New Mexico
EARTH
MATTERS

WINTER 2018

DRONES FOR THE GEOSCIENCES: A NEW EYE IN THE SKY

Studies of planet Earth are best done using a wide variety of tools because geologic processes occur at all scales. For example, satellites and seismometers are used to study Earth at the global scale, whereas microscopes and mass spectrometers are used to study Earth at the crystal and atomic scales. Earth science discoveries often correlate with technological advances in the tools used to record observations and make measurements. In some cases, these advances allow scientists to detect what was previously unknown. One such tool, which is just starting to revolutionize the study of planet Earth, is unmanned aircraft systems (UAS), more commonly known as drones.

Aerial photography and remote sensing (a technique that involves acquiring information about an object and/or area from a distance) produce important data that provide context for field-based studies. Information related to surface topography and landforms—features that are commonly too large to observe at ground level—help geologists understand how their measurements at the outcrop scale fit into a larger regional picture. Evaluating and mitigating geologic hazards (such as floods and volcanic eruptions), monitoring surface processes (such as stream erosion and landslides), managing water resources, and constructing geologic maps are just a few facets of the geosciences that regularly need up-to-date information and observation of Earth's surface. Historically, on-demand aerial photography and remote sensing from planes and helicopters have only been available to large, well-funded studies, or provided as parts of regional studies that often miss the immediate aftermath of unexpected geologic events such as earthquakes and tsunamis.

Drones flown at low altitude can capture surface and topographic information that has traditionally been acquired from Airborne LiDAR (Light Detection and Ranging) or TLS (Terrestrial Laser Scanning). Airborne LiDAR surveys are best for large areas (more than 5 square miles), whereas low-altitude drone surveys are ideal for small to moderate-sized sites (less than 5 square miles). Drone surveys and image processing software can generate maps with similar accuracies and higher resolutions than many established photogrammetry (whereby measurements are made from photographs) techniques for a fraction of the cost. Additionally, most drones are small, lightweight, and highly mobile, and thus are rapidly deployed to capture short-lived events (such as debris flows) or used for repeat photography of long-lived events (such as stream erosion). The combination of these factors is encouraging a growing number of geoscientists to add drones to their geologic toolboxes. In the spring of 2017, the New Mexico Bureau of Geology began exploring the capabilities of drones to conduct geologic research and provide up-to-date information about the geology of our state.

Unmanned aircraft types

Drones are classified into two broad categories, rotary-wing and fixed-wing, each with their own benefits and limitations. The main benefits of rotary-wing drones, such as quadcopters (four propellers) and hexacopters (six propellers), are vertical take-off and landing, and the ability to hover. As a

A New Mexico Tech student (bottom left of photo) flying a modified, off-the-shelf quadcopter to inspect outcrops outside of Socorro, New Mexico.

