Laser rangefinders and ArcGIS combined with three-dimensional photorealistic modeling for mapping outcrops in the Slick Hills, Oklahoma

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ABSTRACT
The mapping of geology is conventionally done visually in a hands-on fashion, and the data are recorded in a field book or with photography. An alternative technique that combines reflectorless laser rangefinders or high-speed terrestrial laser scanners, global positioning system, and the Environmental Systems Research Institute (ESRI) ArcGIS software platform has been developed that is effective for mapping geology at a distance and in three dimensions. Portable handheld reflectorless lasers are used to capture geologic features such as contacts and terrain and can be combined with digital elevation models in ArcGIS software. Fast terrestrial laser scanners capture an entire exposure at the detail and accuracy of (3D) photorealistic (virtual) models with the additional color information from image pixels. This latter method is expensive and complicated and requires significant amounts of field and processing effort. The laser gun approach is simple, portable, and cost effective. When integrated with ESRI ArcGIS software and a module, such as our recently developed ArcGIS extension 3DLT (laser tool), a simple yet sophisticated platform exists for mapping, visualizing, and analyzing outcrops in real time in the field. The potential of laser mapping is demonstrated in the Paleozoic outcrops of a structural geology teaching site in the Slick Hills, Oklahoma. Fast laser scanning and digital photography are used to build a 3D photorealistic model of an area of the anticline. The 3DLT is used for mapping specific detailed features such as contacts and faults. Three-dimensional quantitative information can be extracted from the geology with these methods. A laser rangefinder combined with 3DLT can image and display terrain and outcrop features in the field, in real time. Mapping with fast scanners requires several steps in processing of the point cloud data utilizing a variety of sophisticated and expensive software, but can capture an entire outcrop, such as a mountainside. The resulting model then can be analyzed in the lab. When combined with digital photography, virtual photorealistic models derived from point clouds can be even more effectively analyzed. The most appropriate method for digitally mapping geology depends on a variety of issues, such as cost, time, complexity, portability, and the project goals.

Keywords: digital outcrop mapping, reflectorless laser rangefinder, geographic information system, photorealistic model, Oklahoma, Slick Hills, geological mapping.

INTRODUCTION
Common methods for digital geologic mapping have included aerial photography, global positioning system (GPS), and the utilization of conventional laser and/or optical based surveying tools. Digital geologic mapping of outcrops has also been carried out with various combinations of GPS, cameras, high-speed laser scanners, and survey instruments (Xu et al., 2001; McCaffrey et al., 2005; Thurmond et al., 2005; Bellian et al., 2005; Pringle et al., 2006; Oldow et al., 2006). Methods and technology developed in geographic information system (GIS) mapping applications, such as remote sensing, are used in geologic mapping, but for detailed mapping of exposures on steep slopes and cliffs it is necessary to map digitally and obliquely at relatively close range (often <1 km) using portable and perhaps handheld equipment. Reflectorless laser rangefinders (Gilbert, 1996) such as handheld guns and total stations (Lyman et al., 1997; Nielsen et al., 1999, 2000; Xu et al., 1999, 2001; Zeng et al., 2004; Xu, 2000; Ramirez-Ugalde, 2002) have been an effective technology for geological mapping, operating at 1–250 points/s out to ranges of as much as 1 km and vertical and horizontal angle accuracy as precise as 0.001° (total station) and 0.01° (handheld rangefinders). Terrestrial laser scanners (TLS) programmed to run at high speed (thousands to hundreds of thousands of points per second) generate dense point clouds (millions of points) at angle and range accuracies better than the handheld rangefinders. These scanners have been used to map geology, creating three-dimensional (3D) models that capture entire mountainsides (Thurmond et al., 2005; Bellian et al., 2005).

