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REMOTE SENSING OF GEOMORPHOLOGY

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Developments in Earth Surface Processes

REMOTE SENSING OF GEOMORPHOLOGY

VOLUME 23

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Developments in Earth Surface Processes

REMOTE SENSING OF GEOMORPHOLOGY

VOLUME 23

Volume Editors

Paolo Tarolli
Department of Land, Environment, Agriculture and Forestry, University of Padova, Legnaro (PD), Italy

Simon M. Mudd
University of Edinburgh, School of GeoSciences, Edinburgh, United Kingdom

ELSEVIER

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CHAPTER

11

Zero to a trillion: Advancing Earth surface process studies with open access to high-resolution topography

Christopher J. Crosby[a], *J Ramón Arrowsmith*[b], *Viswanath Nandigam*[c]

[a]UNAVCO, Boulder, CO, United States [b]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, United States [c]San Diego Supercomputer Center—UC San Diego, La Jolla, CA, United States

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1 Introduction

Topography is a fundamental three-dimensional observable phenomenon for Earth and environmental science and engineering. These data are collected from satellite, airborne, and terrestrial platforms with technologies such as lidar, radar, sonar, and photogrammetry, with increasingly finer resolutions, greater accuracy, and shorter repeat times. Understanding Earth-surface processes requires the ability to discover, manage, share, and process this ever-growing volume of topographic data. OpenTopography (OT—www.opentopography.org) democratizes access to topographic data, processing tools, and knowledge, enabling discoveries and applications in surface processes and many other disciplines. OT focuses on improved topographic data access using best practices in cyberinfrastructure and geoinformatics. In this chapter, we review scientific motivations for OT, focusing on geomorphology and surface processes and associated broader impacts facilitated by open access to topographic data (especially high-resolution topography (HRT); defined here as data <1 m/pixel) based on our experiences over the last decade leading the OpenTopography project. Built originally to address challenges related to airborne lidar point cloud data, OT, by fall of 2018, had more than a trillion points available on-demand, and continues with regular additions of new data. In addition, OT also enables access to global topographic data. Over the past decade, the OT community has grown to nearly 86,362 unique users, who have run over 700,000 custom jobs, processing over 5 trillion points.

2 Scientific motivations for open access to topographic data

The availability of HRT and shallow-water bathymetry has been revolutionary for Earth and environmental sciences and engineering (e.g., Carter et al., 2007; Glennie et al., 2013; Meigs, 2013; Tarolli, 2014; Harpold et al., 2015; Jordan, 2015; Passalacqua et al., 2015; Donnellan et al., 2017). These data are powerful tools for studying the Earth's surface, its vegetation cover, and the built environment. Typical surface processes act at fine spatial scales (<1 m) to produce intricate landforms. HRT measures the three-dimensional geometry of the Earth's surface and overlying features at the appropriate resolution. Surface changes due to erosion, transport, and sedimentation, as well as displacements due to earthquakes, landslides, and volcanoes are often <1–10 m in magnitude. Temporal comparisons of HRT enable scientists to quantify such changes in unprecedented ways that inform our understanding of surface processes.

The Landscapes on the Edge study (NRC, 2010) provides a clear articulation of research needs in surface processes research. It presented a number of challenges, at least three of which require HRT:

- *How do geopatterns on Earth's surface arise and what do they tell us about processes?*—requires that we can measure landforms (e.g., Perron et al., 2008; Ewing and Kocurek, 2010; Fryirs, 2013; Pelletier, 2013) (Fig. 1). HRT enables measurements of these patterns at the meter and finer scale over kilometers of length spurring the use of landscape metrics to understand process (e.g., Passalacqua et al., 2010; Milodowski et al., 2015).

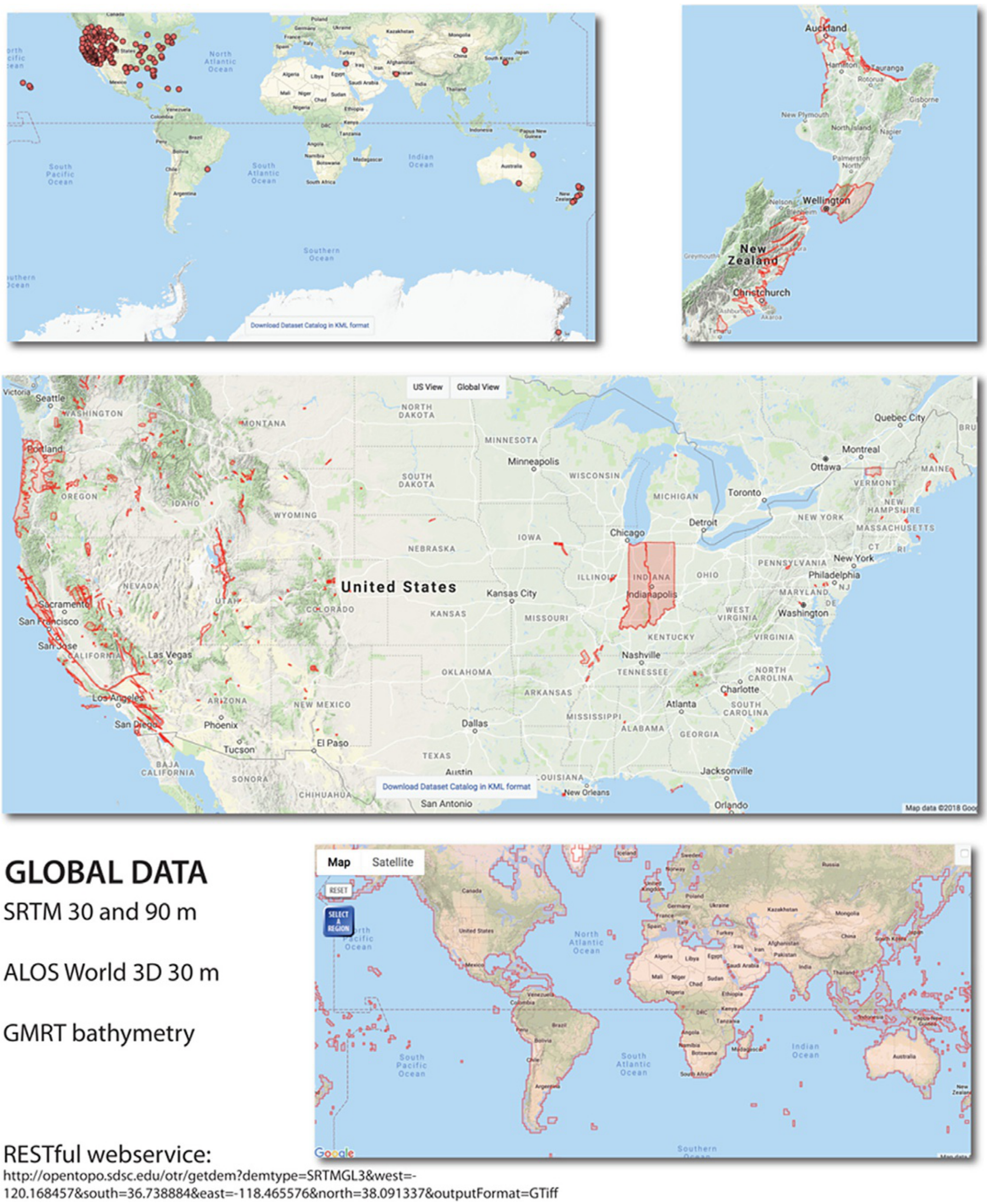

FIG. 1 Data holdings in OpenTopography (Fall 2018) include high-resolution lidar and photogrammetry point clouds and rasters (above) and global rasters including SRTM and ALOS World 3D datasets available from both browser and API/web services.

