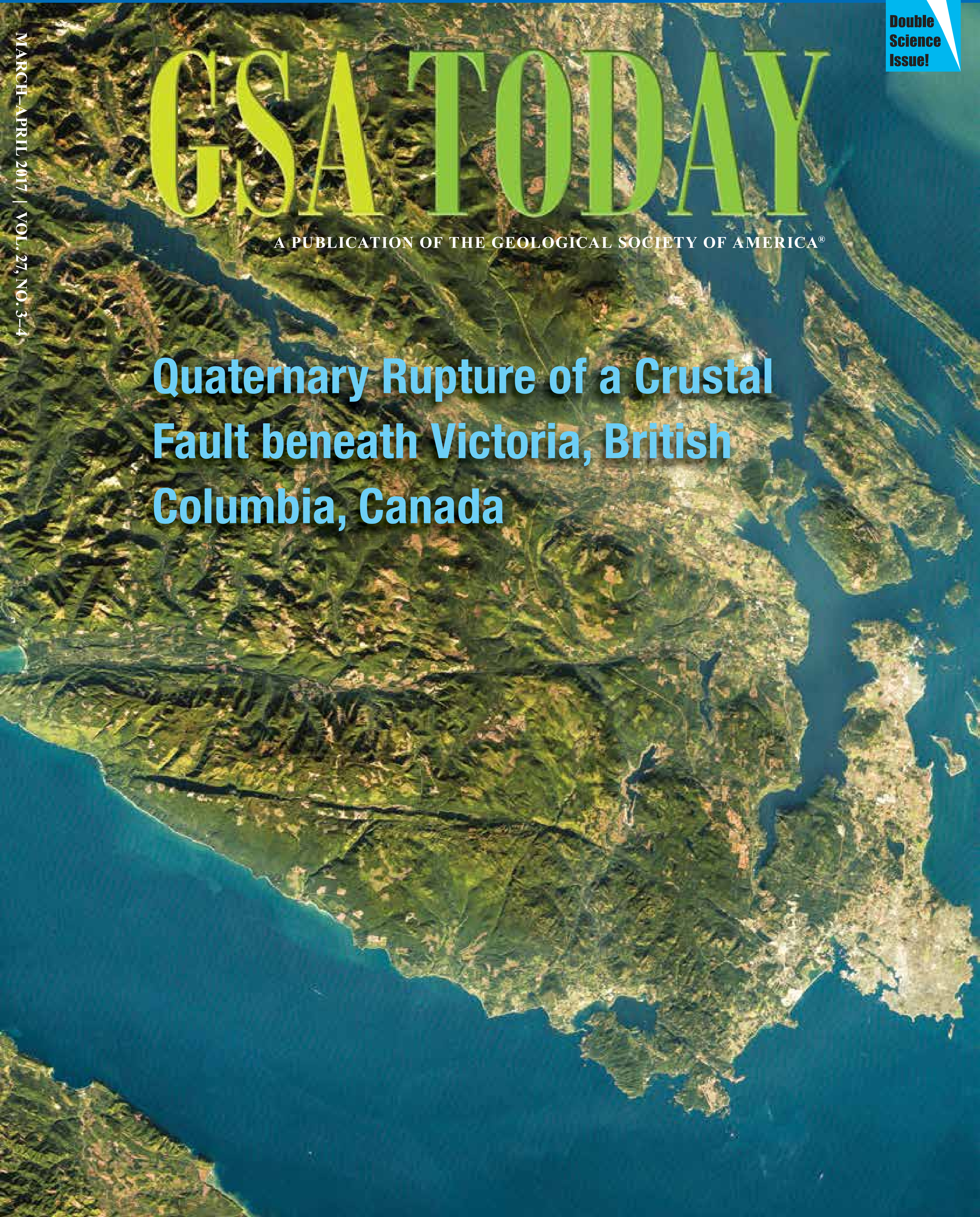
MARCH–APRIL 2017 | VOL. 27, NO. 3–4

Double Science Issue!

GSA TODAY

A PUBLICATION OF THE GEOLOGICAL SOCIETY OF AMERICA®

Quaternary Rupture of a Crustal Fault beneath Victoria, British Columbia, Canada



MARCH–APRIL 2017 | VOLUME 27, NUMBER 3–4

GSA TODAY

GSA TODAY (ISSN 1052-5173 USPS 0456-530) prints news and information for more than 26,000 GSA member readers and subscribing libraries, with 11 monthly issues (March/April is a combined issue). *GSA TODAY* is published by The Geological Society of America® Inc. (GSA) with offices at 3300 Penrose Place, Boulder, Colorado, USA, and a mailing address of P.O. Box 9140, Boulder, CO 80301-9140, USA. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of race, citizenship, gender, sexual orientation, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Subscriptions: GSA members: Contact GSA Sales & Service, +1-888-443-4472; +1-303-357-1000 option 3; gsaservice@geosociety.org for information and/or to place a claim for non-receipt or damaged copies. **Nonmembers and institutions:** *GSA TODAY* is US$97/yr; to subscribe, or for claims for non-receipt and damaged copies, contact gsaservice@geosociety.org. Claims are honored for one year; please allow sufficient delivery time for overseas copies. Periodicals postage paid at Boulder, Colorado, USA, and at additional mailing offices. Postmaster: Send address changes to GSA Sales & Service, P.O. Box 9140, Boulder, CO 80301-9140.

***GSA TODAY* STAFF**

Executive Director and Publisher: Vicki S. McConnell

Science Editors: Steven Whitmeyer, James Madison University Dept. of Geology & Environmental Science, 800 S. Main Street, MSC 6903, Harrisonburg, VA 22807, USA, whitmesj@jmu.edu; **Gerald Dickens,** Rice University School of Earth Science, MS-126, 6100 Main Street, Houston, Texas 77005, USA, jerry@rice.edu.

Member Communications Manager: Matt Hudson, mhudson@geosociety.org

Managing Editor: Kristen "Kea" Giles, kgiles@geosociety.org, gsatoday@geosociety.org

Graphics Production: Margo McGrew, mmcgrew@geosociety.org

Advertising Manager: Ann Crawford, +1-800-472-1988 ext. 1053; +1-303-357-1053; Fax: +1-303-357-1070; advertising@geosociety.org; acrawford@geosociety.org

GSA Online: www.geosociety.org
GSA TODAY: www.geosociety.org/gsatoday

Printed in the USA using pure soy inks.

THE GEOLOGICAL SOCIETY OF AMERICA®

Double Science Issue!

Cover: Landsat 7 image of southern Vancouver Island, showing the surface trace of the Leech River fault and its intersection with the population centers surrounding Victoria, British Columbia, Canada. See related article, p. 4–10.

***Inside* Cover:** The St. Bathans Range, Otago, New Zealand, shows three key elements of Zealandia. The bedrock is Mesozoic Haast Schist, a major geological unit that can be tracked across the continent. The flat top of the range is a diachronous Late Cretaceous to Oligocene marine planation surface that was cut as Zealandia subsided. Like the rest of the South Island of New Zealand, the 2000-m-high range was lifted up in the Neogene in response to intracontinental transpression across the Pacific-Australian plate boundary. Image credit Lloyd Homer/GNS Science. See related article, p. 27–35.

Quaternary Rupture of a Crustal Fault beneath Victoria, British Columbia, Canada

Kristin D. Morell, *School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia V8P 5C2, Canada, kmorell@uvic.ca;* **Christine Regalla,** *Department of Earth and Environment, Boston University, Boston, Massachusetts 02215, USA;* **Lucinda J. Leonard,** *School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia V8P 5C2, Canada;* **Colin Amos,** *Geology Department, Western Washington University, Bellingham, Washington 98225-9080, USA; and* **Vic Levson,** *School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia V8P 5C2, Canada*

ABSTRACT

The seismic potential of crustal faults within the forearc of the northern Cascadia subduction zone in British Columbia has remained elusive, despite the recognition of recent seismic activity on nearby fault systems within the Juan de Fuca Strait. In this paper, we present the first evidence for earthquake surface ruptures along the Leech River fault, a prominent crustal fault near Victoria, British Columbia. We use LiDAR and field data to identify >60 steeply dipping, semi-continuous linear scarps, sags, and swales that cut across both bedrock and Quaternary deposits along the Leech River fault. These features are part of an ~1-km-wide and up to >60-km-long steeply dipping fault zone that accommodates active forearc transpression together with structures in the Juan de Fuca Strait and the U.S. mainland. Reconstruction of fault slip across a deformed <15 ka colluvial surface near the center of the fault zone indicates ~6 m of vertical separation across the surface and ~4 m of vertical separation of channels incising the surface. These displacement data indicate that the Leech River fault has experienced at least two surface-rupturing earthquakes since the deglaciation following the last glacial maximum ca. 15 ka, and should therefore be incorporated as a distinct shallow seismic source in seismic hazard assessments for the region.

INTRODUCTION

Unlike plate boundary faults that often exhibit a strong seismic or geodetic expression (e.g., Rogers, 1988), active faults within the adjacent crust can have long recurrence intervals (e.g., 5–15 k.y.; Rockwell et al., 2000), and they may not be detectable by seismic or geodetic monitoring (e.g., Mosher et al., 2000; Balfour et al., 2011). This point was exemplified by the 2010 M_W 7.1 Darfield, New Zealand (Christchurch), earthquake and aftershocks that ruptured the previously unidentified Greendale fault (Gledhill et al., 2011). This crustal fault showed little seismic activity prior to 2010, but nonetheless produced a 30-km-long surface rupture, caused more than 180 casualties, and resulted in at least US$10 billion in damage (Quigley et al., 2012).

In the forearc of the Cascadia subduction zone (Fig. 1), where strain accrues due to the combined effects of northeast-directed subduction and the northward migration of the Oregon forearc block (McCaffrey et al., 2013), microseismicity data are sparse and do not clearly elucidate planar crustal faults (Cassidy et al., 2000; Balfour et al., 2011). But geomorphic,

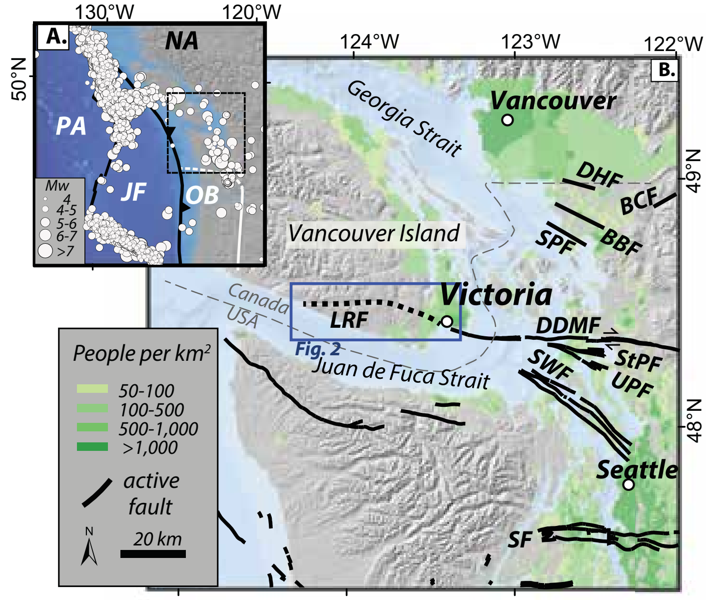


Figure 1. (A) Tectonic setting. White circles—locations of historical earthquakes (USGS NEIC) between AD 1946 and 2015, scaled by magnitude. White line—boundary between Oregon Block (OB) and North America plate (NA) (McCaffrey et al., 2013; Wells and Simpson, 2001). JF—Juan de Fuca plate; PA—Pacific plate. (B) Population centers (Balk et al., 2006) relative to mapped active faults in black (Sherrod et al., 2008; USGS, 2010; Kelsey et al., 2012; Personius et al., 2014; Barrie and Greene, 2015). The Leech River fault (LRF) is shown as dashed line. BBF—Birch Bay fault; BCF—Boulder Creek–Canyon Creek fault; DDMF—Darrington–Devil's Mountain fault; DHF—Drayton Harbor fault; SPF—Sandy Point fault; StPF—Strawberry Point fault; SF—Seattle fault; SWF—South Whidbey Island fault; UPF—Utsalady Point fault.

GSA Today, v. 27, no. 3–4, doi: 10.1130/GSATG291A.1

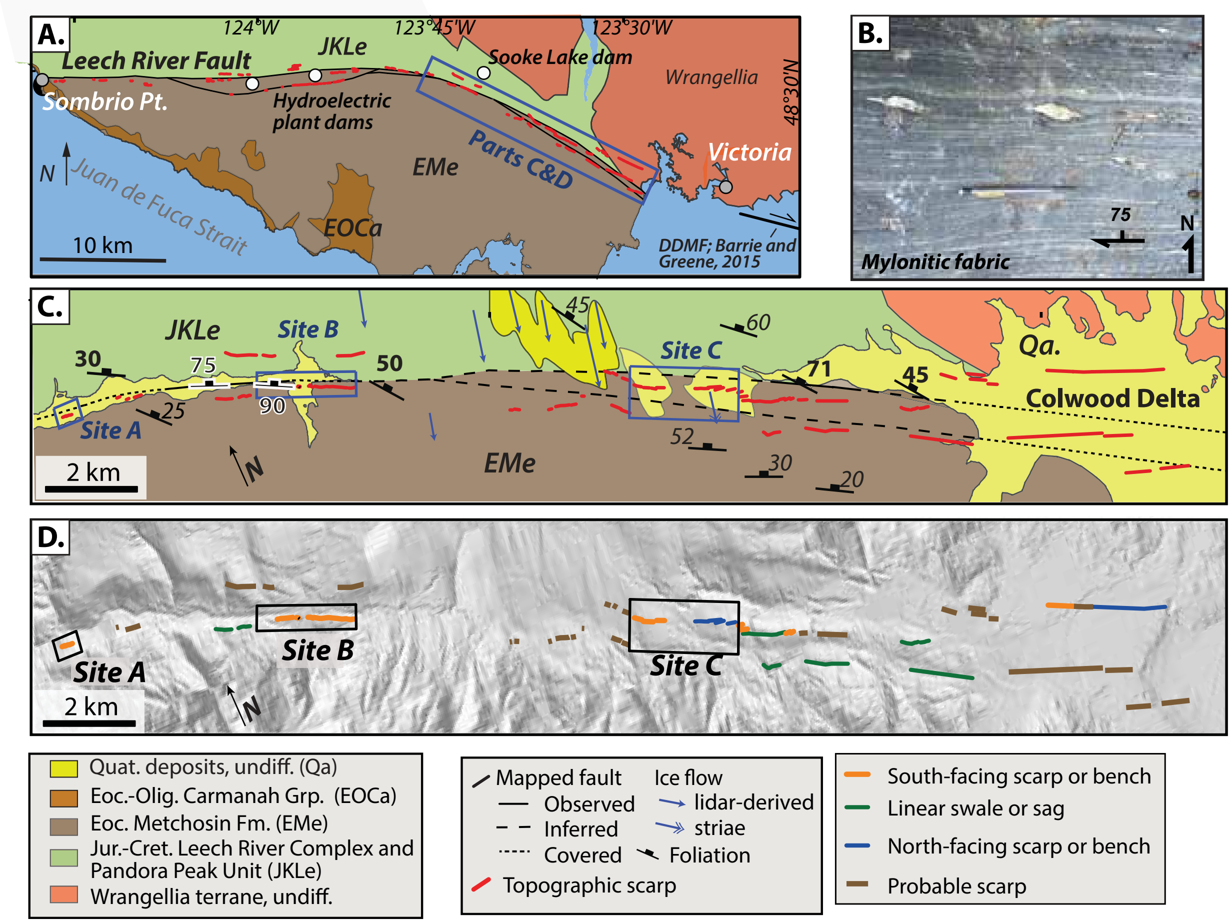


Figure 2. (A) Simplified geologic map of the Leech River fault and surroundings (after Massey et al., 2005). Red lines denote topographic scarps, pressure ridges, topographic benches, and linear swales and sags identified in this study. See geological legend at base of figure. DDMF—Darrington–Devil's Mountain fault. (B) Mylonitic fabrics within the Leech River Complex near its contact with the Metchosin Fm. (C) Map showing trace of identified features relative to bedrock (Massey et al., 2005), surficial deposits (Blyth and Rutter, 1993), and local ice flow indicators (blue arrows, this study). Foliation measurements from this study are shown in bold and those from Muller (1983) are shown in italics. Foliation data outlined in white are at the lithologic contact (this study). (D) Fault traces as in part C, colored according to facing direction and feature type, draped on LiDAR hillshade image.

trenching, and geophysical studies have proven successful at highlighting a network of oblique reverse forearc faults, both on- and offshore of Washington and Oregon, that can produce earthquakes up to 7.5 in magnitude (McCaffrey and Goldfinger, 1995; ten Brink et al., 2006; Blakely et al., 2014; Sherrod et al., 2016). In particular, LiDAR, seismic, and aeromagnetic data have been paramount in the recognition of the Seattle fault as a significant seismic hazard source within the greater Seattle region (SF, Fig. 1) (Johnson et al., 1999; Blakely et al., 2002; Kelsey et al., 2008; Nelson et al., 2014).

The potential Quaternary activity of the Leech River fault, an ~60-km-long terrane-bounding fault in the southern Vancouver Island forearc (Muller, 1977; MacLeod et al., 1977), has drawn significant attention in recent years because of the seismic hazard it may pose to the nearby population of Victoria, British Columbia (Figs. 1 and 2A) (see Cassidy et al., 2000; Mosher et al., 2000; Balfour et al., 2011). Several previous authors suggest that this fault, which places Jurassic-Cretaceous schists of the Leech River Complex to the north against Eocene basalts of the Metchosin Formation to the south (Fig. 2A) (Fairchild and Cowan, 1982; Rusmore and Cowan, 1985), was last active in the Eocene (MacLeod et al., 1977; Johnston and Acton, 2003). Yet, trenching, coring, and geophysical studies indicate multiple Quaternary ruptures of adjacent fault systems in Washington state, USA, including the Southern Whidbey Island fault, the Utsalady Point fault, and the Darrington–Devil's Mountain fault (Fig. 1) (Johnson et al., 1996, 2001; Sherrod et al., 2008; Personius et al., 2014). Quaternary seismic activity is also recognized 10–20 km offshore of the Leech River fault along a structure in the Juan de Fuca Strait (Barrie and Greene, 2015) (Figs. 1 and 2A), but direct evidence for recent rupture onshore has remained ambiguous.

Here, we use a combination of techniques to delineate Quaternary fault-related features along the Leech River fault, including (1) mapping of fault scarps from hillshade and local slope images generated from a high resolution (~2 m horizontal by ~10 cm vertical) LiDAR digital elevation model (DEM) collected by Natural Resources Canada (James et al., 2010); (2) first-order bedrock and surficial field mapping; (3) collection of detailed structural and geomorphic data at key sites; and (4) compilation of our observations with data from previous studies (e.g., Fairchild and Cowan, 1982; Blyth and Rutter, 1993;

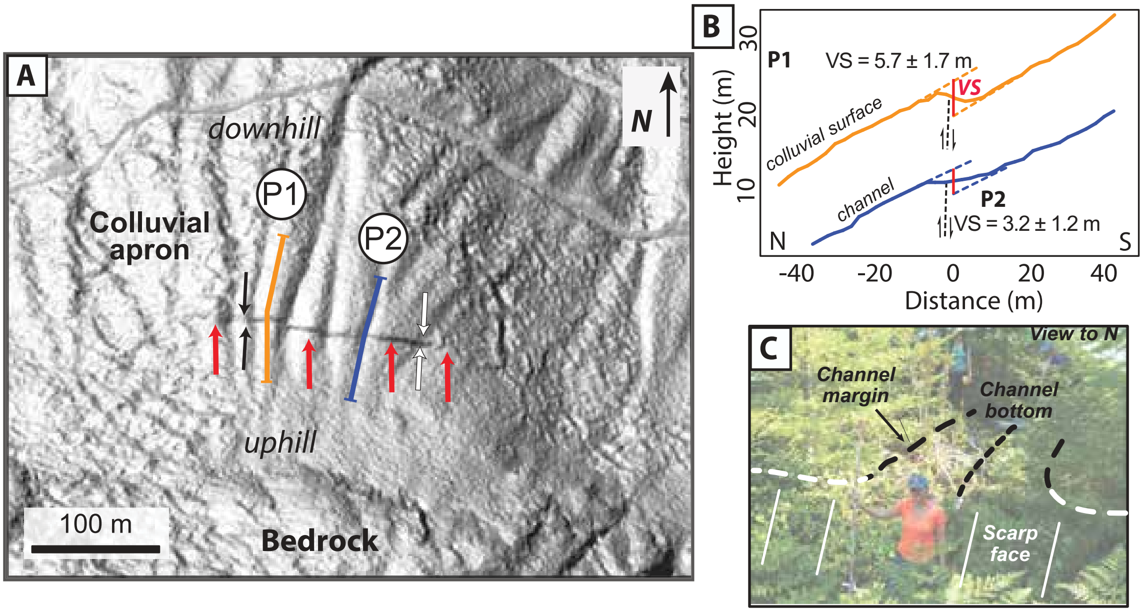


Figure 3. (A) LiDAR hillshade map of Site A, showing an uphill (south) facing scarp cutting the surface of a steeply north-sloping colluvial apron and channels. Red arrows point to steep face. Black and white arrows show apparent left and right (respectively) lateral separations of channel margins. Example profile lines (P1 and P2) locations shown. Additional profile lines are shown in Figure DR2 (see text footnote 1). (B) An example of LiDAR-derived elevation profiles from interfluve P1 and channel P2. VS—vertical separation. (C) Field photo showing tectonic scarp in a channel at site C.

Massey et al., 2005). We identify several strands of the Leech River fault that displace post-glacial sediments and record at least two M_W >6 earthquakes since the Cordilleran deglaciation ca. 15 ka (Clague and James, 2002). These data provide the first evidence for Quaternary surface rupture along a crustal fault that lies within close proximity of Victoria, British Columbia, and suggest that the Leech River fault is only one of a network of active faults that accommodate forearc deformation in southwestern Canada.

OBSERVATIONS

We mapped >60 topographic features along the Leech River fault that together extend >60 km in length and span ~1 km in width. Individual features range in length from hundreds of meters to >2.5 km, reach up to ~5 m in height, and form linear ridges, sags, and scarps with both north- and south-facing directions (Fig. 2). Along the eastern half of the fault, where we focused our analysis, these topographic features coincide with displaced geomorphic surfaces, steeply dipping brittle faults, and uphill-facing bedrock scarps.

In order to exclude topographic features that were produced by differential erosion along steeply dipping foliation planes, we mapped the position of lithologically distinct units and collected structural data on the occurrence and orientation of foliation and fault deformation fabrics. The topographic scarps we identified are roughly parallel to the previously mapped location of the Leech River fault (Fairchild and Cowan, 1982; Massey et al., 2005), but none of the identified fault scarps coincide exactly with the fault contact between the Leech River Complex and the Metchosin Formation (Fig. 2). Instead, individual topographic features occur both north and south of the lithologic fault boundary by as much as hundreds of meters. Where a discrete contact between the basalt and schist units is exposed at two locations in the area, the fault strikes parallel to regional foliation (300–310°) but dips more steeply (70–90° NE) than the foliation (~45° NE) (Figs. 2B and 2C, and GSA Data Repository[1] Fig. DR1A). The westernmost of these sites contains a 10- to >200-m-wide mylonitic shear zone within both units, but exhibits no brittle deformation at the outcrop scale (Figs. 2B and 2C). Because the mapped features do not coincide with the lithologic terrane boundary, they cannot be explained by differential erosion across this strong lithologic contrast.