Improvements have been made to these methods for digital mapping of geology by using enhancements to the laser rangefinders (e.g., Bluetooth communications), centimeter accuracy real-time kinematic global positioning system (RTK GPS), and an ArcGIS-based mapping software system. The improvements create more effective 3D analysis and allow for real-time visualization of the results. TLS scans, when combined with digital photography, can be used to build 3D photorealistic (virtual) models to capture large areas of geology at great detail, and this workflow has been changed and made

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more efficient with new software and techniques. How these laser mapping approaches can be or should be applied is explored, and these concepts are applied to map geology in the Slick Hills, Oklahoma.

Reflective Laser Rangefinding

Reflective laser rangefinders are designed to measure distance to low-reflectance surfaces such as buildings, soil, rock, and vegetation. They do not require highly reflective targets such as corner cube prisms (Lichti et al., 2002). The maximum range that can be measured is dependent upon the physical properties of the target surface (electric permittivity and magnetic permeability, which determine the absorption characteristics of the surface), geometric characteristics of the surface, such as roughness, and the angle of incidence of the laser beam to the surface (Fowles, 1975). A dark surface, such as coal or basalt, will absorb more of the laser energy than a lighter surface such as limestone. A low angle of incidence will increase the reflection of the beam away from the laser and will spread the beam over a greater area, diminishing the strength of the returned signal. A smooth surface, such as fine, compacted dirt, will cause the laser beam to reflect away from the laser rather than backscatter toward it. The negative impact on range caused by the surface smoothness increases as the angle of incidence between the laser beam and the surface decreases, and at very low angles of incidence there will be little returned signal. When specifications of the range of a laser rangefinder are noted by a manufacturer, they list two ranges depending on the degree of reflectivity of the material: 20% reflectivity (typical for most rocks) and 80% reflectivity (white surfaces typical for coniferous magnetic fields such as power lines. The data from each laser shot are stored on media compatible with the particular laser, such as internal memory and flash memory devices (PC card, compact flash card, secure digital card), or the rangefinder can be connected directly to a portable computer. Various software programs have been developed to support connection of the rangefinder directly to a portable computer. The CyberMap program of the University of Texas at Dallas (UTD) (built with Environmental Systems Research Institute [ESRI] ArcView and MapObjects) (Xu et al., 2000) provides an interface to both a rangefinder and a total station and maps the points as they are shot. Other programs that provide an interface to rangefinders are Condor Earth Technologies PenMap (Hillman, 1995), the University of California at Berkeley GeoMapper, which uses ESRI PenMap (Brimhall and Vanegas, 2001), Carlson’s Tsunami (Turner, 2002), and the Geological Survey of Canada’s (GSC) GanFeld, using the ESRI ArcPad (Guy and Buller, 2004). The GSC was a pioneer in developing data logging geology software, where one stands on a point and records into a program what is measured or observed (Brodaric, 2000). Far more common are non-geological application software programs, such as the Trimble Navigation GPS receiver software program TerraSync, which can be linked to a rangefinder. However, the lack of a continuous sampling mode and the inability to view the data as points, lines, and polygons in a 3D viewer on the computer have made them less effective, especially for geological applications.

In order to capture the features of a geological outcrop or terrain, a laser rangefinder is used to sketch the features to form a 3D image of the feature. A total station or rangefinder in continuous sampling mode can be swiveled to sketch the terrain or the features of the geological outcrop. Single-shot measurements can be made, but the preferable mode of operation, due to operator fatigue, is a continuous sampling, or “trigger on” mode. The resolution with which the feature is sketched is determined by the rate at which the laser is swept across the feature. A faster sweep rate results in a lower resolution sketch. By sweeping the mounted rangefinder along salient features in the terrain, the features are sketched as a 3D digital image. Xu (2000) used a handheld rangefinder mounted on a custom-designed cradle with an angular encoder to map terrain features such as bedding layers. The rangefinder was operated at a slow 1 shot/s rate up to the maximum rate of 250 shots/s. Features as much as 1 km away were sketched in this fashion.