- *How do landscapes influence and record climate and tectonics?*—requires access to HRT to assess the balance between tectonic displacements and erosion and deposition (e.g., Frankel et al., 2007; Hilley and Arrowsmith, 2008).
- *What are the transport laws that govern the evolution of the Earth's surface?*—needs topographic parameters as rate controls (e.g., Dietrich et al., 2003; Roering, 2008; Hurst et al., 2013). Differencing repeat measurements of topography helps to test predictions of erosion, deposition, and mass transport rates (e.g., Young and Ashford, 2006; Wheaton et al., 2010; Wang et al., 2011; DeLong et al., 2012) especially in the face of human landscape impacts (e.g., Walter and Merritts, 2008).

Understanding how faults slip, meter-scale fault geometry, the balance between on-and-off, fault deformation, and the initial modifications to rupture by surface processes are informed by immediate post-earthquake mapping and differencing of topographic data spanning the events (e.g., Hudnut et al., 2002; Borsa and Minster, 2012; Haddad et al., 2012; Nissen et al., 2012, 2014; Oskin et al., 2012; Clark et al., 2017; Scott et al., 2018) (Fig. 1). Our understanding of slip along the San Andreas Fault (SAF) system was transformed studying B4 lidar topography data (Bevis et al., 2005) processed by OT (Zielke et al., 2010, 2015; Salisbury et al., 2012; Gold et al., 2015). Photogrammetric analysis refined the SAF slip history (Salisbury et al., 2018). Spectral and wavelet-based approaches offer significant potential for scaling up across OT's extensive active fault coverage (e.g., DeLong et al., 2010, Hilley et al., 2010, Sare et al., 2019).

The Critical Zone Observatories (CZO) study the Earth's surface from the top of the canopy to the bottom of the tree roots (Brantley et al., 2006; NRC, 2010, 2012). HRT motivates new models that incorporate hydrology, sediment transport, and land cover at scales over which the relevant processes are acting.

3 Broad impacts from openly available topographic data

Open access broadens the impact of increasing investments in topographic data by expanding access and enhancing usability for communities beyond academic research (e.g., educators, public agencies, and commercial sector) and applications (e.g., infrastructure, sustainability, and hazards).

HRT data in the classroom address science standards (e.g., NRC, 2013) and enable Earth as a system and technology/geodesy to be taught via active learning (Robinson et al., 2017). Data cover places familiar to students, encouraging place-based learning (Semken, 2012), and 3D remote sensing is of great interest to students (e.g., Reed et al., 2014). Fig. 1D shows how the easily discoverable and accessible Indiana Statewide lidar data were used to 3D print a model of the Indiana School for the Blind & Visually Impaired campus for tactile exploration (3D, 2017). In January 2018 alone (~2000 total point cloud jobs) more than 200 were executed as part of student tutorials, laboratory exercises, practicals, and self-teaching. Culminating several years exploring HRT as an educational tool, Robinson et al. (2017) have demonstrated its significant value for teaching Earth-science concepts. Motivated by undergraduate geoscience textbooks, the US Next Generation Science Standards, and the Earth Science Literacy Initiative, activities using HRT improve novice students' ability to evaluate topography for geologic features and come to accurate conclusions about landscape evolution. The GETSI—GEodesy Tools for Societal Issues (SERC, 2018) curriculum directs students to OT resources for lessons on imaging the signal of tectonics in the landscape.

Increasingly, national and regional governments are investing in large-scale HRT mapping efforts. These programs are motivated by the proven return on investment that comes from applications of HRT to infrastructure and civil engineering, urban planning, hazard mitigation, and public safety, and use in the private sector. In the United States, the US Geological Survey 3DEP Program (USGS, 2018) partners with state and local agencies with a goal to collect consistent HRT data across the whole lower 48. The US Interagency Elevation Inventory (NOAA, 2018) shows growing HRT coverage for the United States, achieved through the 3DEP program as well as efforts by other state and local agencies. Similar national investments in HRT data collection are occurring across the globe. Numerous European countries are engaged in national HRT mapping programs (e.g., Environment Agency UK, 2015; Swiss Office of Topography, 2018), as well as Asia (e.g., PHiL-LIDAR 1, 2018), and Oceania (e.g., LINZ, 2018). A considerable challenge related to this large scale, HRT mapping effort is the variable access to these datasets (Isenberg, 2016). In many cases, point cloud data and/or derivative products are available for online download via simple ftp or http file servers. In very few cases, tools to make data easier to discover, access, download, and process are provided.

Lidar is also recognized as an essential element of remote sensing of ecosystems with fundamental value in characterizing their 4D changes and applications to sustainability. The National Ecological Observatory Network's (NEON) Airborne Observing Platform (AOP) is collecting data annually over NEON field sites to "... build a robust time series of landscape-scale changes in numerous physical, biological and biochemical metrics" (NEON, 2018). Similarly, the Carnegie Airborne Observatory measures and monitors tropical forests and their exploitation (CAO, 2018).

HRT data are also essential for responding to, and mitigating natural disasters, with specific applications including hazard mapping and identification, and the rapid characterization of landscapes following landslides, earthquakes, volcanic eruptions, wildfires, and floods. This includes the use of rapidly accessible, pre-event data and immediate collection and dissemination of post-event data (e.g., Cowgill et al., 2012; Ekhtari and Glennie, 2017). The data have great value for structural engineering in assessment and simulation of collapsed buildings (Elberink et al., 2011; Ma et al., 2015) and liquefaction effects on critical infrastructure (Bray et al., 2013).

4 OpenTopography overview and impact

OpenTopography focuses on improving topographic data access through best practices in cyberinfrastructure and geoinformatics. This approach democratizes access to topographic data and has enabled discoveries and applications in surface processes and many other disciplines (Figs. 1–6). An early tenet of OT was the colocation of data and processing services to streamline access for nonexpert users (Jaeger-Frank et al., 2006; Crosby et al., 2011). This "big data" approach to data distribution began with airborne lidar data, but we now also include topographic data from radar and photogrammetry at a range of scales.