To further exclude topographic features produced by glacial processes, we determined local ice flow directions from bedrock striae and streamlined glacial deposits and collected geomorphic data designed to confirm a tectonic origin. The roughly east-west–oriented topographic features on the eastern half of the Leech River fault are nearly perpendicular to the southerly regional ice flow direction during the last glacial maximum. The LiDAR data delineate large (km-long) drumlinoid ridges with well-defined apices that are distinctively streamlined with steep up-ice (northern) margins and upper surfaces that gently slope in a southerly, down-ice direction (Figs. 2C and 2D). Our field work confirms that these ridges are mantled by glacial sediments (Fig. DR1E [see footnote 1]). South-directed ice flow is further supported by glacial striae data on bedrock near the drumlinoid ridges (Fig. 2C). The observation that the mapped scarps strike perpendicular to the ice flow direction rules out their formation by ice flow–parallel processes, including glacial scouring, grooving, molding, and streamlining.

---

[1] GSA Data Repository Item 2017046, supplementary figures, is online at http://www.geosociety.org/datarepository/2017/. If you have questions, please email gsatoday@geosociety.org.

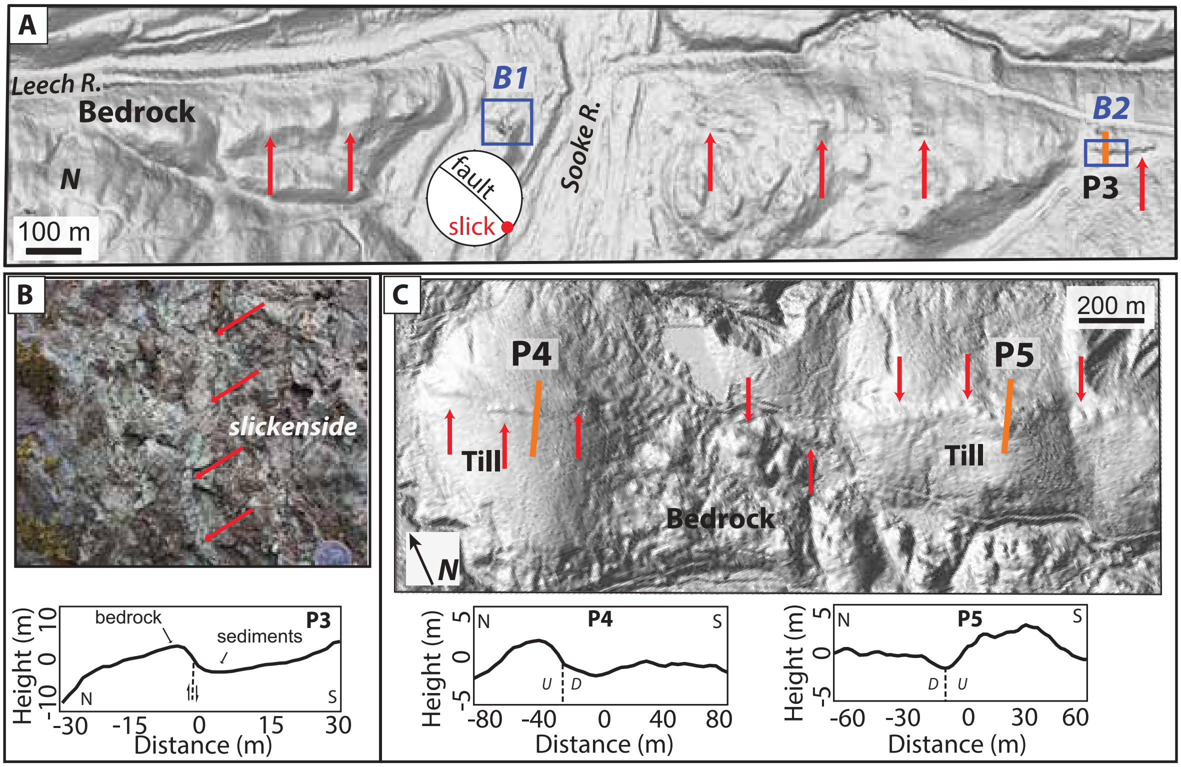


Figure 4. (A) LiDAR hillshade image for site B where there is a >1.5-km-long scarp in bedrock. Red arrows point to steep face. Stereonet from fault at site B1. (B) Field photo of gouge-bearing fault at site B1, with subhorizontal slickenlines. Elevation profile at bottom for site B2. (C) LiDAR hillshade for site C showing topographic features with opposing facing directions and a morphology suggestive of pressure ridges. Red arrows point to the steep face. LiDAR-derived elevation profiles shown below the image. Because structures are buried beneath dense vegetation and glacial till, fault locations are inferred (dashed lines on the profiles). U and D denote up- and downthrown sides, respectively.

FIELD EVIDENCE FOR TECTONIC SCARPS

We identify three key sites (Figs. 2C and 2D, sites A–C) where field and LiDAR data indicate tectonic displacement of bedrock and Quaternary deposits.

Site A

Near the center of the Leech River fault, the LiDAR data reveal a >200-m-long and up to ~3–6-m-high topographic scarp that faces uphill (southward) across a relatively steep (~20°), north-facing slope (Fig. 3A). Beneath an ~1-m-thick mantle of colluvium at the surface, the hillside consists of a dense, matrix-supported diamict with numerous erratics and striated clasts, interpreted as subglacial till. These field observations, the relatively smooth surface morphology, and the lack of a fan apex, indicate that this ~400-m-long by ~300-m-wide hillside is covered by an apron of colluvium. Several steep, linear channels littered with boulders incise this colluvial apron.

LiDAR and field data indicate that both the colluvial surface and the channels incising it are vertically displaced by several meters across the scarp (~3–6 m) (Figs. 3 and DR1B [see footnote 1]). We calculated vertical separations at 12 locations across the fault scarp by linear regression of LiDAR-derived topography and estimated regression uncertainties using a Monte Carlo routine (following Thompson et al., 2002) (Fig. DR2 [see footnote 1]). These data confirm that scarp height is systematically lower within the incised channels than on the colluvial surface. For example, at interfluve P1, the vertical separation across the scarp approaches ~6 m (5.7 ± 1.7 m) (Fig. 3B). At channel P2, however, the LiDAR profiles indicate only ~3 m (3.2 ± 1.2 m) of vertical separation. On average, the interfluves are vertically separated by 5.7 ± 1.3 m ($n = 8$) and the channels by 3.9 ± 0.9 m ($n = 4$) (1σ) (Fig. DR2). These estimates support our field observations of a differential amount of displacement across the scarp between channels versus interfluves (Fig. 3C).

Several field observations suggest this scarp reflects north-side-up dip slip displacement along a steeply north-dipping (60–90°) fault. For instance, the interaction of the scarp with local topography suggests that the fault dips steeply to the north; the scarp trace is nearly linear in map view, but it deviates slightly northward into topographic lows (Fig. DR2A). Additionally, both the apparent north-side-up displacement and the spatial pattern of channel displacement indicate dip slip displacement with little to no lateral displacement. While northeast-trending channels show apparent right separation (white arrows, Fig. 3A), north-northwest–trending channels show apparent left separation (black arrows, Fig. 3A). Together, these data indicate that both the colluvial surface and the channels have been vertically displaced by ~4–6 m due to slip on a steep, north-dipping reverse fault.

Site B

Five kilometers east along strike from site A, a prominent south-facing bedrock scarp extends for ~1.5 km and shows evidence for brittle deformation along its length (site B, Figs. 2 and 4). Near the center of this scarp, an abandoned rock quarry exposes two steeply north-dipping sub-parallel faults (dipping 85° to N40°E) cutting Metchosin Formation basalt (site B1, Figs. 4A and 4B). Both faults have a 1–2-mm-wide gouge zone and exhibit subhorizontal slickenlines (05° toward 129°) consistent with strike-slip motion (Figs. 4B and DR1C [see footnote 1]). At the eastern end of site B, the scarp becomes ~4 m high and uphill facing (Fig. 4A). Here, the northern (upthrown) side of the scarp consists of fractured and brittly deformed Metchosin Formation basalt, whereas the southern (downthrown) side of the scarp contains fine-grained sediment (P3, Fig. 4B). Similar to site A, the apparent north-side-up displacement across the scarp and the northward divergence of the scarp trace into topographic lows signifies dip displacement along a steeply north-dipping reverse fault (Figs. 4B and DR1D). Overall, these observations suggest an origin for this feature as a tectonic scarp.

Site C

Approximately 5 km east of site B, an ~1.5-km-long region contains >300-m-long ridges, linear sags, and swales up to ~2–5 m in height that cut across relatively smooth, gently sloping till-mantled hillslopes (Figs. 4C and DR1E). These topographic features display several differences from those at sites to the west. Whereas sites A and B exhibit discrete topographic scarps, features in this region are 10–15-m-wide elevated zones that sit more than ~5 m above the surrounding landscape. Moreover, while the scarps at sites A and B remain north-facing for hundreds of meters along strike, the facing direction of the features in site C transitions southeastward from south- to north-facing over a short (~200 m) distance (Figs. 2D and 4C).

These scarps have a nearly linear trace across topography, but they do not exhibit clear upthrown fault blocks or a marked increase in surface elevation. We interpret this en echelon arrangement of topographic ridges and the lateral juxtaposition of topographic highs and lows as pressure ridges, common in strike slip or oblique slip systems (e.g., Sylvester, 1988; Sherrod et al., 2008, 2016; Nelson et al., 2014).

QUATERNARY SLIP ON THE LEECH RIVER FAULT

The displaced geomorphic features, faulted bedrock, and prominent scarps collectively argue that several strands of the Leech River fault have been active since the late Pleistocene. Our observations support a tectonic genesis for the topographic features we identify for several reasons. First, several of the identified topographic features show evidence for extensive brittle faulting. For example, the fractured rock and gouge along the scarp at site B (Fig. 4B) require a tectonic origin and exclude formation by either ice plucking or the erosion of a bedrock foliation. Second, the observation that paleo–ice flow was directed to the south, at a high angle to the orientation of the topographic features (Fig. 2C), further rules out formation by glacial processes. Finally, it is unlikely that the topographic scarps in Quaternary deposits were produced by landslide processes. Several of the scarps, including those at sites A and B (Figs. 2C and 2D), are uphill facing, nearly perfectly linear, and do not exhibit curvilinear head scarps that would be expected for landslides.

The most compelling evidence for a tectonic origin for these topographic features comes from site A, where both the hillslope surface and multiple channels are displaced vertically along an uphill facing scarp (Figs. 3A and 3B). The scarp at site A cannot represent the remnants of an abandoned logging road or placer mining excavation because the base of the scarp is not graded, and the upper and lower surfaces are vertically separated by >~4 m (Fig. 3B). Such displacement in hillslope elevation, and in particular the displaced channels, cannot be produced by any mechanism other than fault displacement. Because the colluvial apron at this site remains both in situ and intact, the tectonic scarps crosscutting the colluvial surface and inset channels must be no older than the deglaciation following the last glacial maximum (ca. 15 ka) (Clague and James, 2002).

We suggest that the identified scarps together compose an active fault system that is up to ~1 km wide and 30–60 km long (Fig. 2A). Although individual lineaments can be traced for only hundreds of meters along strike, meter-high fault scarps are not easily preserved in this wet climate, and the fault scarps are semi-continuous with one another along strike. Our recognition of topographic features along the western ~30 km of the fault similar to those on the eastern half (Fig. 2C) suggests that the active fault zone extends the entire 60-km length of the fault onshore (Fig. 2A). Scarp morphology, fault orientations, and fault kinematics suggest that the active strands of the Leech River fault accommodate strike and dip slip motion within a steeply dipping fault zone or flower structure. Within a zone up to 1 km wide, we observe near vertical faults, variable scarp facing directions, laterally discontinuous surface scarps, and field evidence for strike-slip and reverse faulting. These characteristics are typical of strike slip systems and are similar to features observed along active oblique-reverse faults in the adjacent Pacific Northwest (e.g., Johnson et al., 2001; Sherrod et al., 2008, 2016; Kelsey et al., 2012; Nelson et al., 2014; Personius et al., 2014; Blakely et al., 2014).

These new results challenge the prevailing view that the Leech River fault was primarily an Eocene structure (cf. MacLeod et al., 1977). This interpretation was partly based on the observation that relatively undeformed Oligocene sediments of the Carmanah Group (Sooke Fm.) lie unconformably above healed fractures and mylonitic fabrics close to the trace of the Leech River fault near Sombrio Point (Fig. 2A) (MacLeod et al., 1977). However, our results from the eastern half of the Leech River fault show that active fault strands occur within a zone as much as 1 km wide and these strands are not always co-located with observed fault-related fabrics. Therefore, the location of fault fabrics may not coincide with the surface trace of the active fault.

IMPLICATIONS FOR PALEOSEISMICITY

The displaced channels and colluvial surface at site A suggest this section of the Leech River fault has experienced at least two, and possibly three or more, large, surface-rupturing earthquakes since the formation of the surface ca. 15 ka. For a 60–90° reverse fault, the displacements across the scarp require minimum dip displacements of 6.4 ± 1.5 m for interfluves ($n = 8$) and 4.4 ± 1.1 m for channels ($n = 4$). The ~2 m difference in displacement between the channels and interfluves implies multiple episodes of fault activity and suggests that at least one event with ~2 m displacement occurred after the formation of the colluvial apron but before channel incision. In addition to this early event, the ~4 m of displacement of the channels (Fig. 3B and DR2 [see footnote 1]) requires either one large event with ~4 m of slip, or multiple smaller events that together sum to ~4 m of slip. Global empirical relationships suggest that surface displacements on the order of meters correspond to earthquakes of M_W 6 or greater (e.g., Wells and Coppersmith, 1994).

IMPLICATIONS FOR REGIONAL SEISMOTECTONICS

Several observations indicate the active Leech River fault zone is part of a network of high-angle oblique faults that accommodate regional transpression across the Juan de Fuca Strait and Puget Sound region. Barrie and Greene (2015) trace the Devil's Mountain fault of Washington state, USA, to within 10–20 km of the fault scarps on Fig. 2, and their bathymetric and seismic surveys reveal a steeply dipping oblique -slip fault zone similar to our observations of the Leech River fault zone. Both the Darrington–Devil's Mountain fault and the Southern Whidbey Island fault systems of Washington state (Fig. 1) are likewise near-vertical fault zones with oblique slip histories (Sherrod et al., 2008; Personius et al., 2014) similar to many of the crustal fault systems throughout the Puget Sound region (e.g., McCaffrey and Goldfinger, 1995; ten Brink et al., 2006; Blakely et al., 2014; Nelson et al., 2014; Sherrod et al., 2016). Considering these similarities in orientation and slip sense, we suggest that the Leech River fault is part of this regional active forearc fault system. Although it remains possible that the timing of past ruptures along these fault systems was influenced by stress loading or release related to the last glaciation (e.g., Hetzel and Hampel, 2005), repeated earthquakes on crustal faults including the Leech River should be expected in order to accommodate ongoing tectonic strain in the forearc of the active Cascadia subduction zone.

IMPLICATIONS FOR SEISMIC HAZARD

The length of the active Leech River fault zone (30–60 km; Fig. 2A) and its history of multiple Quaternary ruptures suggest it is capable of producing earthquakes of $M_W > 6$. This active fault zone lies within tens of kilometers of downtown Victoria and in close proximity to three local water dams. One of these dams is located within 2 km of the active fault zone and supports the region's principal water supply reservoir (Fig. 2A). The other two dams lie within the active fault zone and support a hydroelectric power plant. Thus, our new identification of a significant shallow seismic source has considerable implications for the seismic risk exposure of this populated region. Surface-rupturing earthquakes with shallow hypocenters can be highly destructive, and it is therefore important that the Leech River fault zone be incorporated into seismic hazard assessments of southwestern British Columbia and neighboring regions.

ACKNOWLEDGMENTS

We thank CRD watersheds and BC Hydro for access to key field sites. This manuscript benefitted from comments by Jack Loveless, Alan Nelson, Christie Rowe, and two anonymous reviewers. We thank Steven Whitmeyer for editorial handling. This research was supported by an NSERC Discovery grant to KM and NSF EAR IRFP Grant #1349586 to CR.

REFERENCES CITED

Balfour, N., Cassidy, J., Dosso, S., and Mazzotti, S., 2011, Mapping crustal stress and strain in southwest British Columbia: Journal of Geophysical Research: Solid Earth (1978–2012), v. 116, B03314, doi: 10.1029/2010JB008003.

Balk, D., Deichmann, U., Yetman, G., Pozzi, F., Hay, S., and Nelson, A., 2006, Determining global population distribution: Methods, applications and data: Advances in Parasitology, v. 62, p. 119–156, doi: 10.1016/S0065-308X(05)62004-0.

Barrie, V., and Greene, G., 2015, Active faulting in the northern Juan de Fuca Strait, Implications for Victoria, British Columbia: Geological Survey of Canada Current Research 2015-6, p. 10, doi: 10.4095/296564.

Blakely, R.J., Wells, R.E., Weaver, C.S., and Johnson, S.Y., 2002, Location, structure, and seismicity of the Seattle fault zone, Washington: Evidence from aeromagnetic anomalies, geologic mapping, and seismic-reflection data: GSA Bulletin, v. 114, no. 2, p. 169–177, doi: 10.1130/0016-7606(2002)114<0169:LSASOT>2.0.CO;2.

Blakely, R.J., Sherrod, B.L., Weaver, C.S., Wells, R.E., and Rohay, A.C., 2014, The Wallula fault and tectonic framework of south-central Washington, as interpreted from magnetic and gravity anomalies: Tectonophysics, v. 624–625, p. 32–45, doi: 10.1016/j.tecto.2013.11.006.

Blyth, H., and Rutter, N., 1993, Surficial geology of the Sooke area (nts 92b/5): British Columbia Ministry of Energy Mines and Petroleum Resources, Open File 1993-25.

Cassidy, J.F., Rogers, G.C., and Waldhauser, F., 2000, Characterization of active faulting beneath the Strait of Georgia, British Columbia: Bulletin of the Seismological Society of America, v. 90, no. 5, p. 1188–1199, doi: 10.1785/0120000044.

Clague, J.J., and James, T.S., 2002, History and isostatic effects of the last ice sheet in southern British Columbia: Quaternary Science Reviews, v. 21, no. 1–3, p. 71–87, doi: 10.1016/S0277-3791(01)00070-1.

Fairchild, L., and Cowan, D., 1982, Structure, petrology, and tectonic history of the Leech River complex northwest of Victoria, Vancouver Island: Canadian Journal of Earth Sciences, v. 19, p. 1817–1835, doi: 10.1139/e82-161.

Gledhill, K., Ristau, J., Reyners, M., Fry, B., and Holden, C., 2011, The Darfield (Canterbury, New Zealand) M_W 7.1 earthquake of September 2010: A preliminary seismological report: Seismological Research Letters, v. 82, no. 3, p. 378–386, doi: 10.1785/gssrl.82.3.378.

Hetzel, R., and Hampel, A., 2005, Slip rate variations on normal faults during glacial–interglacial changes in surface loads: Nature, v. 435, 7038, p. 81–84, doi: 10.1038/nature03562.

James, T., Bednarski, J., Rogers, G., and Currie, R., 2010, LiDAR and digital aerial imagery of the Leech River Fault Zone and coastal regions from Sombrio Point to Ten Mile Point, southern Vancouver Island, British Columbia: Geological Survey of Canada, Open-File 6211, doi: 10.4095/285486.

Johnson, S., Potter, C., Miller, J., Armentrout, J., Finn, C., and Weaver, C., 1996, The southern Whidbey Island fault: An active structure in the Puget Lowland, Washington: GSA Bulletin, v. 108, p. 334–354, doi: 10.1130/0016-7606(1996)108<0334:TSWIFA>2.3.CO;2.

Johnson, S., Dadisman, S., Mosher, D., Blakely, R., and Childs, J., 2001, Active tectonics of the Devil's Mountain Fault and related structures, Northern Puget Lowland and Eastern Strait of Juan de Fuca Region, Pacific Northwest: U.S. Geological Survey Professional Paper 1643.

Johnston, S.T., and Acton, S., 2003, The Eocene Southern Vancouver Island Orocline: A response to seamount accretion and the cause of fold-and-thrust belt and extensional basin formation: Tectonophysics, v. 365, no. 1–4, p. 165–183, doi: 10.1016/S0040-1951(03)00021-0.

Johnson, S.Y., Dadisman, S.V., Childs, J.R., and Stanley, W.D., 1999, Active tectonics of the Seattle fault and central Puget Sound, Washington—Implications for earthquake hazards: GSA Bulletin, v. 111, no. 7, p. 1042–1053, doi: 10.1130/0016-7606(1999)111<1042:ATOTSF>2.3.CO;2.

Kelsey, H.M., Sherrod, B.L., Nelson, A.R., and Brocher, T.M., 2008, Earthquakes generated from bedding plane-parallel reverse faults above an active wedge thrust, Seattle fault zone: GSA Bulletin, v. 120, no. 11–12, p. 1581–1597, doi: 10.1130/B26282.1.

Kelsey, H.M., Sherrod, B.L., Blakely, R.J., and Haugerud, R.A., 2012, Holocene faulting in the Bellingham forearc basin: Upper-plate deformation at the northern end of the Cascadia subduction zone: Journal of Geophysical Research, Solid Earth, v. 117, B03409, doi: 10.1029/2011JB008816.

MacLeod, N., Tiffin, D., Snavely, P., Jr., and Currie, R., 1977, Geologic interpretation of magnetic and gravity anomalies in the Strait of Juan de Fuca, U.S.–Canada: Canadian Journal of Earth Sciences, v. 14, no. 2, p. 223–238, doi: 10.1139/e77-024.

Massey, N.W.D., MacIntyre, D., Desjardins, P., and Cooney, R., 2005, Digital geology map of British Columbia: BC Ministry of Energy and Mines, Geological Survey Branch, scale: 1:250,000.

McCaffrey, R., and Goldfinger, C., 1995, Forearc deformation and great subduction earthquakes: Implications for Cascadia offshore earthquake potential: Science, v. 267, 5199, p. 856–859, doi: 10.1126/science.267.5199.856.

McCaffrey, R., King, R.W., Payne, S.J., and Lancaster, M., 2013, Active tectonics of northwestern U.S. inferred from GPS-derived surface velocities: Journal of Geophysical Research, Solid Earth, v. 118, p. 709–723, doi: 10.1029/2012JB009473.

Mosher, D.C., Cassidy, J.F., Lowe, C., Mi, Y., Hyndman, R.D., Rogers, G.C., and Fisher, M., 2000, Neotectonics in the Strait of Georgia: First tentative correlation of seismicity with shallow geological structure in southwestern British Columbia: Current Research, p. A22.