Laser rangefinders with continuous sampling have proven to be effective in mapping terrain and outcrop features, especially when mapping linear features such as bedding layers, faults, and contacts between different lithologies. The details of the characteristics of the different rangefinder guns vary, but the dominant issues in determining whether it is acceptable for a given application are equipment cost (much less than that of a high-speed terrestrial scanner), range accuracy (10 cm), sample rate (1–250 Hz), horizontal accuracy (0.5°), vertical accuracy (0.2°) with built-in compass and inclinometer, and whether it can be adapted to angular encoders. In addition, the size, weight, and power requirements of the rangefinder will affect the applications for which it is suitable, or preferable to high-speed terrestrial scanners.

3DLT Extension

Because GIS software platforms provide powerful tools to manage, edit, and visualize spatial data, a software extension to ESRI ArcGIS has been developed to support 3D field analysis of geological features and terrain using laser rangefinders. The program combines many of the capabilities of the UTD Cybermapping program and the GCS GanFeld program, integrating the rangefinder data with GPS, and implementing it in the ArcGIS environment. The 3DLT extension operates the laser rangefinder from the ArcGIS environment (Fig. 1) and in real time displays the data in 2D and 3D views as points. The ability to display the work in progress in the 3D ArcScene viewer allows the geologist to monitor his or her work, as it is being captured, on top of a previously loaded digital elevation model (DEM) or other 3D model of the terrain or outcrop. There is the ability to assign feature names to the point attribute table while capturing the data, as well as the ability to convert the points to lines and polygons as the outcrop or terrain are being scanned. These abilities provide real-time feedback to the geologist as he or she sketched the features.

The 3DLT extension is written in the Visual Basic for Application (VBA) language and combined with ESRI ArcObjects. ArcObjects are the C++ building blocks of the ArcGIS software platform. They provide services to support GIS applications on the computer desktop. With ArcObjects, menus, tools, workflows, applications, and custom feature classes can be created for use by the VBA (Visual Basic for Applications) code, which implements the 3DLT extension.
In real time, the 3DLT extension can create 3D point, polyline, and polygon shape files from the rangefinder point data. The rangefinder can operate in either single-shot mode or continuous-shot mode, and the data are displayed on the screen as they are captured by the rangefinder. The 3DLT extension will accept angular data for each point from both the rangefinder’s internal compass and inclinometer or from external angular encoders. If the scanner was georeferenced with a backsight prior to starting work, the 3D features that are produced will be georeferenced at the time of capture. The point data (X, Y, and Z) can be exported as ASCII (American Standard Code for Information Interchange) files, and ASCII point data can be imported into the program.

The 3DLT extension was tested against the clean lines of a constructed structure, a corridor at UTD (Fig. 2). The points in Figure 2 are shown in 3D mode as they were captured. The corners, walls, and doors of the corridor were sketched with the rangefinder and then converted to polygons and polylines (Fig. 3): the walls are polygons and the door frames are polylines. Sketching the corridor in continuous sampling mode resulted in the straight lines of the wall intersections and doorways not being perfectly straight. This was caused by a combination of the operator’s inability to hold the rangefinder absolutely steady when tracing a straight line and the accuracy of the laser range measurement.

Figure 1. Three-dimensional laser tool (3DLT) System. A laser rangefinder with an encoder (precise external compass), attached to a laptop to capture the data and store captured points in the computer in real time.

Figure 2. Capturing points in the corridor using continuous trigger mode laser rangefinder. Upper right shows the sides of the corridor from the outside. Lower left corner shows the corridor from the inside (view from the position of the laser rangefinder). Different colors represent different features.
ranging and the accuracy of the angles from the vertical inclinometer (a horizontal encoder was used).

**TLS**

An alternative to the handheld laser rangefinder is the high-speed TLS, or ground light detection and ranging (LIDAR). Reflectorless ground LIDAR systems can scan outcrops and terrain from thousands of points per second to hundreds of thousand of points per second. Systems such as Cyrax (McCaffrey et al., 2005) use rotating mirrors to deflect the laser beam in order to scan across the image field. Systems such as the Riegl LPM swivel the laser up and down and rotate the laser horizontally in order to scan the image field.