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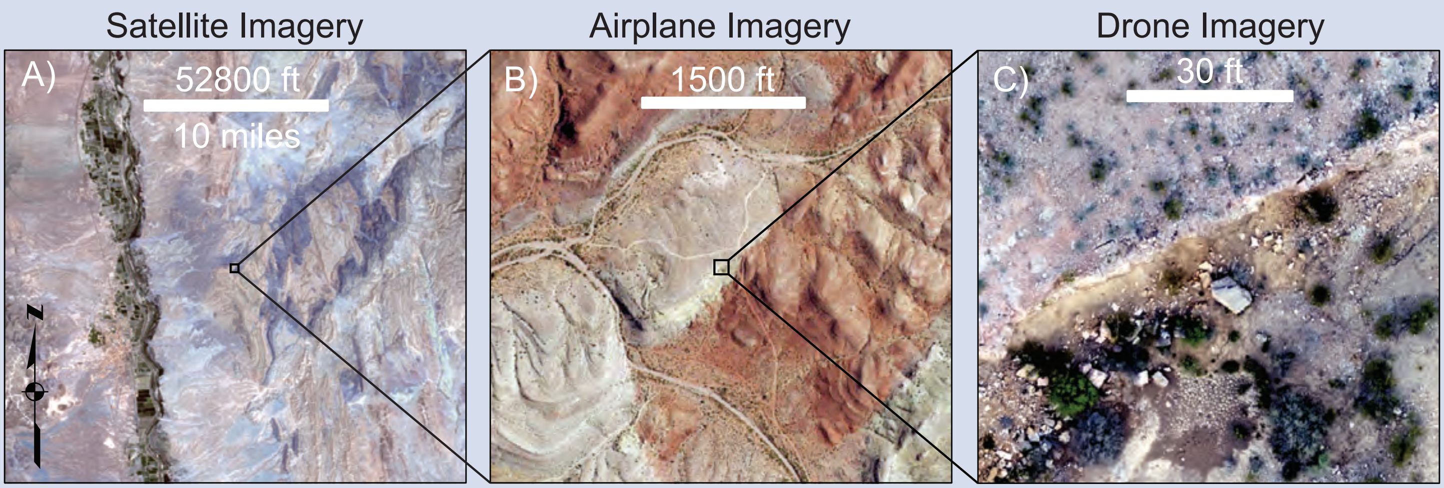
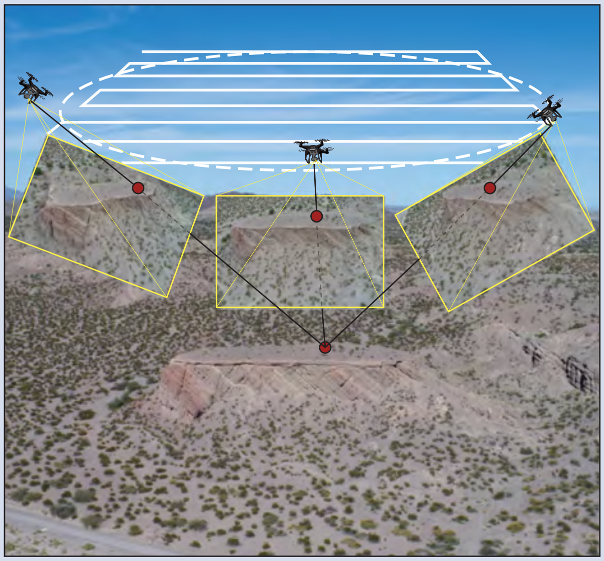


Comparison of different types of imagery used in the geosciences. (A) is an orthomosaic map generated from LANDSAT satellite images, where each pixel is 30 m (98.43 feet) x 30 m. (B) is a NAIP (National Agricultural Imagery Program) orthomosaic map generated from fixed-wing airplane images where each pixel is 1 m (3.28 feet) x 1 m. (C) is an orthomosaic map generated from drone images where each pixel is 1.5 cm (0.59 inches) x 1.5 cm. Maps are zoomed to their highest resolution such that zooming further creates pixilation. Note the change in scale between the three maps. The box at the center of map (A) shows the extent of map (B). The box at the center of map (B) shows the extent of map (C). The drone orthomosaic is best for imaging small- to medium-scale features (such as mud cracks, boulders, outcrops, and individual vegetation elements), whereas the 1-m and 30-m images are best for medium- to large-scale features (such as rivers and mountains). This comparison demonstrates the amazing detail that can be captured by drone imaging and the complimentary natures of different imaging techniques.

result, rotary-wing drones are ideal for small areas where precision flying is critical (such as in narrow canyons) or when hovering is necessary to make repeat measurements. Furthermore, hovering capabilities and the slower speeds of rotary-wing aircraft allow for more time to assess environmental conditions, which typically provides a safer learning environment for new users. In contrast, fixed-wing drones are usually of simpler construction, fly at faster speeds, and thus can survey larger areas with a single battery charge (typically about 20 to 60 minutes, depending on the model and operating conditions). Both rotary- and fixed-wing drones can be outfitted with cameras mounted on motorized gimbals, a device that steadies the camera, ensuring that the images are high resolution and free of motion blur. A professional-level, research-ready drone kit (drone, one or more batteries, camera, and controller) begins at about $1,500 to $3,000, plus additional costs for advanced hardware such as thermal cameras and differential GPS. However, entry-level drones for hobbyists cost as little as a few hundred dollars, and may be suitable for some earth science applications.