Muller, J.E., 1977, Evolution of the Pacific Margin, Vancouver Island, and adjacent regions: Canadian Journal of Earth Sciences, v. 14, no. 9, p. 2062–2085, doi: 10.1139/e77-176.

Muller, J., 1983, Geology of Victoria map-area: Geological Survey of Canada, "A" Series Map 1553A, 1 sheet, scale: 1:100,000 doi: 10.4095/119507.

Nelson, A.R., Personius, S.F., Sherrod, B.L., Kelsey, H.M., Johnson, S.Y., Bradley, L.A., and Wells, R.E., 2014, Diverse rupture modes for surface-deforming upper plate earthquakes in the southern Puget Lowland of Washington State: Geosphere, v. 10, no. 4, p. 769–796, doi: 10.1130/GES00967.1.

Personius, S.F., Briggs, R.W., Nelson, A.R., Schermer, E.R., Maharrey, J.Z., Sherrod, B.L., Spaulding, S.A., and Bradley, L.A., 2014, Holocene earthquakes and right-lateral slip on the left-lateral Darrington–Devils Mountain fault zone, northern Puget Sound, Washington: Geosphere, v. 10, no. 6, p. 1482–1500, doi: 10.1130/GES01067.1.

Quigley, M., Van Dissen, R., Litchfield, N., Villamor, P., Duffy, B., Barrell, D., Furlong, K., Stahl, T., Bilderback, E., and Noble, D., 2012, Surface rupture during the 2010 M_W 7.1 Darfield (Canterbury) earthquake: Implications for fault rupture dynamics and seismic-hazard analysis: Geology, v. 40, no. 1, p. 55–58, doi: 10.1130/G32528.1.

Rockwell, T., Lindvall, S., Herzberg, M., Murbach, D., Dawson, T., and Berger, G., 2000, Paleoseismology of the Johnson Valley, Kickapoo, and Homestead Valley faults: Clustering of earthquakes in the eastern California shear zone: Bulletin of the Seismological Society of America, v. 90, no. 5, p. 1200–1236, doi: 10.1785/0119990023.

Rogers, G.C., 1988, An assessment of the megathrust earthquake potential of the Cascadia subduction zone: Canadian Journal of Earth Sciences, v. 25, no. 6, p. 844–852, doi: 10.1139/e88-083.

Rusmore, M.E., and Cowan, D.S., 1985, Jurassic-Cretaceous rock units along the southern edge of the Wrangellia terrane on Vancouver Island: Canadian Journal of Earth Sciences, v. 22, no. 8, p. 1223–1232, doi: 10.1139/e85-124.

Sherrod, B., Blakely, R., Weaver, C., Kelsey, H., Barnett, E., Liberty, L., Meagher, K., and Pape, K., 2008, Finding concealed active faults: Extending the southern Whidbey Island fault across the Puget Lowland, Washington: Journal of Geophysical Research, v. 113, B05313, doi: 10.1029/2007JB005060.

Sherrod, B.L., Blakely, R.J., Lasher, J.P., Lamb, A., Mahan, S.A., Foit, F.F., and Barnett, E.A., 2016, Active faulting on the Wallula fault zone within the Olympic-Wallowa lineament, Washington State, USA: GSA Bulletin, v. 128, no. 11–12, p. 1636–1659, doi: 10.1130/B31359.1.

Sylvester, A.G., 1988, Strike-slip faults: GSA Bulletin, v. 100, no. 11, p. 1666–1703, doi: 10.1130/0016-7606(1988)100<1666:SSF>2.3.CO;2.

ten Brink, U., Song, J., and Bucknam, R.C., 2006, Rupture models for the AD 900–930 Seattle fault earthquake from uplifted shorelines: Geology, v. 34, no. 7, p. 585–588, doi: 10.1130/G22173.1.

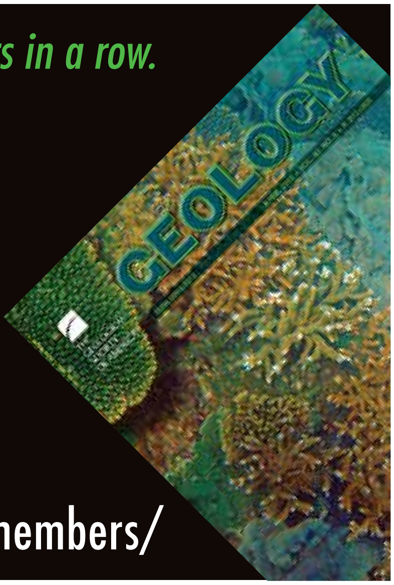
Thompson, S.C., Weldon, R.J., Rubin, C.M., Abdrakhmatov, K., Molnar, P., and Berger, G.W., 2002, Late Quaternary slip rates across the central Tien Shan, Kyrgyzstan, central Asia: Journal of Geophysical Research, Solid Earth, v. 107, no. B9, doi: 10.1029/2001JB000596.

USGS, 2010, Quaternary fault and fold database for the United States: http//earthquakes.usgs.gov/hazards/qfaults/ (last accessed April 2015).

Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, no. 4, p. 974–1002.

Wells, R., and Simpson, R., 2001, Northward migration of the Cascadia forearc in the northwestern U.S. and implications for subduction deformation: Earth, Planets and Space, v. 53, p. 275–283, doi: 10.1186/BF03352384.

Manuscript received 28 March 2016
Revised manuscript received 20 June 2016
Manuscript accepted 6 July 2016



ELECTIONS: GSA OFFICERS and COUNCILORS

GSA ELECTIONS BEGIN 17 MARCH 2017

GSA's success depends on you—its members—and the work of the officers serving on GSA's Executive Committee and Council. Members will receive instructions for accessing a member-only electronic ballot via our secure website, and biographical information on the nominees will be online for you to review at that time. Paper versions of both the ballot and candidate information will also be available upon request. Please help continue to shape GSA's future by voting on these nominees.

2017 OFFICER NOMINEES

PRESIDENT	**PRESIDENT-ELECT / PRESIDENT**	**TREASURER**
(July 2017–June 2018) **Isabel P. Montanez** University of California Davis Davis, California, USA *We congratulate our incoming president!*	(July 2017–June 2018) / (July 2018–June 2019) **Robbie R. Gries** Gries Energy Partners LLC Lakewood, Colorado, USA	(July 2017–June 2018) **Richard C. Berg** Illinois State Geological Survey Champaign, Illinois, USA

2017 COUNCIL NOMINEES

COUNCILOR POSITION 1	**COUNCILOR POSITION 2**	**COUNCILOR POSITION 3**
(July 2017–June 2021) **Rónadh Cox** Williams College Williamstown, Massachusetts, USA **Carmala N. Garzione** University of Rochester Rochester, New York, USA	(July 2017–June 2021) **Joan E. Fryxell** California State University San Bernardino San Bernardino, California, USA **Michael L. Williams** University of Massachusetts–Amherst Amherst, Massachusetts, USA	(July 2017–June 2021) **Margaret R. Eggers** Eggers Environmental Inc. Oceanside, California, USA **Suzanne O'Connell** Wesleyan University Middletown, Connecticut, USA

To be counted, ballots must be submitted electronically, faxed to GSA Headquarters, or postmarked before midnight on 16 April 2017.

Get Published in *GSA Today*

- **Science:** Free color and now posted online ahead of print. Check **www.geosociety.org/gsatoday/science.htm** for the latest articles.
- **Groundwork:** Two pages, free color, and also posted online ahead of print at **www.geosociety.org/gsatoday/groundwork.htm.**
- **Rock Stars:** Into science bios? Each Rock Stars article, managed by GSA's History and Philosophy of Geology Division (**http://www.geosociety.org/RockStarGuide**) provides a two-page profile of a notable geoscientist whose contributions have impacted geoscience in a significant way.

THE GEOLOGICAL SOCIETY
OF AMERICA®

www.geosociety.org/gsatoday

Call for Nominations
GSA DIVISION AWARDS

---

www.geosociety.org/divisions

Give recognition where it is due—nominate a deserving colleague today! For award descriptions and nomination details, see the January issue of *GSA Today*, or visit **www.geosociety.org/divisions.**

■ ARCHAEOLOGICAL GEOLOGY DIVISION

Nomination and application information is at http://rock.geosociety.org/arch/.

Claude C. Albritton, Jr., Award
Nominations due 5 March
Submit nominations to gsa.agd@gmail.com.

Richard Hay Student Paper/Poster Award
Nominations due 20 Sept.
Submit nominations to gsa.agd@gmail.com.

■ HISTORY AND PHILOSOPHY OF GEOLOGY DIVISION

Nomination information is at http://community.geosociety.org/histphildiv/awards.

History and Philosophy of Geology Student Award
Nominations due 15 June
Submit nominations to Kathleen Lohff, kathylohff@msn.com.

■ MINERALOGY, GEOCHEMISTRY, PETROLOGY, AND VOLCANOLOGY (MGPV) DIVISION

Nomination information is at http://community.geosociety.org/mgpvdivision/awards.

Nominations due 31 March.
Submit nominations to J. Alex Speer, Mineralogical Society of America, 3635 Concorde Pkwy Suite 500, Chantilly, Virginia 20151-1110, USA; jaspeer@minsocam.org.

MGPV Distinguished Geologic Career Award

MGPV Early Career Award

■ QUATERNARY GEOLOGY AND GEOMORPHOLOGY DIVISION

Nomination and application information is at http://community.geosociety.org/qggdivision/awards/awardsoverview.

Farouk El-Baz Award for Desert Research
Nominations due 1 April

Distinguished Career Award
Nominations due 1 April

■ SEDIMENTARY GEOLOGY DIVISION AND STRUCTURAL GEOLOGY AND TECTONICS DIVISION JOINT AWARD

Nomination information is at http://community.geosociety.org/sedimentarygeologydiv/awards/laubach.

Stephen E. Laubach Structural Diagenesis Research Award
Nominations due 1 April.
Submit nominations to Mark Evans, evansmaa@ccsu.edu.

An IUGS Event

IUGS

RFG2018

RESOURCES FOR FUTURE GENERATIONS | **VANCOUVER, CANADA**

PREMIER INTERNATIONAL CONFERENCE ON
ENERGY · MINERALS · WATER · THE EARTH

June 16-21, 2018

Vancouver Convention Centre
Vancouver, British Columbia, Canada

CALL FOR SESSIONS

EMPOWER A GENERATION – GET RESOURCEFUL

Submit a session proposal by May 1, 2017

Grounded in our understanding of the Earth, this **first ever IUGS Inter-Congress Conference** will bring participants together from industry, government, academia, civil society and the next generation to discuss their initiatives and research related to the key resource issues shaping the future of energy, minerals, and water.

TAKE THE CHALLENGE – CREATE A SESSION

The opening #RFG2018 Call for Sessions successfully focused the global community on resources and our collective commitment to a sustainable future. We invite you to join your colleagues by proposing new sessions on the five key themes:

- **The Earth** - processes that have led to and constrain resource availability
- **Energy** - future of energy needs, opportunities, and delivery
- **Minerals** - discovery and clean extraction of mineral resources
- **Water** - source and management of water to meet societal needs
- **Resources and Society** - sustainable development of resources to provide benefits for all

Contribute your vision for the future of geoscience, environmental science and engineering, and sustainable solutions - in the key themes, and especially at the interface between them. We want new innovative sessions that increase the scope of the conference.

SUBMIT YOUR SESSION PROPOSALS BY MAY 1, 2017 AT RFG2018.ORG

Discovery
4-day technical program / 2,500+ oral presentations and poster sessions / Opening and theme-based plenaries

Education
Short courses and field trips

Community
4,000 to 5,000 Canadian and international participants

Exhibition
3-day trade show

Students & Emerging Leaders
Dedicated sessions and events

Networking
Knowledge exchange and business opportunities

Organizers

Canadian Institute of Mining, Metallurgy and Petroleum CIM ICM Institut canadien des mines, de la métallurgie et du pétrole

GEOLOGICAL ASSOCIATION

MINERALOGICAL ASSOCIATION OF CANADA ASSOCIATION

Supporters

CFES FCST

IUGS

Canada

Technical Partner

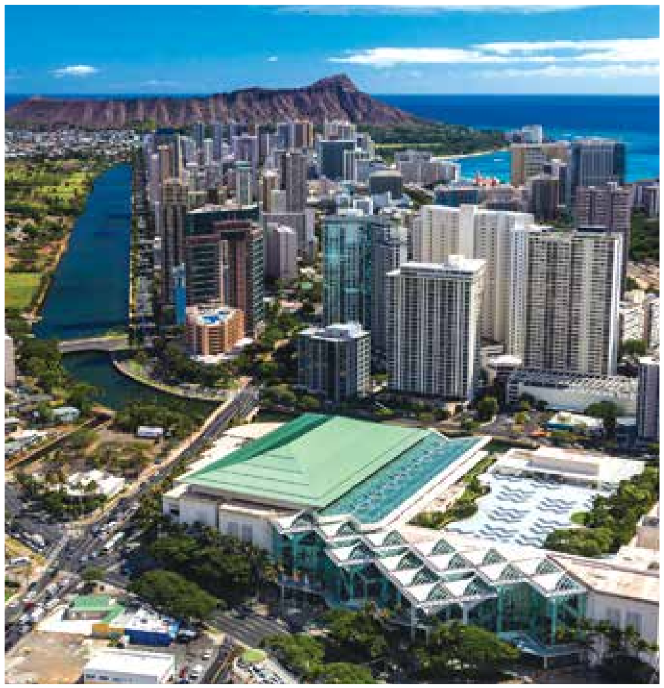
THE GEOLOGICAL SOCIETY OF AMERICA®

Second Announcement

CORDILLERAN SECTION

113th Annual Meeting of the Cordilleran Section, GSA
Hawai‘i Convention Center
Honolulu, Hawai‘i, USA
23–25 May 2017

www.geosociety.org/cd-mtg



Convention Center. Hawai‘i Tourism Authority. Photo by Tor Johnson.

The Geoscience Hotspot

MEETING DESCRIPTION

We are excited to announce that the 2017 Cordilleran Section Meeting will be held at the stunning Hawai‘i Convention Center in Honolulu. The technical program includes 34 Topical Sessions and Symposia, complemented by six Science and Education Short Courses and Workshops, and 11 Field Trips on the islands of Hawai‘i, Maui, O‘ahu, and Kaua‘i. Short courses, workshops, and field trips will occur both before and after the technical sessions.

Other special events include student mentoring programs and career workshops that will offer exceptional opportunities for networking. The meeting venue is steps away from Waikīkī and your gateway to national monuments and the stunning mountains, gardens, parks, and warm waters of the tropical Pacific. *E komo mai* (welcome) to you and your family to our tropical paradise!

LOCATION

Hawai‘i is one of the most beautiful places in the world, and Honolulu, on the island of O‘ahu, is known worldwide as a premier visitor destination. Honolulu is famous for its Aloha Spirit, multicultural mix, surfing, Waikīkī beach, and glorious weather. A broad range of restaurant cuisines is within easy walking distance of the convention center and the Ala Moana Hotel. Other local attractions include Diamond Head, Hanauma Bay (voted the best beach in the United States for 2016), Pearl Harbor, the Arizona Memorial, the Waikīkī Aquarium, and the Bishop Museum.

DEADLINES

- Exhibit space reservation deadline: 1 April
- Early registration deadline: 17 April
- Student travel application deadline: 17 April
- Student volunteer for registration wavier deadline: 17 April
- Registration cancellation deadline: 24 April
- Hotel reservation rate deadline: 1 May

REGISTRATION

Early registration deadline: 17 April
Cancellation deadline: 24 April
Register online at http://www.geosociety.org/GSA/Sections/cd/2017mtg/registration.aspx.
Fees are shown in U.S. Dollars

	Early		**Standard**	
	Full Meeting	**One day**	**Full Meeting**	**One day**
Professional Member	$285	$180	$335	$195
Professional Member (70+)	$145	$95	$240	$145
Professional Non-Member	$320	$215	$180	$230
Early Career Professional	$205	$135	$240	$155
Student Member	$115	$90	$145	$110
Student Non-Member	$160	$115	$195	$145
K–12 Professional	$55	$40	$65	$45
Guest or Spouse	$90	n/a	$110	n/a
Field Trip/Workshop Only	$65	n/a	$80	n/a

FIELD TRIPS

SPECIAL NOTICE: Costs shown below for field trips on the islands of Hawai‘i, Maui, and Kaua‘i ***do not*** include (1) airfare to and from those islands, (2) lodging while on those islands, and (3) breakfasts and dinners while on those islands. *Please see the website for details on each trip.* For additional information, please contact field trip co-chair Scott Rowland.

Pre-Meeting

1. **Geology of East and West Maui**. Cost: US$296. 8 a.m. Fri., 19 May, to 4 p.m. Sun., 21 May.
2. **Eruptions, Structure, and History of the Kīlauea Summit Area, Island of Hawai‘i**. Cost: US$169. 8 a.m. Sat., 20 May, to 4:30 p.m. Sun., 21 May.
3. **Geologic Features of Hualālai Volcano, Island of Hawai‘i.** Cost: US$228. 8 a.m. Sat., 20 May, to 4:30 p.m. Sun., 21 May.
4. **Mauna Loa: Eruptive History, Hazards, and Risk, Island of Hawai‘i.** Cost: US$166. 8 a.m. Sat., 20 May, to 6:30 p.m. Sun., 21 May.

5. **Structural Geology and Geothermal Energy of Kīlauea Volcano, Island of Hawai‘i.** US$242. 8 a.m. Sat., 20 May to 4:30 p.m. Sun., 21 May.
6. **Coastal Geology of Southern O‘ahu.** Cost: US$79. 8:30 a.m.–4 p.m. Mon., 22 May.
7. **Geology of Southeast Ko‘olau Volcano, Island of O‘ahu.** Cost: US$90. 8:30 a.m.–4 p.m. Mon., 22 May.

Post-Meeting

8. **Hydrology of O‘ahu.** Cost: US$68. 7:30 a.m.–3 p.m. Fri., 26 May.
9. **Geology of Wai‘anae Volcano, Island of O‘ahu.** Cost: US$92. 8:30 a.m.–4 p.m. Fri., 26 May.
10. **The Geology and Current Activity of Kīlauea Volcano, Island of Hawai‘i.** Cost: US$275. 7 a.m. Fri., 26 May, to 4 p.m. Sat., 27 May.
11. **Volcanic History and Coastal Processes of Kaua‘i.** Cost: US$208. 8 a.m. Fri., 26 May, to 4 p.m. Sat., 27 May.

SHORT COURSES & WORKSHOPS

Pre-Meeting

1. **Generic Mapping Tools for Geologists.** Mon., 22 May, 8:30 a.m.–4:30 p.m. US$10.
2. **Tsunami Awareness.** Mon., 22 May, 8:30 a.m.–4:30 p.m. US$5.

During the Meeting

3. **Hawaiian Volcanoes and Hazards Education Using Jigsaw Activities**. Tues., 23 May, 1:30–5 p.m. US$10. Principal Organizer: Andrew R. Greene, Hawai‘i Pacific Univ., agreene@hpu.edu. Co-Organizer: Michael O. Garcia, Univ. of Hawai‘i, mogarcia@hawaii.edu. This course will be held mid-meeting in conjunction with the Technical Sessions.

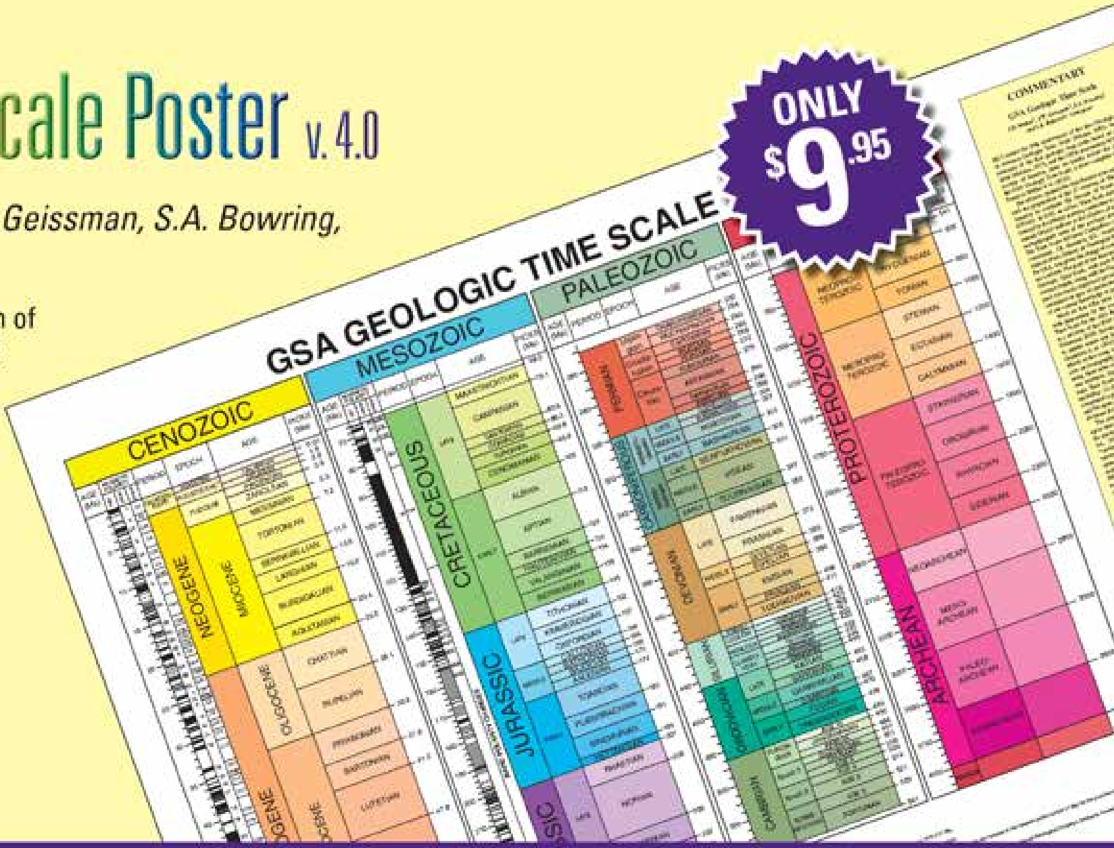
Post-Meeting

4. **Volcanic Crisis Awareness.** Fri., 26 May, 8:30 a.m. –4:30 p.m. US$5.
5. **Integrating Augmented Reality Grand Canyon Field Trips into Your High-Enrollment Introductory Geoscience Class.** Fri., 26 May, 8 a.m.–noon. US$10.
6. **Earth in Context: Resources for Integrating Earth Literacy with Societal Issues across the Curriculum.** Fri., 26 May, 1 p.m.–5 p.m. US$10.

EXHIBITS

Exhibit space reservation deadline: 1 April

Exhibition spaces are available on a first come first serve basis. Package descriptions, rates, exhibition hours, and a registration form are online at http://www.geosociety.org/documents/gsa/section/cd/2017/Sponsor_Exhibitor_Brochure.pdf. Please contact Garrett Ito at gito@hawaii.edu for additional information.



GeoCareers—2017 Section Meetings

GEOCAREERS

Geoscience Career Workshops

For more information, contact Jennifer Nocerino at jnocerino@geosociety.org.

