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Overcoming the momentum of anachronism: American geologic mapping in a twenty-first-century world

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ABSTRACT

The practice of geologic mapping is undergoing conceptual and methodological transformation. Profound changes in digital technology in the past 10 yr have potential to impact all aspects of geologic mapping. The future of geologic mapping as a relevant scientific enterprise depends on widespread adoption of new technology and ideas about the collection, meaning, and utility of geologic map data. It is critical that the geologic community redefine the primary elements of the traditional paper geologic map and improve the integration of the practice of making maps in the field and office with the new ways to record, manage, share, and visualize their underlying data. A modern digital geologic mapping model will enhance scientific discovery, meet elevated expectations of modern geologic map users, and accommodate inevitable future changes in technology.

INTRODUCTION

Geologic mapping is a cornerstone in the foundation of geological science. A good geologic map combines complex graphical representations of an area's geologic character and history with an abstraction of the intellectual and technical processes used to create the map. Portrayals of such complex information require a firm understanding of the science, as well as an artistic attention to cartographic detail and principles of visual design. Here, in the early part of the twenty-first century, both the art and science of geological mapping lie on the cusp of transformation, wherein the collection and representation of map data and processes of their interpretation can be created, shared, and visualized in useful and unexpected new ways.

The potential for transformation is fueled by a revolution in digital technology that has already wrought tremendous and global cultural change and will continue to marginalize more traditional methods of data collection and portrayal. In just the past 10 yr, developments in geographic information system (GIS) capabilities, global positioning system (GPS) technology, internet and data connectivity, and related applications that integrate them have opened up new possibilities for the collection, management, analysis, and distribution of geologic map data. The past few years have seen a remarkable proliferation of powerful mobile computing and communication devices coupled with major growth in online interconnectivity, allowing interaction and collaboration among millions of users. This phenomenon has permeated all aspects of culture and has a global impact; for

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geologists, it has the potential to transform the ways in which field data are collected, shared, and analyzed. However, the extent to which these new possibilities have been embraced by practicing geologic mappers varies considerably.

Innovative combinations of these digital mapping technologies have awakened unexpected and great public interest in geospatial concepts and applications. Consequently, rapidly evolving tools and applications for mapping are being developed that are raising expectations for types and availability of geospatial scientific data sets and related visualization and representation possibilities. These trends are gradually transforming traditional lines of thinking within geology. As an integrative and deeply geospatial component of geological inquiry, geologic mapping can be at the crux of transformation, and geologic mappers have an opportunity to influence the future direction of their practice and to ensure its continuing and growing relevance to scientific discovery and societal needs.

THE GEOLOGIC MAP

> "A geologic map is a textbook on a single sheet of paper … it reflects (or should reflect) … all the important research that has been done on any geologic topic within its boundaries."
>
> —John McPhee, *Annals of the Former World* (2000, p. 378)

> "Geologic maps are our most important and complete compilation of information about the solid Earth we live on, and we cannot understand the Earth without them."
>
> —American Geological Institute, *Meeting Challenges with Geologic Maps* (Thomas, 2004, back cover)

Geologic mapping is essential to discovery and rich data documentation in geological science. The quote by McPhee confirms feelings among mappers about the hard work that goes into making maps; it also foreshadows the true potential for digital geologic maps in the twenty-first century. A map on a sheet of paper is only a graphic abstraction of the deeper information content on which it is based; much more information can be accessed and displayed in the digital environment. The second quote further portends the future of geologic mapping wherein the traditional paper map model is subsumed into a "living" digital map model that is founded on an extensible and updatable digital database of scientific data, interpretations, and explanations. Modern digital maps can be created, accessed, and consumed in more contextually meaningful and intuitive ways than a printed sheet of paper (e.g., Condit, 2010; Whitmeyer et al., 2010; Shufeldt et al., 2012).

Whether paper or digital, a geologic map is an intellectual commitment to a complex, interrelated series of scientific judgments that are portrayed as a plexus of lines and colored shapes on a meaningful base. This has traditionally been expressed on paper, but can now be expressed as an analogous plexus of shapes in digital form for depiction on any number of illustrative base layers, on a computer screen, or in printed form with a prescribed or user-specified symbolic representation. In any format, it is intended to be a reliable documentation of geologic materials, their structures, distributions, and stratigraphic relationships—a condensed expression of geologic history. It must be carefully constructed to distill key geologic information into a meaningful representation that balances detail and scale. The task of geologic mapping requires competence in a broad array of geologic topics, agile spatial reasoning skills, and working knowledge of concepts of cartography and graphic design. The modern task includes the elements of new geospatial technologies, digital data management, and awareness of the diverse arrays of platforms for map data visualization and distribution.

Some aspects of geologic mapping will remain unchanged in the transition from paper to digital (traditional to modern). For example, the basic mechanics of creating a paper or digital map involve field and office components. No amount of technological advance will obviate the need for field verification of geologic interpretation from imagery or older geologic maps, but many advances will and do increase efficiencies in planning, performing, and recording fieldwork. Finishing a good geologic map involves an iterative process of increasing amounts of office work and decreasing amounts of fieldwork and focused "ground-truthing" and data collection. In the office, it can require months of data compilation and interpretation. Getting the map reviewed, revised, edited, and printed are major hurdles that can take years. In many cases for paper and digital maps, the final step involves transition from fully viable geologic map data into a piece of carefully crafted cartographic art. That process can separate maps from underlying data and can result in unacceptable delays in data distribution. In a rapidly changing world, it is prudent to favor publication mechanisms that are streamlined and consistent with funding, staffing, and the needs of map users. As new technologies for creating map data are adopted, it is critical for new and appropriate modes of review, publication, and distribution to be adopted as well.

TOOLS OF TRANSFORMATION

Traditionally, the commitment of geologic lines to paper implied permanence. The entire paper-map production process was dictated by the pace of base map preparation, compilation of lines from field sheets, editing, review, and an evolving printing and distribution process. Thus, the process was well defined and could be streamlined, but it was founded on old technology and old concepts and expectations. Today, the legacy of past methods for creating, printing, and distributing maps is incompatible with modern, digital capabilities and the needs and expectations of end users. Predigital paper geologic maps have inertia and longevity in excess of their specific relevance by years to decades because of lags between changes in the scientific basis of the map, generation of new source data, and the pace of traditional map production methods. One of the greatest practical benefits of the digital revolution is the demise of the practice of treating a published printed map as an unchangeable archive of data, as opposed to a derivative product and printed archive of an evolving geologic data set.

We occupy a point in time in which it is possible to create great efficiencies in geologic mapping using widely available tools and enhance the availability and utility of geologic map information for an increasing variety of users. Major technological and conceptual advances that allow more dynamic geologic maps have transpired over the past 20 yr, including particularly important ones in only the last decade. Major technological developments in GIS and GPS alone have transformed many of the ways that we can collect, create, manage, store, visualize, and distribute geospatial data. The integration of these two technologies with digital photography, seamless digital base maps, light detection and ranging (LiDAR) technology, mobile computing devices, and social networking platforms engenders new ways to think about mapping (Pavlis et al., 2010) and data sharing. Modern technologies provide means of seamless collaboration in data development, model formulation, and scientific interpretation. This changes the intellectual and operational approaches that geologists can use to construct, interpret, and share geologic maps.

The meaning and intention of the basic activity of generating lines and plotting points on maps has not changed, but the tools and techniques for recording, storing, explaining, and sharing them have. The most cursory application of modern tools can make field and office work more efficient and improve the generation and distribution of data. More advanced and systemic applications of new field and office tools open new avenues for scientific collaboration, discovery, outreach, public education, and emergency managment. They ensure a broader audience among end users with increasing expectations for data availability and interoperability.

GIS: The Core of Modern Geologic Mapping

A geologic map is a structured representation of the geospatial relationships between different types of earth materials. The most fundamental type of data that a field geologist collects is the precise location of various geologic features. In the past much of this location data was approximated via dead reckoning, topographic inference, triangulation, and barometric altimetry. Modern GPS technology allows geologists to record geospatial information much more accurately. The accumulation of geospatial data points requires a geographically aware data management system, namely, a geographic information system (GIS).

Geologists make interpretations of the geologic landscape based not just on field observations and measurements, but also on their analysis of a wide variety of base data, including: topography, represented either as topographic lines, or in more modern systems, digital elevation models (DEM), geophysical data, aerial photography, and satellite imagery, among others. As these and new data sources continue to improve, they will play increasing roles in all geologic mapping projects. Using such a breadth of base data types requires their precise geographic alignment. GIS technologies are not only the key to georeferencing, but they also have led to the development of software allowing us to visualize these data layers in new ways and combinations. No longer must we settle for a single base layer for our maps; rather, we can now choose specific base layers and combinations for more robust scientific analysis and contextually appropriate portrayals.

GIS provides powerful tools for data analysis, visualization, and collaboration. The cornerstone of these opportunities rests in the standardized digital format in which GIS requires us to spatially encode geologic information. Because of that geospatial standardization, data can be used by a growing variety of software tools. Data generated as part of a two-dimensional (2-D) geologic map can be used to constrain the development of three-dimensional (3-D) block models using new and developing software applications (e.g., Berg et al., 2007; Kessler et al., 2009; Thorleifson et al., 2010; Jones et al., 2009). No longer must the only representation of our geologic map be a piece of paper. Instead, our data can be used to fuel visualizations draped over and compared to various, end-user–defined base layers. No longer must our maps be constrained to a single scale; we can develop online applications that can, when appropriate, reveal observations at larger and larger scales, or smaller and smaller scales. No longer must interested parties come to our libraries and check out copies of our paper maps; our data can be hosted in online environments that provide unprecedented potential for data distribution to any device with an Internet connection. Such availability presents us with new opportunities for scientific collaboration that were simply impossible using traditional geologic maps.

In summary, because the precise location of geological observations is of the utmost importance to proper interpretation of a geologic map, not using GIS and related technologies to create new maps renders a serious mapping project obsolete before it is completed. Nonetheless, the level of integration of GIS into the mapping process at academic and government agencies can vary widely. The capabilities of GIS programs are often marginalized by graphic arts programs that have circuitous, minimal, or no connection to a digital geologic database and introduce tremendous inefficiencies in creating GIS layers demanded by end users. As a community, geologists have been relatively slow to adopt new and useful mapping technologies, but we must if we intend to recognize the full potential for modern scientific collaboration, more robust data management, and modern visualization techniques.

Base Map Materials: Traditional and Modern

In the United States, fixed-scale topographic maps have long been the base map of choice for geologic mapping because they are standardized, familiar, and show essential reference and useful (though time-bound) cultural information. Topographic maps have been the standard field mapping base for many geologists, as well as a common base for depicting the geologic map. Their use of elevation contours is clean and intuitive, and the maps are generally legible beneath overprinted geologic data. However, within the past 10 yr, the availability of high-resolution and timely aerial and satellite imagery has increased dramatically, and to the significant advantage of geologic mapping in the office and the field. Many of these high-resolution sources can be “streamed” from a Web-based image service to a mobile or desktop GIS platform, and many can be cached in the memory of mobile-computing devices. The ready access to a variety of crisp, georectified imagery is transformative. Individual mappers (and data consumers) are able to choose a preferred portrayal of base layers to help evaluate geologic map data within specifically meaningful contexts.