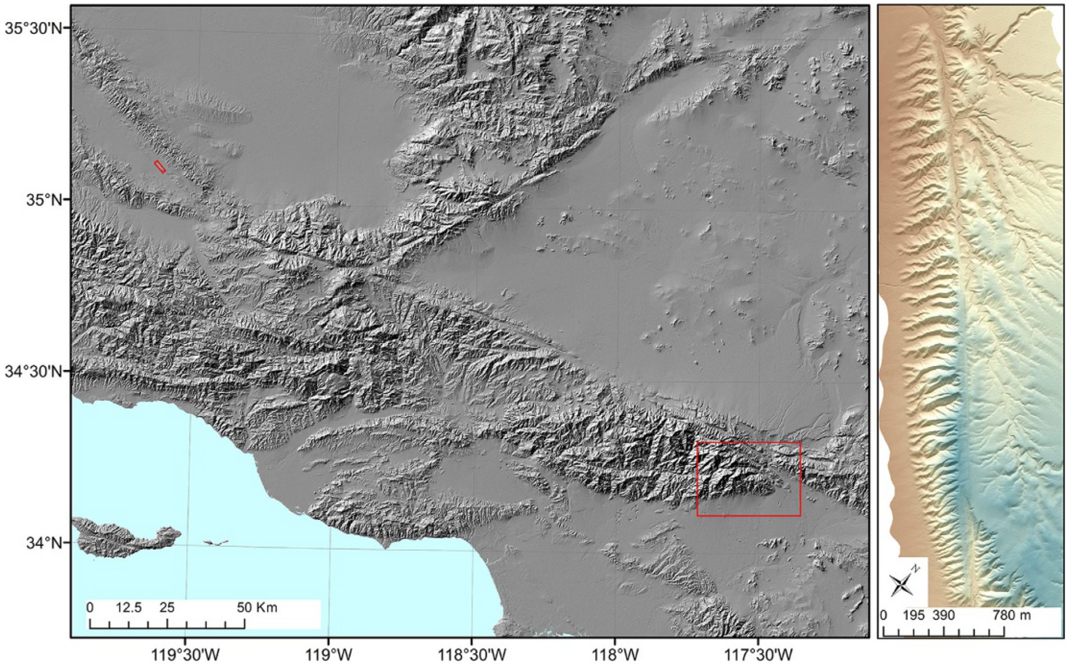

FIG. 2 OpenTopography global and high-resolution rasters. Shuttle Radar Topography (https://doi.org/10.5069/G9445JDF) 30 m per pixel hillshade on the left showing the eastern Transverse Ranges, Mojave Desert, and southern Sierra Nevada of California. *Inset at right* shows high-resolution (0.5 m/pixel) digital elevation model colored by elevation (B4 project—https://doi.org/10.5069/G97P8W91; the site is the Dragon's Back Pressure Ridge—Hilley and Arrowsmith, 2008). Fig. 3 location is the *red box at the lower right*.

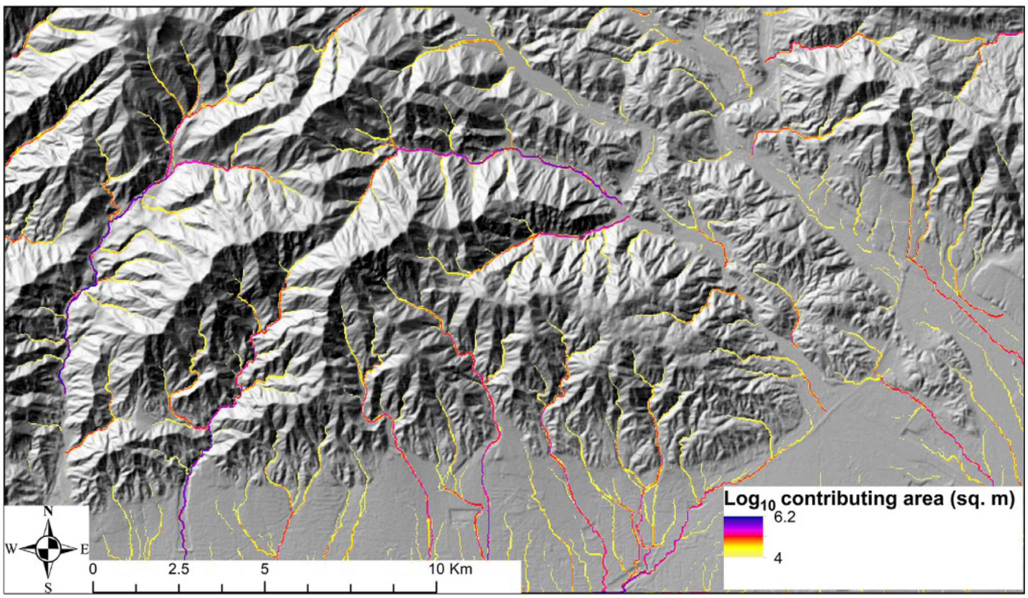

FIG. 3 Log10 contributing area in the San Gabriel Mountains, California (see Fig. 2 for location) computed using TauDEM in OpenTopography on the ALOSWorld 3D data (https://doi.org/10.5069/G94M92HB) (Tadono et al., 2014; Takaku et al., 2014).