A typical drone flight includes taking pictures from a grid pattern looking straight down (white solid line) and/or an orbital path taking photos at an angle (white dashed line). The overlapping drone photos (yellow colored boxes) show how the spatial relationship of a keypoint (the red dot) changes from picture to picture. The three black lines show how triangulating the keypoint among images can locate features and generate 3-D information. The 3-D model of this outcrop is found in the figure on page 4.

One of the most important reasons why drones have seen such a recent increase in popularity is operational ease of use. Even for inexperienced users, operating a drone at a moderate level of expertise can be accomplished within a short time frame. This is largely the result of advances in software, such as machine vision (where a computer recognizes objects) and the miniaturization of electronics, which not only offers smaller sensors but more computing power in a smaller and lighter package. Almost all modern drones, especially those designed for high-end consumers and industrial missions, are equipped with onboard GPS units, barometers, and inertial measurement units that allow pilots to navigate aircraft smoothly and precisely. Additionally, the newest drone models contain highly advanced, obstacle-avoidance equipment, such as infrared cameras, dual vision sensors, and ultrasonic rangefinders. These features help prevent crashes from operator error and weather conditions that would otherwise result in loss of equipment and data, and downtime for maintenance. Furthermore, the latest versions of popular flight-planning software prevent flying near major airports and in restricted areas, helping to minimize the danger of drone traffic in the national airspace.

Image acquisition and processing

Advances in image processing software, in particular those that use Structure-from-Motion (SfM) algorithms, have paralleled the technological advances in aircraft design and operation. SfM is a photographic technique capable of generating 3-dimensional (3-D) information from 2-dimensional photos. The process involves identifying and matching 'keypoints' (such as fractures on a boulder) between overlapping photos, and uses triangulation calculations and related methods to determine the 3-D location for the set of data points (known as a point cloud) that are generated. Each point within the point cloud has a unique latitude, longitude, and elevation value. SfM map products include ultra high-resolution orthomosaics (an image that is geometrically corrected for distortions) and digital surface models (elevation maps that include surficial features such as trees and structures). User-friendly, proprietary (such as Drone2Map™) and open-source (such as OpenDroneMap) software is readily available for automated image processing, usually requiring nothing more than uploading the photos and minor tweaking of the image processing settings.

Photo acquisition via drones shares similarities to traditional aerial surveys, but also involves significant differences. Drone photos are typically captured along a grid-pattern flight path that encompasses an area larger than the target of interest. In general, processing the images with the SfM technique works best when there is a high-degree of overlap between photos (more than or equal to 70% overlap) and the photos are taken at a cruising altitude of 250–400 feet above ground surface. Currently, the maximum altitude that commercial drone pilots can operate under Federal Aviation Administration (FAA) rules is 400 feet above the ground. Flying at low altitudes can improve the resolution of the maps, but increases flying time, may involve multiple battery exchanges, and requires more computational power due to the increased number of photos per unit area.

In addition to capturing photos in a grid pattern, pilots commonly take oblique photos to image vertical features, such as cliffs and canyon walls, or complicated 3-D features. Oblique photos are useful for increasing the accuracy of elevation measurements, and are necessary if the end product is a high-resolution 3-D model of a feature.

Because the SfM technique involves matching 'keypoints' between overlapping images, care must be taken to choose camera settings that minimize motion blur. Furthermore, moving objects (such as people, vehicles, cloud shadows, and foliage in breezy winds) can result in distorted maps.

Finally, lighting conditions can also affect the quality of the maps. The best lighting conditions for drone mapping are: 1) overcast skies, when clouds diffuse the light over large areas; 2) immediately before and after sunrise and sunset, when there is enough light but no shadows; and 3) near solar-noon, when the sun is at its highest and the impact from shadows is minimized. Features within long shadows at dawn and dusk may be hard to recognize and could negatively affect the map quality.