Accurate and illustrative base materials provide essential context for creating, comprehending, and interpreting geologic maps. Traditionally, base maps for geologic maps in the United States have primarily been U.S. Geologic Survey (USGS) topographic quadrangle maps. Base maps not confined to quadrangle shapes (less common) have been created as photomosaics. It is now much easier to aggregate seamless mosaics of digital images of these and other types of maps to cover irregular or non-gridbound areas. New technologies allow for simple combination of different types of data layers, for example, contour maps atop high-resolution imagery. Sets of contours can be generated that are specifically appropriate for areas of interest, whereas prior to digital base data, interpretation or portrayal was commonly compromised by an inappropriate contour interval.

It is now easy to create base layers tailored to particular types of maps. Contours can be created from digital elevation data or by digitally extracting field-surveyed contours from appropriate legacy data sets for a given area (e.g., 1:31,680 topographic map series). The U.S. National Elevation Dataset (NED) provides DEM data based on 10 m to 30 m grid cell sizes and can be used to generate contours. However, this data set has limitations of relative scales of actual topography and grid dimensions used to characterize the topography (Gesch et al., 2002; Gesch, 2007). NED-based calculated contours are sufficient in some cases but are commonly deficient for complex areas or large-scale portrayals, particularly in relation to LiDAR data (Fig. 1).

LiDAR: Panacea or Just Near-Panacea?

The advent of LiDAR technology is a transformative development in topographic mapping and landscape visualization. LiDAR elevation data sets have revolutionized geologic mapping in the areas for which they are available. They can be used to generate very high-resolution, precisely georeferenced, and data-rich base maps that are amenable to various types of visualization alone or in combination with other imagery types. LiDAR scanning systems record very precise

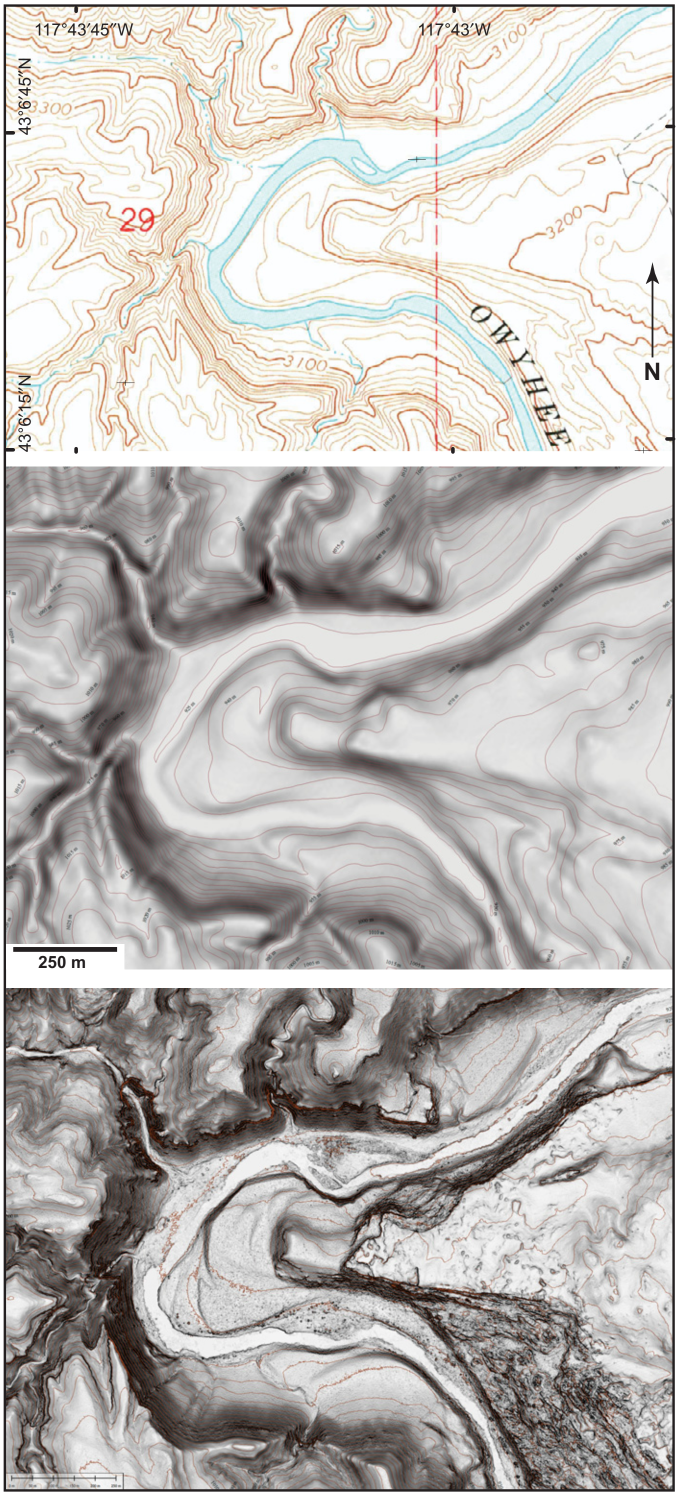

Figure 1. Three different types of base maps of the Dogleg Bar area, Owyhee River, Oregon, showing differences in topographic visualization. This is a diverse map area containing a river, river terraces, boulder bars, lava flow, landslides, and layered bedrock (Ely et al., 2012). Upper map: excerpt of conventional U.S. Geological Survey (USGS) topographic map (Lambert Rocks, Oregon); middle map: slopeshaded grid and 5 m contours from 10 m National Elevation Dataset (NED) data; and lower map: slopeshade and 5 m contours from 1 m light detection and ranging (LiDAR) digital elevation model (DEM). With appropriate tools, the conventional USGS topographic map can be supplanted or greatly supplemented by the development of alternative base map layers that better correspond to mapping needs.

relative point positions and elevations. LiDAR scanning of vegetated swaths of land results in multiple return values for proximate points that can isolate vegetation cover (early returns) from bare earth surface (late returns). The multireturn aspect has revolutionized geologic mapping because it can be exploited to generate high-resolution digital terrain models of the land surface beneath heavy forest cover, revealing rich detail (Fig. 2). This aspect of the method creates stunning topographic representations of forested lands and leads to new discoveries and insights in geologic studies (e.g., Haugerud et al., 2003; Haneberg et al., 2005).

Postprocessed LiDAR point data provide a robust basis for developing DEMs and contour maps to facilitate geologic mapping. Landscape representations from high-resolution LiDAR data form fantastic base maps for geologic mapping because of their clarity, resolution, and geometric precision. LiDAR point data can be generalized into DEMs of a range of resolutions to create realistic and astoundingly revealing hillshade and slopeshade representations of the land surface (Fig. 3). They are particularly useful for surficial geologic maps because of their strong affinity to geomorphic representation (Frankel and Dolan, 2007; Howle et al., 2012), but they provide accurate topographic data and precise positioning relevant to any kind of geologic mapping and characterization (e.g., Glenn et al., 2006; Deardorff and Cashman, 2012; Jones et al., 2009; Burton et al., 2011; Crow et al., 2008).

Ideally, LiDAR would form the basis of a national, updateable topographic mapping program because it can generate map data that are superior to traditional topographic maps and the relatively new U.S. Topo map product (USGS, 2009). The availability of LiDAR data have had and will certainly continue to have a major impact on topographic and geologic mapping (Buckley et al., 2008). The availability of high-resolution LiDAR on a national scale in the United States would have incalculable value for science, land management, emergency management, and regional planning. Recently, the Oregon Department of Geology and Mineral Industries (DOGAMI) and the Oregon Lidar Consortium have developed a series of topographic quadrangle maps based on LiDAR of selected parts of the state. These maps are more accurate, timely, and far more easily updateable than corresponding USGS topographic quadrangles. The accuracy of the data sets allows generation of contours down to intervals of 2 ft (0.6 m) (DOGAMI-OLC, 2013).

Seamless Digital Maps and Virtual Globes

Imagine if your first glimpse of a globe was of one that could be spun, panned, and zoomed at will to any spot on the planet, or if your first experience with a map outdoors was a seamless image of Earth on the screen of your mobile computing and telecommunication device that followed your progress through the world. These are the realities of modern digital maps and globes that are ever-present on tens of millions of desktop computers and mobile devices. Their forerunners, no matter how integrated with traditional thinking they may be, are quaint by comparison. Seamless digital maps offer tremendous promise in the development and dynamic display of geological maps and data sets. They are mesmerizing sources of insight with great potential for illustrating, understanding, and sharing the context of geologic map data sets and related ideas and interpretations.

Functional seamless digital maps and globes with extensive collections of high-resolution imagery have only been widely available since 2005 and have had profound impact on geoscience in this short time (cf. Whitmeyer et al., 2012). They are particularly useful tools for education and virtual geologic exploration and reconnaissance (e.g., Lisle, 2006; Fig. 4). They are also extremely useful for fieldwork planning and field data archiving, management, and sharing. On mobile platforms, seamless digital maps can be used for virtual and real-time reconnaissance. In areas with particularly good exposures and high-resolution imagery coverage, it is easy to identify and record the coordinates of key exposures of geologic units for future investigation in the field. Furthermore, it is possible to quickly scan a map area (or surrounding area) for particularly good sites to help characterize regional and local geology. Seamless digital map services that update regularly, and retain archives of historical aerial (e.g., Google Earth, National Agriculture Imagery Program [NAIP]), oblique (e.g., Bing Bird's Eye) and georeferenced ground-based photography (e.g., Google Streetview) provide important historical context and can highlight existing and new exposures created by geologic processes, construction, or land-use change for targeted fieldwork related to map revision (Fig. 5). Current research in Virtual Globes as "virtual geologic instruments" with exceptional spatial resolution shows great promise for detailed geologic mapping and field data collection on this intuitive type of platform (Bernardin et al., 2011).

New Tools: Digital in the Field

Field gear preferences and personal protocols for observation and data collection are the core of geologic fieldwork. Some field gear items have iconic status that stems from utility and deep-rooted traditions. For example: the pocket transit, the rugged field book, the acid bottle, and the rock hammer are all time-honored traditional equipment. No technological advance has obviated the utility of the acid bottle or the hammer, but other tools have capable modern counterparts that can be astonishingly useful in comparison to traditional tools. Foremost examples among these are the handheld GPS unit, the digital camera, and the mobile computing device. Each of these items can be used to great advantage for improved efficiency of time and effort in creating geologic maps and can support a consistent flow of digital data from the field to the office and to collaborators. Indeed, as technology and software continue to evolve, each of these functions is now possible with some singular mobile devices.