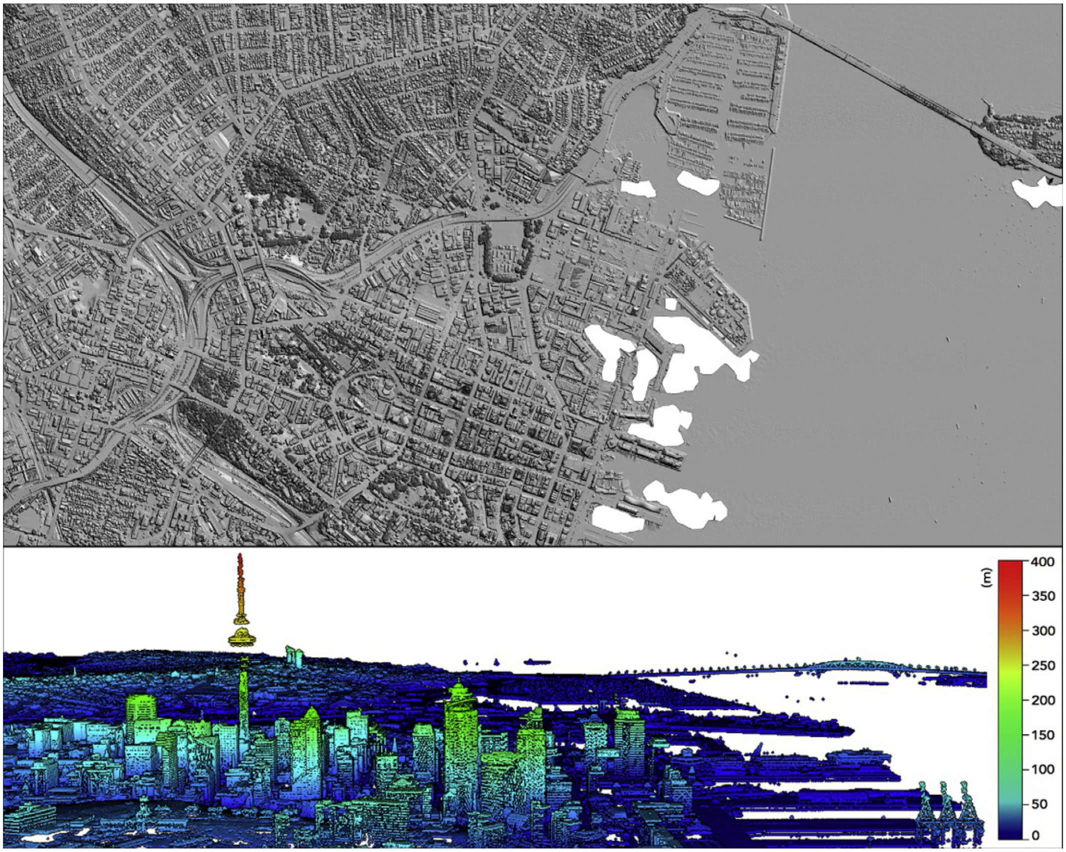

FIG. 4 Auckland New Zealand hillshaded DSM above and point cloud visualized in a web browser below (https://doi.org/10.5069/G9KW5CZ5) with approximately the same extent and with the point cloud viewed from the south (bottom edge of DSM). OT provides interactive 3D visualization of point cloud data powered by Potree (2018) and Entwine (2018) open-source tools.

The underlying cyberinfrastructure platform that powers OpenTopography was originally prototyped as part of the National Science Foundation (NSF)-funded GEON Project (Seber et al., 2003) as an R&D application called the GEON LIDAR Workflow (GLW) (Jaeger-Frank et al., 2006; Crosby et al., 2011). The success of the GLW illustrated the need for a production-quality online portal to serve the rapidly growing community of Earth science.

Now a decade old, OT is an example of early investment in domain cyberinfrastructure (Keller et al., 2005; Crosby et al., 2011) evolving to become a production data facility upon which rely researchers, educators, and many others (Fig. 7). On the cyberinfrastructure side, OT works in a "development and production" mode rather than in pure research and development. This enables the deployment of stable and reliable systems as well as their regular enhancement and renovation to meet the evolving demands of the user community.

Today, OT supports a broad interdisciplinary user base in academia and beyond. As of fall 2018, over 28,300 users have registered with OT, and 86,362 unique users have processed data

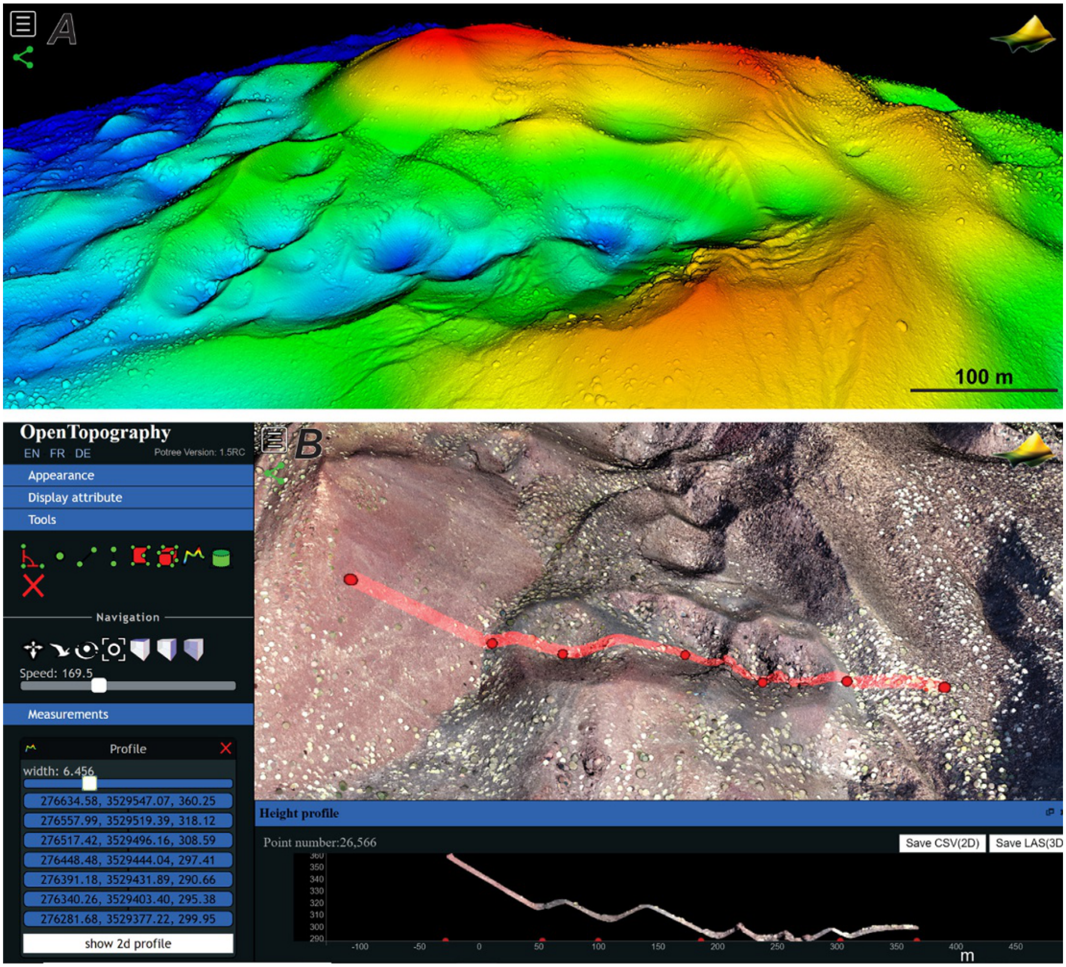

FIG. 5 View of SfM photogrammetry-derived (UAS platform) drone point cloud from Tecolote Volcano, Pinacate Volcanic Field, Sonora, Mexico (https://doi.org/10.5069/G9028PFR; −113.360278° long, 31.877148° lat). The data are visualized using OT's Potree and Entwine-enabled point cloud viewer. (A) Colored point cloud by elevation. (B) Point cloud colored by RGB of the photogrammetric point cloud with a topographic profile drawn (below) using the Potree viewer.

via OT. OT holds 283 lidar point cloud datasets covering 236,364 km^2. More than a trillion points are available for on-demand processing and download. In 2017, 66,061 browser-based jobs were run with another 33,344 jobs via API calls. These computations and analyses support substantial academic, educational, and applied use and reuse of the OT data holdings. At least 290 peer-reviewed articles along with numerous theses and other publications have been produced using OT resources (Fig. 8). These include academic works in Earth science, ecology, hydrology, geospatial and computer science, and engineering.

OT's hosting policy requires that data be *Earth science-related, research-oriented, in the public domain without restriction on use or redistribution, and fully documented and meaningfully*

FIG. 6 SfM-derived point cloud delivered from the OpenTopography Community Dataspace. (A) Location of the survey: Faraglione rock outcropping, Vulcano Island, Italy (https://doi.org/10.5069/G9WD3XPD). (B) Single UAS-derived image used as part of the photogrammetry and downloaded from the OT community dataspace. (C) Point cloud rendered using CloudCompare (https://www.danielgm.net/cc/).