Depending on the purpose of the project, researchers must make choices on the desired accuracy (how close a measurement is to the true value) and resolution (the smallest "thing" that can be measured) of their SfM maps. The "ground sampling distance" (the distance from the center of a pixel to the adjacent pixel) of SfM maps is largely controlled by camera settings and the altitude of the drone. Given the 400-foot altitude limit and the camera resolution on modern drones, the average ground sampling distance for most maps is 1–5 cm (0.4-2.0 inches) with a "relative accuracy" (the accuracy of features within the map itself) of 1 to 3 times that of the ground sampling distance. At this resolution and accuracy, both large and ultra-small topographic features can be identified, mapped, and analyzed. The "absolute accuracy" of the maps (the location of features in the map compared to their true position on Earth) is mostly controlled by the accuracy of the GPS unit used for the survey. The GPS units built into most drones have meter-scale accuracy, similar to the accuracy of handheld GPS units. If the goal of the study is to understand the spatial relationships of only the features within the map, then such accuracy is sufficient. However, both relative and absolute accuracy can be improved by placing precisely measured ground control points in the map area, which are later used to calibrate the maps during image processing.

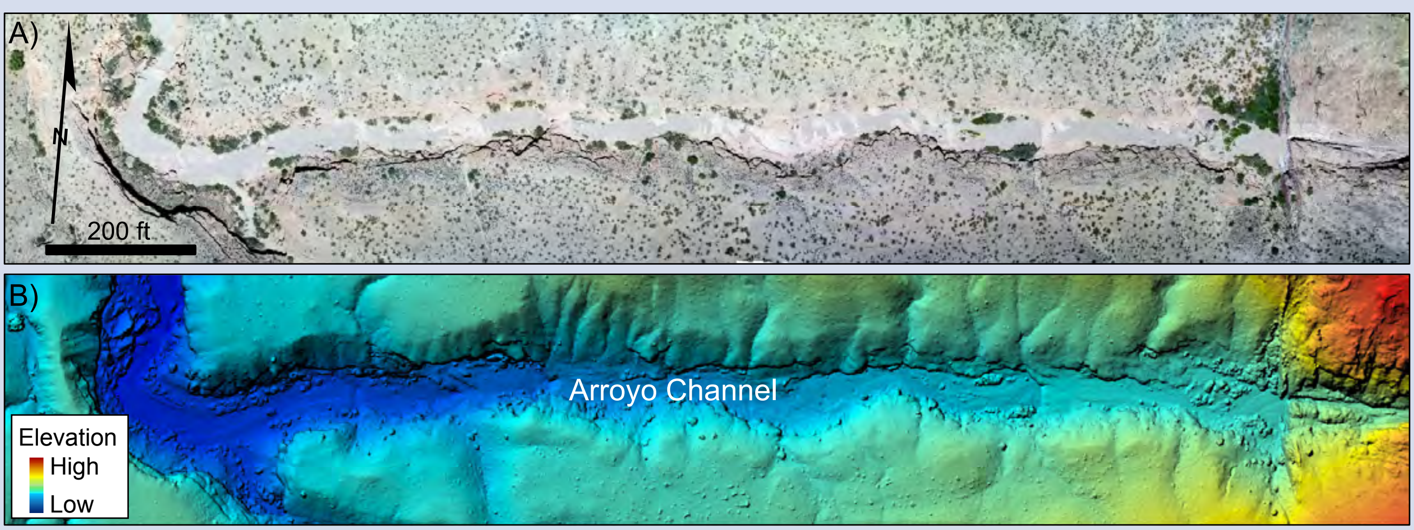
Drone Applications

The affordability and mobility of drones, coupled with the high resolution and accuracy of SfM generated maps, has led to widespread drone use by geoscientists at universities, federal and state geologic surveys, and within industry. The following discussion summarizes how geoscientists are currently using drones, the potential for their use here in New Mexico, and how the technology may advance in the coming years.