Geoscience Career Workshop Part 1: Career Planning and Informational Interviewing. Your job-hunting process should begin with career planning, not when you apply for jobs. This workshop will help you begin this process and will introduce you to informational interviewing.

Geoscience Career Workshop Part 2: Geoscience Career Exploration. What do geologists in various sectors earn? What do they do? What are the pros and cons?

Geoscience Career Workshop Part 3: Cover Letters, Résumés, and CVs. How do you prepare a cover letter? Does your résumé need a good edit? Learn how to prepare the best résumé possible and avoid typical pitfalls.

Early Career Professional Focus Group

(NE/NC and SC meetings only)

Have you graduated in the last five years and are either a working professional or still looking for a job? GSA would like to support you in pursuing your professional goals. During this 45-minute session, participants will be asked a series of questions regarding potential programming and activities that GSA could offer to help you reach your goals. For more information, contact Tahlia Bear at tbear@geosociety.org.

MENTOR PROGRAMS

Enjoy a free lunch while meeting with geoscience mentors working in the applied sector. The popularity of these programs means that space is limited, so plan to arrive early, because lunch is first-come, first-served. For further information, contact Jennifer Nocerino at jnocerino@geosociety.org.

South-Central Section Meeting
San Antonio, Texas, USA
Shlemon Mentor Luncheon Program: Mon., 13 March
Mann Mentors in Applied Hydrology Luncheon: Tues., 14 March

Northeastern/North-Central Joint Meeting
Pittsburgh, Pennsylvania, USA
Shlemon Mentor Luncheon Program: Mon., 20 March
Mann Mentors in Applied Hydrology Luncheon: Tues., 21 March

Southeastern Section Meeting
Richmond, Virginia, USA
Shlemon Mentor Luncheon Program: Thurs., 30 March
Mann Mentors in Applied Hydrology Luncheon: Fri., 31 March

Cordilleran Section Meeting
Honolulu, Hawaii, USA
Shlemon Mentor Luncheon Program: Tues., 23 May
Mann Mentors in Applied Hydrology Luncheon: Wed., 24 May

Rocky Mountain Section Meeting
Calgary, Alberta, Canada
Shlemon Mentor Luncheon Program: Fri., 9 June
Mann Mentors in Applied Hydrology Luncheon: Sat., 10 June

MENTORING OPPORTUNITIES

Professionals: Interested in sharing information about your applied geoscience career with students? Being a mentor is a rewarding experience. If you can volunteer to mentor at one of the GSA Section Meetings, please contact Jennifer Nocerino at jnocerino@geosociety.org. *Early career professionals are encouraged to volunteer.*

THE
GEOLOGICAL
SOCIETY
OF AMERICA

250 Million Years of Earth History in Central Italy: Celebrating 25 Years of the Geological Observatory of Coldigioco

25–29 September 2017 • Apiro, Marche Region, Italy

Conveners

Alessandro Montanari, Osservatorio Geologico di Coldigioco, I-62020 Frontale di Apiro (MC), Italy; sandro.coldigioco@gmail.com

Christian Koeberl, Dept. of Lithospheric Research, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria, and Natural History Museum, Burgring 7, A-1010 Vienna, Austria; christian.koeberl@univie.ac.at

Sponsors

GSA Foundation, Barringer Crater Company, and Associazione Le Montagne di San Francesco

Description and Objectives

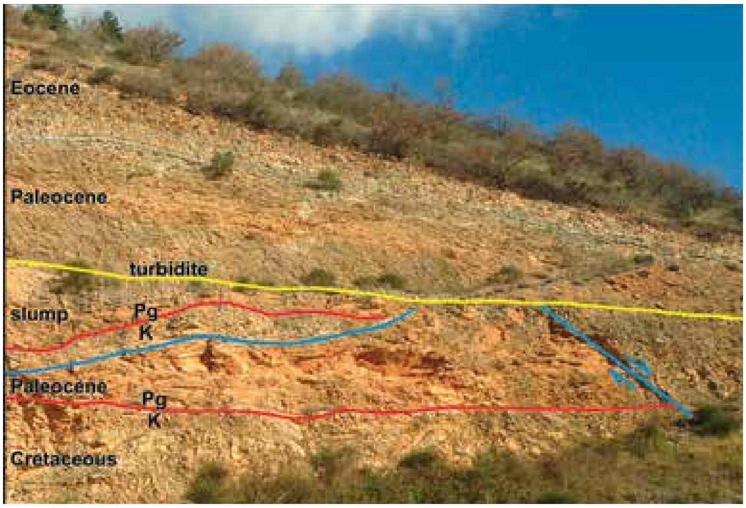
Central Italy has been a cradle of geology for centuries. Since the beginning of the last century, the Triassic to Miocene carbonate succession exposed along the valleys of the Umbria and Marche Apennines of Italy has been a fertile playground for generations of earth scientists, particularly paleontologists, sedimentologists, stratigraphers, geophysicists, and structural geologists, from all over the world. It is in this geological theater that pioneering studies in the most disparate disciplines of the earth sciences have led to the understanding of novel principles and natural phenomena of the past, the development of new methodologies and experimental research approaches, and ultimately to discontinuities in scientific thinking, with the birth of such concepts as Event Stratigraphy, Integrated Stratigraphy, and Cyclostratigraphy applied to astronomical tuning, let alone Quaternary Geology, Neotectonics, and Speleogeology. The Umbria-Marche Apennines of northeastern Italy are a foreland fold-and-thrust belt, which was formed in the latest phase of the Alpine-Himalayan orogenesis. These mountains are entirely made of marine sedimentary rocks of the so-called Umbria-Marche Succession, which represents a continuous record of the geotectonic evolution of an epeiric sea from the Early Triassic to the Pleistocene. Studies of these rocks have promoted sensational discoveries, particularly about major events that have punctuated the history of Earth, such has the Cretaceous Oceanic Anoxic Events (OAE1 and OAE2), the Cretaceous-Paleogene (K-Pg) Boundary Event (with the global mass extinction caused by a catastrophic extraterrestrial impact), the events across the Eocene-Oligocene transition from a greenhouse to an icehouse world, and the Messinian Salinity Crisis of the Mediterranean, just to name the most famous ones.

View of the town of Apiro in front of Monte San Vicino (image credit: C. Koeberl).

The objective of this conference is to present an updated vision of 250 million years of earth history as recorded in the sedimentary succession of the northern Apennine orogeny in central Italy. At the conference, besides keynote review presentations, original research works will be presented covering specific subjects of Tectonics and Structural Geology, Integrated Stratigraphy and Astronomical Tuning, Extraterrestrial Event Stratigraphy, and Quaternary Geology and Geo-Bio Speleology. These research works are either still in progress or they were accomplished but never published before, all with the support of the Geological Observatory of Coldigioco, an independent research and educational center, which was founded in an abandoned medieval hamlet near Apiro in 1992 by Alessandro Montanari, Walter Alvarez, and David Bice.

Studies are now in progress about the recent tectono-seismic and structural history of the still active Umbria-Marche Apennines (as is exemplified by the recent seismic activity in 2016). More studies by international teams of stratigraphers are being conducted through long and continuous stretches of the Umbria-Marche sedimentary succession, focusing on the integration of bio-magneto-chemostratigraphy and radioisotopic geochronology with astronomical tuning via multiproxy cyclostratigraphic analysis.

One of the primary results that have been derived from the Umbria-Marche sedimentary succession in the past 25 years with the support of the Geological Observatory of Coldigioco has been the development of the subject of the role that extraterrestrial



Ten million years of geologic history across the Cretaceous-Paleogene boundary in the Frontale quarry near Coldigioco (image credit: A. Montanari).

events, such as meteoritic impacts, comet showers, and asteroidal breakups, had in the biologic, environmental, and climatic changes of planet Earth. Studies about this subject will be presented in this Penrose Conference.

Last but not least are the tremendous advancements in the studies on the Pleistocene and Holocene history of this part of the world, which were focused on the extraordinary speleologic record of the Frasassi hypogenic cave complex (i.e., karstic geomorphology, slack water deposits, extremophile sulfidic ecosystems, speleo-archeology). Interdisciplinary studies by international teams of speleo-geologists, geochemists, radioisotopic and cosmogenic geochronologists, biologists, and archaeologists will be presented at the meeting.

The main topics that will be emphasized as part of the program include:

- Tectonics and Structural Geology
- Integrated Stratigraphy and Astronomical Tuning
- Extraterrestrial Event Stratigraphy
- Quaternary Geology and Geo-Bio Speleology

Preliminary Agenda

Day 1: Monday, 25 Sept.: Oral and poster sessions, Apiro
Day 2: Tuesday, 26 Sept.: Oral and poster sessions, Apiro
Day 3: Wednesday, 27 Sept.: Oral and poster sessions, Apiro
Day 4: Thursday, 28 Sept.: Field trip to Gubbio and surrounds
Day 5: Friday, 29 Sept.: Field trip to Frasassi Gorge; visit to and reception at Coldigioco, with art opening

The conference will be held in the historical Teatro Mestica in the medieval hilltop town of Apiro, and the poster sessions will be set up in locales adjacent to the main theater auditorium. To the attendees arriving with their own means of transportation, accommodations in B&Bs in the immediate vicinity of Apiro are recommended, whereas for all others, a shuttle service from/to the Ancona airport or the Jesi train station can be organized; these participants will stay at the Hotel Tetto delle Marche in Cingoli (about 12 km from Apiro; half-board), and there will be bus shuttling in the morning and in the late afternoon to-and-from the conference site in Apiro. Lunches during the conference will be at the Biroccio Restaurant in Apiro. Field trips to Gubbio, Monte Conero, and Frasassi will be organized with tourist buses, using local companies. It is recommended that participants arrive in Central Italy on Sunday, 24 Sept.; the ice-breaker reception is scheduled for the evening of that day. On Saturday, 30 Sept., an optional field trip to Monte Conero will be offered.

The field trips will visit classic geological sites, such as at Gubbio, where the asteroid impact hypothesis at the K-Pg boundary started; or Massignano near Monte Conero, where the GSSP of the Eocene-Oligocene Boundary is located; or the Frasassi caves, which are the largest show caves in Italy, and thus are of great importance for the work that is discussed at the meeting.

Attendees and Estimated Costs

The normal registration fee will cover hotel lodging for six nights (double occupancy), breakfast, lunch, dinner, and coffee breaks for five days, handouts, local transportation, and transportation for the field trips. Airfare is not included and participants must make their own travel arrangements. A reduced fee will be available for those participants who have their own local transportation and accommodation arrangements. We anticipate to be able to support some students and possibly a few other participants through the generosity of our sponsors. Registration fees have not been finalized. Please check the GSA website for the registration fee (**http://www.geosociety.org/PenroseConferences/**).

Applications and Registration

Application deadline: 31 May
Registration deadline: 31 July

Participants will have to commit to attending the full five days of the conference. Attendance is limited, for logistical reasons, to 60 people. **To apply,** please contact the conveners at sandro.coldigioco@gmail.com with a letter of intent that includes a brief statement of interests, the relevance of the applicant's recent work to the themes of the Conference, the subject of a proposed presentation, and contact information. Interested graduate students and early career faculty are strongly encouraged to apply. Once you have been selected to participate, you will be sent registration information.

COMMENTARY

Is it “the earth” or Earth?

A.M. Celâl Şengör, İTÜ Maden Fakültesi, Jeoloji Bölümü,
and Avrasya Yerbilimleri Enstitüsü, Ayazağa 34469 İstanbul,
Turkey, sengor@itu.edu.tr

Student:

> *But each word, I think, should harbour some idea*

Mephistopheles:

> *Yes, yes, indeed, but don’t torment yourself too much*
> *because precisely where no thought is present,*
> *a word appears in proper time.*
> *Words are priceless in an argument,*
> *Words are building stones of Systems.*
> *It’s splendid to believe in words;*
> *from words you cannot rob a single letter.*
>
> — J.W. von Goethe, *Faust*

As a non-English speaker I was taught that when referring to our planet, native speakers say and/or write “the earth.” I wondered why all other planets have capitalised names with no definite article preceding them, but not ours. Moreover, both our satellite and the star have definite articles in front of their names, although their names are capitalised: the Moon and the Sun.

Years later, in the Department of Geosciences in the University of Houston, where I had started my undergraduate education, my good friend Mrs. Irene “Cookie” Jones, a senior graduate student in the same department, asked me why all planet names are capitalised, but not ours. I had no idea. Cookie answered it for me: because all other planets carry proper names; they are names of Greek and Roman gods. Our planet also has a divine name, *Gaia* (Γαῖα), or simply *Ge* (Γῆ) in less poetical form in Greek and *Tellus* or *Terra* in Latin, but we do not use these names except as adjectives: telluric, terrestrial, terran.... Instead, we use for our planet what we also call the regolith and the soil of the land surface. So far, Cookie.

When we started calling our planet “earth,” we did not know that it was a planet in a solar system, let alone that it had also siblings. It was simply where we lived, later tilled it and grew our food in it and in places used it to make our dwellings. Something similar happened with the Sun and the Moon. The word Sun simply comes from the Indo-European root “to shine.” It was what shone to us and thereby enlightening and warming us. So we gave it a descriptive name. The name Moon has also an Indo-European root that it shares with meter (*not* metre; American English unfortunately confuses the *unit*, i.e., *metre* with the *tool*, i.e., *meter*), i.e., “measurer,” because our ancestors used its phases to measure time. So our satellite also has a descriptive name, not a divine one. Both the Sun (the enlightener) and the Moon (the measurer) also have divine names: *Helios* (῞Η λιος) in Greek, *Helius* in Latin for the Sun and *Selene* (Σελήνη) in Greek and *Luna* in Latin for the Moon.

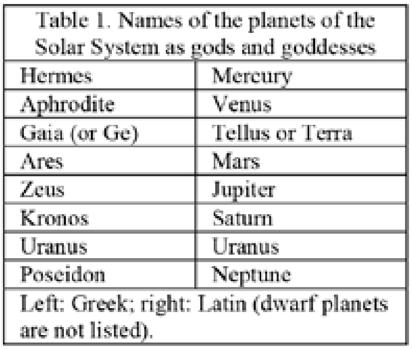


Table 1. Names of the planets of the Solar System as gods and goddesses

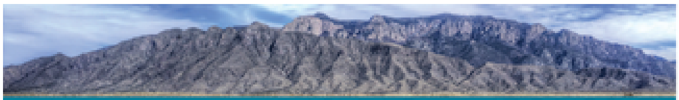
Hermes	Mercury
Aphrodite	Venus
Gaia (or Ge)	Tellus or Terra
Ares	Mars
Zeus	Jupiter
Kronos	Saturn
Uranus	Uranus
Poseidon	Neptune

Left: Greek; right: Latin (dwarf planets are not listed).

Recently it has become fashion to write and speak of “Earth” without a definite article and to capitalise it. Using Earth as a planet name in the Solar System violates the time-honoured rules of how we name its planets. In addition, this new fashion has created the necessity of explaining what we are referring to. A plant may grow in the earth or on Earth. This context is not too unclear (but think of exclaiming “where on earth is this plant?”). The meaning is not so clear if we say we walked on the sacred earth or on Sacred Earth. What if Sacred Earth is the proper name of a sacred place and does not refer to our planet? Or just remember the famous phrase, often attributed to the English poet W.H. Auden, but actually first formulated by the British comedian John Foster Hall: “We are all here on earth to help others; what on earth the others are here for, I don’t know.” Which earth would you capitalise in this quote? Thus, in many instances, the whole e versus E distinction and the employment or non-employment of a definite article become useless to distinguish different concepts.

If we are so keen to have the name of our home planet capitalised and get rid of the definite article in front of it, we should simply call it *Gaia*. We have already done so when we named our science geology, *Gaia* + *logos,* and its parent science geography, *Gaia* + *graphein.* I personally never use earth without a definite article and never capitalise it in my publications. I respect the historical roots of our usage. But if people are unhappy about it, let us switch to *Gaia*.

However, there is a much weightier reason that we should continue calling our planet “the earth” and not “Earth”: it is our abode, not any old planet in the Solar System. If we called our planet *Gaia*, it would be just one of the eight siblings named according to a certain rule, i.e., giving it a divine name, which is fine. It would be one among equals. If we called it Earth, it would be similar. But “the earth” is not the equal of the others: it is where humanity arose to question its origins, its place and its meaning. The rise of humanity is dependent on the planet, its peculiar distance from the Sun, its ability to harbour water and develop soil, i.e., “earth” that feeds us and makes our life and thought possible. When we say and write “the earth” we mean both the planet and signify that it is our home.



Why GSA Membership is Important to Me

Christopher A. Gellasch

I joined GSA as an undergraduate student more than 25 years ago and have remained a member since then. As a military geologist I typically move across the country (or overseas) to a new assignment every few years and am frequently the only geologist assigned to my organization. I am a hydrogeologist working primarily with environmental and public health professionals in a mix of academic and applied settings, so GSA is my professional home where I can interact with other geologists. I frequently attend the GSA Annual Meeting each fall and enjoy catching up with my friends and colleagues while also meeting new geoscientists.

Being a part of GSA gives me the opportunity to share my research and learn about a variety of relevant, high-impact geoscience research presented by others. The interdisciplinary nature of GSA's Section and Annual Meeting technical sessions is appealing because my interests span a wide spectrum, including hydrogeology, geochemistry, geology and health, and military geology. In addition to giving research presentations at meetings, I have also published my research through GSA publications. The GSA short courses and field trips allow me to engage in lifelong learning and remain current in my field.

My GSA membership also allows me to give back to the profession in many ways. I have organized several technical sessions at meetings, served on GSA committees, participated in numerous mentoring programs, and recently was the Hydrogeology Division Technical Program Chair for GSA's Annual Meeting. I find these volunteer opportunities to be both personally and professionally rewarding because they allow me make a difference and broaden my network of colleagues. Why is GSA membership important to me? For all of the opportunities it provides to me and for the opportunity to help others through my service to the organization.

Christopher A. Gellasch
GSA member since 1991

Help Shape the Future of Geoscience
Serve on a GSA Committee

Deadline: 15 June 2017
Terms begin 1 July 2018 (unless otherwise indicated)

If you are looking for the opportunity to work toward a common goal, give back to GSA, network, and make a difference, then we invite you to self-nominate (or nominate a fellow GSA member) to serve on a Society committee or as a GSA representative to another organization.

Learn more and access the nomination form at **www.geosociety.org/committees.** Use the online form to make a nomination or self-nomination. GSA Headquarters Contact: Dominique Olvera, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA; fax: +1-303-357-1060; dolvera@geosociety.org.

Key: **B**—Meets in Boulder or elsewhere; **E**—Communicates by phone or electronically; **M**—Meets at the Annual Meeting; **T**—Extensive time commitment required during application review period.

ACADEMIC AND APPLIED GEOSCIENCE RELATIONS COMMITTEE

One member-at-large vacancy (industry-related; 3-year term) (E/M)

This committee is charged with strengthening and expanding relations between GSA Members in applied and academic geosciences. As such, it proactively coordinates the Society's effort to facilitate greater cooperation between academia, industry, and government geoscientists. **Qualifications:** Committee members must work in academia, industry, or government and be committed to developing a better integration of applied and academic science in GSA meetings, publications, short courses, field trips, and education and outreach programs. Professional Interest: Environmental & Engineering Geology, Hydrogeology, Karst, Quaternary Geology & Geomorphology, Structural Geology & Tectonics, Sedimentary Geology. Members must also be active in one or more GSA Division.

ANNUAL PROGRAM COMMITTEE

Three member-at-large vacancies (4-year terms) (B/E/M)

This committee is charged with developing a plan for increasing the quality of the annual and other society-sponsored meetings in terms of science, education, and outreach; evaluating the technical and scientific programs annually to identify modifications necessary for accomplishing the Society's long-range goals; conducting short and long-range planning for the society meetings as a whole, and developing a long-term logistical plan/strategy for the technical programs of all GSA meetings and other society-sponsored meetings. One member-at-large should have previous meeting experience.

ARTHUR L. DAY MEDAL AWARD

Two member-at-large vacancies (3-year terms) (E/T)

This committee selects candidates for the Arthur L. Day Medal. **Qualifications:** Members should have knowledge of those who have made "distinct contributions to geologic knowledge through the application of physics and chemistry to the solution of geologic problems." All of the committee's work will be accomplished during the months of February/March. All committee decisions must be made by 1 April.

DIVERSITY IN THE GEOSCIENCES COMMITTEE

Three member-at-large vacancies (3-year terms) (E/M)

This committee provides advice and support to GSA Council and initiates activities and programs that will increase opportunities for people of ethnic minority, women, and persons with disabilities and raise awareness in the geosciences community of the positive role these groups play within the geosciences. The committee is also charged with stimulating recruitment and promoting positive career development for these groups. **Qualifications:** Members of this committee must be familiar with the employment issues these groups face; expertise and leadership experience in such areas as human resources and education is also desired.

EDUCATION COMMITTEE

Three vacancies: One graduate educator and one informal science educator (museum, visitor center, interpretation officer, etc.) (4-year terms); and one undergraduate student representative (2-year term) (B/E/M)

This committee works with GSA members representing a wide range of education sectors to develop informal, pre-college (K–12), undergraduate, and graduate earth-science education and outreach objectives and initiatives. **Qualifications:** Members of this committee must have the ability to work with other interested scientific organizations and science teachers' groups.

GEOLOGIC MAPPING AWARD COMMITTEE

One member-at-large vacancy (government; 3-year term) (E)

The purpose of this committee is to generate, receive, and evaluate candidates for the Geologic Mapping Award. This award acknowledges contributions in published, high-quality geologic mapping that led the recipient to publish significant new scientific or economic-resource discoveries, and to contribute greater understanding of fundamental geologic processes and concepts. The objective is to encourage training and support toward production of excellent, accurate, detailed, purposeful geologic maps and cross sections. With respect to size or scale, there are no restrictions on map products. GSA's Geological Mapping Award will be made on an annual basis, leaving the option open for multiple awards to be given under unusual circumstances in any given year; or to make no award in any given year.

GEOLOGY AND PUBLIC POLICY COMMITTEE

Three vacancies: two members-at-large (3-year terms) and one student representative (2-year term) (B/E/M)

This committee provides advice on public policy matters to Council and GSA leadership by monitoring and assessing international, national, and regional science policy; formulating and recommending position statements; and sponsoring topical white papers. This committee also encourages active engagement in geoscience policy by GSA members. **Qualifications:** Members should have experience with public-policy issues involving the science of geology; ability to develop, disseminate, and translate information from the geologic sciences into useful forms for the general public and for GSA Members; and familiarity with appropriate techniques for the dissemination of information.

GSA INTERNATIONAL

Three vacancies: one member-at-large (International Associated Society), one member-at-large (North America), and one member-at-large (outside North America) (4-year terms) (E/M)

Serve as GSA's coordination and communication resource seeking to promote, create, and enhance opportunities for international cooperation related to the scientific, educational, and outreach missions shared by GSA and like-minded professional societies, educational institutions, and government agencies. Build collaborative relationships with Divisions and Associated Societies in International issues and serve as a channel for member-generated proposals for international themes.