The scanners are larger and heavier than the handheld rangefinders and considerably more expensive. They require more power than the handheld scanner, which involves carrying larger batteries when the scan site is not accessible by vehicle. Real-time conversion of the scanned image into a 3D georeferenced framework is not yet available. The scanned point clouds are post-processed and georeferenced by scanning georeferenced control points during the work phase and then using a six variable affine transformation to convert the point coordinates from the scanner coordinate system to the georeferenced coordinate system.

When viewed from the perspective of the scanner, the point clouds appear almost like a photograph, especially if the points have been texture mapped with an integrated camera image, as can be done with the Riegl Z420i. The intensity of the reflected signal for each point is saved and can be viewed in grayscale, which often highlights features in the outcrop or terrain. The point cloud can later be converted into a triangular irregular network (TIN) model, and photographs that were taken of the outcrop or terrain can be draped onto the model (Xu et al., 2000), creating a photorealistic model of the outcrop or terrain. These techniques have been used to map geological structures with point clouds (Bellian et al., 2005), and by others to create surface models using TIN meshes and photographic texture mapping (Thurmond et al., 2005). Few, so far, have used these techniques for mapping geological structures due to the complexity and cost of the equipment and associated specialized software.

**Digitally Mapping Geological Features**

In order to assess the effectiveness of the developed tools and software, geological features in the Slick Hills of Oklahoma were mapped using both the 3DLT handheld laser rangefinder system and a high-speed terrestrial LIDAR. UTD developed software was used to convert the LIDAR point cloud into a 3D photorealistic model. The Slick Hills area is ~24 km north of Lawton, Oklahoma, along State Highway 58 (Fig. 4). A UTD structural geology class (lead by Weldon Beachamp) combined with the UTD Cybermapping Laboratory to map part of the Kimbell anticline located in the Kimbell Ranch, which is in the southern part of Blue Creek Canyon (Fig. 5). The area includes rocks from the Kindblade and Cool Creek Formations of the Arbuckle Group that are exposed along the Kimbell anticline. Both the Kindblade and Cool Creek Formations are marine carbonate buildups deposited during the Early Ordovician Period (Rigby and Toomey, 1978). Throughout the Pennsylvanian Period, tectonics associated with the formation of the Wichita Mountains resulted in left-lateral shearing throughout the canyon that led to the development of several major faults, creating a horst and graben terrain (Donovan et al., 1986). Over time, the intense tectonic forces acting on this region began to subside, and erosion during the Permian reduced it to its present Slick Hills topography (Donovan et al., 1988). It is dominated by large-scale deformation; there are several major anticlines and synclines present. The steeply dipping resistant ledges characteristic of the Slick Hills makes the anticlines and synclines obvious. Vegetation in the area is low to the ground; therefore the geology is very well exposed. The area that was digitally mapped includes rocks from the Kindblade and Cool Creek Formations.
of the Arbuckle Group exposed along the Kimbell anticline. A hillside exposure of the Kimbell anticline consists of intermittent bed-scale outcrops in tall dry grasses and small juniper trees. This was the area of detailed mapping.

A soft-copy raster image of a hand-drawn map was georeferenced, then converted into a shapefile to be able to geographically compare in GIS the newly captured features. The features were then integrated with the vectorized georeferenced version of the original hard-copy map and an available 10 m DEM. All shapefiles were imported into GPS TrackMaker (GPSTM), free software, and then used in conjunction with shapefiles, ArcGIS, and Google Earth software to form an integrated model of the area.