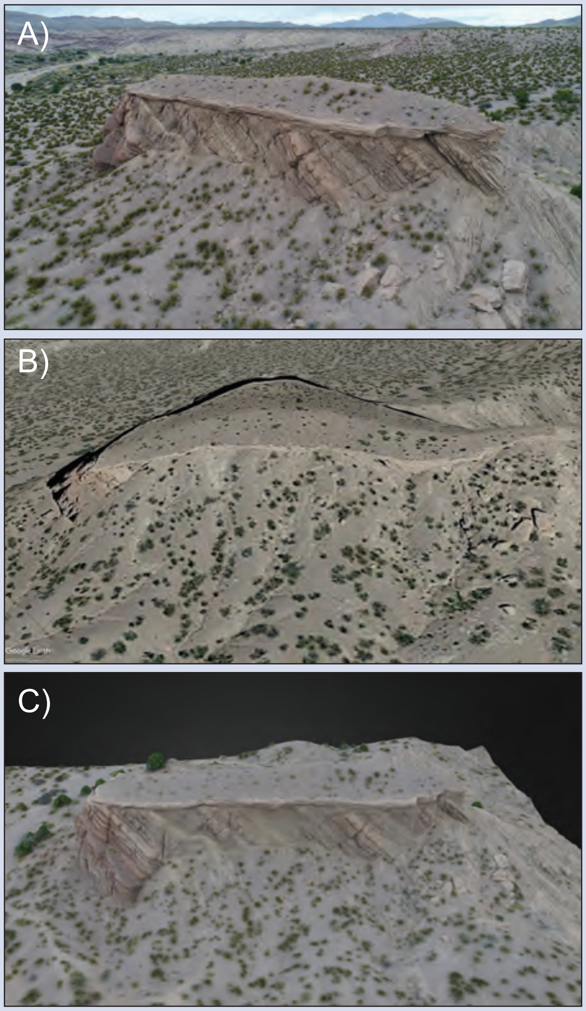
Drones for geomorphic and field geology studies

The majority of published drone studies have focused on the mapping of relatively young features and landforms on Earth's surface. The high-resolution of SfM maps can provide better characterization of such features, or, in some cases, help discover unknown landforms. High-frequency (hourly to weekly) repeat drone observations are leading to new insights into geologic processes such as mass wasting (landslides, rockfalls, mudflows, etc.), stream incision, dune migration, and erosion. High-resolution SfM maps can capture grain-size variations within streams and glacial moraines, and is therefore a powerful tool for studying rivers and glacial processes.

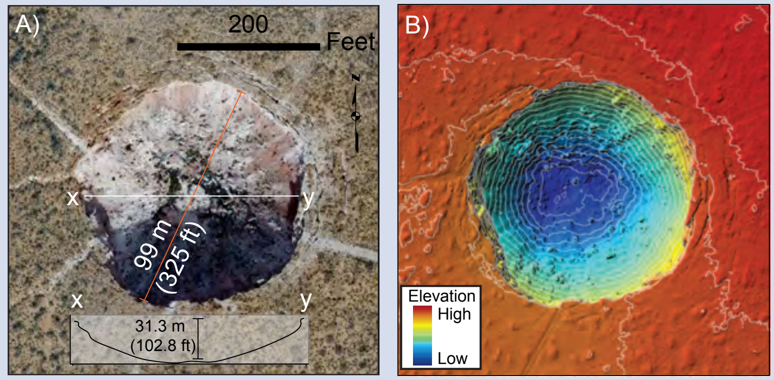
In addition to geomorphology, drones are cost effective for outcrop-scale studies,



Drone-generated orthomosaic (A) and digital surface model (B) of Arroyo del Tajo, an arroyo east of Socorro. The colors of Map B represent elevation, from higher in red colors to lower in blue colors. The images used to generate this map were captured at about 200 feet above ground level and processed using SfM software. The average resolution is 1.74 cm (0.69 inches).



Comparison of visualization tools for a beautifully exposed angular unconformity (A) in the face of a mesa at San Lorenzo Canyon, Socorro County. Google Earth images (B) sometimes distort steep vertical features, such as this outcrop, or are incapable of showing them at all. In contrast, the 3-D SfM model (C) accurately shows features such as inclined sedimentary layers. The 3-D model was generated from 229 orthogonal and oblique drone photos. The view is about 95 m (312 feet) across. A 3-D video tour of the outcrop can be found at ***http://geoinfo.nmt.edu/repository/index.cfml?rid=20180001.***



UAS-SfM orthomosaic (A) and digital surface (elevation) model (B) of the JWS sinkhole in Eddy County, southeastern New Mexico, which collapsed in 2008. Map A also includes a measurement of the diameter of the sinkhole and a topographic profile (inset graph at bottom of the figure) from ArcGIS. The digital surface model contains topographic contours at 5-foot intervals. Repeat drone surveys can show if such sinkholes change over time.

mapping and characterizing intermediate-scale features such as fault traces, sedimentary layering, and stratigraphic relationships. Highly detailed mapping projects, such as those related to paleoseismicity (ancient earthquakes) and infrastructure development (such as construction projects), can use drones to create high-resolution orthomosaics and digital surface models. Important geologic relationships are commonly exposed in cliff faces or similar inaccessible locations. Ground-based photos and laser scanning may be inadequate to resolve these outcrops, and other visualization tools like Google Earth tend to distort large vertical features. However, oblique-drone photos captured at altitude, and 3-D SfM models, are an attractive solution.