There is a persistent, progressive thread of interest in developing a complete digital geologic mapping solution for the field (e.g., Brimhall et al., 2002; Clegg et al., 2006; Alfarhan et al.,

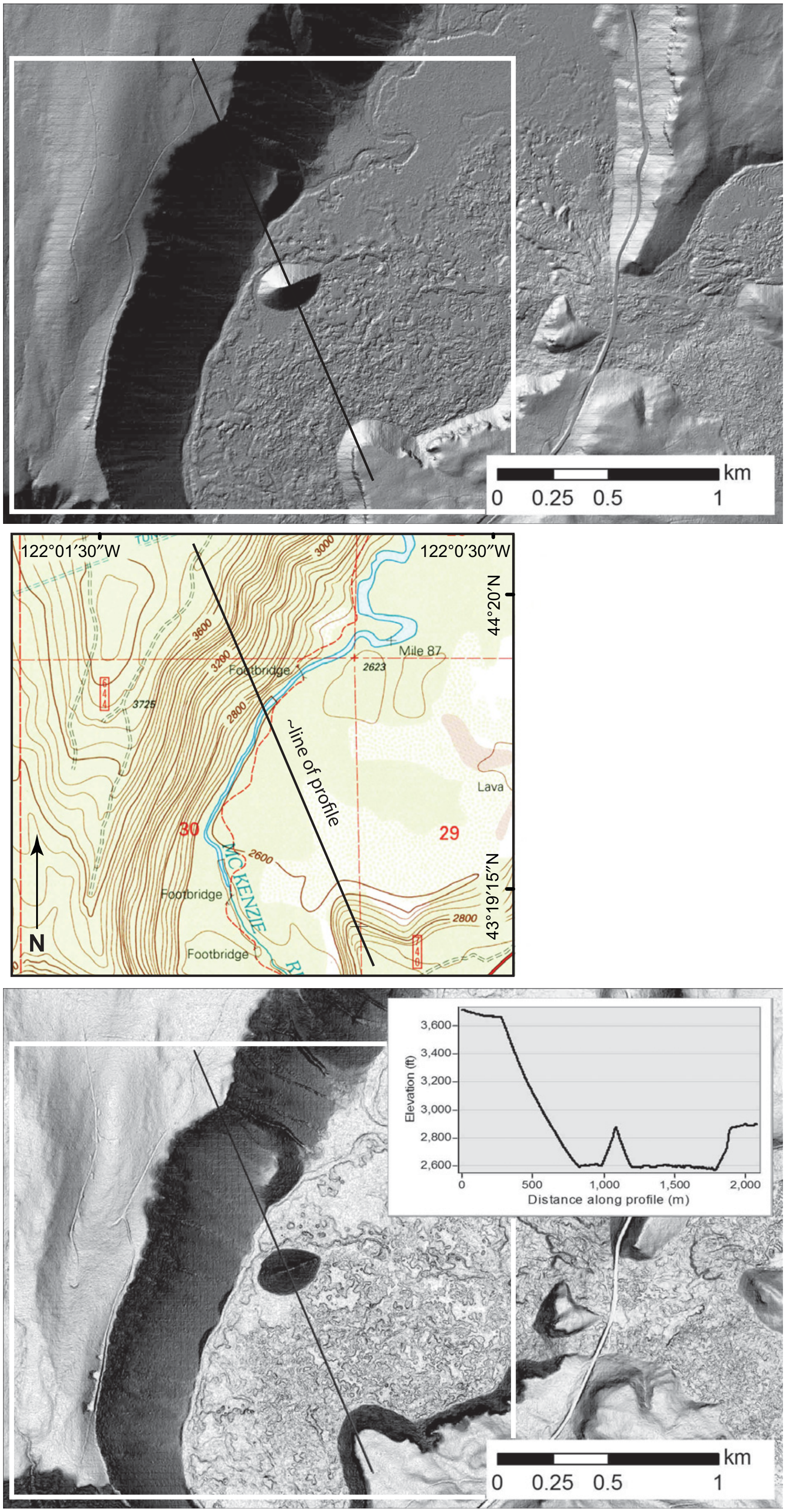

Figure 2. Light detection and ranging (LiDAR) maps (hillshade, top; slopeshade, bottom) and corresponding topographic map excerpt (center) of McKenzie River area, central Oregon (Tamolitch Falls, Oregon, U.S. Geological Survey 7.5′ quadrangle). In this comparison, the LiDAR visualizations highlight details that are absent from the conventional topographic map, including: the textured surface of heavily forested young lava flows and a prominent topographic "pimple" in excess of 100 m (330 ft) high (profile in lower image), in addition to other topographic features. LiDAR images courtesy of Natalia Deligne.

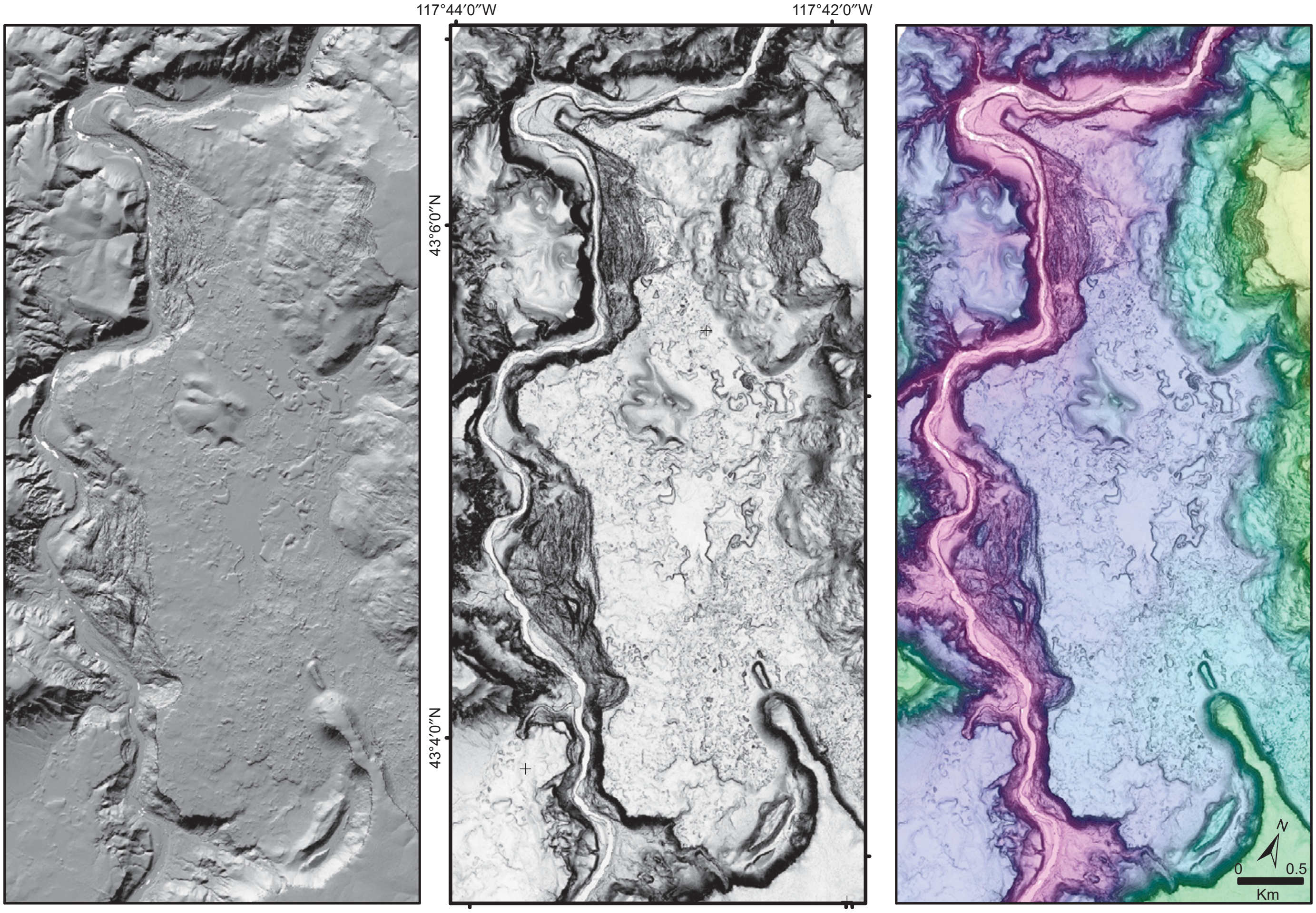

Figure 3. Light detection and ranging (LiDAR) digital elevation model (DEM) visualizations of an 11 km segment of the Owyhee River, Oregon. Left: hillshade; center: slopeshade; right: slopeshade with semitransparent, colored elevation ramp (lowest: pink-purple along river; highest: green-yellow along rim of canyon). Width of each panel is ~2.5 km. Slopeshade maps, unlike hillshade maps, do not have modeled shadows. Their tonality indicates variation in slope and is, thus, independent of an illumination direction. Geologic map of this area can be seen in Ely et al. (2012).

2008; Jordan, 2010; Knoop and van der Pluijm, 2006). However, while methods of direct creation of digital lines and database editing in the field are available, it is neither appropriate nor ideal under all circumstances. The quality of sophisticated GIS editing in the field varies with equipment, scale, environmental conditions, comfort, and the type of data being recorded. For example, point data types, notes, and photos are ideal for collection in the field. It is inevitable that improvements in the ease of direct field collection of all data types will eventually see important technological and methodological innovations. However, a complete field solution may not be necessary if it is possible to approximate or maintain seamless integration of one's field and office efforts. For example, high-resolution custom base maps can be printed from a virtual globe or desktop GIS application; these field maps can be marked up with pens and then scanned or photographed in the field (or office) and subsequently digitized or used to guide compilation on the same imagery on a desktop computer (Pavlis et al., 2010). Final compilation of a complicated geologic map in one's climate-controlled office may currently be the better solution as it allows for some degree of post-fieldwork quality control.

Geocoded Field Data Collection and Sharing

Geology is deeply if not recursively embedded in the "geospatial" realm. Knowing one's location on Earth is essential to characterizing that location's geology. Traditional skills of self-location on the map with maps and photos are crude in comparison with modern geologic mapping in an era with easy access to the GPS. GPS-enabled devices can create accurate records of one's movement through a field area, and the corresponding geospatial data can be recorded and embedded on digital media created in the field, including photographs of geology, photos of field notes and sketches, video and audio recordings, and textual data. Most digital data collected in the field can be instantly shared with colleagues for review and archiving.