**Digitally Mapping the Kimbell Anticline**

Geologic contacts such as stratigraphy were captured as points using the 3DLT system, RTK GPS for georeference control, and a modified Laser Atlanta Optics rangefinder with a Bogen/horizontal encoder configuration tripod. This is not the most stable configuration, but it is relatively lightweight and portable. The points were then converted to lines using 3DLT to define stratigraphic contacts (Fig. 6) and subsequently were overlain on the previous geologic mapping and a digital terrain model (Fig. 7). The points were converted into polygons in order to define a plane that allows computation of their strike and dip orientations. At this stage the various strike and dip routines available can be used, such as MicroImages TOOL SCRIPT (MicroImages, 2005), and those of Vacher (1989), and Fienen (2005), to compute the strikes and dips. The data were imported into GPS TrackMaker to import and/or export shapefiles from and to ArcGIS and Google Earth, exported as shapefiles into ArcGIS, and then imported into Google Earth and overlain on terrain models of the Slick Hills (Fig. 8). Integrating the data with Google Earth maps provides a global context and a visualization evaluation of the accuracy of the captured field data points as well as lines and planes processed from the data in the lab.

**TLS of the Kimbell Anticline**

A TLS scan was carried out to a range of 150–200 m on the north side of the anticline with a Riegl LPM i800 scanner (Fig. 9) from the University of Idaho. At this distance a scan increment of 4 mgon (400 gons = 360°) sufficiently captures at ~1000 points/s detail outcrops at an interval of a few centimeters. Note in the figures the gaps in the data, due to the angle of the scanners with relation to the terrain across drainage. At least two scan locations would have been required to completely map the area to fill in where shadowing creates gaps in the point data and possibly in the surfaces, but for our purpose the scans were sufficient. Vegetation usually does not allow coherent mesh building and therefore results in holes. Four scans, over 2 h, from one site captured the area of interest (Fig. 10). While the scanner scanned the outcrop, digital photographs were taken of the hillside. After data acquisition, the raw scan data were loaded into Riegl LPMScan software and exported as an ASCII file with X, Y, Z and intensity data. The data were then loaded into point cloud software, InnovMetric Polyworks software. The IMAlign module was used to create a merge of the point cloud (Fig. 11). The merged point was loaded into the IMMerge module and a polygonal surface was created. The polygonal mesh (triangulated irregular network, TIN model) was edited and made ready for photo draping, which can be very time consuming if outward appearance is important. If the geologic mapping appearance is not as important, then less editing would be necessary, except in the area to be analyzed.

It has been said that the point cloud is sufficient for any 3D geologic analysis (Bellian et al., 2005) with 3D data extraction accomplished by point-cloud editing software such as Polyworks. Even a colored point cloud loses its information when it is observed at close range (Aiken et al., 2004a, 2004b), whereas a photographic image is only limited by the pixel density on a
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Figure 5. The 3DLT (three-dimensional laser tool) data sets overlaid with the original geology map (note strike and dip traverses from original geology maps of Beachamp, 1983) and the digital terrain model (DTM).

Focus Area: The points represent the data captured using 3DLT system and the lines are hand drawn by Beauchamp.

Center image location:
540773.95m E
3855535.68m N
UTM zone 14S

Figure 6. Captured point data using 3DLT (three-dimensional laser tool) integrated with hand-drawn structural geology by Beachamp (1983) displayed in ArcMap.
triangulated mesh or other such surface. For this reason, if surface analysis is to be performed on a model generated from a laser scan point cloud, it is best to have the photographic texture draped onto the model. The photographs highlight discontinuities in the lithology of the surface.