As 3-D mapping methods and software continue to develop, drones flights and SfM maps will likely be a major component of the workflow. Some new drones are as small and light as smartphones, easily fit in backpacks, and will likely become handy tools for geologists to scout outcrops, plan routes, and perhaps even to collect samples from hard-to-reach areas.

Drones for industrial geology

For many of the same reasons drones are used to document geomorphic changes to Earth's surface, drones are becoming increasingly important for industrial geologic applications. Drones are now used throughout the life-cycle of mining and drilling operations. Drones outfitted with magnetometers (a device used to locate magnetic minerals) are useful for mineral exploration. Repeat surveys of active mines and drill pads provide near real-time information regarding daily operations. High-resolution digital surface models allow mine operators to measure stockpiled inventories, and to quickly quantify how material is transported through the work area. Drones can monitor the slope stability of open-pit walls and waste-rock piles, as well as rapidly inspect equipment such as drilling rigs and offshore drilling platforms, thus limiting human exposure to hazardous working environments. Drones also play a role in the environmental impacts of mining and drilling. High-resolution pre- and post-mining and drilling maps are useful for reclamation efforts. Drone reconnaissance surveys have the potential to find abandoned mines and mining equipment. Here in New Mexico, large plumes of methane, a potent greenhouse gas, exist over the natural gas fields and drilling operations of the San Juan and Permian Basins. Whereas satellites and planes surveys are used to understand the large-scale aspects of methane leaks, drones could be deployed for local "well-to-well" monitoring. Small, thermal cameras and gas-sensing equipment mounted on drones can investigate point sources of escaping gas at drilling sites and along pipelines. Such inexpensive studies could lead to reduced emissions, increased profits, and more tax revenue for the state.

Drones for hazards

One of the most significant uses of drones is assessing and monitoring geologic hazards. Following the November 2016 magnitude 7.8 earthquake on New Zealand's South Island, drones provided critical, initial information about the surface ruptures along faults and the locations and magnitudes of landslides. Volcano observatories are using drone-based, optical and thermal imagery to track lava flows and changes in the shape of volcanic vents. Drone-mounted gas monitoring equipment can be flown through volcanic plumes to directly measure the gases that geologists use to help predict eruptions. Emergency organizations that respond to geological and weather-related hazards are using drones on search and rescue missions, for infrastructure assessment, and for surveying damage. Drone manufacturers are developing aircraft capable of delivering goods such as medical supplies, food, and water for disaster relief. Likewise, researchers are designing drones that are themselves mobile wireless hotspots to assist with emergency communication operations.

New Mexico is a geologically active state, and many of our geologic hazards can be investigated with drones. For example, measurements of land subsidence related to sinkholes in eastern New Mexico or detecting slope movement in the Rio Grande gorge, are well within the capabilities of drone photogrammetry. Burned landscapes are notoriously unstable and destructive debris flows are common after wildfires. However, these landscapes can be investigated with repeat deployment of drones in a safer manner than ground-based surveys. Although large, damaging earthquakes and volcanic eruptions are infrequent in New Mexico, when they do occur, drones would inevitably provide some of the earliest data needed by scientists and first responders.

Drones for climate change

Researchers from around the world are using drones to study climate change. Glaciologists are finding that repeat surveys with drones are a useful tool for tracking rapid physical changes to glaciers. Scientists are also using drones to monitor the annual progression of moss on the Antarctic Peninsula to approximate the pace of climate change. In the southwestern U.S., increasing temperatures are causing longer and more severe droughts. One impact is declining forest health, both from decreased precipitation and an expansion of invasive species. Drones equipped with a basic digital camera can identify water-deprived vegetation, and images can be processed to determine the relative "greenness" of a forest, which is directly related to its health. Drones outfitted with multi-spectral cameras capable of photographing the near-infrared spectrum are becoming common tools for farmers to monitor crop health. Such technology could also be used to map the declining health of the largest cottonwood-willow forest in North America, the bosque along the Rio Grande. Drone surveys to inspect irrigation ditches and water retention structures, monitor surface water runoff, and even map the levelness of farmland, may provide New Mexican water managers with new strategies to deal with declining water resources.