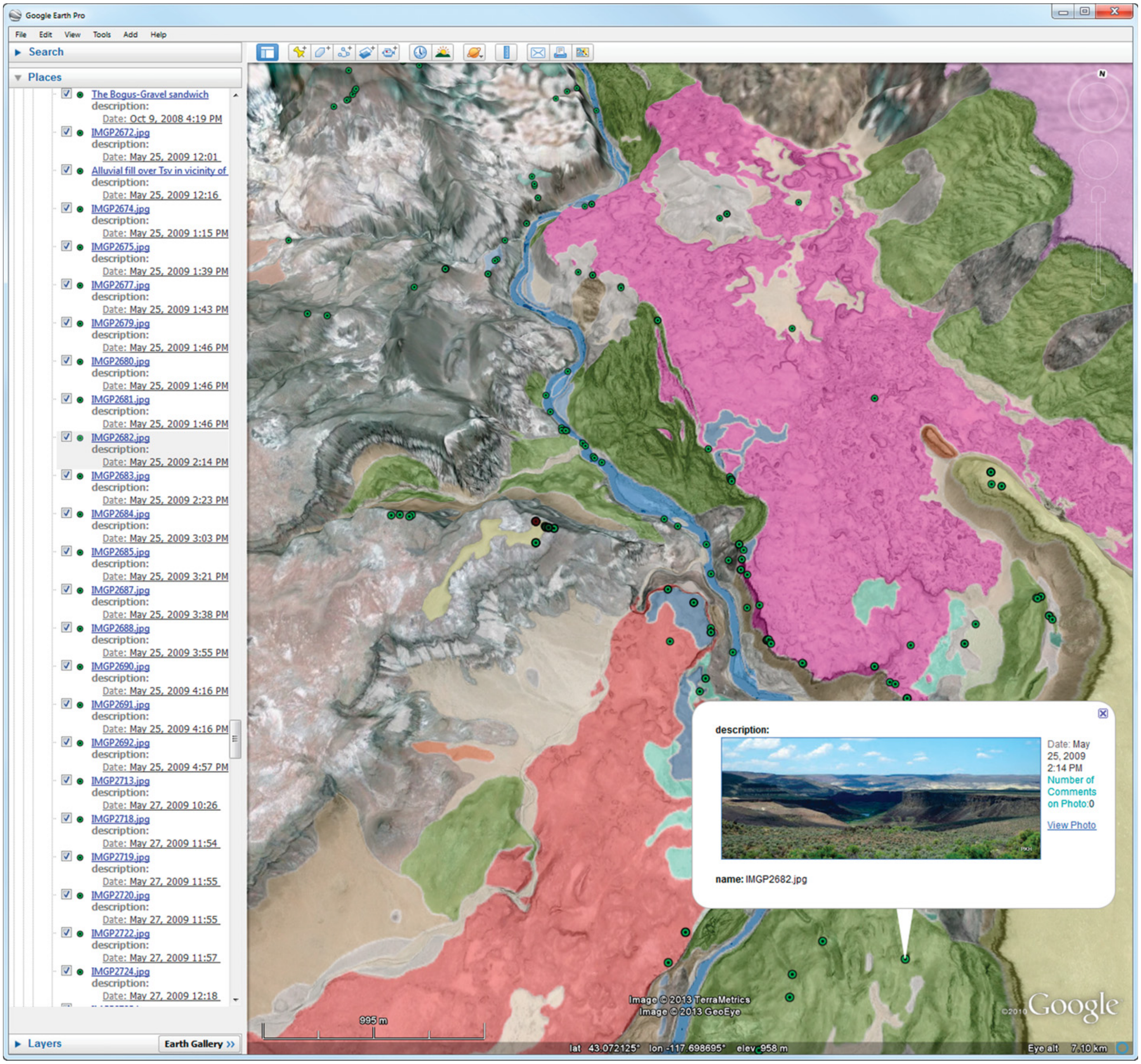

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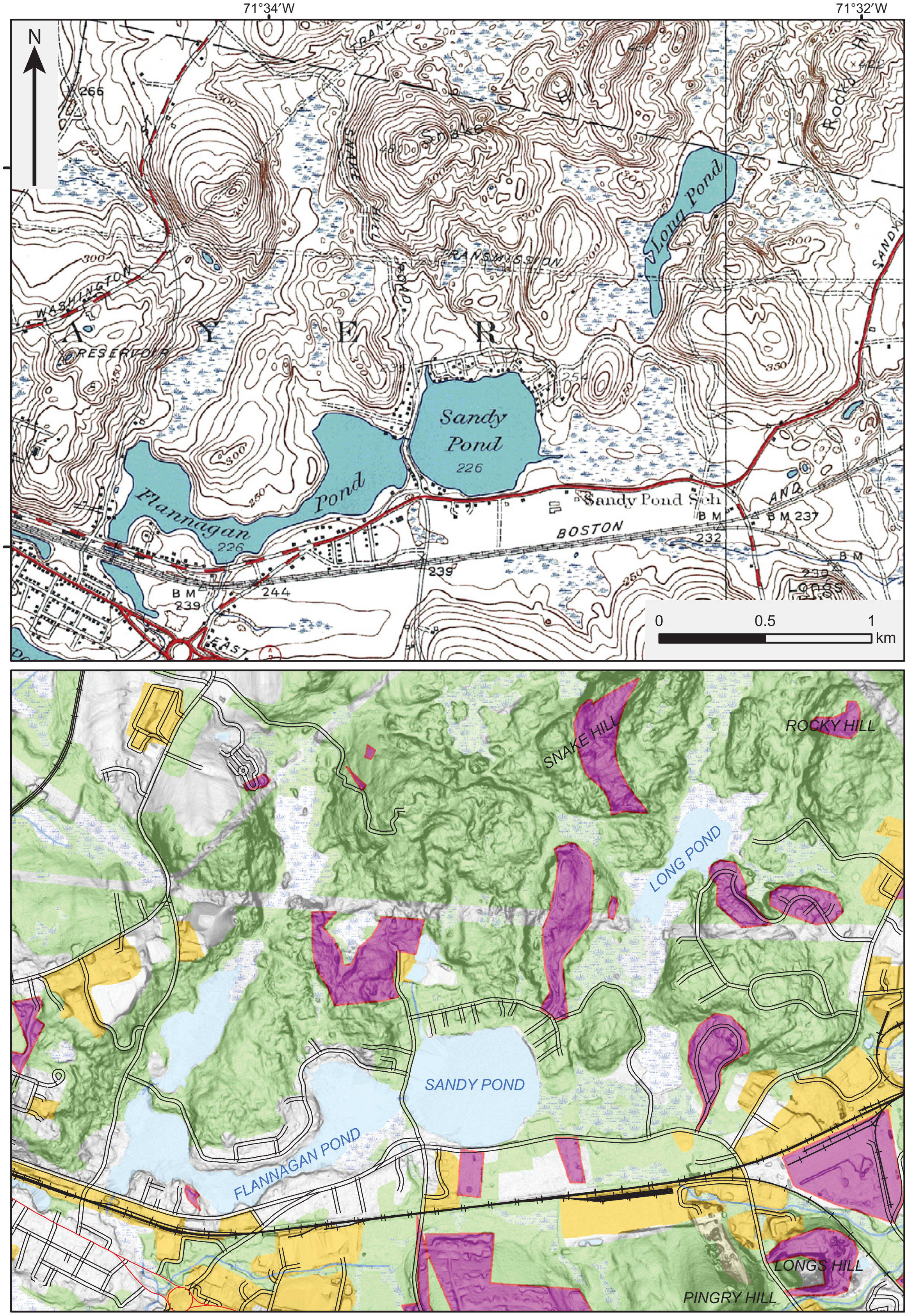
Figure 4. An example of field observation documentation on a virtual globe. This image shows the locations of geotagged field photographs collected in the Owyhee River area, Oregon (including part of the area shown in Fig. 3). These images were collected on a series of traverses. The traverse lines can also be plotted, but are not shown to preserve clarity of the map. Photograph locations (green dots) are shown on a terrain-enabled virtual globe (Google Earth) with semitransparent light detection and ranging (LiDAR) slopeshade overlay and geologic map overlay. Small photograph shown in lower right is from link to higher-resolution image. The view in the photograph is to the north. See Ely et al. (2012) for geologic map information.

Figure 5 (*on following page*). A portion of a traditional topographic map (top) (Ayer 7.5′ quadrangle, Massachusetts; U.S. Geological Survey [USGS], 1950) compared with a modern custom printable base map of the same area quickly constructed in a geographic information system (GIS) from slopeshaded light detection and ranging (LiDAR) data (bottom) (USGS, 2011), overlain by recent land cover data (2005; green—forest, yellow—commercial, gray—open/new power/natural gas lines), hydrography and wetlands (2010 and 2009), roads (2012), and areas that have undergone development or other land-cover change (magenta) and may contain new and unmapped bedrock exposures. The areas of potential new exposure were identified by comparing U.S. Department of Agriculture (USDA) 2004 vs. 2012 National Agriculture Imagery Program (NAIP) orthophotography via the "difference" method in GIS software. The custom base map is superior to the traditional map for planning traverses and relating outcrop-scale features to map-scale geomorphology. It is also useful in conjunction with traditional map data for highlighting features such as abandoned forest roads and railroads, new buried gas pipelines and transmission lines, etc. Data obtained from MassGIS (www.mass.gov/mgis).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PINGRY HILL

Figure 5.

Judicious use of a digital camera and a GPS-enabled device in the field is essential field practice and a simple means of compiling part of a digital data archive (Fig. 4). Data from each device can be integrated in a simple way to create "geotagged" media that are meaningful to the development and understanding of the map. Related methods allow simple geocoding of scanned historical photos and slides to build useful archives of one's predigital work in the field.

Most social media and online photo-sharing applications recognize geotags and can create links to online map services that allow viewing on a seamless digital map or mosaic of high-resolution imagery. Albums of geotagged images can be created and shared for purposes of collaboration, peer review, and supplementing published geologic maps and data sets. The simple process of geotagging photos, notes, data, and related media should be a default protocol for all field scientists who are concerned with the location of things they deem worthy of documentation. It is also a very effective *aide-memoire* during compilation of field efforts (Fig. 4). Geo-encoded pictures, notes, and illustrations can also enhance the peer-review process by providing meaningful context for map content in lieu of field visits if necessary.

New Tools: Mobile Computing Devices

Rugged laptop computers and tablets or smart phones in protective cases are becoming essential to geologic fieldwork. As technological advances have accrued, the functionalities of individual devices have been combined. For example, in the (only) 5 yr since the development of the first iPhone, it and similar Android smartphone devices and tablets have quickly become remarkably useful field tools, with or without cellular data signals. Numerous, affordable handheld devices come equipped with the following: cameras (video and still), GPS chips, magnetometers, triaxial accelerometers, compasses, fast computer processors, cellular telephone, and gigabytes of available digital storage. These capabilities allow field geologists to record traverses, take and annotate pictures, navigate on high-resolution imagery, collect and record structural data, take voice or text notes, and share data instantly with colleagues when cellular data coverage allows. Having these functions in a single device reduces the weight and bulk of field equipment. Adequately appointed mobile devices can also house large repositories of scientific literature, making it possible to enter the field with a complete reference library about the map area in a very portable format. This can also include copies of geologists' field notes, georeferenced geologic maps of the area, historical and contemporary aerial photography, and virtual field guides of rock characteristics, fossils, grain size, soil color charts, etc. The utility of having these things immediately at your disposal while composing a site description or geologic summary in your notebook or in a note-taking application on a mobile device is transformative. Of course, modern devices are fragile, can be lost, and have specific power requirements—caveats that apply equally or in varying degrees to traditional field tools. Similarly, their use also involves a learning curve.

MAPPING DIFFERENTLY—THE LIVING GEOLOGIC MAP

The aforementioned tools are fundamental to the transformation of geologic thinking in the development of geologic maps and underlying data sets. The transformation is away from geologic maps as static and singular representations to diverse portrayals of singular and composite aspects of underlying, dynamic geologic data sets in a sense, a living geologic map.

A living geologic map is one that can accommodate collaborative mapping and editing from remote locations and shared high-resolution imagery sets. It incorporates digital field data (notes, photos, etc.), covers an area of thematic interest, or is driven by other priorities, and it resides in or as part of a well-managed and adaptable master database. It can output digital and paper maps that reflect core data and related derived data at any point in time, but it will be explicitly known that all such disconnected outputs are time-bound archives. In other words, a living geological map easily accommodates map changes in response to geologic, societal, and scientific changes.

These and other ideas put forth in this paper reflect the sentiments in the following parts of the National Cooperative Geologic Mapping Reauthorization Act of 2009 and data management principles outlined by the National Research Council (2009):

> § 31c. Geologic Mapping Program
> (c) Program objectives
> (3) application of cost-effective mapping techniques that assemble, produce, translate and disseminate geologic-map information and that render such information of greater application and benefit to the public; and
> (4) development of public awareness of the role and application of geologic-map information to the resolution of national issues of land use management.