JOINT TECHNICAL PROGRAM COMMITTEE

Two member-at-large vacancies: one paleoclimatology & paleoceanology and one Precambrian geology (2-year terms, 1 Dec. 2017–30 Nov. 2019) (B/E)

Members of this committee help finalize the technical program for GSA's annual meetings by participating in the Web-based selection and scheduling of abstracts, as well as topical session proposal review. **Qualifications:** Members must be familiar with computers and the Internet, be a specialist in one of the specified fields, and be available in late July through mid-August for the organization of the annual meeting technical program.

MEMBERSHIP AND FELLOWSHIP COMMITTEE

One member-at-large vacancy (government; 3-year term) (B)

This committee contributes to the growth of the GSA membership, enhances the member experience, and serves a vital role in the selection of Fellows, all with the goal of fostering a membership community as pertinent and global as our science. Committee members should understand what various segments of our members want from GSA and should be familiar with outstanding achievers in the geosciences who would be worthy of fellowship.

NOMINATIONS COMMITTEE

Two member-at-large vacancies (industry, government) (3-year terms) (B/E)

This committee recommends nominees to GSA Council for the positions of GSA Officers and Councilors, committee members, and Society representatives to other permanent groups. **Qualifications:** Members must be familiar with a broad range of well-known and highly respected geoscientists. Meets in Boulder in July or August.

PENROSE CONFERENCES AND THOMPSON FIELD FORUMS COMMITTEE

Two member-at-large vacancies (3-year terms) (E)

This committee reviews and approves Penrose Conference and Field Forum proposals and recommends and implements guidelines for the success of these meetings. **Qualifications:** Committee members must be past conveners of a Penrose Conference or Field Forum.

PENROSE MEDAL AWARD COMMITTEE

Two member-at-large vacancies (3-year terms) (E/T)

Members of this committee select candidates for the Penrose Medal Award. Emphasis is placed on "eminent research in pure geology, which marks a major advance in the science of geology." **Qualifications:** Members should be familiar with outstanding achievers in the geosciences worthy of consideration for the honor. All of the committee's work will be accomplished during the months of February/March. All committee decisions must be made by 1 April.

PROFESSIONAL DEVELOPMENT COMMITTEE

One member-at-large vacancy (3-year term) (E)

This committee directs, advises, and monitors GSA's professional development program; reviews and approves proposals; recommends and implements guideline changes; and monitors the scientific quality of courses offered. **Qualifications:** Members must be familiar with professional development programs or have adult education teaching experience.

PUBLICATIONS COMMITTEE

Two vacancies: one member-at-large and one young professional member-at-large (4-year terms) (B/E/M)

The primary responsibilities of the committee are: nomination of candidates for editors when positions become vacant; reviewing the quality and health of each Society publication; and reporting with an annual report to Council that shall include recommendations for changes in page charges, subsidies, or any other publishing matter on which Council must make a decision. To carry out this charge, GSA headquarters will provide the committee with all necessary financial information.

RESEARCH GRANTS COMMITTEE

Eleven member-at-large vacancies and one NSF delegate (3-year terms) (B/T)

The primary function of this committee is to evaluate the research grant applications received, by delegation of the Council's authority and within the limits of the research grants budget, to award specific grants to chosen recipients. The committee will also act on the distribution of funds derived from any other gifts or memorial or award funds that are to be administered by it. **Qualifications:** Members should have experience in directing research projects and in evaluating research grant applications. **Extensive time commitment required 15 Feb.–15 April.**

RESEARCH GRANTS COMMITTEE—ALTERNATES

Ten member-at-large vacancies (3-year terms; B/T)

This has the same functions/requirements as the research grants committee, but the positions are only used when necessary depending on the number of research grants received.

YOUNG SCIENTIST AWARD (DONATH MEDAL) COMMITTEE

One member-at-large vacancy (3-year term) (E/T)

Committee members investigate the achievements of young scientists who should be considered for this award and make recommendations to GSA Council. **Qualifications:** Members should have knowledge of young scientists with "outstanding achievement(s) in contributing to geologic knowledge through original research which marks a major advance in the earth sciences." All of the committee's work will be accomplished during the months of February/March. All committee decisions must be made by 1 April.

GSA REPRESENTATIVES TO OTHER ORGANIZATIONS

GSA Representative to the AAAS Consortium of Affiliates for International Programs (CAIP)
One vacancy (3-year term, 1 Jan. 2018–1 Jan. 2021) (B/E): CAIP encourages cooperation on projects with international aspects and facilitates networking in its member societies. **Qualifications:** Interest in the international area of his/her society, but no other specific qualifications.

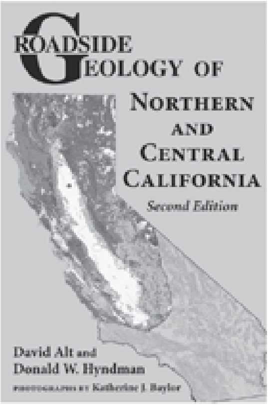
GSA Representative to the AGI Environmental Geoscience Advisory Committee (EGAC)
One vacancy (3-year term, 1 Jan. 2018–1 Jan. 2021) (E/M): Fosters communications within the community about issues related to serving the broader international community; helps identify and focus on the highest priority environmental informational needs and issues best addressed by the geoscience community. **Qualifications:** Well-acquainted with GSA programs in environmental geoscience.

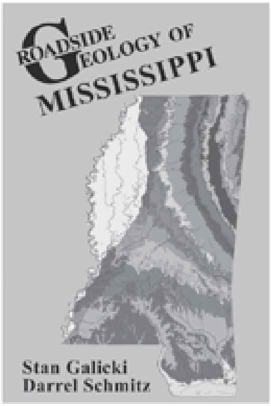
North American Commission on Stratigraphic Nomenclature: One vacancy (3-year term, Nov. 2018–Nov. 2021) (E/M): This committee develops statements of stratigraphic principles, recommends procedures applicable to classification and nomenclature of stratigraphic and related units, reviews problems in classifying and naming stratigraphic and related units, and formulates expressions of judgment on these matters.

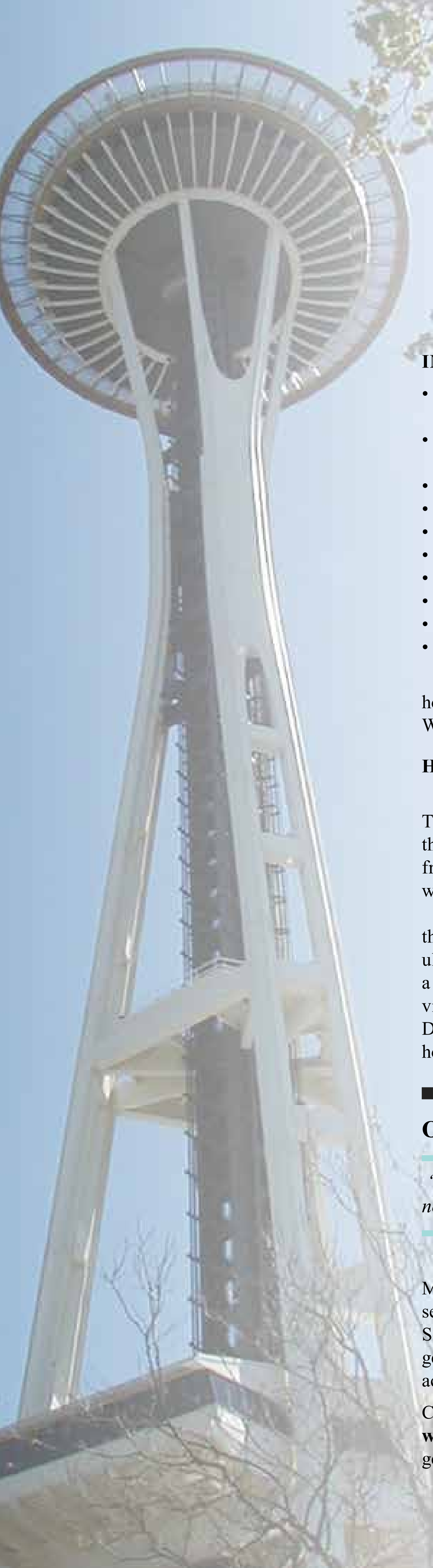
GSA Representative to the U.S. National Committee for Soil Science (USNC/SS): One vacancy (3-year term, 1 July 2018–30 June 2021) (B/E): The mission of the USNC/SS is to promote the advancement of soil science in the United States and throughout the world in order to strengthen U.S. soil science as a contributor to the international scientific community and to inform the U.S. scientific community of soil science activities carried out elsewhere in the world.

Committee, Section, and Division Volunteers: Council Thanks You!

GSA Council acknowledges the many member-volunteers who, over the years, have contributed to the Society and to our science through involvement in the affairs of the GSA. Your time, talent, and expertise help build a solid and lasting Society.







GSA 2017

22–25 October

Seattle, Washington, USA

IMPORTANT DATES

- Late March: Meeting room request system opens (non-technical, social, and business meeting room requests);
- Mid-May: Housing opens (Orchid Events is the official housing bureau for GSA 2017 Seattle);
- Early June: Registration and Travel Grant applications open;
- 6 June: Meeting room request deadline—fees increase after this date;
- Early August: Student volunteer program opens (new timing this year);
- 1 August: Abstracts deadline;
- 18 September: Early registration deadline;
- 18 September: GSA Sections travel grants deadline;
- 25 September: Registration and student volunteer cancellation deadline;
- 27 September: Housing deadline for discounted hotel rates.

With more than 50% of Washington wines scoring 90+ points in *Wine Spectator*, flying home with your perfect souvenir might take some pre-planning! Source: Washington State Wine Commission.

HOTEL INFORMATION

The official GSA Housing Bureau, Orchid Events, will open for reservations in mid-May. The Sheraton Seattle Hotel will serve as GSA headquarters, and it's just half a block from the Washington State Convention Center. The GSA block includes 10 hotels offering rates from US$169 to US$219 single/double occupancy (per night, plus tax). All hotels are within walking distance of the Washington State Convention Center.

Protect yourself: As the number of online hotel bookings continues to increase, so does the rate of booking scams. According to the American Hotel & Lodging Association, fraudulent websites con 2.5 million North Americans out of US$220 million every year. Use only a trusted source to make your hotel reservation and beware of anyone contacting you directly via email, phone, or fax. If you have any questions, please contact the GSA Meetings Department at meetings@geosociety.org. We will post information to our website regarding hotel reservations in mid-May.

ON TO THE FUTURE

> *"The On To the Future (OTF) program made me feel like I belonged at this conference no matter what my background was and where I was from which was amazing."*

Join more than 400 students who have received travel funding to attend a GSA Annual Meeting. On To the Future provides students from groups that are traditionally underrepresented travel funding and mentorship to their first GSA Annual Meeting, this year in Seattle, Washington, USA, on 22–25 October 2017. Awardees will be exposed to an array of geoscience research, career options, networking opportunities, and the opportunity to interact with GSA leadership. The deadline to apply is 26 May.

Check the OTF website for eligibility guidelines and application information: **www.geosociety.org/GSA/OTF/Home.aspx.** Questions? Contact Tahlia Bear at tbear@geosociety.org.

National Park Service Geoscientists-In-the-Parks (GIP) Opportunities

FALL/WINTER 2017–2018

The NPS GIP program places college students and early career professionals (18–35 years old) in National Park Service units for three months to one year to assist with geology and integrated science projects. This program is a partnership between the National Park Service, the Geological Society of America, and Environmental Stewards. Opportunities for fall/winter will be posted by GSA and open for application starting 1 May. The application deadline is 1 July.

www.geosociety.org/GSA/Education_Careers/Field_Experiences/gip/GSA/fieldexp/gip.aspx

THE
GEOLOGICAL
SOCIETY
OF AMERICA®

ENVIRONMENTAL
STEWARDS

GeoCorps™ America

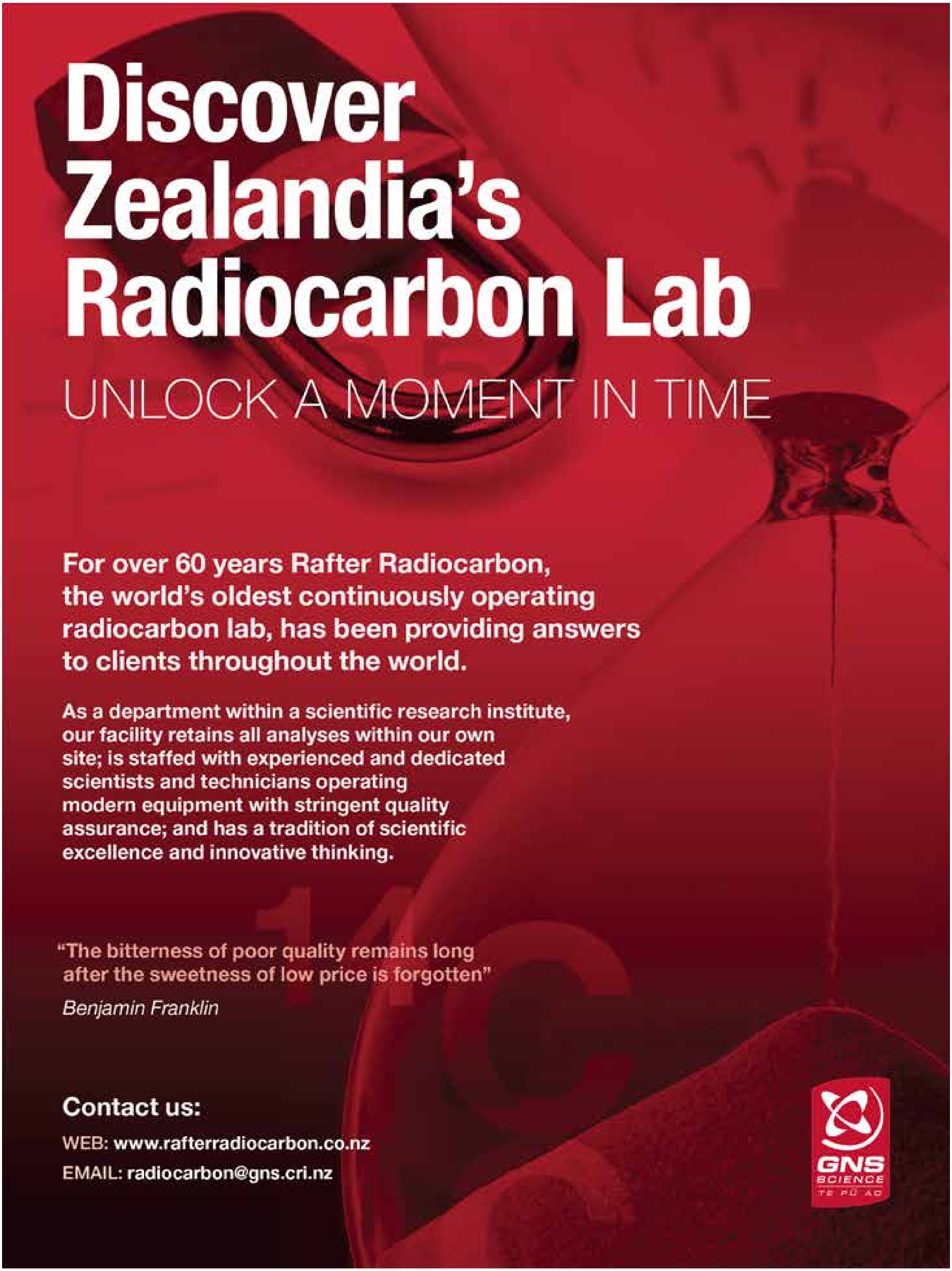
FALL/WINTER 2017–2018

The next GeoCorps America fall/winter season runs from September 2017 through May 2018. All fall/winter GeoCorps positions will be posted on the GeoCorps website and be open for applications starting 1 May. The application deadline is 1 July.

GeoCorps provides paid geoscience opportunities in partnership with government agencies and other organizations committed to science and stewardship, including the U.S. Forest Service and the Bureau of Land Management (BLM). All levels of geoscientists—students, educators, professionals, retirees, and others—are encouraged to apply.

www.geosociety.org/geocorps **www.facebook.com/GeoCorps**

THE
GEOLOGICAL
SOCIETY
OF AMERICA®



Double Science Issue!

Zealandia:

Earth's Hidden Continent

Zealandia: Earth's Hidden Continent

Nick Mortimer, *GNS Science, Private Bag 1930, Dunedin 9054, New Zealand;* ***Hamish J. Campbell,*** *GNS Science, P.O. Box 30368, Lower Hutt 5040, New Zealand;* ***Andy J. Tulloch****, GNS Science, Private Bag 1930, Dunedin 9054, New Zealand;* ***Peter R. King, Vaughan M. Stagpoole, Ray A. Wood, Mark S. Rattenbury,*** *GNS Science, P.O. Box 30368, Lower Hutt 5040, New Zealand;* ***Rupert Sutherland,*** *SGEES, Victoria University of Wellington, P.O. Box 600, Wellington 6140, New Zealand;* ***Chris J. Adams,*** *GNS Science, Private Bag 1930, Dunedin 9054, New Zealand;* ***Julien Collot,*** *Service Géologique de Nouvelle Calédonie, B.P. 465, Nouméa 98845, New Caledonia; and* ***Maria Seton,*** *School of Geosciences, University of Sydney, NSW 2006, Australia*

ABSTRACT

A 4.9 Mkm^2 region of the southwest Pacific Ocean is made up of continental crust. The region has elevated bathymetry relative to surrounding oceanic crust, diverse and silica-rich rocks, and relatively thick and low-velocity crustal structure. Its isolation from Australia and large area support its definition as a continent—Zealandia. Zealandia was formerly part of Gondwana. Today it is 94% submerged, mainly as a result of widespread Late Cretaceous crustal thinning preceding supercontinent breakup and consequent isostatic balance. The identification of Zealandia as a geological continent, rather than a collection of continental islands, fragments, and slices, more correctly represents the geology of this part of Earth. Zealandia provides a fresh context in which to investigate processes of continental rifting, thinning, and breakup.

INTRODUCTION

Earth's surface is divided into two types of crust, continental and oceanic, and into 14 major tectonic plates (Fig. 1; Holmes, 1965; Bird, 2003). In combination, these divisions provide a powerful descriptive framework in which to understand and investigate Earth's history and processes. In the past 50 years there has been great emphasis and progress in measuring and modeling aspects of plate tectonics at various scales (e.g., Kearey et al., 2009). Simultaneously, there have been advances in our understanding of continental rifting, continent-ocean boundaries (COBs), and the discovery of a number of microcontinental fragments that were stranded in the ocean basins during supercontinent breakups (e.g., Buck, 1991; Lister et al., 1991; Gaina et al., 2003; Franke, 2013; Eagles et al., 2015). But what about the major continents (Fig. 1)? Continents are Earth's largest surficial solid objects, and it seems unlikely that a new one could ever be proposed.

The *Glossary of Geology* defines a continent as "one of the Earth's major land masses, including both dry land and continental shelves" (Neuendorf et al., 2005). It is generally agreed that continents have all the following attributes: (1) high elevation relative to regions floored by oceanic crust; (2) a broad range of siliceous igneous, metamorphic, and sedimentary rocks; (3) thicker crust and lower seismic velocity

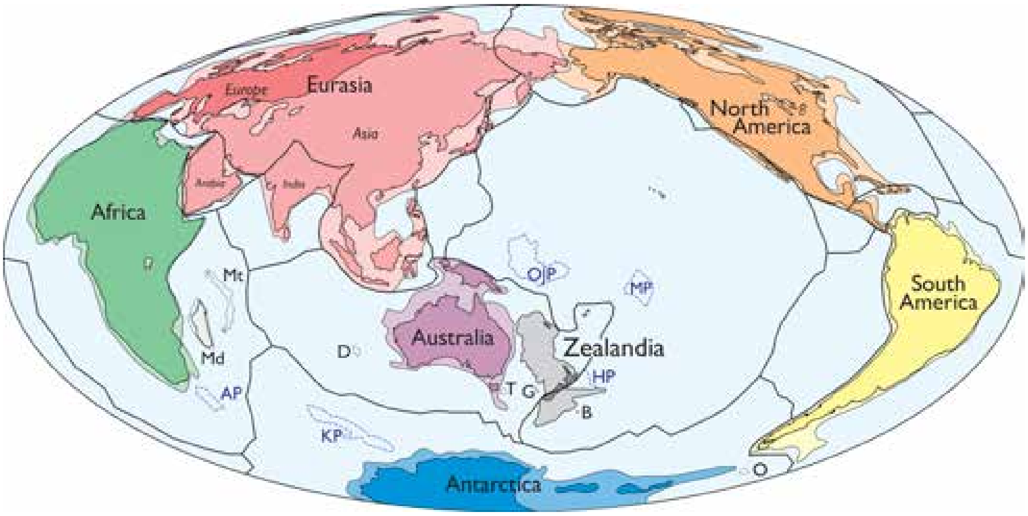


Figure 1. Simplified map of Earth's tectonic plates and continents, including Zealandia. Continental shelf areas shown in pale colors. Large igneous province (LIP) submarine plateaus shown by blue dashed lines: AP—Agulhas Plateau; KP—Kerguelen Plateau; OJP—Ontong Java Plateau; MP—Manihiki Plateau; HP—Hikurangi Plateau. Selected microcontinents and continental fragments shown by black dotted lines: Md—Madagascar; Mt—Mauritia; D—Gulden Draak; T—East Tasman; G—Gilbert; B—Bollons; O—South Orkney. Hammer equal area projection.

GSA Today, v. 27, no. 3–4, doi: 10.1130/GSATG321A.1

structure than oceanic crustal regions; and (4) well-defined limits around a large enough area to be considered a continent rather than a microcontinent or continental fragment. The first three points are defining elements of continental crust and are explained in many geoscience textbooks and reviews (e.g., Holmes, 1965; Christensen and Mooney, 1995; Levander et al., 2005; Kearey et al., 2009; Condie, 2015). To our knowledge, the last point—how "major" a piece of continental crust has to be to be called a continent—is almost never discussed, Cogley (1984) being an exception. Perhaps this is because it is assumed that the names of the six geological continents—Eurasia, Africa, North America, South America, Antarctica, and Australia—suffice to describe all major regions of continental crust.

The progressive accumulation of bathymetric, geological, and geophysical data since the nineteenth century has led many authors to apply the adjective *continental* to New Zealand and some of its nearby submarine plateaus and rises (e.g., Hector, 1895; Hayes, 1935; Thomson and Evison, 1962; Shor et al., 1971; Suggate et al., 1978). "New Zealand" was listed as a continent by Cogley (1984), but he noted that its continental limits were very sparsely mapped. The name Zealandia was first proposed by Luyendyk (1995) as a collective name for New Zealand, the Chatham Rise, Campbell Plateau, and Lord Howe Rise (Fig. 2). Implicit in Luyendyk's paper was that this was a large region of continental crust, although this was only mentioned in passing and he did not characterize and define Zealandia as we do here.