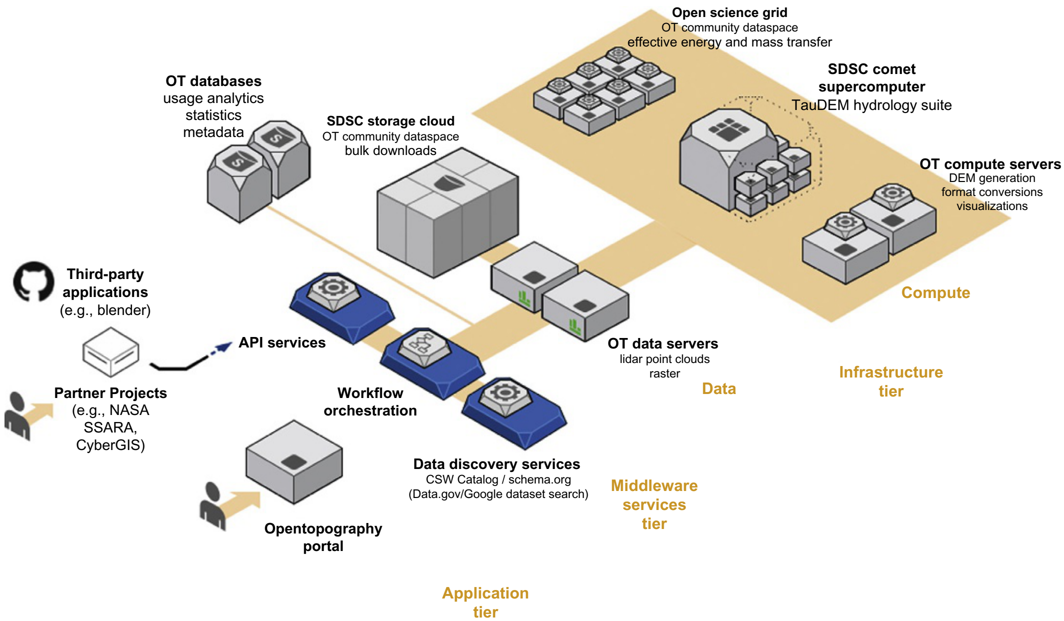

FIG. 7 OpenTopography system architecture consists of three tiers—application, middleware services, and infrastructure (Krishnan et al., 2011).

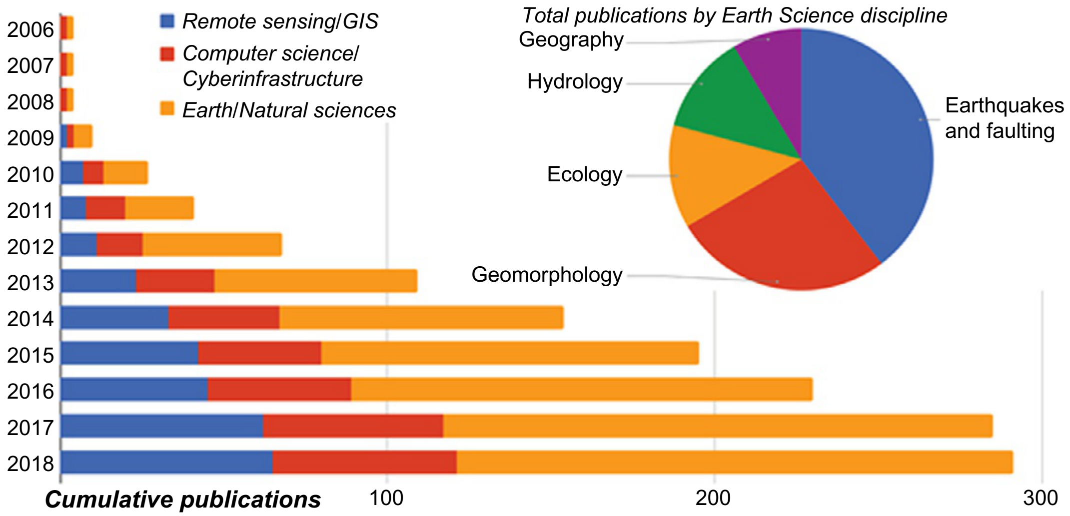

FIG. 8 Cumulative publications produced by OpenTopography users through the first quarter of 2018. The 291 publications include Earth/Natural sciences (breakdown by subdiscipline in the pie chart) as well as remote sensing/GIS and computer science/cyberinfrastructure attesting to the value of the easily accessible data products. *Y*-axis is the calendar year.

organized. OT hosts data collected by many partners. OT is the official distribution pathway for all US NSF-funded data collected by the National Center for Airborne Laser Mapping (NCALM), including EarthScope (Prentice et al., 2009), the B4 southern SAF dataset (Bevis et al., 2005), and the CZO. Of the 196 NCALM datasets hosted by OT, many are graduate student seed awards, covering many geologic domains and landscapes. OT services are identified in NSF proposal Data Management Plans, and as online repositories (e.g., Geophysical Research Letters).

As a cyberinfrastructure-enabled facility with a large set of users, it is possible to measure the growth and style of access to the various OT assets. We have seen exponential growth in users and jobs. We averaged 425 new registrations per month, and the total number of unique users (including unregistered guests) doubled from 31,291 to over 62,971 from 2015 to 2017 (Fig. 9). With the growth in OT users and data, a corresponding increase has occurred in processing service use (Fig. 9). Since 2009, users have run 330,232 custom, point cloud, and raster jobs via the portal, processing over 5 trillion points. An additional 394,369 jobs were invoked via global dataset APIs (OT, 2018).

While the greatest computational and data discovery challenges are with HRT point clouds and derived data, OT's global raster services have seen considerable use. We made available the workhorse 30 and 90 m/pixel Shuttle Radar Topography Mission (SRTM) (Fig. 2; Farr et al., 2007), the ALOS Global Digital Surface Model (Fig. 3; Takaku et al., 2014, Tadono et al., 2014), and the Global Multiresolution Topography Data Synthesis (Ryan et al., 2009). These datasets have been accessed more than 927,000 times. Their ease of access has been valuable for InSAR topographic correction (Baker et al., 2014), base maps for study context, and topographic analyses examining questions such as drainage basin disequilibrium (e.g., Beeson et al., 2017).