In order to achieve these goals listed in the act, the conceptual and operational frameworks of geologic mapping must be aligned with new technologies for collecting, managing, and distributing usable data. This will involve rethinking core, traditional components of geologic mapping. Synergistic combinations of GIS, seamless digital maps, modern field tools, and network-based data sharing will permanently transform our conceptions of geologic maps and their continuing role in geological science. The wide availability and adoption of these technologies have already forever changed cultural perceptions of maps: how they work, what they are for, how to access them, and even how to edit them. Maps are now seen as interchangeable, seamless, timely, and containing links to new and more detailed information. Global network interconnections and access to all manner of online mapping and media-sharing applications have increased global geographical awareness significantly, including the impacts of natural hazards and climate variability on society and landscapes. It is inevitable that these cultural changes will influence the future of geologic mapping and increase expectation levels of users of geologic information. The geologic mapping community needs to be able to deftly adapt to changing technology and changing expectations to remain viable and relevant.

MAPPING BEYOND THE BOX: MEANINGFUL MAP BOUNDARIES

The consumption of maps on computers and mobile devices has permanently transformed cultural perceptions of maps as static pictures on rectangular paper. Maps are now being produced and consumed as unbounded, fluid, and multilayered representations of regions of interest (e.g., Google Earth, Bing Maps). A corresponding transformation in traditional concepts of geologic map boundaries should also occur, although the likelihood of them soon becoming seamless at a broad range of scales is low. Physically irrelevant grid designations (i.e., USGS topographic maps), constraints of printing technology, institutional preferences, and some program requirements have dictated the boundaries of the majority of traditional paper geologic maps. The promulgation of a quadrangle-mapping model occurs at progressively greater detriment to scientific discovery and collaboration in the face of modern mapping methods and steadily increasing end-user expectations.

The use of more intuitive and pragmatic boundaries based on physical geologic system domains is preferable in many areas and can be readily accommodated in the digital mapping environment. Modern digital methods have all but eliminated any need for a quadrangle-mapping model. A philosophical and operational shift toward mapping within limits defined by geologic or other physical domains instead of grid cells may engender a transformation in geologic thinking. John Wesley Powell's (1890a, 1890b) forward-thinking map of proposed drainage districts in the arid states is a notable case in point (Fig. 6). This kind of approach is more consistent with how geologists think when making a geologic map and related interpretations. It is literally thinking outside of and beyond the box and focusing on phenomena related to scales of natural systems. A flexible perspective on meaningful map boundaries will lead to greater intellectual continuity and interest, and greater responsiveness to social and scientific needs. Contextually meaningful boundaries and improved interagency collaboration will help mitigate the common frustrating problem of inconsistent or mismatched mapping along boundaries between geologic maps by different agencies or authors. The reliance on natural system boundaries may confine the problem of harmonization of map units to zones where changes actually occur in the geology. The standard 7.5′ topographic quadrangle renowned in the United States nicely serves as an informal unit of areal measurement and progress tracking in regional mapping projects, but it need not necessarily be the basis for delimiting geologic mapping efforts.

Traditional topographic maps were not compiled with the notion of digital in mind. They suffer from similar liabilities as traditional geologic maps. Cultural data are commonly out of date the day the maps are printed, and their depiction of hydrologic features can vary tremendously. The maps are confined to grid cell windows on the landscape and have characteristics (e.g., contour interval and measurement unit) that do not accord well in all cases with adjacent grid cells. In the United States, the response to this has been the development of the USTopo program or, "the next generation of topographic maps" (USGS, 2009). This relatively new program is an earnest but only partial accommodation to the needs of the modern map user. It includes a digital map with multiple layers, including: imagery, contours calculated from DEM data, hydrography, cultural features, grid, and collar. Unfortunately, it is currently constricted by the quadrangle format, requires proprietary software, and is not cleanly interoperable with GIS software.

MAPPING INEVITABLE CHANGE

A printed (or cached) map is only a representation of an area at a single point in time—a temporal or contextual snapshot of an instantaneous status of an evolving database of geospatial information. The liberation of maps from an exclusively paper format opens many possibilities for creating living geologic maps that are updateable in meaningful and important ways and in useful time frames. Geologic maps are impermanent and incomplete representations of both the state of scientific knowledge and the state of the landscape. Their traditionally apparent permanence belies dynamics in geologic processes and thinking, and mapping technology. Like any snapshot, a static geologic map is instantly obsolete except as an archive with respect to future changes. Thus, geologic maps should change as regularly as is practical in response to three major variables: changes in the geologic character of the landscape, creation of new mappable data, and changes in geologic ideas.

Previously mapped areas that undergo significant geologic or anthropogenic change should be updated as regularly as is warranted or possible. Critical areas with tendencies to undergo frequent change can be mapped in a "monitoring" context in which minor or major changes can be recorded systematically and in a timely fashion in order to characterize the geologic behavior of dynamic, possibly hazardous systems (Fig. 7). This could include areas of recent flooding or active erosion and deposition, including storm-related coastal impacts, major floods, rapid land subsidences, and a variety of active volcanic or seismic events, among other types of geologically driven change. If any of the foregoing events (or others not mentioned) had transpired the day before a mapping project was undertaken, their consequences would be mapped and documented as a matter of course; however, if the events occurred one week after a map was "turned-in" or printed, updating in a timely fashion is less likely. In areas of extensive development, anthropogenic changes can create new geologic data at a pace that renders traditional maps out of date within years. In heavily forested or urban areas with poor exposure, rapid development, mineral exploration, land-use change (Fig. 5), and/or construction of new infrastructure create abundant new surface exposures and subsurface and geophysical data that require map updates.

Figure 6. *Arid Region of the United States Showing Drainage Districts*: A map showing subdivision of the western United States by natural "drainage commonwealths" by John Wesley Powell (1890a, 1890b). He proposed these divisions as units of resource governance circumscribed by meaningful physical boundaries (hydrological in this case).

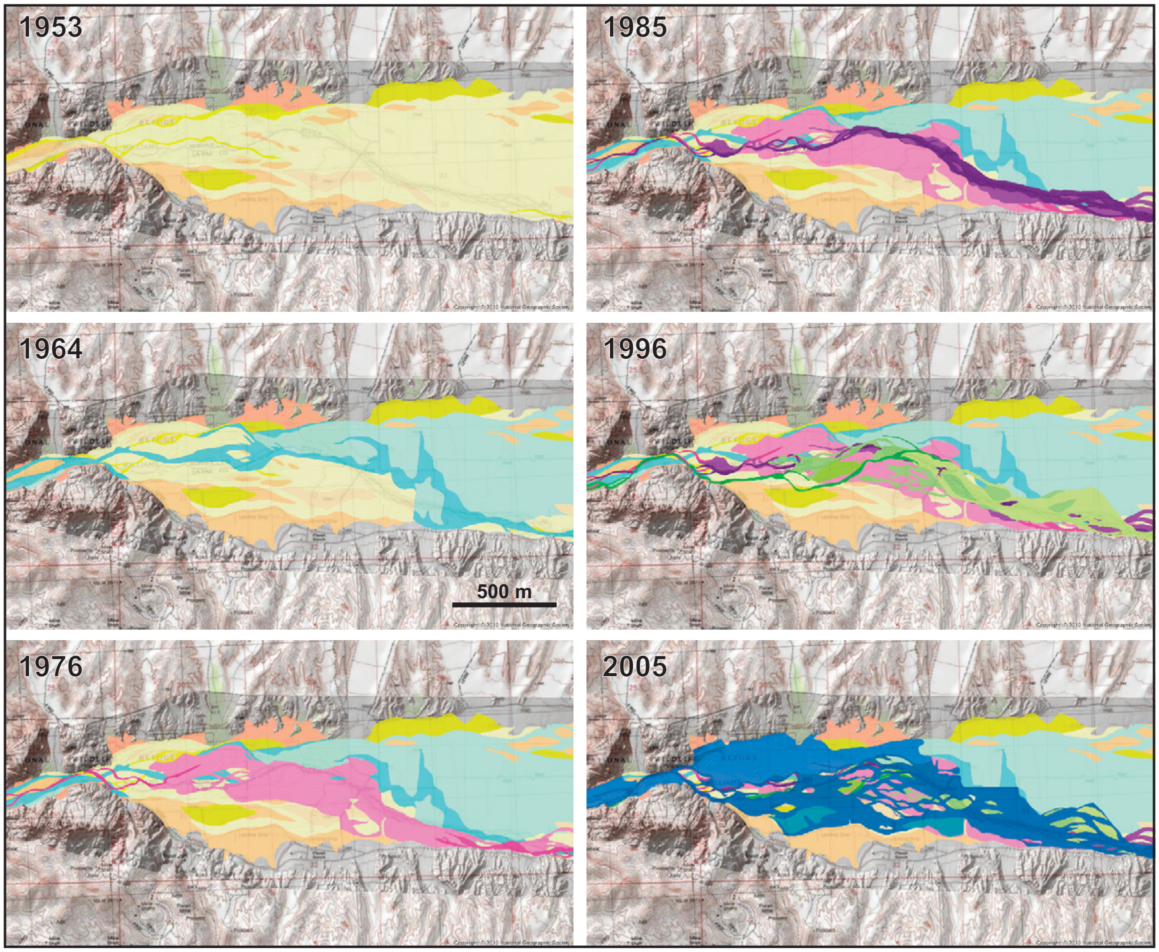

Figure 7. Series of geologic map excerpts showing channel change along an ~3 km reach of the Bill Williams River, Arizona, between 1953 and 2005 (House et al., 1999, 2006; House, 2013, personal obs.). This fluvial system is a prime candidate for inclusion in an easily updateable geologic map database. Each map has a suite of colors that indicates similar channel and floodplain features at discrete points in time between 1953 and 2005. The map polygons from each generation are not overlays in the subsequent generations; they instead are topologically coherent polygons. Thus, each map retains some amount of each previous map's polygons. The maps document an increasingly complex mosaic of young, but different-aged geologic deposits. Creating and analyzing a spatially and temporally intricate geologic map such as this require a geographic information system (GIS) and a series of digital, orthorectified historical aerial photographs. The geomorphology of this river changes significantly on a 5–10 yr time frame, and its present configuration is certainly somewhat different from the most recent mapping (2005) shown in this figure.

The other primary type of change is scientific in nature, including new paradigms (i.e., modern plate tectonics), new geochronological data, recently discovered key beds and exposures, advances in structural and petrologic analysis, and remotely sensed data that reveal previously unrecognized mappable characteristics and relationships. Digital maps can be readily modified to reflect these new data and interpretations.

In order for the approach to creating geologic maps to change, agencies with mapping responsibility need to adopt a practice of accommodating change in previously mapped areas as standard procedure instead of an inconvenience. The geologic mapping community must accept the need for and value of a program of managed mapping wherein significant, high-priority changes can be accommodated in a timely fashion. GIS workflows in fields such as watershed and infrastructure management have demonstrated that this type of managed mapping is both possible and easily facilitated (e.g., Hassey et al., 2010).