The future of drones

Unmanned aircraft systems, structure-from-motion photogrammetry, and a diverse suite of drone-mounted instruments are ushering in an exciting and potentially transformative period in the geosciences. Where on-demand aerial imaging and photogrammetry was unavailable to most, drones are allowing the next generation of researchers to collect data quickly and inexpensively.

The future of drones, however, is not without challenges. The FAA is currently attempting to develop rules for drone pilots that will protect privacy and enhance safety while allowing the industry to achieve its potential. In the summer of 2016, the FAA provided a pathway for drone pilots to obtain licensing for commercial activities. In the fall of 2017, the FAA developed the UAS Integration Pilot Program to explore best practices to safely integrate drones into the airspace.

Stable weather, vast amounts of unrestricted airspace, limited vegetation, and diverse geology make New Mexico a prime location to use and test drones and related scientific instruments. Researchers from the New Mexico Bureau of Geology are continuing to explore the possibilities and capabilities of drones as tools to meet the diverse geologic needs of our state.

—*Matthew Zimmerer*

Matt Zimmerer is a field geologist with the New Mexico Bureau of Geology and Mineral Resources at New Mexico Tech, and a licensed FAA remote pilot. He is currently developing a drone program at the bureau. Anyone interested in using drones for either work or recreation should visit the FAA website (https://www.faa.gov/uas/).

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The bureau's drone "Tommy." See ***http://geoinfo.nmt.edu/repository/index.cfml?rid=20180001****, for a video of Tommy in action.*

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Presented by Susana Martinez, Governor of New Mexico,
to:
Susan Welch
Education Outreach, New Mexico Bureau of Geology
New Mexico Institute of Mining and Technology

It is my privilege to offer my congratulations to you for your outstanding accomplishments, and your contributions to the State of New Mexico have been invaluable. I applaud you on your diligence, and your hard work serves as an inspiration to your peers. You are an asset to the State of New Mexico!

SIGNED AT THE EXECUTIVE OFFICE THIS 24TH DAY OF JULY, 2017

Susana Martinez
Governor

Governor Martinez recognizes Susie Welch

Susie Welch, our recently retired Outreach Coordinator, was cited for outstanding accomplishments and invaluable contributions to the state of New Mexico. The award recognizes Susie's 21 years of leadership in "Rockin' Around New Mexico," our earth science educational program for New Mexico teachers. Congratulations to Susie on the well-deserved citation, and her retirement after 26 years of bureau service!

Cynthia Connolly to run Outreach Program

As our new Education Outreach Manager, Cynthia will work with students, teachers, staff, and administrators, to promote our services, information, teacher training, and K-12 outreach. She will be guiding groups through the Mineral Museum, providing classroom demonstrations, coordinating the annual Rockin' Around New Mexico geology class, and editing Lite Geology. Prior to joining the bureau, Cynthia was a science teacher at Socorro High School.

Bonnie Frey receives IMPACT! Award

In October, the New Mexico Network for Women in Science & Engineering honored Bonnie Frey, Geochemist and Chemistry Laboratory Manager. The award is given to a New Mexico woman who encourages women to enter into science, technology, engineering, mathematics, and allied professions. Bonnie received this award, in part, because of the mentoring that she has provided to students involved in the NM EPSCoR uranium team, of which she is a co-lead.

Nelia Dunbar in PBS NOVA Program "Killer Volcanoes"

Dr. Nelia Dunbar is the Director of the Bureau of Geology and serves as the State Geologist. The program aired in October and is now available online. She specializes in geochemistry and volcanology and previously worked on the documentary "Sleeping Monsters, Sacred Fires: Volcanoes of New Mexico."

Nelia Dunbar looking at volcanic ash in ice cores on NOVA "Killer Volcanoes" program.

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