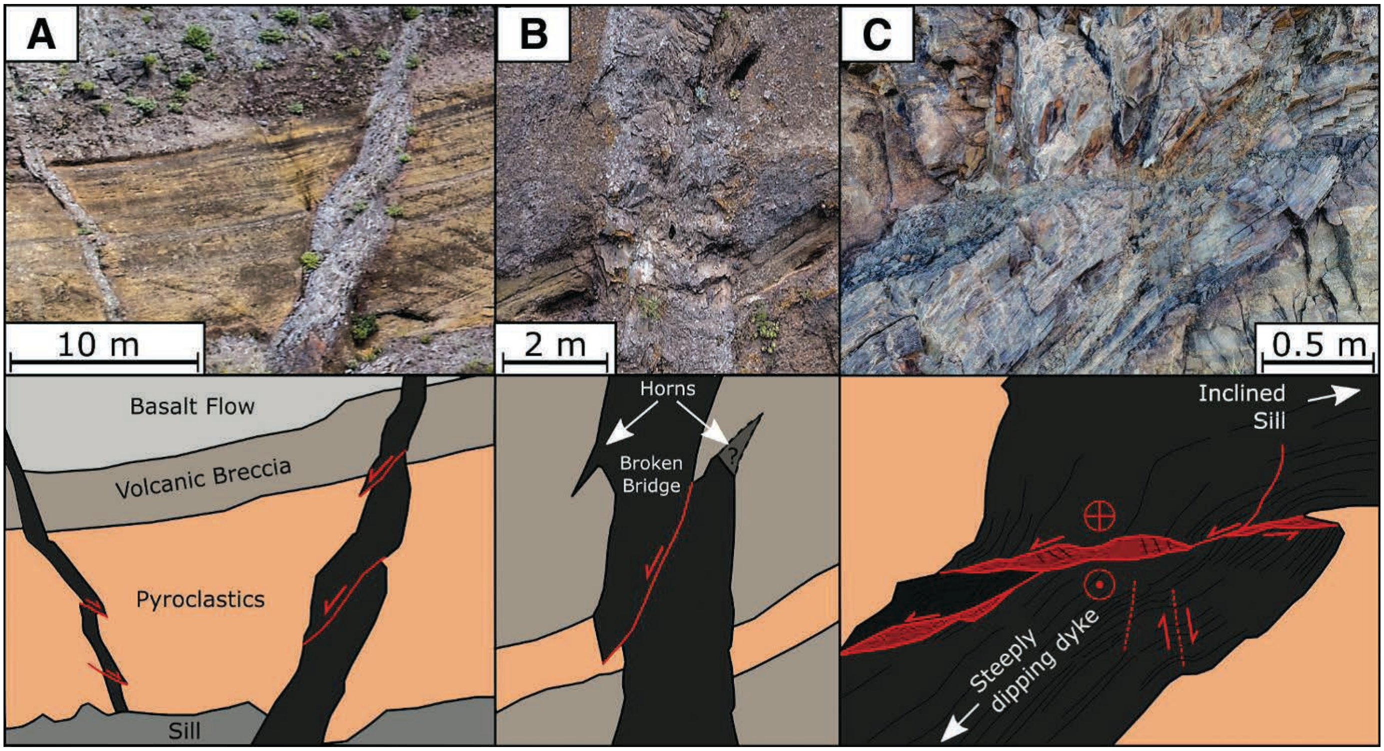

Figure 1. Examples of the small faults observed crosscutting dykes in Caldera de Taburiente. Note that the faults appear to initiate at geometric complexities in the dykes (A), such as broken bridges (B) and changes in orientation (C), and that their offsets are consistent with gravitational loading.