In this paper we summarize and reassess a variety of geoscience data sets and show that a substantial part of the southwest Pacific Ocean consists of a continuous expanse of continental crust. Furthermore, the 4.9 Mkm^2 area of continental crust is large and separate enough to be considered not just as a continental fragment or a microcontinent, but as an actual continent—Zealandia. This is not a sudden discovery but a gradual realization; as recently as 10 years ago we would not have had the accumulated data or confidence in interpretation to write this paper. Since it was first proposed by Luyendyk (1995), the use of the name Zealandia for a southwest Pacific continent has had moderate uptake (e.g., Mortimer et al., 2006; Grobys et al., 2008; Segev et al., 2012; Mortimer and Campbell, 2014; Graham, 2015). However, it is still not well known to the broad international science community. A correct accounting of Earth's continents is important for multiple fields of natural science; the purpose of this paper is to formally put forth the scientific case for the continent of Zealandia (Figs. 1 and 2) and explain why its identification is important.

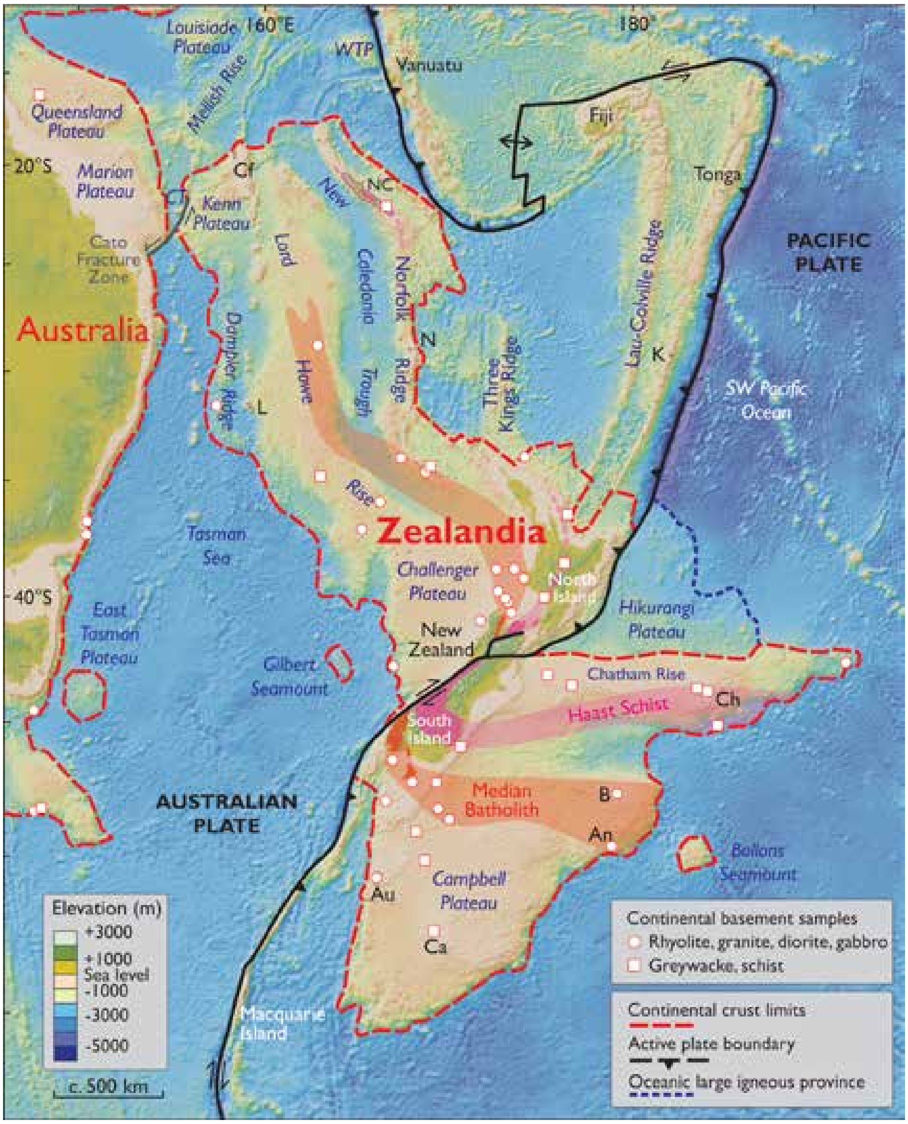


Figure 2. Spatial limits of Zealandia. Base map from Stagpoole (2002) based on data from Smith and Sandwell (1997). Continental basement samples from Suggate et al. (1978), Beggs et al. (1990), Tulloch et al. (1991, 2009), Gamble et al. (1993), McDougall et al. (1994), and Mortimer et al. (1997, 1998, 2006, 2008a, 2008b, 2015). NC—New Caledonia; WTP—West Torres Plateau; CT—Cato Trough; Cf—Chesterfield Islands; L—Lord Howe Island; N—Norfolk Island; K—Kermadec Islands; Ch—Chatham Islands; B—Bounty Islands; An—Antipodes Islands; Au—Auckland Islands; Ca—Campbell Island. Mercator projection.

ZEALANDIA AS A CONTINENT

New Zealand and New Caledonia are large, isolated islands in the southwest Pacific Ocean. They have never been regarded as part of the Australian continent, although the geographic term Australasia often is used for the collective land and islands of the southwest Pacific region. In the following sections, we summarize the four key attributes of continents and assess how Zealandia meets these criteria.

Elevation

Continents and their continental shelves vary in height but are always elevated relative to oceanic crust (Cogley, 1984). The elevation is a function of many features, fundamentally lithosphere density and thickness, as well as plate tectonics (e.g., Kearey et al., 2009). The existence of positive bathymetric features north and south of New Zealand has been known for more than a century (Farquhar, 1906). The accuracy and precision of seafloor mapping have improved greatly over the past decades (Brodie, 1964; Smith and Sandwell, 1997; Stagpoole, 2002) and a deliberately chosen color ramp on a satellite gravity-derived bathymetry map provides an excellent visualization of the extent of continental crust (Fig. 2). The approximate edge of Zealandia can be placed where the oceanic abyssal plains meet the base of the continental slope, at water depths between 2500 and 4000 m below sea level. The precise position of the foot of the continental slope around Zealandia was established during numerous surveys in support of New Zealand's Law of the Sea submission (Wood et al., 2003; UNCLOS, 2008).

Zealandia is everywhere substantially elevated above the surrounding oceanic crust. The main difference with other continents is that it has much wider and deeper continental shelves than is usually the case (Fig. 1). Zealandia has a modal elevation of ~−1100 m (Cogley, 1984) and is ~94% submerged below current sea level. The highest point of Zealandia is Aoraki–Mount Cook at 3724 m.

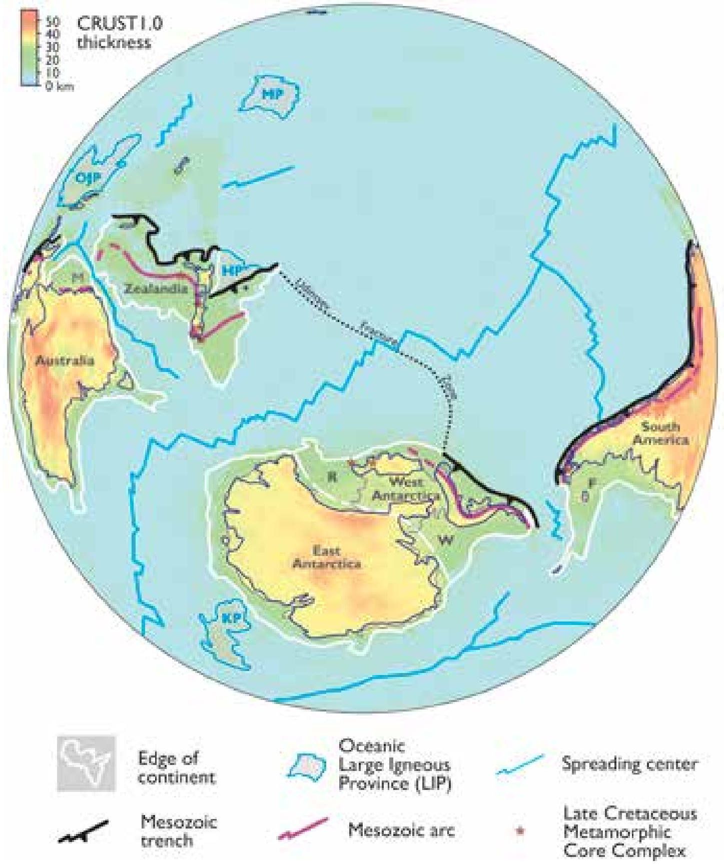


Figure 3. Present day map of CRUST1.0 crustal thickness (Laske et al., 2013) showing the dispersed Gondwana continents of Australia, Zealandia, East and West Antarctica, and South America. Note thin continental crust in vicinity of Mesozoic arc. M—Marion Plateau; R—Ross Sea; W—Weddell Sea; F—Falkland-Malvinas Plateau. LIP abbreviations: KP—Kerguelen Plateau; OJP—Ontong Java Plateau; MP—Manihiki Plateau; HP—Hikurangi Plateau. Thick coastlines in Antarctica are isostatically corrected ice-free coastlines (Jamieson et al., 2014). Orthographic projection.

Geology

By itself, relatively high elevation is not enough to establish that a piece of crust is continental. Oceanic large igneous provinces such as the Ontong Java Plateau (Fig. 1; Coffin and Eldholm, 1994) are elevated but not continental. Rocks of the modern oceanic crust typically comprise basalt and gabbro of Jurassic to Holocene age. In contrast, continents have diverse assemblages of Archean to Holocene igneous, metamorphic, and sedimentary rocks, such as granite, rhyolite, limestone, quartzite, greywacke, schist, and gneiss, arranged in orogenic belts and sedimentary basins.

Essential geological ground truth for Zealandia is provided by the many island outcrop, drill core, xenolith, and seabed dredge samples of Paleozoic and Mesozoic greywacke, schist, granite, and other siliceous continental rocks that have been found within its limits (Fig. 2). Many of these have been obtained from expeditions in the past 20 years (see Fig. 2, caption). Orogenic belts, of which the Median Batholith and Haast Schist are parts, can be tracked through onland New Zealand and across Zealandia (Fig. 2). Thus, there is a predictable regional coherency and continuity to the offshore basement geology.

Traditionally, continents have been subdivided into cratons, platforms, Phanerozoic orogenic belts, narrow rifts, and broad extensional provinces (Levander et al., 2005). Eurasia, Africa, North America, South America, Antarctica, and Australia all contain Precambrian cratons. The oldest known rocks in Zealandia are Middle Cambrian limestones of the Takaka Terrane and 490–505 Ma granites of the Jacquiery Suite (Mortimer et al., 2014). Precambrian cratonic rocks have not yet been discovered within Zealandia, but their existence has been postulated on the basis of Rodinian to Gondwanan age detrital zircon ratios (Adams and Griffin, 2012). Furthermore, some Zealandia mantle xenoliths give Re-Os ages as old as 2.7 Ga (Liu et al., 2015). Geologically, Zealandia comprises multiple Phanerozoic orogenic belts on which a broad extensional province and several narrow rift zones have been superimposed (Mortimer and Campbell, 2014).

Atop its geological basement rocks, Zealandia has a drape of at least two dozen spatially separate Late Cretaceous to Holocene sedimentary basins. These typically contain 2–10-km-thick sequences of terrigenous and calcareous strata (Zealandia Megasequence of Mortimer et al., 2014) and include a widespread continental breakup unconformity of ca. 84 Ma age (Bache et al., 2014). The Zealandia Megasequence provides a Zealandia-wide stratigraphic record of continental rifting, and marine transgression events, similar to that seen in formerly conjugate east Australian basins (Blewett, 2012).

Crustal Structure

Continental crust varies considerably in thickness and physical properties. Christensen and Mooney (1995) give an average P wave velocity of 6.5 km^{-1} and mean density of 2830 kgm^{-3} with an average thickness of 46 km for orogens and 30 km for extended crust. In contrast, oceanic crust is typically 7 km thick, and, in its lower part typically has a P wave velocity of 7.5 km^{-1} (White et al., 1992).

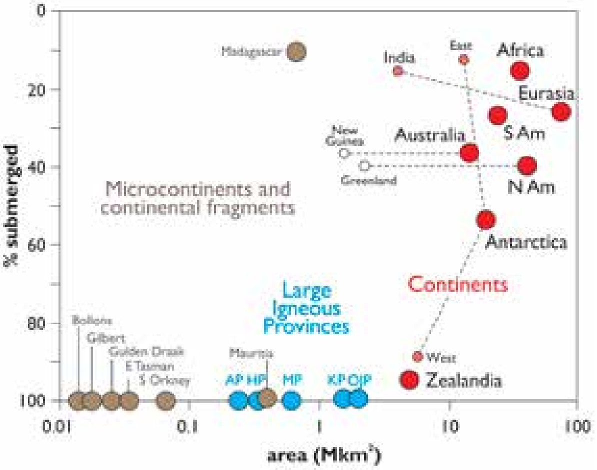


Figure 4. Areas and submergence of all of Earth's geological continents (red symbols) along with microcontinents (brown symbols) and intraoceanic large igneous provinces (LIPs, blue symbols) shown in Figures 1 and 2. Note *x*-axis is log scale. Data mainly after Cogley (1984) except Zealandia data from Mortimer and Campbell (2014); microcontinents after Gaina et al. (2003) and Torsvik et al. (2013). Emergent land area for Antarctica is the isostatically-corrected ice-free bedrock surface from Jamieson et al. (2014). New Guinea and Greenland are arbitrarily given the same submergence value as their parent continents. AP—Agulhas Plateau; KP—Kerguelen Plateau; OJP—Ontong Java Plateau; MP—Manihiki Plateau; HP—Hikurangi Plateau; N Am—North America; S Am—South America.

From geophysical work, we know that Zealandia has a continental crust velocity structure, *Vp*, generally <7.0 km^{-1}, and a thickness typically ranging from 10 to 30 km throughout its entire extent to >40 km under parts of South Island (Shor et al., 1971; Klingelhoefer et al., 2007; Grobys et al., 2008; Eberhart-Phillips et al., 2010; Segev et al., 2012). Whereas most of Zealandia's crust is thinner than the 30–46 km that is typical of most continents, the above studies show that it is everywhere thicker than the ~7-km-thick crust of the ocean basins. This result is visible in the global CRUST1.0 model of Laske et al. (2013) shown in Figure 3. Collectively, the crustal structure results show that the rock samples of Figure 2 are not from separate continental fragments or blocks now separated by oceanic crust, but are from a single continental mass.

The thinnest crust within Zealandia is in the 2200-km-long and 200–300-km-wide New Caledonia Trough, where the water depth varies from 1500 to 3500 m (Fig. 2). This raises the question as to whether the trough is floored by oceanic crust or is a failed continental rift. Two wide-angle seismic profiles across the trough near New Caledonia (Klingelhoefer et al., 2007) both show ~2–5 km of sedimentary cover over 8.5 km of crustal basement that has a velocity of ~7 km^{-1} throughout much of its thickness. Klingelhoefer et al. (2007) noted these profiles as atypical of normal oceanic crust. Sutherland et al. (2010) and Hackney et al. (2012) interpreted the New Caledonia Trough as continental crust that was thinned in the Late Cretaceous and re-deepened in the Eocene due to lithosphere delamination.

Limits and Area

Where oceanic crust abuts continental crust, various kinds of continent-ocean boundaries (COBs) define natural edges to continents (Fig. 1; Eagles et al., 2015). Despite its large area, Greenland is uncontroversially and correctly regarded as part of North America (Figs. 1 and 4). This is because, despite oceanic crust intervening between southern Greenland and Labrador and Baffin Island, North American continental geology is continuous across Nares Strait between northernmost Greenland and Ellesmere Island (Pulvertaft and Dawes, 2011). Tectonic plate boundaries, with or without intervening oceanic crust, provide the basis for continent-continent boundaries between Africa and Eurasia, and North and South America (Fig. 1). Large area is an inherent part of the definition of a continent *sensu stricto* (Neuendorf et al., 2005). Cogley (1984) defined Central America (1.3 Mkm^2), Arabia (4.6 Mkm^2), and greater India (4.6 Mkm^2) as modern-day continents. This schema has not been generally adopted, probably because Central America (the Chortis block) is a piece of displaced North America, and Arabia and India are transferring to, and are now contiguous with, Eurasia and have clearly defined COBs in the Red Sea and Indian Ocean (Fig. 1). The six commonly recognized geological continents (Africa, Eurasia, North America, South America, Antarctica, and Australia) are thus not only large but they are also spatially isolated by geologic and/or bathymetric features.

At the other end of the size spectrum, a number of continental crust fragments in the world's oceans are referred to as microcontinents. Examples include the Madagascar, East Tasman, Jan Mayen, Mauritia, and Gulden Draak microcontinents (Gaina et al., 2003; Torsvik et al., 2013; Whittaker et al., 2016). Discriminating between what is a continent and what is a microcontinent may be considered an arbitrary exercise. Nonetheless, maps like Figure 1 need labels. Therefore, following Cogley (1984) and the vagaries of general conventional usage, we propose that the name continent be applied to regions of continental crust that are >1 Mkm^2 in area and are bounded by well-defined geologic limits. By this definition India, prior to its collision with Eurasia, would be termed a continent.

The edges of Australia and Zealandia continental crust approach to within 25 km across the Cato Trough (Fig. 2). The Cato Trough is 3600 m deep and floored by oceanic crust (Gaina et al., 1998; Exon et al., 2006). The Australian and Zealandian COBs here coincide with, and have been created by, the Cato Fracture Zone along which there has been ~150 km of dextral strike slip movement, linking Paleogene spreading centers in the Tasman and Coral seas (Fig. 2; Gaina et al., 1998). This spatial and tectonic separation, along with intervening oceanic crust, means that the Zealandia continental crust is physically separate from that of Australia. If the Cato Trough did not exist, then the content of this

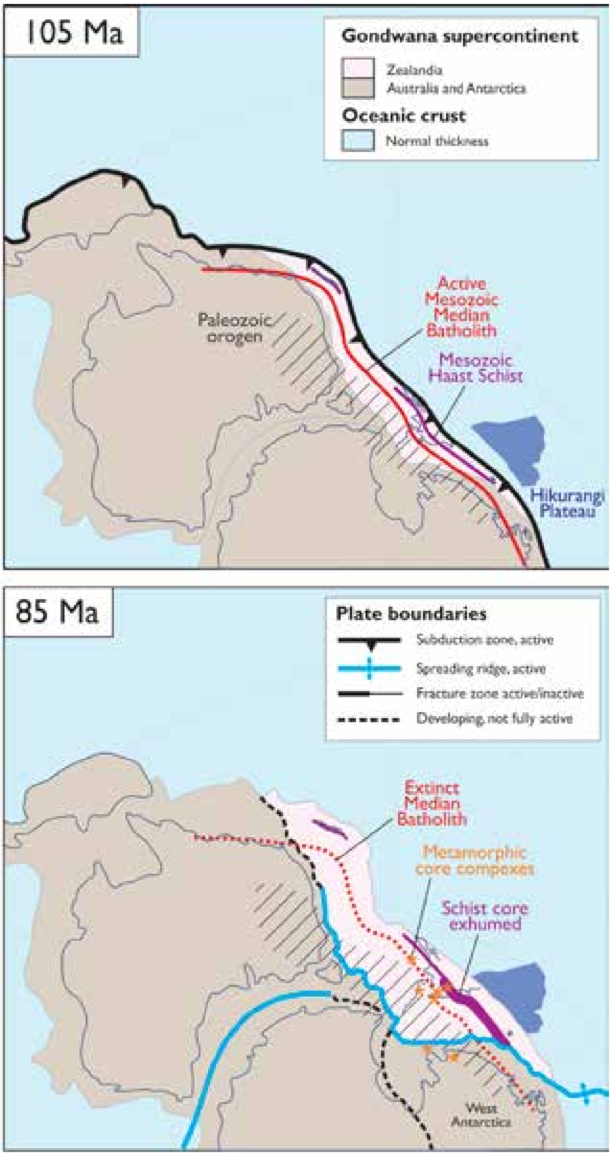


Figure 5. Zealandia as part of the former Gondwana supercontinent. Upper panel shows Mesozoic orogen convergent margin that was active until ca. 105 Ma. Lower panel shows pre-breakup intra-continental extension of Zealandia and West Antarctica from 105 to 85 Ma; seafloor spreading subsequently split Gondwana into its present-day constituent continents (Fig. 3). Orthographic projections with East Antarctica fixed. From Mortimer and Campbell (2014).

paper would be describing the scientific advance that the Australian continent was 4.9 Mkm^2 larger than previously thought.

Being >1 Mkm^2 in area, and bounded by well-defined geologic and geographic limits, Zealandia is, by our definition, large enough to be termed a continent. At 4.9 Mkm^2, Zealandia is substantially bigger than any features termed microcontinents and continental fragments, ~12× the area of Mauritia and ~6× the area of Madagascar (Fig. 4). It is also substantially larger than the area of the largest intraoceanic large igneous province, the Ontong Java Plateau (1.9 Mkm^2). Zealandia is about the same area as greater India (Figs. 1 and 4). Figure 4 makes a case for a natural twofold grouping of continents and microcontinents.

DISCUSSION AND IMPLICATIONS

Recognition

Satellite gravity-derived bathymetry maps (e.g., Fig. 2) have been of immense use in visualizing Zealandia, clarifying its limits, focusing attention on intra-Zealandia structures, and planning research voyages. If the elevation of Earth's solid surface had first been mapped in the same way as those of Mars and Venus (which lack the arbitrary datums of opaque liquid oceans), we contend that Zealandia would, much earlier, have been investigated and identified as one of Earth's continents. Even relatively recently, some papers refer to the offshore ridges and plateaus of Zealandia as an amalgam of continental fragments and slivers (e.g., Gaina et al., 2003; Blewett, 2012; Higgins et al., 2015) with the explicit or implicit notion that oceanic crust intervenes between the continental fragments. The way in which Zealandia has been divided into blocks to make it amenable to rigid plate reconstructions and the way in which coastlines and outlines have been drafted as "floating" in the Pacific Ocean (e.g., Gaina et al., 1998, 2003; Lisker and Läufer, 2013; Higgins et al., 2015) has probably sustained this false impression of remote and discombobulated tectonic allochthony and poorly defined COBs. In contrast, we view Zealandia as a coherent, albeit thinned and stretched, continent with interconnected and throughgoing geological provinces (Figs. 2 and 5; Mortimer et al., 2006; Grobys et al., 2008; Tulloch et al., 2009; Adams and Griffin, 2012; Bache et al., 2014; Graham, 2015). Like parts of North America and Eurasia, Zealandia has undergone active deformation in a zone between two essentially rigid plates—in Zealandia's case, the Pacific and Australian (Fig. 2).

Several elevated bathymetric features north of Zealandia are possible candidates for Zealandia prolongations or separate microcontinents (Fig. 2). These include the Three Kings, Lau-Colville, and Tonga-Kermadec ridges and Fiji, which are known Cenozoic volcanic arcs (Graham, 2015), and the Mellish Rise and Louisiade and West Torres plateaus. However, no continental basement rocks have yet been sampled from any of these features, so their continental nature remains unproven.

Development and Submergence

As shown in Figure 4, ~94% of the area of Zealandia currently is submerged. It is not unique in this regard: an ice-free, isostatically corrected West Antarctica would also largely be submerged (Figs. 3 and 4; Jamieson et al., 2014). Zealandia and West Antarctica were formerly adjacent to each other along the southeast Gondwana margin and, prior to thinning and breakup, the orogenic belts, Cordilleran batholiths, and normal continental crustal thickness of eastern Australia would have projected along strike into these areas (Figs. 3 and 5).