DERIVATIVE MAP PRODUCTS

Traditional bedrock and surficial geologic maps are ultimately a niche product, the embodied utility of which is largely limited to geologists. They are not readily accessible to those without geological training. Nontraditional and unanticipated derivative uses of geologic maps, to great societal benefit, have been long established (e.g., Bernknopf et al., 1993; Bhagwat and Ipe, 2000;

Thomas, 2004). Derivative map products, compiled from traditional geologic maps and combined with additional types of data not necessarily collected during original field mapping (such as digital topography, material strengths, rock fractures, mineralization and oxidation zones, landslide features, stream-bank erosion, and springs, as well as borehole data, geophysical data, and geotechnical data) constitute primary interests of many consumers of geologic maps. GIS has made the construction of such maps far simpler and more efficient than using traditional methods. Examples are abundant (Thomas, 2004) and include flood hazard maps (House, 2006; House et al., 2010a), seismic hazard maps (Wills, 2010), landslide hazard maps (Radbruch-Hall et al., 1982; Godt, 1997), land-use planning maps, karst maps, hydrostructural domain maps (Kopera et al., 2006), and maps of sand and gravel resources (e.g., Walling, 2000), among many others. Derivative uses of geologic data with societal benefit are now the implied mandate and primary justification for mapping programs in the United States (U.S. Congress, 2009, 43 USCS § 31c; USGS, 2012), with some states mandating production of derivative map products (e.g., Wills, 2010). As such, developing digital geologic map products with an aim toward their derivative use, including collecting nontraditional field data during mapping, and generating derivative products to meet contemporary stakeholder demands, should be considered a normal component of geologic map production.

COLLABORATION: CREATING, EDITING, AND SHARING DIGITAL GEOLOGIC MAP DATA IN REAL TIME

Traditional methods in paper geologic mapping have commonly been relatively insular undertakings for many mappers, in part because of basic methods, materials, and nonoptimal means of collaboration. However, modern digital methods make working in isolation or solely with manual methods anachronistic and counterproductive. A larger interest in the broad dissemination of geologic map data for application in the research of others requires greater emphasis on scientific collaboration, sharing, and interoperability in digital geologic map development. The traditional insularity of geologic mapping will yield to expanding opportunities for collaborations that are possible with new technologies and, ideally, new demands for geologic map data. Collaboration on complex maps is essential, and there are new ways to coordinate and manage groups of mappers and field scientists. This transformation can significantly enhance efficiency in data generation and collection.

Crowdsourcing

Crowdsourcing is a popular term for a surprisingly powerful mode of collective action or distributed collaboration (e.g., Shirky, 2008) that leverages global Internet connectivity via smart phones and computers to coordinate large numbers of people to attain a common goal. The online encyclopedia Wikipedia (Wikimedia Foundation, 2013) is a stellar example of the potential for crowdsourcing to achieve constructive goals that were unthinkable only 10 yr ago. A growing trend in online social media involves active (and occasionally inadvertent) sharing of geocoded digital media (e.g., photos and messages). Striking patterns result when large numbers of these posts are aggregated in a passive form of map-data crowdsourcing. For example, Fischer (2010) has developed a series of maps of world cities by aggregating geospatial data from thousands of independently collected and geolocated posts using various social media sharing services (Fig. 8). The increasing amount of geocoded and shared information on the Internet allows for a surprising diversity of thematic maps (Graham and Zook, 2011). This cartographic outcome derived from independently collected information portends great possibilities for coordinated collection of specific types of geocoded data (Heipke, 2010).

The development of maps with crowdsourcing is a relatively new idea. OpenStreetMap (OSM) is probably the best example. It is a "collaborative project to create a free editable map of the world" (OSMF, 2013) that has leveraged the efforts of a large number of dispersed contributors to generate a free, feature-rich, and seamless map of the world. The OSM platform for collaborative editing is very popular and offers important potential for collaborative geologic mapping. For example, the USGS (Wolf et al., 2011) has evaluated the OSM approach for crowdsourcing road and trail data to include in the *National Map* (USGS, 2013a, 2013b). Goodchild (2007) termed the phenomenon of crowdsourcing in relation to geolocated information "volunteered geographic information" (VGI). The OSM model may be better characterized as an example of "contributed" geographic information (CGI), wherein the contributors are focused on a single goal, and the input is mediated or vetted by community members.

The crowdsourcing approach has seen great success in disaster response situations in which reliable and timely geospatial data are badly needed. Following the Haitian M 7.0 earthquake in December 2010, satellite high-resolution imagery collected soon after the disaster was made available by GeoEye, Inc., for use as base imagery in crowdsourced mapping efforts to create near real-time maps of the affected area (Zook et al., 2010). A combination of crowdsourced mapping and geocoded social media postings was critical in rescue and relief efforts in this instance. Such focused efforts attest to the value of crowdsourcing geospatial information, particularly when the goal is well defined. It is important to note that unmediated application of crowdsourced data may face real concerns about validity and reliability (e.g., Elwood et al., 2012; Sui et al., 2013). A data vetting process is warranted in most cases, but it has been argued that the benefits of crowdsourced data may outweigh the risks in emergency response situations (Goodchild and Glennon, 2010).

Collaborative GIS: Crowdsourcing for Geologic Mapping

In the context of geologic mapping, "crowdsourcing" refers to a distributive model of effort-pooling and coordination toward a common goal. An efficient and high level of organized

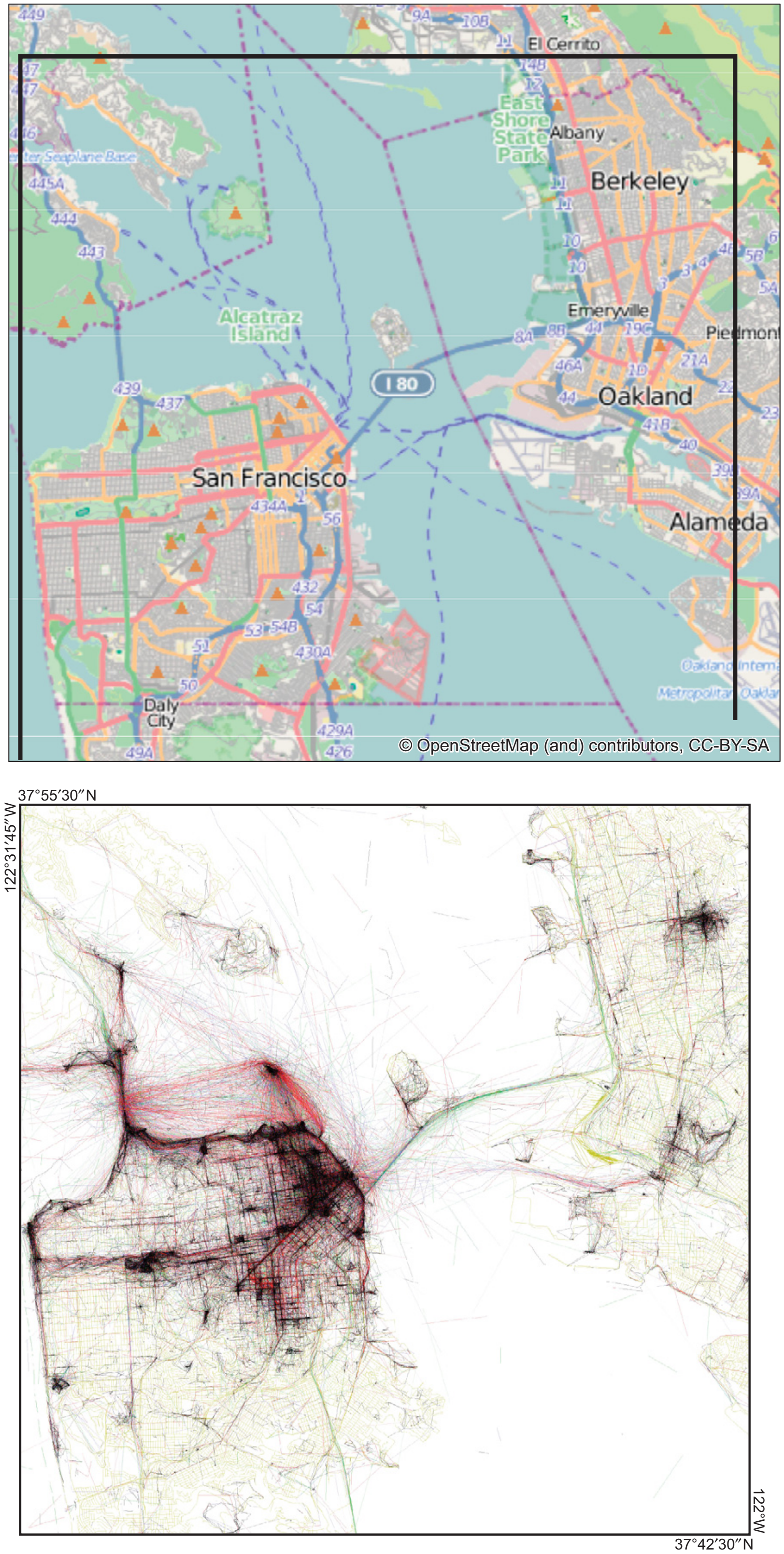

Figure 8. Map of the San Francisco Bay region from OpenStreetMap.org (top; 2013) compared to crowdsourced virtual street map of the San Francisco Bay Area, California, derived from geotagged photographs aggregated from online photo sharing services Flickr and Picasa in 2010 (bottom; Fischer, 2010); Online linkage to the bottom image: http://www.flickr.com/photos/walkingsf/4622375804/in/set-72157623971287575. Figure used with permission from Eric Fischer.

collaboration is possible with a multi-user, versioned geodatabase structure within an application like ArcSDE™ or ArcGIS for Server (ESRI, 2013). A version-based approach allows the management of simultaneous and nonconflicting edits of controlled duplicates (versions) of all or part of a large, multi-user geodatabase. This approach is the only feasible way to seamlessly manage a team of map contributors in a geologic mapping effort (including geologists, editors, and cartographers). It can be managed for efficient data entry in ways that are mediated by rules and permissions. Thus, multiple contributors can interact with the database simultaneously from remote locations. Populating and coordinating a team of highly skilled geologists and GIS specialists can generate high-quality maps with great efficiency using this approach. This is a promising model for the future of geologic mapping. It can solve many practical and logistical difficulties frequently encountered in a multi-authored geologic mapping effort and allow for rapid and efficient production of geologic maps of large areas in a reasonable time frame.

The Nevada Digital Dirt Map Experiment (House, 2010) is an example of a successful collaborative geologic mapping project that employed a multi-user, versioned database to develop a surficial geologic map of Clark County, Nevada (20,960 km^2), in 18 mo. It involved simultaneous editing of a shared geologic map database by a team of up to 18 GIS-savvy geologic mappers and editors at a single time (Fig. 9). The multiple mapper approach was managed to handle a common suite of basic issues in regional geologic mapping: compilation and refinement of published geologic linework; addition of newly created data; harmonization of inconsistent nomenclature over broad areas and at "boundary faults" between compiled map sources; and optimization of mapping scale across very large areas spanned by compiled and new mapping. The effort demonstrated that efficient production of multi-authored geologic maps could be accomplished given appropriate means of effort and skill coordination among the mapping and editing team.

RAMIFICATIONS OF THE DIGITAL MAPPING PARADIGM

All of the aforementioned tools, methods, and concepts are promising, though complicated. There are variably steep learning curves and potential data "avalanches" that require workflow and protocol adjustments, and training and planning. Nonetheless, transformation is under way, and it is critical for our science that we act collectively to best determine our direction. Digital geologic data and map products, in spite of all their advantages, do have various pitfalls that commonly make them no more a panacea than traditional paper geologic maps. Most of these issues, however, stem from individual and/or institutional attitudes toward digital data and a lack of foresight, knowledge, planning, and appreciation for the scope of complex issues involved in reaping the full benefits of transitioning to digital data models (National Research Council, 2009). This section hopes to address some of these issues.