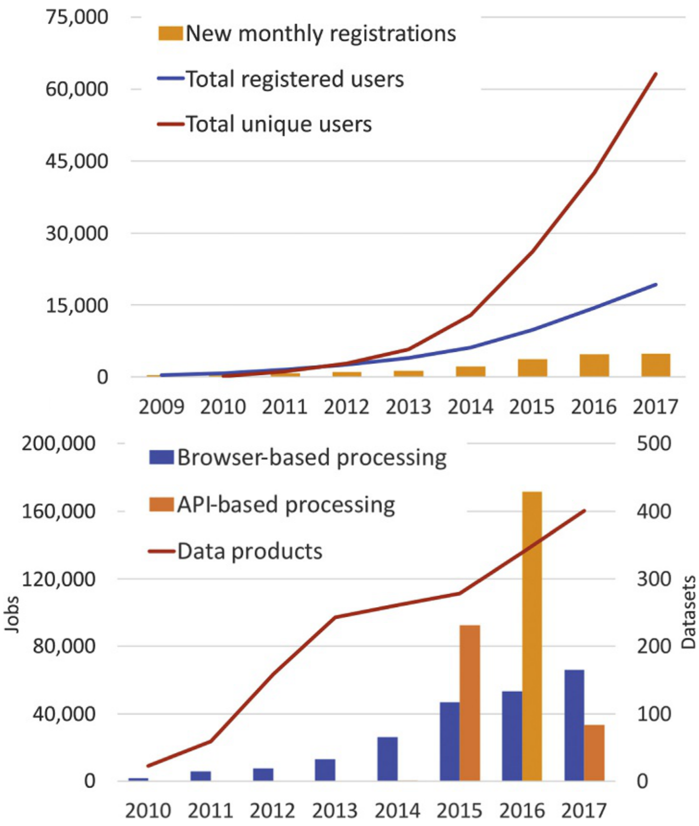

FIG. 9 OpenTopography usage statistics as of the end of 2017. Over 62,971 unique users have run custom jobs (20,621 registered users + guests) (*top plot*). 2016 and 2017 saw more than 4700 new registrations per year (*bars*). Some 66,061 processing jobs were run via the web portal (browser) in 2017 (*bottom plot bars* left axis scale). The year 2016 was an unusual time for API access with heavy use of global rasters. Dataset growth has been steady and was nearly 400 (right axis scale).

The OT cyberinfrastructure is a robust and highly scalable, multitiered, service-oriented architecture for efficient access to topography data and processing tools (Krishnan et al., 2011). It includes an infrastructure tier, a middleware services tier, and an application tier (Fig. 7). The infrastructure tier comprises the data management systems for managing the HRT data and compute resources for processing and visualization. The modular services-oriented nature of the cyberinfrastructure also enables integration of distributed, high-performance computing systems (e.g., NSF XSEDE resources) that ensures that the growing demands of the research community are met—including demands for more compute-intensive algorithms (e.g., spectral analysis of topography, effective energy and mass transfer, extraction and analysis of hydrologic information); growth in overall dataset sizes and individual job sizes; and the growth of the user community itself. Access to the infrastructure tier is provided to users via the middleware services tier which primarily comprises the workflow orchestration, application program interfaces (APIs), and other data discovery services, among others. The scientific applications running on both dedicated OT commodity clusters and HPC resources are wrapped as web services and made accessible within the OT workflow as data and processing resources. External projects can also access data and processing tools via the middleware services tier. For example, the CyberGIS project (Wang et al., 2013) uses OT web services in its Viewshed Analysis application. Similarly, the NASA-supported Seamless SAR Archive system (SSARA, Baker et al., 2014), as well as third-party applications like TopoToolbox (Schwanghart and Scherler, 2014), access global topographic data in OT via RESTful API. Most users access data and processing via the OT portal in the application tier. A robust interface guides users through data selection, processing, and parameterization. The portal also includes the capability for users to perform in browser visualization of their subsetted point cloud data. OT has developed a “Community Dataspace,” a service built on a low-cost storage cloud to make it easy for researchers to upload, curate, annotate, and distribute their datasets (e.g., Fig. 6). The system’s ingestion workflow will extract metadata from data uploaded; validate it; assign a digital object identifier (DOI); and create a searchable catalog entry, before publishing via the OT portal.

OT also employs a number of tools and technologies to ensure the broad discovery of its data holdings. Datasets in OT enforce the ISO 19115 (Data) metadata standard and are assigned DOIs for persistence and citation. OT also implements an Open Geospatial Consortium (OGC) CSW interface (Catalog Service for Web) that allows metadata to be easily federated with other geoscience catalog services like Data.gov and Thompson Reuters Web of Science. Additionally, the schema.org metadata standard implementation at the dataset level improves the discovery of datasets on the internet. The combination of federated catalogs and schema.org markup standards enables wider discovery of the OpenTopography data catalog (including the Community Dataspace datasets), making these data an asset that can be used and reused.

5 OpenTopography partnerships

OT is built on strong partnerships with data providers who value OT’s cyberinfrastructure and community to increase the impact of their HRT data investments. As a testament to OT’s success, numerous entities (inc. NCALM, the CZOs, and state and regional agencies) rely solely on OT for online data distribution. Many of these partnerships are codified as Memoranda of Understanding, or through Service Agreements (SA).

In addition to data funded by the US NSF Directorate for Geosciences, data in the OT catalog have been collected by NEON, NOAA, NASA, US Bureau of Reclamation, USGS, BLM, USFS, National Park Service, Oregon Department of Geology and Mineral Industries, the states of Utah and Indiana, Tahoe Regional Planning Authority, Teton Conservation District, the World Bank, Land Information New Zealand, Geological Survey of Israel, Sonoma County, and Pacific Gas & Electric.

One key to OT’s successful partnerships with data providers is ensuring that each dataset is appropriately “branded,” giving full credit to the dataset funder, collector, and project partners. A dashboard allows providers to report real-time usage statistics for OT hosted datasets including a number of unique users, jobs submitted, points processed, and user domain (e.g., ucsd.edu).

6 Lessons learned and challenges for supporting open access to topographic data

Advancing research in geomorphology requires strong coupling between the development of underlying process rules and testing them with observations in an open scientific approach. Innovation in process understanding and in observational constraints can come from the exploration of patterns in easily accessible data. As OpenTopography has evolved and contributed to geomorphic research by enabling access to a range of topographic data products for a broad community, we have monitored and responded to the user needs to refine OT. As a consequence, a number of lessons and challenges of potentially wide interest associated with science infrastructure are evident.

By the late 1990s, lidar technology for airborne, mobile, and terrestrial scanning had advanced sufficiently that it becomes widely available to industry and academia (Glennie et al., 2013). The oldest datasets in the OT holdings were collected in 2003: Northern San Andreas Fault, CA (https://doi.org/10.5069/G9MW2F2H) and West Rainier Seismic Zone, WA (https://doi.org/10.5069/G9CC0XMC) with USGS and NASA support. The 2005 collection of the B4 dataset (Bevis et al., 2005) which scanned the southern SAF system (Figs. 1 and 2) built on another fault scanning, for example, of the 1999 Hector Mine earthquake rupture (Hudnut et al., 2002). Distribution of the B4 dataset with on-demand point cloud subselection and computation of DEMs and other derived products was an immediate need addressed by OT (as of this writing, nearly 2200 unique users had run 8800 custom point cloud processing jobs on the B4). The enthusiasm for airborne laser-scanning data and the facility for its collection and use in Earth science research in the United States were largely addressed by the National Center for Airborne Laser Mapping (e.g., Carter et al., 2007; Glennie et al., 2013). As the primary data distribution pathway for NCALM data, OT has been able to help make these data broadly accessible and the OT holdings and usage grew, tracking a boom in data acquisition. Important additional partnerships are reviewed below.