Several continental metamorphic core complexes (Lister and Davis, 1989) of Late Cretaceous age have been identified in Zealandia and West Antarctica, but not in Australia or East Antarctica (Figs. 3 and 5; Kula et al., 2007). These have been explained by Lister et al. (1991) and Kula et al. (2007) in terms of an asymmetric continent-scale detachment fault model in which Zealandia and West Antarctica are highly extended, lower-plate passive continental margins, and Australia and East Antarctica are relatively unstretched upper plate margins. There is also abundant supporting sedimentary basin evidence that Zealandia experienced widespread Late Cretaceous (ca. 105–85 Ma) extension prior to Gondwana supercontinent breakup (e.g., Luyendyk, 1995; Klingelhoefer et al., 2007; Bache et al., 2014; Mortimer et al., 2014; Higgins et al., 2015). The situation of Zealandia's Phanerozoic orogen overlying Precambrian mantle (Liu et al., 2015) possibly suggests major tectonic detachments along the Moho.

Thermal relaxation and isostatic balance of the thinned continental crust of Zealandia and West Antarctica ultimately led to their submergence. Despite the pervasive thinning, the only part of Zealandia that might qualify as a hyper-extended zone (i.e., stretched by a factor of 3–4 with crustal thinning to 8 km or less; Doré and Lundin, 2015) is the New Caledonia Trough. Zealandia and West Antarctica seemingly record a mode of continental crust deformation in which extension, although substantial, is more distributed and less focused than in most examples of continental breakup. Zealandia has a widespread synrift Late Cretaceous volcanic record (Tulloch et al., 2009; Mortimer et al., 2014); thus, processes that operate at volcanic rifted margins (Menzies et al., 2002) may be applicable to the broad area of Zealandia.

Significance

Zealandia once made up ~5% of the area of Gondwana. It contains the principal geological record of the Mesozoic convergent margin of southeast Gondwana (Mortimer et al., 2014) and, until the Late Cretaceous, lay Pacificward of half of West Antarctica and all of eastern Australia (Figs. 3 and 5). Thus, depictions of the Paleozoic-Mesozoic geology of Gondwana, eastern Australia, and West Antarctica are both incomplete and misleading if they omit Zealandia.

The importance of Zealandia is not so much that there is now a case for a formerly little-known continent, but that, by virtue of its being thinned and submerged, but not shredded into microcontinents, it is a new and useful continental end member. Zealandia started to separate from Gondwana in the Late Cretaceous as an ~4000-km-long ribbon continent (Fig. 5) but has since undergone substantial intracontinental deformation, to end up in its present shape and position (Figs. 1–3). To date, Zealandia is little-mentioned and/or entirely overlooked in comparative studies of continental rifting and of COBs (e.g., Buck, 1991; Menzies et al., 2002; Franke, 2013). By including Zealandia in investigations, we can discover more about the rheology, cohesion, and extensional deformation of continental crust and lithosphere.

Gondwana breakup along the paleo-Pacific margin resulted in continents with wide, thinned shelves, such as Zealandia and West Antarctica (Figs. 1 and 3). In contrast, breakup of Gondwana's core resulted in continents with narrow shelves, such as Africa and its neighbors (Fig. 1). Various lithospheric versus mantle controls on styles of continental rifting and breakup are still debated (Ebinger and van Wijk, 2014; Whittaker et al., 2016). The broad spatial association of stretched continental crust with a pre-softened, Mesozoic, paleo-Pacific convergent margin from the Falkland Plateau, through West Antarctica and Zealandia to the Marion Plateau (Fig. 3), is possibly no coincidence (cf. Rey and Müller, 2010). Other proposed controls on the localization of Zealandia-Gondwana breakup include a mantle plume (Weaver et al., 1994), plate capture (Luyendyk, 1995), and/or impingement of an oceanic spreading ridge (Mortimer et al., 2006).

Gaina et al. (2003) proposed that microcontinents are created by plume-controlled ridge jumps during the early stages of supercontinent breakup. The general cohesion of continental crust in extension is attested to by the contrast in size between Zealandia and its neighboring continental fragments of East Tasman, Gilbert, and Bollons seamounts (Figs. 2 and 4). Condie (2015) postulated that ancient and modern continent-continent collisions were a leading cause of continental elevation. The geological history of Zealandia would support this hypothesis: The Paleozoic and Mesozoic orogens of Zealandia are noncollisional (Mortimer et al., 2014), and there is only incipient collision between northern and southern Zealandia across the present-day Pacific-Australian plate boundary. Ironically, for a continent so thoroughly shaped by extensional processes and subsidence, it is the more widely recognized and better-studied convergence across the Cenozoic Pacific-Australian plate boundary that has resulted in any of Zealandia being above the sea.

CONCLUSIONS

Zealandia illustrates that the large and the obvious in natural science can be overlooked. Based on various lines of geological and geophysical evidence, particularly those accumulated in the last two decades, we argue that Zealandia is not a collection of partly submerged continental fragments but is a coherent 4.9 Mkm^2 continent (Fig. 1). Currently used conventions and definitions of continental crust, continents, and microcontinents require no modification to accommodate Zealandia.

Satellite gravity data sets, New Zealand's UNCLOS program, and marine geological expeditions have been major influences in promoting the big picture view necessary to define and recognize Zealandia (Fig. 2). Zealandia is approximately the area of greater India and, like India, Australia, Antarctica, Africa, and South America, was a former part of the Gondwana supercontinent (Figs. 3 and 5). As well as being the seventh largest geological continent (Fig. 1), Zealandia is the youngest, thinnest, and most submerged (Fig. 4). The scientific value of classifying Zealandia as a continent is much more than just an extra name on a list. That a continent can be so submerged yet unfragmented makes it a useful and thought-provoking geodynamic end member in exploring the cohesion and breakup of continental crust.

ACKNOWLEDGMENTS

We thank Belinda Smith Lyttle for GIS work and Patti Durance, Ron Hackney, and Brendan Murphy for comments. Formal reviews by Peter Cawood, Jerry Dickens, and an anonymous referee greatly improved the focus and content. This paper is based on work supported by New Zealand Government core funding grants to GNS Science.

REFERENCES CITED

Adams, C.J., and Griffin, W.L., 2012, Rodinian detrital zircons in Late Cretaceous sandstones indicate a possible Precambrian basement under southern Zealandia: Precambrian Research, v. 212–213, p. 13–20, doi: 10.1016/j.precamres.2012.04.003.

Bache, F., Mortimer, N., Sutherland, R., Collot, J., Rouillard, P., Stagpoole, V.M., and Nicol, A., 2014, Seismic stratigraphic record of transition from Mesozoic subduction to continental breakup in the Zealandia sector of eastern Gondwana: Gondwana Research, v. 26, p. 1060–1078, doi: 10.1016/j.gr.2013.08.012.

Beggs, J.M., Challis, G.A., and Cook, R.A., 1990, Basement geology of the Campbell Plateau: Implications for correlation of the Campbell Magnetic Anomaly System: New Zealand Journal of Geology and Geophysics, v. 33, p. 401–404, doi: 10.1080/00288306.1990.10425696.

Bird, P., 2003, An updated digital model of plate boundaries: Geochemistry Geophysics Geosystems, v. 4, p 1027, doi: 10.1029/2001GC000252.

Blewett, R.S., editor, 2012, Shaping a Nation: A Geology of Australia: Canberra, Geoscience Australia and ANU Press, 571 p.

Brodie, J.W., 1964, Bathymetry of the New Zealand region: New Zealand Oceanographic Institute Memoir 11, 54 p.

Buck, W.R., 1991, Modes of continental lithospheric extension: Journal of Geophysical Research, v. 96, p. 20,161–20,178, doi: 10.1029/91JB01485.

Christensen, N.I., and Mooney, W.D., 1995, Seismic velocity structure and composition of the continental crust: A global view: Journal of Geophysical Research, v. 100, p. 9761–9788, doi: 10.1029/95JB00259.

Coffin, M.F., and Eldholm, O., 1994, Large igneous provinces: Crustal structure, dimensions, and external consequences: Reviews of Geophysics, v. 32, p. 1–36, doi: 10.1029/93RG02508.

Cogley, J.G., 1984, Continental margins and the extent and number of the continents: Reviews of Geophysics and Space Physics, v. 22, p. 101–122, doi: 10.1029/RG022i002p00101.

Condie, K.C., 2015, Earth as an Evolving Planetary System, 3rd edition: Amsterdam, Elsevier, 350 p.

Doré, D., and Lundin, E., 2015, Hyperextended continental margins—knowns and unknowns: Geology, v. 43, p. 95–96, doi: 10.1130/focus012015.1.

Eagles, G., Pérez-Díaz, L., and Scarselli, N., 2015, Getting over continent ocean boundaries: Earth-Science Reviews, v. 151, p. 244–265, doi: 10.1016/j.earscirev.2015.10.009.

Eberhart-Phillips, D., Reyners, M., Bannister, S., Chadwick, M., and Ellis, S., 2010, Establishing a versatile 3-D seismic velocity model for New Zealand: Seismological Research Letters, v. 81, p. 992–1000, doi: 10.1785/gssrl.81.6.992.

Ebinger, C., and van Wijk, J., 2014, Roadmap to continental rupture: Is obliquity the route to success?: Geology, v. 42, p. 271–272, doi:10.1130/focus032014.1.

Exon, N.F., Hill, P.J., Lafoy, Y., Heine, C., and Bernardel, G., 2006, Kenn Plateau off northeast Australia: A continental fragment in the southwest Pacific jigsaw: Australian Journal of Earth Sciences, v. 53, p. 541–564.

Farquhar, H., 1906, The New Zealand Plateau: Transactions and Proceedings of the New Zealand Institute, v. 39, p. 135–137.

Franke, D., 2013, Rifting, lithosphere breakup and volcanism: Comparison of magma-poor and volcanic rifted margins: Marine and Petroleum Geology, v. 43, p. 63–87, doi: 10.1016/j.marpetgeo.2012.11.003.

Gaina, C., Müller, R.D., Royer, J.-Y., Stock, J.M., Hardebeck, J., and Symonds, P., 1998, The tectonic history of the Tasman Sea: A puzzle with 13 pieces: Journal of Geophysical Research, v. 103, p. 12,413–12,433, doi: 10.1029/98JB00386.

Gaina, C., Müller, D., Brown, B.J., and Ishihara, T., 2003, Microcontinent formation around Australia, *in* Hillis, R., and Müller, R.D., eds., Evolution and Dynamics of the Australian Plate: Geological Society of Australia Special Publication v. 22, p. 405–416.

Gamble, J.A., Wright, I.C., and Baker, J.A., 1993, Seafloor geology and petrology in the oceanic to continental transition zone of the Kermadec-Havre-Taupo Volcanic Zone arc system, New Zealand: New Zealand Journal of Geology and Geophysics, v. 36, p. 417–435, doi: 10.1080/00288306.1993.9514588.

Graham, I.J., chief editor, 2015, A continent on the move: New Zealand geoscience revealed, 2nd edition: Wellington, New Zealand, Geoscience Society of New Zealand, 397 p.

Grobys, J.W.G., Gohl, K., and Eagles, G., 2008, Quantitative tectonic reconstructions of Zealandia based on crustal thickness estimates: Geochemistry Geophysics Geosystems, v. 9, Q01005, doi: 10.1029/2007GC001691.

Hackney, R., Sutherland, R., and Collot, J., 2012, Rifting and subduction initiation history of the New Caledonia Trough, southwest Pacific, constrained by process-oriented gravity models: Geophysical Journal International, v. 189, p. 1293–1305, doi: 10.1111/j.1365-246X.2012.05441.x.

Hayes, R.C., 1935, Seismic waves and crustal structure in the New Zealand region: New Zealand Journal of Science and Technology, v. 17, p. 519–528.

Hector, J., 1895, Note on the geology of the outlying islands of New Zealand: Transactions and Proceedings of the Royal Society of New Zealand, v. 28, p. 736–738.

Higgins, K., Hashimoto, T., Rollet, N., Colwell, J., Hackney, R., and Milligan, P., 2015, Structural analysis of extended Australian continental crust: Capel and Faust basins, Lord Howe Rise, *in* Gibson, G.M., Roure, F., and Manatschal, G., eds., Sedimentary Basins and Crustal Processes at Continental Margins: From Modern Hyperextended Margins to Deformed Ancient Analogues: Geological Society [London] Special Publication 413, p. 9–33.

Holmes, A., 1965, Principles of physical geology, revised edition: London, Thomas Nelson, 1288 p.

Jamieson, S.S.R., Stokes, C.R., Ross, N., Rippin, D.M., Bingham, R.G., Wilson, D.S., Margold, M., and Bentley, M.J., 2014, The glacial geomorphology of the Antarctic ice sheet bed: Antarctic Science, v. 26, p. 724–741, doi: 10.1017/S0954102014000212.

Kearey, P., Klepeis, K.A., and Vine, F.J., 2009, Global Tectonics, 3rd edition: Chichester, U.K., Wiley-Blackwell, 482 p.

Klingelhoefer, F., Lafoy, Y., Collot, J., Cosquer, E., Géli, L., Nouzé, H., and Vially, R., 2007, Crustal structure of the basin and ridge system west of New Caledonia (southwest Pacific) from wide-angle and reflection seismic data: Journal of Geophysical Research, v. 112, B11102, doi: 10.1029/2007JB005093.

Kula, J.L., Tulloch, A.J., Spell, T.L., and Wells, M.L., 2007, Two-stage rifting of Zealandia-Australia-Antarctica: Evidence from ^{40}Ar/^{39}Ar thermochronometry of the Sisters shear zone, Stewart Island, New Zealand: Geology, v. 35, p. 411–414, doi: 10.1130/G23432A.1.

Laske, G., Masters, G., Ma, Z., and Pasyanos, M., 2013, Update on CRUST1.0—A 1-degree global model of Earth's crust: Geophysical Research Abstracts 15, Abstract EGU2013–2658.

Levander, A., Lenardic, A., and Karlstrom, K., 2005, Structure of the continental lithosphere, *in* Brown, M., and Rushmer, T., eds., Evolution and differentiation of the continental crust: Cambridge University Press, p. 21–66.

Lisker, F., and Läufer, A.L., 2013, The Mesozoic Victoria Basin, vanished link between Antarctica and Australia: Geology, v. 41, p. 1043–1046, doi: 10.1130/G33409.1.

Lister, G.S., and Davis, G.A., 1989, The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, U.S.A.: Journal of Structural Geology, v. 11, p. 65–94, doi: 10.1016/0191-8141(89)90036-9.

Lister, G.S., Etheridge, M.A., and Symonds, P.A., 1991, Detachment models for the formation of passive continental margins: Tectonics, v. 10, p. 1038–1064, doi: 10.1029/90TC01007.

Liu, J., Scott, J.M., Martin, C.E., and Pearson, D.G., 2015, The longevity of Archean mantle residues in the convecting upper mantle and their role in young continent formation: Earth and Planetary Science Letters, v. 424, p. 109–118, doi: 10.1016/j.epsl.2015.05.027.

Luyendyk, B., 1995, Hypothesis for Cretaceous rifting of East Gondwana caused by subducted slab capture: Geology, v. 23, p. 373–376, doi: 10.1130/0091-7613(1995)023<0373:HFCROE>2.3.CO;2.

McDougall, I., Maboko, M.A.H., Symonds, P.A., McCulloch, M.T., Williams, I.S., and Kudrass, H.R., 1994, Dampier Ridge, Tasman Sea, as a stranded continental fragment: Australian Journal of Earth Sciences, v. 41, p. 395–406, doi: 10.1080/08120099408728150.

Menzies, M.A., Klemperer, S.L., Ebinger, C.J., and Baker, J., 2002, Characteristics of volcanic rifted margins, *in* Menzies, M.A., Klemperer, S.L., Ebinger, C.J., and Baker, J., eds., Volcanic Rifted Margins: Geological Society of America Special Paper 362, p. 1–14.

Mortimer, N., and Campbell, H.J., 2014, Zealandia: Our continent revealed: Auckland, New Zealand, Penguin, 272 p.

Mortimer, N., Tulloch, A.J., and Ireland, T.R., 1997, Basement geology of Taranaki and Wanganui basins, New Zealand: New Zealand Journal of Geology and Geophysics, v. 40, p. 223–236, doi: 10.1080/00288306.1997.9514754.

Mortimer, N., Herzer, R.H., Gans, P.B., Parkinson, D.L., and Seward, D., 1998, Basement geology from Three Kings Ridge to West Norfolk Ridge, southwest Pacific Ocean: Evidence from petrology, geochemistry and isotopic dating of dredge samples: Marine Geology, v. 148, p. 135–162, doi: 10.1016/S0025-3227(98)00007-3.

Mortimer, N., Hoernle, K., Hauff, F., Palin, J.M., Dunlap, W.J., Werner, R., and Faure, K., 2006, New constraints on the age and evolution of the Wishbone Ridge, southwest Pacific Cretaceous microplates, and Zealandia–West Antarctica breakup: Geology, v. 34, p. 185–188, doi: 10.1130/G22168.1.

Mortimer, N., Hauff, F., and Calvert, A.T., 2008a, Continuation of the New England orogen, Australia, beneath the Queensland Plateau and Lord Howe Rise: Australian Journal of Earth Sciences, v. 55, p. 195–209, doi: 10.1080/08120090701689365.

Mortimer, N., Dunlap, W.J., Palin, J.M., Herzer, R.H., Hauff, F., and Clark, M., 2008b, Ultra-fast early Miocene exhumation of Cavalli Seamount, Northland Plateau, Southwest Pacific Ocean: New Zealand Journal of Geology and Geophysics, v. 51, p. 29–42, doi: 10.1080/00288300809509848.

Mortimer, N., and 22 others, 2014, High-level stratigraphic scheme for New Zealand rocks: New Zealand Journal of Geology and Geophysics, v. 57, p. 402–419, doi: 10.1080/00288306.2014.946062.

Mortimer, N., Turnbull, R.E., Palin, J.M., Tulloch, A.J., Rollet, N., and Hashimoto, T., 2015, Triassic–Jurassic granites on the Lord Howe Rise, northern Zealandia: Australian Journal of Earth Sciences, v. 62, p. 735–742.

Neuendorf, K.K.E., Mehl, J.P., and Jackson, J.A., 2005, Glossary of Geology, 5th edition: Alexandria, Virginia, American Geological Institute, 779 p.

Pulvertaft, T.C.R., and Dawes, P.R., 2011, North Atlantic spreading axes terminate in continental cul-de-sacs of Baffin Bay and the Laptev Sea: Canadian Journal of Earth Sciences, v. 48, p. 593–601, doi: 10.1139/E11-004.

Rey, P.F., and Müller, R.D., 2010, Fragmentation of active continental plate margins owing to the buoyancy of the mantle wedge: Nature Geoscience, v. 3, p. 2547–261.

Segev, A., Rybakov, M., and Mortimer, N., 2012, A crustal model for Zealandia and Fiji: Geophysical Journal International, v. 189, p. 1277–1292, doi: 10.1111/j.1365-246X.2012.05436.x.

Shor, G.G., Jr., Kirk, H.K., and Menard, H.W., 1971, Crustal structure of the Melanesian area: Journal of Geophysical Research, v. 76, p. 2562–2586, doi:10.1029/JB076i011p02562.

Smith, W.H.F., and Sandwell, D.T., 1997, Global sea floor topography from satellite altimetry and ship depth soundings: Science, v. 277, p. 1956–1962, doi: 10.1126/science.277.5334.1956.

Stagpoole, V.M., 2002, The New Zealand continent, version 1.0: Institute of Geological and Nuclear Sciences Geophysical Map GPM15, scale: 1:7,500,000.

Suggate, R.P., Stevens, G.R., and Te Punga, M.T., eds., 1978, The geology of New Zealand: Wellington, New Zealand, Government Printer, 819 p.

Sutherland, R., Collot, J., Lafoy, Y., Logan, G.A., Hackney, R., Stagpoole, V., Uruski, C., Hashimoto, T., Higgins, K., Herzer, R.H., Wood, R., Mortimer, N., and Rollet, N., 2010, Lithosphere delamination with foundering of lower crust and mantle caused permanent subsidence of New Caledonia Trough and transient uplift of Lord Howe Rise during Eocene and Oligocene initiation of Tonga-Kermadec subduction, western Pacific: Tectonics, v. 29, TC2004, doi: 10.1029/2009TC002476.

Thomson, A.A., and Evison, F.F., 1962, Thickness of the Earth's crust in New Zealand: New Zealand Journal of Geology and Geophysics, v. 57, p. 402–419.

Torsvik, T.H., Amundsen, H., Hartz, E.H., Corfu, F., Kusznir, N., Gaina, C., Doubrovine, P.V., Steinberger, B., Ashwal, L.D., and Jamtveit, B., 2013, A Precambrian microcontinent in the Indian Ocean: Nature Geoscience, v. 6, p. 223–227, doi: 10.1038/ngeo1736.

Tulloch, A.J., Kimbrough, D.L., and Wood, R.A., 1991, Carboniferous granite basement dredged from a site on the southwest margin of the Challenger Plateau, Tasman Sea: New Zealand Journal of Geology and Geophysics, v. 34, p. 121–126, doi: 10.1080/00288306.1991.9514449.

Tulloch, A.J., Ramezani, J., Mortimer, N., Mortensen, J., van den Bogaard, P., and Maas, R., 2009, Cretaceous felsic volcanism in New Zealand and Lord Howe Rise (Zealandia) as a precursor to final Gondwana break-up, *in* Ring, U., and Wernicke, B., eds., Extending a Continent: Architecture, Rheology and Heat Budget: Geological Society (London) Special Publication 321, p. 89–118.

UNCLOS (United Nations Commission on the Limits of the Continental Shelf), 2008, Recommendations of the Commission on the Limits of the Continental Shelf (CLCS) in regard to the submission made by New Zealand 19 April 2006: http://www.linz.govt.nz/system/files_force/media/pages-attachments/un-continental-shelf-recommendations.pdf (last accessed June 2016).

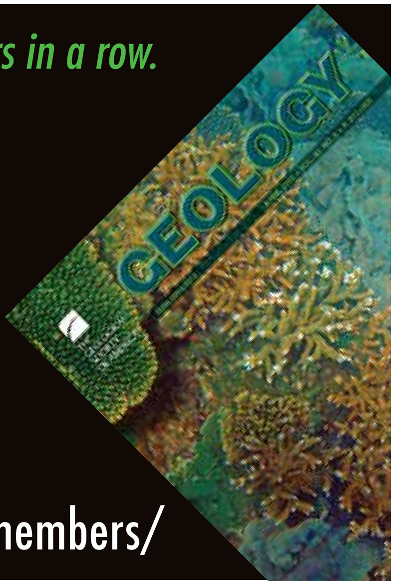
Weaver, S.D., Storey, B.C., Pankhurst, R.J., Mukasa, S.B., DiVenere, V.J., and Bradshaw, J.D., 1994, Antarctica–New Zealand rifting and Marie Byrd Land lithospheric magmatism linked to ridge subduction and mantle plume activity: Geology, v. 22, no. 9, p. 811–814, doi: 10.1130/0091-7613(1994)022<0811:ANZRAM>2.3.CO;2

White, R.S., McKenzie, D., and O'Nions, R.K., 1992, Oceanic crustal thickness from seismic measurements and rare earth element inversions: Journal of Geophysical Research, v. 97, p. 19,683–19,715, doi: 10.1029/92JB01749.