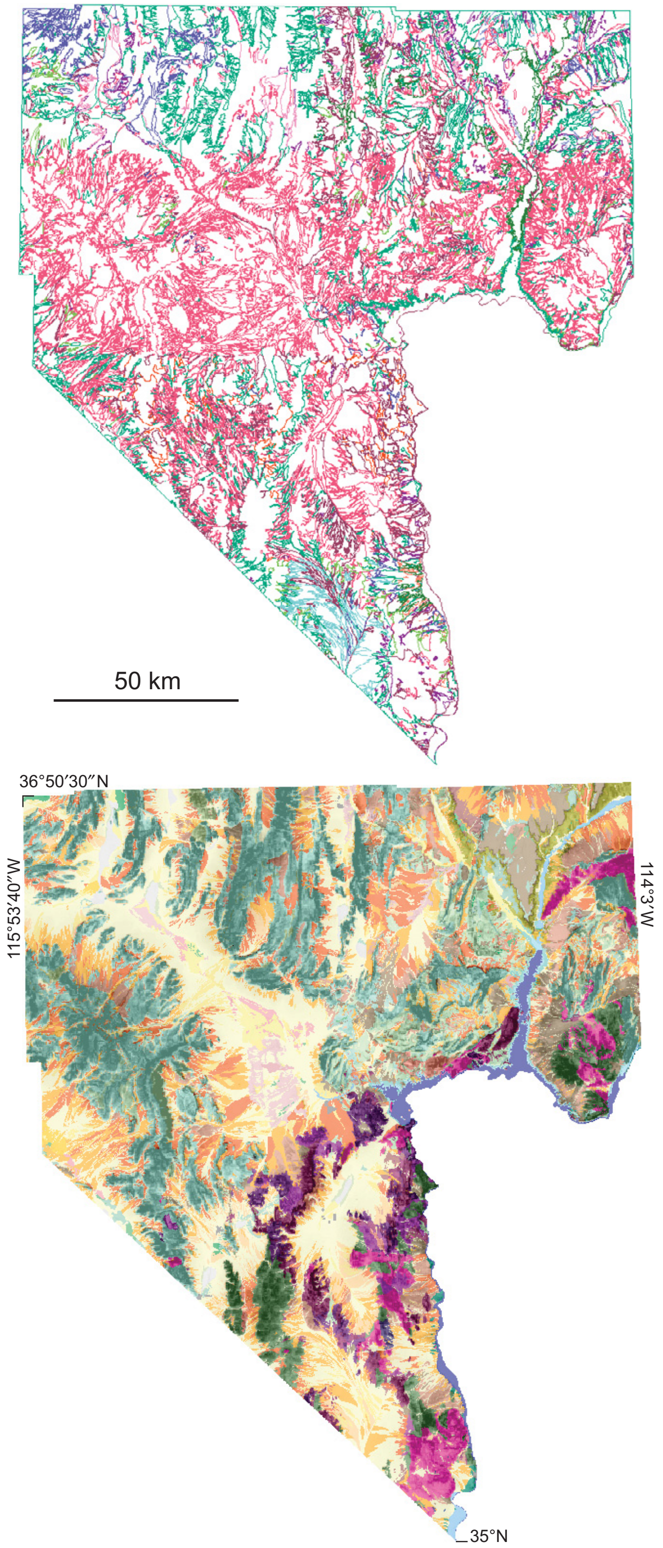

Figure 9. Screen-captured images of two stages of progress in the "crowdsourced" Nevada Digital Dirt Mapping Project (House, 2010; House et al., 2010b). Colors in upper image show compiled, previously published mapping (red) and "personalized" contributions and edits by the team of 18 mappers (various other colors). Lower map shows a near-final version overlain on a 30 m digital elevation model (DEM).

Delineation of Patterns, Not Necessarily Geology

A potential criticism of mapping with GIS and high-resolution imagery is that it can degrade the intellectual process of creating a geologic map to one involving spatial inventory. It is relatively easy to delineate like-kinds of objects, patterns, and textures observable on high-resolution imagery in absence of a clear understanding of their geological meaning, thus diluting the intellectual field-based experience of geologic mapping. However, the advantage of technological developments cannot be outweighed by a potential loss of intellectual insight. Modern digital methods in geologic mapping and 2-D/3-D map visualization can help engender a deeper, more intuitive understanding of the landscape that is significantly enhanced through subsequent or even concurrent field investigations (Whitmeyer et al., 2009). It is the same situation as holds for analysis of aerial photograph stereopairs: It contributes to more effective fieldwork and leverages that fieldwork to efficiently produce quality maps.

The Persistent Need for Fieldwork

The increasing availability of diverse, high-resolution imagery does not eliminate the need for fieldwork—consider the example of the exploration of Mars. Early expeditions beginning in the 1960s collected remotely sensed data of unprecedented value for interpreting the planet's geology (Carr and Head, 2010). Years of analyzing the remotely collected data led to great discoveries and to the development of increasingly complex supporting technologies. It is, however, remarkable to consider that the follow-up to years of data collection through remote sensing of the Martian surface was to send robot geologists as human proxy to collect samples and photographs (e.g., Crumpler and Arvidson, 2011). This may be the ultimate example of how ground-truthing or field-checking of remote interpretation is fundamental to modern geology. As we gain more outstanding imagery of Earth's surface, our need to document what it is actually on the ground is likely to increase, although it may become focused on progressively more specific features. Furthermore, some aspects of geologic study, such as sample and fossil collection, description of lithologic characteristics, or resolution of structural complexity in areas of dense vegetative cover, cannot be replaced by analysis of remotely collected data.

Challenges Inherent with Digital Data

The use of GIS and other software for geologic data organization, management, analysis, and distribution has become much more efficient and robust than traditional, paper-based means of data organization. The inherent geospatial component of all data in a self-contained GIS eliminates the need for methods of data organization that use separate paper maps commonly employed for different types of data. Unfortunately, the learning curve for fluency in GIS and associated software can be quite steep, and maintaining knowledge of current best practices for data visualization and management can require a very significant organizational investment in time and resources.

The number and nature of ways in which end users can find a map they need, collectively known as "data discovery," have exploded in the past decade and can rapidly change. Simply producing a map, filing it away in a library, and/or perhaps posting it on a Web site offer no guarantee that people will be able to find and access it. A sophisticated and evolving knowledge of contemporary Web publishing practices, inclusive of the constant maintenance of file formats, online data linkages, search engine dynamics, social media, commonly used map databases, keyword management, etc., is crucial to ensuring that a geologic map will not disappear into obscurity as soon as it is published.

By providing geologic data online and in GIS formats, we allow GIS-savvy end users to construct their own maps and interpretations from raw source data in useful and powerful new ways. Unfortunately, such secondary interpretations may suffer from a lack of understanding of the primary data. Thus, it is critical to design digital map products in ways that preserve and convey interpretations and intentions of the primary authors in a format interpretable by secondary users. Various solutions exist amongst proprietary software packages for controlling the depiction of map elements in GIS, but dependence on such proprietary solutions only solves the problem for the community of users of that proprietary tool, and hence it is not an adequate general solution. Standardized metadata (i.e., Federal Geographic Data Committee [FGDC]), including thorough layer and feature attribution, is an essential component of ensuring that the user can properly interpret elements within a GIS database. The present lack of good metadata describing our geologic data is indicative of the difficulty of its generation, and of the lack of investment of resources toward what is a necessity in modern data management practice.

Maintaining longevity of digital data requires a sustained and consistent human effort over decades to address a host of perennial issues (e.g., The Commission on Preservation and Access and The Research Libraries Group, 1996; Digital Preservation Coalition, 2008; National Research Council, 2009). Data need to be frequently transferred to new physical media ("refreshing"). The useful lifetime of physical digital storage media is short, with digital archive organizations typically retiring media after 3–5 yr (e.g., Internet Archive Collections Team, 2011). The physical location of the storage media needs to be considered for data security and resilience to natural and societal disasters. The format of the data itself needs to be routinely updated ("data migration") to formats that can be accessed by contemporary software. Online links to map products and map databases need to be maintained. Working relationships need to be established with the library science community and appropriate digital data repositories, which research and conduct many, if not all, of the previously mentioned functions. Full recognition of the foregoing issues will be crucial to map publishing in the digital age.

The ability to collect, store, and distribute vast quantities of digital data in ways that allow for widespread application requires systematic and standard methods of data management.

Increased efficiencies in and uptake of digital map data generation can result in an indecipherable avalanche of data without a well-planned management structure. The nature of digital data introduces vulnerability to a variety of problems unique to the digital age. If these problems are left unchecked, they can render data completely useless. Digital data management is fundamental and unavoidable, and it absolutely must be recognized as an essential component of modern geologic mapping that requires dedicated GIS and information technology (IT) professionals. These complex responsibilities should not fall exclusively on the shoulders of geologic mappers:

> Although all researchers should understand digital technologies well enough to be confident in the integrity of the data they generate, they cannot always be expected to be able to take full advantage of new capabilities. In an increasing number of fields, professionals with expertise specifically in the generation, analysis, storage, or dissemination of data are playing an essential role in taking advantage of digital technologies and ensuring the integrity of research data. … Research institutions, professional societies, and journals should ensure that the contributions of data professionals to research are appropriately recognized. In addition, research sponsors should acknowledge that financial support for data professionals is an appropriate component of research support in an increasing number of fields. (National Research Council, 2009, p. 5)

Sound data management is fundamentally a computer and library science problem, and it requires a solid foundation in database design, an understanding of a variety of software packages, some understanding of the technology of modern computer networks, and knowledge of the ever-changing landscape of digital distribution mechanisms. These are not areas in which a geologist is traditionally trained. Likewise, those trained in computer and library science lack the background and investment required to understand the details of the information that the geologist strives to convey. This means that geologic mapping teams need to have access to computer and library science professionals who help geologists efficiently collect digital data, and who are also responsible for the maintenance of those data. We cannot expect a geologist to invest the time and resources that would be required to take care of these data management issues and still be able to focus on being a good geoscientist. Conversely, geologists need at least some level of fluency in the digital world in order to communicate their needs to those capable of performing appropriate data management.

Thus, the inevitable burden of digital data management requires the provision of resources (i.e., time and money) toward the employment of GIS professionals (IT specialists and cartographers), rather than solely to geologists. While the advantages and efficiency of using modern digital tools can pay for themselves over time, often the initial adoption of such systems requires significantly more resources than may presently be allocated to geologic mapping projects. Many traditional funding sources for geologic mapping fail to recognize this necessity, thus degrading the potential for digital geoscientific progress. Efforts are under way to help bridge this gap, and to make digital data management more than just an unfunded mandate in the digital world. Earthcube (NSF, 2013) is an example of such an effort; it attempts to bring together geologic experts with computer scientists to find effective solutions for problems inherent to digital geoscientific data management. The goal is to develop mechanisms by which the National Science Foundation can make such digital data management a fundamental part of all geologic research that they fund, without making that management a sweeping, unfunded mandate.

Interoperability of the Vocabulary and Structure of Digital Geologic Data

Conceptually, interoperability is the attempt to make information accessible to as broad an audience as possible, without sacrificing any data integrity. Traditional paper geologic maps and accompanying textual documents once comprised the record in which geologic mappers described and stored geologic findings. In a modern computing environment, geologic data are managed in a digital database, a group of shapefiles, or any number of other formats. This introduces new problems for geologists to deal with: Which digital format should be chosen? Will these formats persist indefinitely? How does a chosen format affect data accessibility? The foregoing questions are at the core of the issue of interoperability.