The emergence of structure-from-motion (SfM) photogrammetry and low-cost, unmanned aerial systems (UAS) (James and Robson, 2012; Westoby et al., 2012; Fonstad et al., 2013; Bemis et al., 2014; Johnson et al., 2014) has enabled researchers to produce their own HRT data (Figs. 5 and 6). This explosion in researcher-generated, "longtail" (Heidorn, 2008) topographic datasets poses a new set of data management and curation challenges. These valuable data must be archived for reproducible science and broader reuse. We have begun to address this need with the OT Community Dataspace (http://opentopo.sdsc.edu/dataspace/datasets), which is a service built on the low-cost academic storage cloud at San Diego Supercomputer Center (SDSC). It allows researchers to upload, curate, annotate, publish, and distribute point and raster data products produced from small aerial and terrestrial lidar and photogrammetry surveys (see Fig. 6 as an example). These data are thus published and receive a DOI for data citation.

The distribution, processing, and analysis of topographic data (HRT in particular) are computationally challenging given their heterogeneity and broad utility in science and engineering, yet the problem is tractable given their semantic simplicity. OpenTopography developed early on to fill a need to make HRT datasets such as those along the SAF discoverable, subsettable, and available in common usable formats (DEMs and point clouds). While easing the technical burden and thus contributing significantly early on to studies of the topography along the SAF, this service also helped to make OT (and its prototype the GLW) visible to a growing and engaged user community.

Having a genuine connection between domain scientists (in particular, geomorphologists) and computer scientists helped to ensure that what was built was immediately useful. For example, lidar data provide dense, heterogeneous point clouds sampling the terrain, vegetation, and the built environment. However, many geomorphologists need to analyze topography as rasters (DEMs). Efficient computation of DEMs from lidar point clouds in 2005 was challenging so our geomorphologist team prototyped a local gridding algorithm that was then adapted by the computer science team into a stable, scalable software application that ran for many years in the OT productions system (Kim et al., 2006; P2G, 2018), now available as an open-source tool described at https://opentopography.org/otsoftware/points2grid. We also realized that users were interested in multiple levels of data products: some wanted access to the point clouds and detailed metadata, whereas others wanted standard DEM products. Further, imagery derived from the lidar data, such as hillshades that are easily browsable as kmz files in Google Earth enables easy exploration (Crosby, 2012). In another example, drainage network extraction on DEMs is computationally intensive and adding them to a processing chain in OT that was already running on high-performance computing resources made sense (e.g., Fig. 3). Adapting research software to production-computational environments is challenging. We were also successful in implementing hydrologic terrain analysis on high-resolution DEMs by deploying the hydrology package TauDEM (Fig. 3; Tarboton, 2005) on SDSC's *Gordon-Simons* supercomputer (dedicated I/O node and 16 compute nodes) (Youn et al., 2014; Gordon, 2018). This service now runs in production mode on SDSC's latest *Comet* supercomputer cluster. Since its release in June 2014, the TauDEM suite of hydrology tools on the *Gordon-Simons* HPC system has been used 18,830 times.

The strong domain–cyberinfrastructure partnership with a priority on user-friendly implementation has enabled broad access to the OT platform. This infrastructure has benefited from the SDSC production environment with its relative low-cost hosting, robust and fast network, and storage infrastructure. OT is a highly scalable and well-instrumented system. We are aware of technical problems and outages before our users are. We maintain frequent "agile" software releases and quickly resolve problems and enhance functionality via regular system updates. This approach has made a difference between a satisfied user community and one that is delighted to use the system and eager to support it.

OT maintains high standards for metadata and best practices in data management procedures to ensure that the OT collection has persistent value and is useful for the long term. The OT data-ingestion process includes file-level checks on data quality, coordinate systems, and attributes. Where possible, we recognize separately the funders, collectors, and providers of datasets. Data publication through the use of DOIs ensures that the record of the data is persistent. It also allows us to expose the dataset as an entry in the OT OGC Catalog Service (CSW—ISO 19115 Data metadata standard)—the CSW endpoint (CSW, 2018) is federated by Data.gov, EarthCube CINERGI, and Thomson Reuters Web of Science. Thus, these open data are widely discoverable and citable.

Cultivating and supporting a user community for OpenTopography has been a priority. Although we have not directly interacted with the 86,362 unique users running jobs over the last decade, OT provides "helpdesk" support via email and social media, and we have taught many short courses and contributed to numerous workshops. Social media, and regular News and Blog posts on the OT website engage the OT community. OT's social media presence is a key pathway to users globally, promoting our activities to the commercial sector and the public. OT was an early geoscience leader in the use of social media (for example, we joined twitter in 2009). We found that the different platforms addressed different audiences. For example, our Twitter followers are a wide range of academic and industry users and collectors of HRT data. Our OT social media experience was an inspiration for other large-scale science community efforts (e.g., EarthScope, Bohon et al., 2013). OT short courses focus on undergraduate and graduate students and early career professionals (https://opentopography.org/community/workshops). Our first short courses were in 2007. Sharing practical skills and knowledge for how to make HRT data useful for numerous Earth-science applications was attractive to the participants. Numerous participants in the early course and workshops are now influential in academia and industry. All short course training materials are available online and are a valuable knowledge base resource. In 2017 alone, 11,182 unique users downloaded 70,594 workshops and educational resources. In 2017, 7 courses engaged over 125 participants. The top 5 video tutorials have been viewed nearly 140,000 times on OT's YouTube channel which has over 1000 subscribers (YouTube, 2018).

Uncertainties in funding levels and competition for tight funds with other large-scale research infrastructure in the United States have been a major challenge for OT. Given the open data ethos and Earth-science applications, OT's support by the US NSF has been greatly appreciated. In times of sustained flat government budgets for science, renewal proposals, and steady funding have been possible. However, we also recognize the wide global interest and the broad applications beyond Earth science and into education and commercial realms. Balancing open access with the real costs of maintaining the cyberinfrastructure, data storage and transport, supporting staff, providing quality user support, and new developments are difficult. Open access to data means free data to many. At a basic user level that is sensible, but as mentioned above in the partnerships section, SA with data providers have generated additional revenue and have enabled OT to deliver specific large data collections by leveraging NSF's investments to build and refine the platform (e.g., Indiana Statewide data—https://doi.org/10.5069/G9959FHZ). Moving forward, we are exploring a diversified sustainability model for OT that we hope will include ongoing academic funding from NSF, as well as expanded collaborations with data partners, sponsorship, and potentially a fee-for-use for specific new data access and processing features.