Whittaker, J.M., Williams, S.E., Halpin, J.A., Wild, T.J., Stilwell, J.D., Jourdan, F., and Daczko, N.R., 2016, Eastern Indian Ocean microcontinent formation driven by plate motion changes: Earth and Planetary Science Letters, v. 454, p. 203–212, doi: 10.1016/j.epsl.2016.09.019.

Wood, R.A., Stagpoole, V.M., Wright, I., Davy, B., and Barbes, P., 2003, New Zealand's continental shelf and UNCLOS Article 76: Institute of Geological and Nuclear Sciences Information Series, v. 56, 56 p.

Manuscript received 12 Sept. 2016
Revised manuscript received 19 Dec. 2016
Manuscript accepted 21 Dec. 2016



Positions Open

CHIEF EXECUTIVE OFFICER (CEO) NATIONAL GROUND WATER ASSOCIATION

The National Ground Water Association (NGWA) seeks a collaborative, forward-thinking Chief Executive Officer to lead the organization in partnership with the Board of Directors. NGWA is a hybrid international trade association and scientific professional society working together to advance groundwater knowledge and the success of members through education and outreach; advocacy; cooperation and information exchange; and enhancement of professional practices. NGWA's vision is to be the leading groundwater association advocating the responsible development, management, and use of groundwater. NGWA also operates a charitable foundation, the NGWA Foundation, focused on education, research and charitable activities related to broader public understanding of groundwater.

The current CEO will retire at the end of 2017. The next CEO must be a talented leader who recognizes successes of the past and charts a course for future impact and growth.

NGWA has four membership sections—contractors, scientists and engineers, manufacturers, and suppliers. The national board has 19 voting members and each membership section has an oversight board. The CEO manages a staff of 29 and a budget of $5.5 Million, and serves roughly 10,500 members.

In close partnership with the Board of Directors and staff, the CEO provides strategic vision and leadership to steward the future of NGWA and cultivates relationships with key policymakers, stakeholders, the media, and partners to advance NGWA's goals. The CEO has a strong external presence and the ability to engage stakeholders.

As an international association, NGWA works with a network of state and professional associations as well as foreign counterparts serving groundwater professionals. The CEO has a strong external presence and needs a natural ability to collaborate, harness the collective voice of the groundwater industry, and cultivate relationships globally.

The CEO is a visible leader for NGWA and will

- Be the operational leader that the Board needs to achieve NGWA's strategic plan.
- Successfully achieve NGWA's goals as established by the Board.
- Have strategic vision to assist the Board in setting the best goals.
- Work in a collegial, transparent and highly participatory manner.
- Be highly knowledgeable about, attuned to, and effective in researching member needs and industry issues.
- Identify and foster opportunities to diversify and grow the organization's revenue through new partnerships and services.
- Manage and nurture an exceptional staff.
- Possess a high level of business and financial acumen along with experience improving operational efficiencies.
- Have excellent communication skills, media experience, and the ability to positively influence others.
- Seek opportunities to strengthen cross-organizational collaboration.
- Effectively influence public policy and regulatory issues affecting members.
- Work to secure legislation and grants from federal government to better our industry and members.
- Represent NGWA regionally, nationally and internationally to achieve NGWA goals. Regular travel and public speaking engagements are an important part of this position.
- The ideal candidate will be a seasoned executive leader with a strong track record of successfully leading and developing teams, working with an engaged Board, diversifying revenue streams, leading strategic planning, and cultivating relationships with a wide spectrum of stakeholders, vendors, and partners.

This describes the general nature of the CEO position. A full position description will be provided to candidates.

To Apply: NGWA has retained Nancy Rummel of Nancy Rummel & Associates to assist in this search. Candidates should submit a letter of interest with salary requirement and resume to: Nancy@nancyrummel.com. Deadline for application is March 31, 2017.

Salary package is commensurate with experience.

The National Ground Water Association headquarters is located in Westerville, Ohio. To learn more about NGWA, visit: www.ngwa.org.

GEOLOGY: SOLID EARTH GEOLOGY, GUSTAVUS ADOLPHUS COLLEGE

Starting September 2017

Gustavus Adolphus College seeks a full-time one-year position of visiting assistant professor to begin September 1, 2017. We seek candidates with a PhD or ABD and demonstrated excellence in undergraduate teaching. Assignments include courses in earth materials/mineralogy, structural geology, petrology, introductory geology, a January Term experiential course, and senior thesis supervision. The strongest candidates will articulate their intersections with emerging employment opportunities in the geosciences, and complement our existing department strengths. Visit http://gustavus.edu/jobs for application instructions. Application review will begin immediately, and continue until the position is filled.

Gustavus Adolphus College is a EOE Employer/Disabled/Vet employer.

DIRECTOR, KANSAS GEOLOGICAL SURVEY THE UNIVERSITY OF KANSAS, LAWRENCE

Full-time position serving as the Director of the Kansas Geological Survey (KGS) and State Geologist. Must develop and articulate a vision of KGS programs, understand the concept of serving Kansas through high-quality research in the applied geosciences, and embrace a collegial leadership style. Requires doctorate in the geosciences with 10 years professional experience, prior administrative and/or leadership experience, national recognition in geoscience research, excellent communication skills, knowledge of natural resources and the environmental aspects of their use, and demonstrated ability to deal with natural-resource policy issues. Will have the opportunity to jointly hold a tenured faculty position in an academic department at the University of Kansas (KU).

The KGS is a research and service division of KU. Created in 1889, the KGS studies the geology of Kansas, develops new techniques for exploring and analyzing geologic data, and produces and disseminates maps, reports, and scientific papers. Among the premier earth-science research and service institutions in the U.S., the KGS has an annual state budget of $5.8 million, a fiscal year 2016 grant and contract budget of $4.6 million, and employs more than 112 researchers, support staff, and students engaged in a variety of disciplines. Staff collaborate extensively with faculty and students in academic departments at KU.

Full announcement and application info at www.kgs.ku.edu/General/jobs.html. Review will begin March 1, 2017, position open until filled. For further information contact Greg Ludvigson (gludvigson@kgs.ku.edu), www.kgs.ku.edu. KU is an EO/AAE, http://policy.ku.edu/IOA/nondiscrimination.

Opportunities for students

Ph.D. position in Sedimentology and Paleolimnology, Missouri University of Science and Technology. We seek a qualified Ph.D. candidate to investigate the sedimentology of modern lacustrine environments. The objective of the project is to better understand processes controlling sedimentation in an evolving lacustrine basin within an active tectonic setting. Full financial support is available for at least three years at a competitive rate through research and teaching assistantships. Candidates with a strong background and interest in sedimentology, paleolimnology, and paleoclimate are strongly encouraged to apply. Starting date, August 2017.

If interested, please submit C.V. and one page summary of research interests to Dr. Jonathan Obrist at obristj@mst.edu.

John W. (Jack) Hess, *GSA Foundation President*

From Field Camp to Profession: One Step in the Career Path for Emerging Geoscientists

One of the pillars of GSA's mission is advancement of the geosciences profession, and as geologists from all disciplines, we know how important fieldwork is to our careers. Opportunities to experience fieldwork are dwindling, and so GSA's efforts to help provide this opportunity, with partner support, are important for our student members.

Starting in 2009, the GSA/ExxonMobil Bighorn Basin Field Camp awarded 20 undergraduate and/or graduate students and five faculty members participation in a high-quality seven-day field seminar for seven conscutive years. Run in the Bighorn Basin of north central Wyoming, USA, participants had costs covered for transportation, meals, and living expenses. The camp was taught by ExxonMobil professionals with specific skills in tectonics, geochemistry, structure, sequence stratigraphy, sedimentology, paleontology, hydrocarbon systems analysis, and integrated play analysis. GSA's Committee on Professional Development selected participants based on grades, cover letters, and letters of recommendation.

Kimberly Gloersen was an undergraduate student at Clemson University when she attended the Bighorn Basin Field Camp in 2014. After the field camp, she was offered an internship as a production geologist. At the conclusion of the internship, Kim was offered a full-time position with ExxonMobil Exploration Company beginning in early 2016 and is now working with the Gulf of Mexico team.

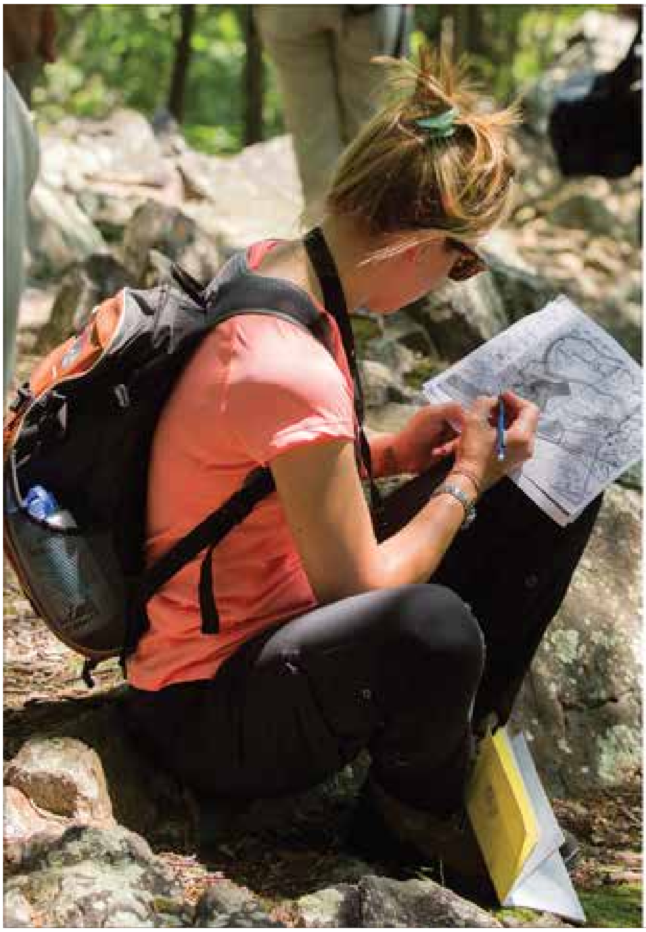
As one of many participants over the years, Kim's story conveys the value of field experience for geology students hoping to pursue careers in industry:

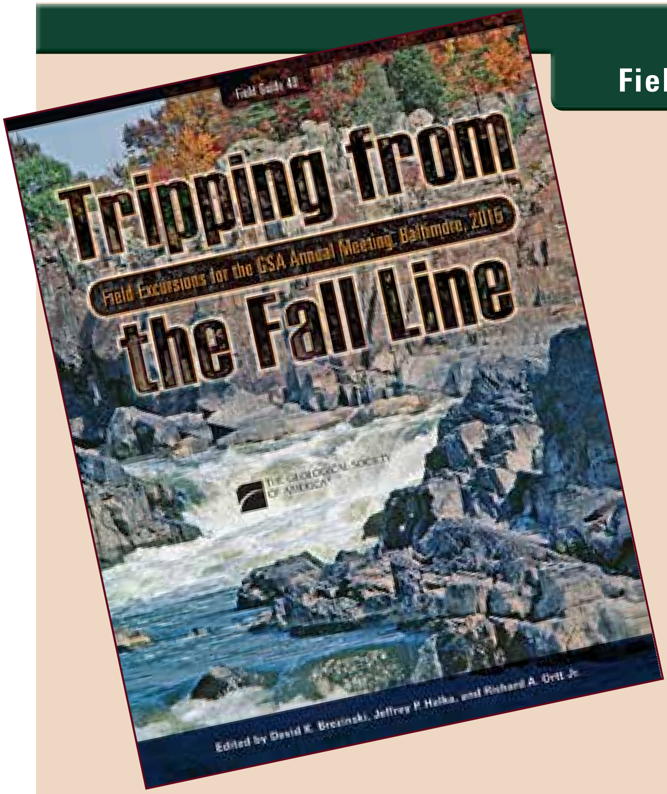
> The Bighorn Basin Field Camp was an excellent, well-rounded program that provided a fundamental, hands-on look as to how hydrocarbon systems form and how industry views and attempts to develop an understanding of them.
>
> Students and professors were split into teams and given a week to develop different play elements and concepts. I felt this system was effective because team members came from a variety of geologic backgrounds and experiences, and were able to draw upon that and integrate a diverse spectrum of ideas into a final product.
>
> As an undergraduate student with little to no prior experience in the oil and gas industry, it was initially quite intimating to be in the field with and presenting to company and industry experts. I soon realized our mentors shared the same passion and curiosity for the geological sciences as I did, and it inspired me to pursue a career in industry.

Kim's success is encouraging to all of us at GSA, at the GSA Foundation, at companies like ExxonMobil and others who have hired alumni of the Bighorn Basin Field Camp, and to students following in her footsteps. If you feel as strongly as we do about the vital component of field experience for students moving toward careers in the geosciences, please join us in support of our future geoscientists at **https://www.gsafweb.org/donate/#fund=field-camp-opportunities**. To discuss support of field camp opportunities like this one, please contact Debbie Marcinkowski at +1 303 357-1047 or dmarcinkowski@geosociety.org.

Kim's participation in the 2014 GSA/ExxonMobil Bighorn Basin Field Camp.

www.gsafweb.org

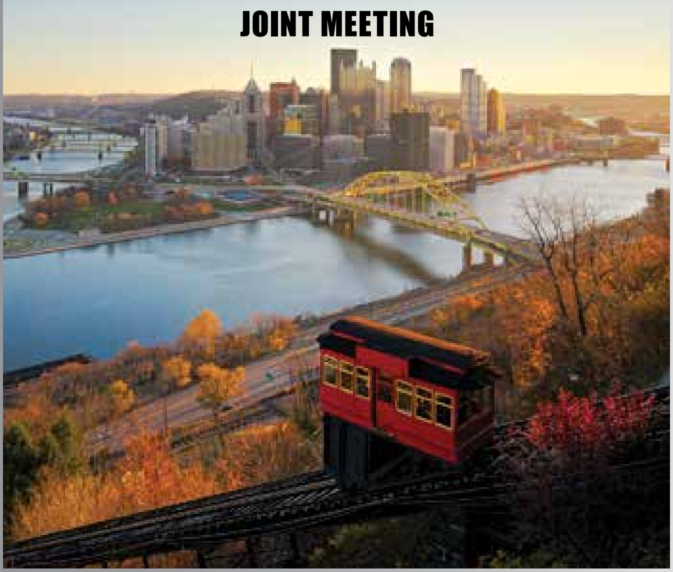



Field Guide 40
Tripping from the Fall Line
Field Excursions for the GSA Annual Meeting, Baltimore, 2015
The Geological Society of America
Edited by David K. Brezinski, Jeffrey P. Halka, and Richard A. Ortt Jr.

2017 GSA Section Meetings

Aerial overview of the Canyon Lake spillway of south-central Texas. Photo by Larry Walther.

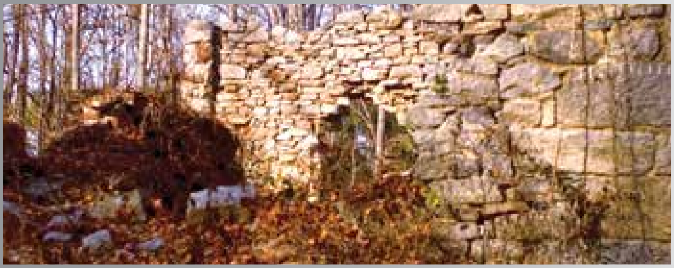
South-Central Section
Location: San Antonio, Texas, USA
Dates: 13–14 March
Meeting Chair: Benjamin Surpless, bsurples@trinity.edu
www.geosociety.org/sc-mtg



Downtown Pittsburgh from Duquesne Incline.

Northeastern Section
(Joint with North-Central Section)
Location: Pittsburgh, Pennsylvania, USA
Dates: 19–21 March
Meeting Chair: Patrick Burkhart, patrick.burkhart@sru.edu
www.geosociety.org/ne-mtg

North-Central Section
(Joint with Northeastern Section)
Location: Pittsburgh, Pennsylvania, USA
Dates: 19–21 March
Meeting Chair: Timothy G. Fisher, timothy.fisher@utoledo.edu
www.geosociety.org/nc-mtg



Midlothian Mines. Photo used with permission from Richmond Region Tourism.

Southeastern Section
Location: Richmond, Virginia, USA
Dates: 30–31 March
Meeting Co-Chairs: David Spears, david.spears@dmme.virginia.gov; Karen Layou, klayou@reynolds.edu
www.geosociety.org/se-mtg

Used with permission from Hawai‘i Tourism Authority. Photo by Tor Johnson.

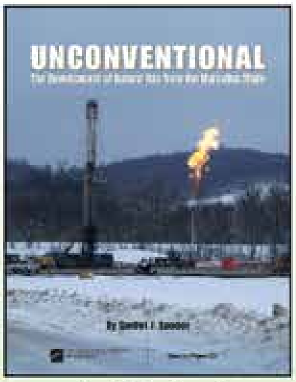
Cordilleran Section
Location: Honolulu, Hawaii, USA
Dates: 23–25 May
Meeting Chair: Craig R. Glenn, glenn@soest.hawaii.edu
www.geosociety.org/cd-mtg

Three Sisters from the Front Ranges along the Trans Canada Highway near Canmore. Photo by Larry Lane.

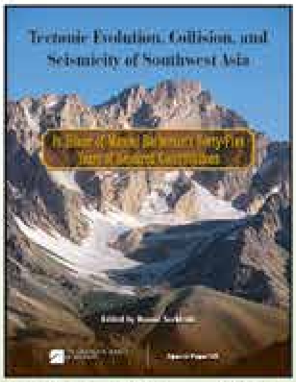
Rocky Mountain Section
Location: Calgary, Alberta, Canada
Dates: 9–10 June
Meeting Chair: Katherine Boggs, kboggs@mtroyal.ca
www.geosociety.org/rm-mtg

www.geosociety.org/sections

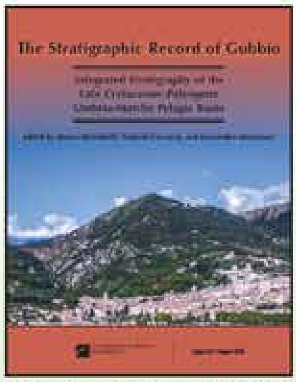
Shop at the GSA Store



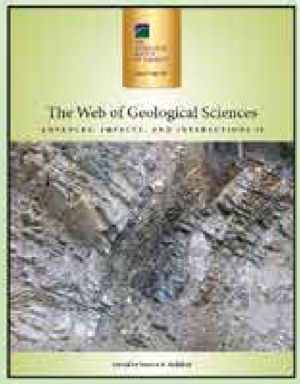
Unconventional: The Development of Natural Gas from the Marcellus Shale
by Daniel J. Soeder
SPE527, ISBN 9780813725277
IN PRESS



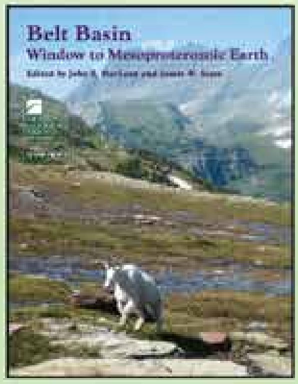
Tectonic Evolution, Collision, and Seismicity of Southwest Asia: In Honor of Manuel Berberian's Forty-Five Years of Research Contributions
edited by Rasoul Sorkhabi
SPE525, ISBN 9780813725253
IN PRESS



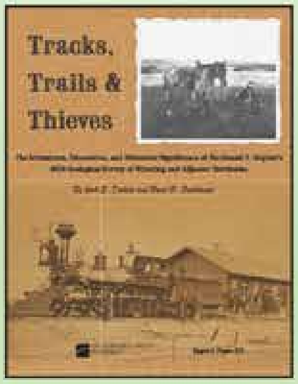
The Stratigraphic Record of Gubbio: Integrated Stratigraphy of the Late Cretaceous–Paleogene Umbria-Marche Pelagic Basin
edited by Marco Menichetti, Rodolfo Coccioni, and Alessandro Montanari
SPE524, 175 p., ISBN 9780813725246
$60.00 | **member price $42.00**



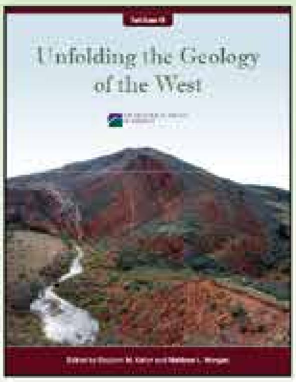
The Web of Geological Sciences: Advances, Impacts, and Interactions II
edited by Marion E. Bickford
SPE523, ISBN 9780813725239
IN PRESS



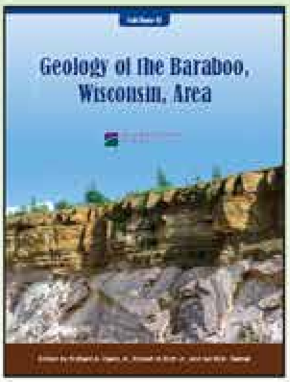
Belt Basin: Window to Mesoproterozoic Earth
edited by John S. MacLean and James W. Sears
SPE522, 394 p., ISBN 9780813725222
$80.00 | **member price $56.00**



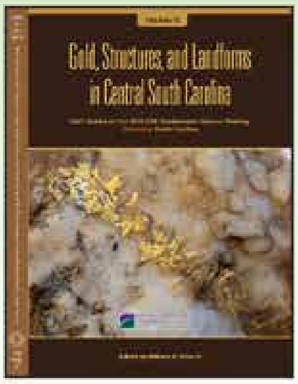
Tracks, Trails, and Thieves: The Adventures, Discoveries, and Historical Significance of Ferdinand V. Hayden's 1868 Geological Survey of Wyoming and Adjacent Territories
by Jack E. Deibert and Brent H. Breithaupt
SPE521, 85 p. plus index, ISBN 9780813725215
$40.00 | **member price $28.00**



Unfolding the Geology of the West
edited by Stephen M. Keller and Matthew L. Morgan
FLD044, 419 p., ISBN 9780813700441
$42.00 | **member price $30.00**



Geology of the Baraboo, Wisconsin, Area: Geological Society of America Field Guide
edited by Richard A. Davis Jr., Robert H. Dott Jr., and Ian W.D. Dalziel
FLD043, 81 p., ISBN 9780813700434
$40.00 | **member price $28.00**



Gold, Structures, and Landforms in Central South Carolina—Field Guides for the 2016 GSA Southeastern Section Meeting, Columbia, South Carolina
Edited by William R. Doar III
FLD042, 51 p., ISBN 9780813700427
$20.00 | **member price $14.00**

http://rock.geosociety.org/store/

toll-free 1.888.443.4472 • 1.303.357.1000, option 3
gsaservice@geosociety.org

THE GEOLOGICAL SOCIETY OF AMERICA®