Through years of working with and creating paper maps, geologists have been solving some of the fundamental issues of interoperability. They have defined a set of conventions, or standards, which allowed for a common framework for communicating mapped geologic information in expected and understandable ways. Many of these conventions are cartographic in nature, and a few examples include contacts represented as solid lines, triangular teeth on a line representing a thrust fault, or simply that different colored areas represent exposure of different types of rocks on Earth's surface (FGDC, 2006). However there are often issues of non-interoperability. Consider the classic issue of the "boundary fault," a false contact between two adjacent maps in which identical geologic units are characterized differently. In some cases, boundary faults may reflect strongly different interpretations on either side of an arbitrary boundary, but more commonly they reflect nonstandard vocabularies for naming and describing map units. Standard vocabulary has been a persistent issue in geologic research and data characterization for years, and efforts to generate unified stratigraphic nomenclature are an ongoing topic of concern (e.g., Soller, 2009). Terminology issues pervade geological science, from descriptions of a rock to naming landscape-scale features. Clearly, we need a common and flexible language with which to describe Earth. Descriptions and interpretations of rocks, structure, and geologic processes in new and unexpected ways are fundamental to the progress of geology as a science and require a growing, adjustable, and ever-expanding vocabulary.

New technologies can help unify geologic vocabularies (e.g., Durbha et al., 2009), but the abundance of available data formats presents a unique interoperability problem. Digital data formats require interpretation by some piece of software, and not all formats can be read by all software. Imagine one geologist who uses expensive, proprietary software and associated data formats to store their geologic map data. Users without access to that software are immediately unable to view, critique, consume, or expand on those data. A particularly frustrating issue arises when a new application discontinues support for or does not support an established data format, leaving important data at risk of being lost. If we assume a situation in which researchers have agreed on a common data format and overcome these obstacles, ensuring flexibility in the way information is structured within that data format presents another layer of complexity. A common example is when a geologist finds a useful data set, only to learn that it includes a table with incomprehensible column headings, or complex and indecipherable encodings of information in any given cell. Without prior knowledge or detailed ancillary information describing the structure of a data set, one geologist is often unable to interpret the data produced by another.

Cartographic standards are required for some level of interoperability across paper geologic maps; likewise, the development and adoption of standards for encoding digital geologic map data are required for digital interoperability. Such standards are difficult to produce because they must strike a balance between standardization and flexibility. As in the case of standardized vocabularies, strict, immutable data formatting hinders a scientist's ability to encode new scientific innovation. However, a lack of standardization means the data are more difficult to share (Gahegan et al., 2009). Many efforts are under way to attempt to build such standard data encodings for geologic map data (e.g., NCGMP09 [USGS, 2011]; FGDC Geologic Standards [FGDC, 2006]; and GeoSciML [Sen and Duffy, 2005]), and finding this balance is a persistent point of concern. Generally, data standards attempt to identify some core information content that is pervasive across all relevant data sets and provide strict encoding for that content. The most successful attempts then provide rules and conventions about how the standard should be "extensible" or designed to include other aspects of the data set that perhaps are not explicitly recognized during or that develop following the initial formulation of the standard.

Even an incredibly well-designed standard is only interoperable if it is widely adopted. The adoption of a standard format is a complicated issue: Software developers generally will not support a standard unless there is a large body of data using it, and scientists generally will not encode data in a standard format unless it is relatively simple, flexible with respect to data types and terminology, and usable by a diversity of software packages. If these criteria are inadequately met, many geologists may be inclined to take an anachronistic approach (opt out) and choose instead a poorly contrived digital database or even a paper map to manage geologic information. As a result, attempts at standardization may have few adopters, and attempts to improve existing standards or develop better ones are pursued by only a small number of researchers. However, once a geologist realizes that modern practice requires digital information, the issue of interoperability cannot be ignored, thus presenting an opportunity that allows for vast improvement in scientific collaboration and progress.

Map Scale Extrapolation

The widening availability of high-resolution, seamless imagery of Earth's surface, the accuracy of modern GPS devices, and the ability to visualize digital map data at any scale present the modern geologist with another new dilemma: At what scale should mapping be done? In the predigital era, the scales chosen for the USGS topographic map series presented a simple answer to this question. Utilizing new, seamless base data, it is now possible to view or print a map at virtually any scale. High-resolution imagery and incredibly detailed LiDAR images expose geologists to features that may have previously been indiscernible. These new data formats seem at first to be extremely beneficial. They offer the ability to identify and visualize geologic features that previously were too small to map, and they allow for geologically meaningful criteria to be the basis for map scale. However, the chosen scale of a mapping effort is constrained by cost-benefit considerations (Goodchild, 2011), and there are some pitfalls to which the modern geologist must pay attention.

The "living geologic map" concept requires that the fundamental data behind these geologic maps reside in a managed digital format, and that portrayals of that data, be they paper maps, downloadable data, or online mapping applications, are only snapshots of the data at a particular location and scale. Thus, one may believe that the data should then be as detailed as possible. However, meeting that expectation is difficult for many reasons. We are growing accustomed to software that allows us to zoom in and out of our data sets and to view them at essentially any scale. However, a geologic map is a complex, often scale-sensitive cartographic work in which the details of the topological relationships between various points, lines, and polygons represent very specific aspects of a complex geologic system.

Geologic map data are generally collected for portrayal at particular scales, but strict adherence is rare; the consistency of map scale varies according to geologic complexity and individual mappers' preferences. Like all maps, geologic maps always represent a very significant amount of generalization. Geologists strive to be objective in the portrayal of what is actually on the ground, but they must always simplify, generalize, and extrapolate from a ground-truth that exists at 1:1 into a much smaller scale that best conveys the geologic history of a given region. Mapping performed with a specific scale in mind can only be interpreted meaningfully when viewed from a relatively restricted range of nearby scales. The fundamental complication relates to the need for ways to generalize our data quickly and efficiently. If our data exist at 1:2000 scale, but we want to take a snapshot at 1:30,000 scale in order to encapsulate a complete geologic story in a single image, we need an efficient way to generalize that large-scale data. Automated algorithms exist that can simplify the network of geometries used to represent geologic features

(Smirnoff et al., 2008). However, these algorithms often generate geometries that look unnatural, obscure or destroy important topological relationships between geologic features, and generally do not produce acceptable, smaller-scale representations of the geology of a region without additional, labor-intensive editing by a knowledgeable geologist.

The process of generalization involves not only simplifying geometric representations of contacts, faults, and rock types exposed between them, but it also involves a myriad of decisions about which features are fundamental to illustrating the geologic framework of a region and which are too insignificant to represent. This is not a new problem, but increasingly complex technologies have given us the ability to be increasingly objective in our data collection, and our generalization procedures need to improve in order to keep up. Generalization of paper geologic map data did not involve automated algorithms that are somehow inaccessible to modern digital environments. Generating a 1:100,000 scale map based on a set of 1:24,000 scale quadrangles involved extensive redrafting and generalization. Such a procedure can just as easily be accomplished in a digital environment. As modern technologies evolve, we will come closer to generating digital data sets that are accurate at increasingly large scales. However, we'll always need to zoom-out from that data in order to get the big picture, and, unfortunately, the generalization required to do so is not a simple mathematical simplification of an array of geographic coordinates. Geologic generalization requires complex decisions and scientific interpretations that presently are difficult to capture in any automated fashion. It is important not to view this as a shortcoming of digital data collection, because in reality what we are dealing with is the opportunity to be more objective in our representations of ground-truth.

In an environment where geologic mapping is accomplished with increasingly tight budgets by fewer and fewer individuals and organizations, it is not practical to develop only intricate, large-scale data that may not even be visible in a preferred or required portrayal. However, it is practical to work in a framework that can accommodate such change should the time, funding, or need arise. It is also important to clearly communicate the scale limitations of existing and evolving data sets. In order to accommodate change, we need to transform our thinking of single-scale paper maps as fundamental end states of map data and realize that the concept of scale is far more flexible now than in the predigital era.

CONCLUSIONS

Geologic mappers are on the cusp of a new conceptual and operational paradigm. This precarious position is influenced by an increasing tide of high expectations from students, colleagues, grantors, and anonymous end users of our data and ideas. The complete process of geologic mapping from the field to the office and then to the end user can be made more relevant, responsive, instructive, and efficient with the systemic adoption of new and widely available methods that take advantage of technological advances. The geologic mapping community must work together in transforming the means of data collection, compilation, integration, publication, and distribution of their efforts in order to keep geologic mapping viable and relevant in the twenty-first century.

Some existing geologic mapping practices support a momentum of anachronism that is fueled by a mixture of institutional "habit," lack of technical training, and lack of financial and technical support. In some cases, it may be a lack of interest or a lack of awareness of potential demand. The revolution in digital mapping is well under way, evolving and permeating culture and science on every level. Opting out is foolish; deciding how to opt in is challenging. Obviously, paper maps will not go away, but they are merely derivative "snapshots" drawn from what is ideally an actively evolving geologic database. This has always been the case, except that in the predigital era, the evolving database was in the minds, notes, and subsequent publications of geologists. Digital mapping technologies now offer unprecedented potential for the timeliness of maps to keep pace with scientific and geologic change. Paper maps will always be outdated upon printing, particularly when they arise from a fertile scientific or dynamic geologic environment, but modern technologies can minimize obsolescence through data management strategies and mechanisms that accommodate map updates; collaborative editing; and wide, open, and easy access.

Perceptions of the longevity of geological maps may be grounded in an awareness of the history of the time-consuming mechanical processes that once went into making them. Much of this effort was traditionally expended in ensuring that a quality graphic product was developed that adhered to a high, institutional aesthetic standard. However, the emphasis needs to be shifted to a digital product that can be resymbolized in ways that best suit users' needs, and can be shown on a base layer (with high geospatial precision) with a particular thematic emphasis, or shown in a novel combination with other data sources. Thus, the new perception should be that geologic data are needed for an array of applications that consume, analyze, and portray digital data sets in ways that can be easily represented in printed form as may be required; however, printing is no longer a final step in the mapping process. The geologic community needs to collectively design a system (or systems) that allows maps to be updated and distributed in accordance with discovery of errors, new ideas, new needs, or new geology. Recent global lessons learned from earthquakes, tsunamis, landslides, land subsidence, volcanic activity, and massive hurricanes and floods make this point emphatically.

The expanding arrays of digital technologies available to geologic mappers do not obviate the need for paper map products, but they do lessen the need for the time-consuming development of highly stylized paper maps. The paper-focused geologic map model is plagued by cost and time commitments of map layout, editing, and production in the face of widespread adoption of digital portrayals that can be generated by users of geologic map data. Up-front demands for high-quality, well-managed, and efficiently distributed data may ultimately have a stronger influence than demands for highly stylized cartographic products. As a community, geologic mappers and mapping agencies need to address the imbalance in emphasis placed on the production of highly stylized printed (or printable) objects at the expense of peer-reviewed interoperable geologic data sets that support a large range of cartographic portrayals by capable end users. In the interest of cost-effectiveness, heavily stylized cartographic treatment should be reserved for maps of notable and significant general interest that are intended to serve an important display function (e.g., national parks and other critical areas). Such products also must be fully supported by funding and staff adequate to transform a perfectly functional geologic map into a high-quality piece of cartographic art while maintaining necessary support for the generation of basic geologic map data in other areas. The promises, challenges, and demands of the digital era thus reaffirm that the primary focus on creating geologic maps should be on data quality, representation, management, and distribution within a dynamic framework that enables analysis and discovery while also promoting greater understanding and dissuading misuse.

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