7 Outlook

Addressing the numerous evident opportunities in topographic data that we have presented demonstrates an enhanced need for high-performance computing and services. Plans for future development in OpenTopography can be described in two themes:

Theme 1: A cloud and HPC platform for scalability and sustainability

OpenTopography is a technology-driven data facility leveraging proven commercial cloud platforms (e.g., Amazon Web Services—AWS) and the US NSF's investments in HPC resources via XSEDE to advance data and compute-intensive HRT-based, Earth science research. The HPC-based implementation of Terrain Analysis Using Digital Elevation Models—TauDEM and its popularity (17,054 jobs; Youn et al., 2014) demonstrate the power of direct integration of HPC resources and data facility environments, as envisaged in the National Strategic Computing Initiative (NSCI, 2015). By continuing to leverage XSEDE resources, OT makes more compute-intensive algorithms (e.g., spectral analysis, differencing) available to the user community. Cost-effective and scalable data management in the cloud will be enabled by migrating our core OT infrastructure to the AWS cloud platform where we can leverage capabilities such as auto scaling, elastic load balancing, and service offerings like AWS batch. OT data will be stored on the AWS S3 object storage cloud, where it will be available via OT APIs for rapid access, experimentation, and large-scale computation. Researchers will have the ability to run custom computations, and test prototype implementations of algorithms by spinning up an AWS EC2 compute instance or launching their custom docker images on AWS batch and accessing OT datasets via OT's S3 APIs. Another use case is a large one-time, Big Data computation. For example, the derivation of hydrologic channel representations for the entire state of Indiana, as part of the National Flood Interoperability Experiment (Maidment, 2017) could be done from dedicated AWS EC2 instances processing Indiana lidar data hosted on OT's S3 storage. And, computations such as that made possible by tools like *scarplet* (Sare and Hilley, 2018) run in the cloud achieving important science results from large-scale analyses.

Theme 2: Enabling community innovation

Algorithm and tool development to extract information from large volumes (billions to trillions) of point cloud data is an area of active research in academia and in the open-source community. We expect to integrate new processing and analysis capabilities and provide foundational infrastructure such as cloud-hosting and API-based data access to enable researchers to more directly process and analyze the ever-growing collection of data available via OT. Multitemporal topography allows us to quantify surface change and deformation from earthquakes, volcanic eruptions, landslides, and flooding events from topographic data spanning the event of interest. We are implementing topographic differencing—both vertical (e.g., raster-based subtraction—running in OT production in Fall 2018) and 3D deformation calculations performed with the Iterative Closest Point algorithm (Besl and McKay, 1992; see also Nissen et al., 2012, 2014; Scott et al., 2018). With newer datasets being delivered in the LAS 1.4 specification, we plan to migrate to the PDAL (Point Data Abstraction Library; https://pdal.io/) open-source project for data read and write, filtering operations, and more processing options. API-based data access and tools such as PDAL's filters allow users to compose custom operations, enabling large-scale fan-out processing across OT data holdings. We also recently implemented web browser-based visualization of point cloud datasets utilizing Entwine (built on PDAL) and Greyhound open-source libraries. Public APIs exist for global datasets in OT, but access to high-resolution data and software services are limited to collaborative projects like CyberGIS (Padmanabhan et al., 2013) and SSARA (Baker et al., 2014).

Increased API-based access to data and processing tools will provide a flexible platform for researchers to design complex data access and processing workflows. Workflow capability enables researchers to independently create custom processing pipelines without relying on OT software developers to produce these tools for them. We plan to support scientific workflow tools starting with Kepler (2018) and Apache Taverna (2018). Kepler is an open-source scientific workflow application designed to help researchers create, execute, and share models and analyses across a broad range of scientific and engineering disciplines. Kepler provides a graphical user interface that allows users to select and connect pertinent analytical components and data sources called "actors" to create a scientific workflow, an executable representation of the steps required to generate results. We plan to develop custom actors for OT data and processing services. These actors can be combined with existing GIS actors built with open-source libraries, e.g., GeoTools (2018) and GDAL (2018), to construct analytical pipelines for OT datasets. The growing popularity of open-source computational notebooks and their widespread adoption by the academic community is driven by the ability to easily document and share reproducible analysis. They can be implemented to access OT data and services via enhanced APIs.

8 Conclusions

We are moving into a period of ubiquitous point clouds and 3D models (Oskin et al., 2015). Autonomous navigation produces massive 3D data. Many cities, regions, and countries are working to produce and use 3D data for a vast array of applications, including understanding surface processes and anticipating and recovering from natural hazards. Along with organized mapping and data collection, more haphazard 3D data are collected and produced (e.g., using internet photo collections for SfM analysis, Snavely et al., 2008). Such 3D data have hardly been exploited for surface processes and hazard assessment and offer a significant opportunity. However, to capitalize on the opportunity, we need open access and cyberinfrastructure such as OpenTopography to support appropriate data management including archive, discovery, rapid query, data handling, preprocessing, and differencing.

We envision a near future in which the global coverage of 3D point clouds (topography, vegetation, built environment, and some bathymetry) meter or finer resolution from many heterogeneous sources (Schumann and Bates, 2018) can be made discoverable, queryable, and processable, including differencing, making it 4D. Such a federation of data distribution into a single interface will enable a wide range of surface-process science. Not only will it allow for the 3D characterization of surface features (see science motivations above) but also directly measuring surface change will provide important new constraints process rates and enable event-driven investigations.

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REMOTE SENSING OF GEOMORPHOLOGY

EDITED BY
PAOLO TAROLLI AND SIMON M. MUDD

In the last decade, new remote-sensing techniques have led to a dramatic increase in availability and quality of geomorphic data. This leap forward in the quality, spatial coverage, and resolution of available data has led to enhanced understanding of surface morphology and a new “golden age” for the Earth science research community. ***Remote Sensing of Geomorphology*** summarizes the major advances in remote sensing techniques for the analysis of Earth surface morphology and processes, while pinpointing key challenges that will be necessary to overcome in the future.

Remote Sensing of Geomorphology is a useful reference for graduate and postgraduate students, academics, and scientists to aid them in acquiring, processing, and interpreting remote sensing data to answer research questions in geomorphology. This book will also be a valuable resource to technicians in the private and public sectors and government agencies interested in survey, conservation, and environmental work.

Key Features:

- Details the advances in remote sensing of geomorphology using specific case studies
- Covers a range of remote sensing techniques including lidar, structure from motion photogrammetry, and advanced satellite platforms
- Explores emerging trends and potential challenges in remote sensing of geomorphology

Paolo Tarolli is Professor of Integrated Watershed Management and Water Resources Management at the University of Padova (Italy). He has a PhD in Environmental Watershed Management and Geomatics. He is Deputy President of the Natural Hazards Division of the European Geosciences Union (EGU) and Vice President of the 7th section (Information and Communication Technologies) of the Italian Association of Agricultural Engineering (AIIA). He is Executive Editor of the journal Natural Hazards and Earth System Sciences (NHESS).

Simon M. Mudd is Professor of Earth Surface Processes at the University of Edinburgh. He has a PhD in Environmental Engineering. Winner of the 2013 Arne Richter award for outstanding young scientists from the European Geoscience Union and the 2014 Gordon Warwick Medal from the British Society for Geomorphology.

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