**Photorealistic Modeling**

Methods used for generating 3D photorealistic models have been developed at UTD using a series of nonlinear transformations to relate features in the real world of XYZ to the pixels on a photograph in UV space (used to define x, y positions on an image). This results in a model where the photograph is accurately “draped” onto the model and is not the result of rubber sheeting methods (Xu, 2000; Xu et al., 2000, Olariu et al., 2006; Thurmond et al., 2005). A new work flow (Fig. 12) utilizing the UTD 3DPM software was used, and resulted in working with the raw point clouds in Riegli RiScan Pro, then exporting them as point clouds in an ASCII format, and subsequently importing them into Innovmetric Polyworks software, in which the different scans from various positions are merged as if referenced to a single reference scan position. In Polyworks, editing of the point cloud and then the triangulated (TIN) mesh can be carried out. The editing is done to the extent necessary to yield the desired results. This is usually the most time-consuming step, taking days to months depending on the size and problems with the data sets (e.g., a lot of vegetation will produce tangled triangulated meshes that may have to be repaired, such as filling the holes and cleaning up the model; the work is then exported as a model in a Wavefront file format [.obj]). All of these steps are performed under Polyworks. Next, at least four common points are picked between each photo and the 3D model using Polyworks and our own 3D photorealistic mapping (3DPM) software. UTD designed software solves for the transformation parameters relating the surface mesh to the photos. Finally, the photos are draped (really transformed) onto the mesh models using the UTD 3DPM software, resulting in a 3D photorealistic (virtual) model (Fig. 13). At this stage in the processing, Polyworks or other such similar 3D photorealistic mapping (3DPM) software can be used to trace (digitize) geologic contacts on the 3D photorealistic model (Fig. 14). This is equivalent to digitizing the rocks directly with a laser gun in 3DLT mapping. In either case a contact mapped as a series of points can be used for solving three-point problems, such as strikes and dips on surfaces fit to the tracing. 3DLT has the capability to carry out this kind of 3D analysis on the virtual model as well as with a laser on a real outcrop (Fig. 15) (e.g., MicroImages, 2005).

**CONCLUSIONS**

The 3D point clouds, triangulated meshes, or the photo models can and were used for extraction of 3D surfaces (Figs. 16A, 16B) so that strikes and dips can be computed. Specific stratigraphic contacts were mapped by 3DLT on both sides of a ridge and overlain onto Google Earth models. Care must be taken when extracting and/or digitizing these geometric shapes. The Slick Hills topography has more resistant layers that stand out in relief, or lines of narrow and parallel ledges. These types of exposures are captured with laser scanners, but raise a question. With either a rangefinder in the field or with a cursor on a 3D photorealistic mesh model in the lab, which linear feature should be digitized in order to define the contact? For example,
Figure 8. Fitting surfaces created by 3DLT (three-dimensional laser tool) mapped features on top of a ridge in the southeast Slick Hills. (A) Laser mapping in 3DLT/ArcGIS with surface fit of two contacts. (B, C) Shapefiles imported into TrackMaker software in UTM zone 14S coordinates to allow data to be imported into Google Earth. Also note 3DLT mapping of stratigraphy around area (red). Black surfaces are surface fitting of points from the 3DLT mapping. Note energy windmills on top of ridge.
the digitizing done along the edge of the ledge, or the contact with the next layer? This is something a geologist must decide. The edges of the resistant layers were consistently digitized in this case. Preferably, it should be done by the geologist familiar with the geology and the features to be extracted, because such extraction is a step in the analysis and interpretation of geology.

The 3DLT approach is very fast and cost effective at an accuracy of centimeters to decimeters, but it only maps features of interest at that time the work is performed. If more information needs to be mapped, then the site must be revisited. The scanner-based 3D photorealistic approach captures everything in an area within line of sight at higher accuracy (centimeters), but it requires much more expensive hardware and software, the procedure is much more complicated, and it takes longer to acquire and build the model (although this is improving). In the Slick Hills example, both of these approaches proved effective in this steeply dipping, grassy environment. The 3DLT provided results in real time at centimeter to decimeter accuracy for immediate evaluation and discussion. 3D photorealistic modeling, after considerable post-processing in the lab, was successful at an accuracy level of a few centimeters and was compared with conventional field and 3DLT mapping. Digitizing with a cursor on the 3D model produced almost the same 3D quantitative results as direct field “digitizing” by laser mapping (tracing) when these points are fit to surfaces for analysis of their orientation. These results were generated at many locations of the geologic exposures, exceeding that which could be done manually with a compass, and these digital results provide statistics of those measurements (e.g., standard deviations) that can be archived allowing future reanalysis. Importing the resultant lines and surfaces in the model also allows effective visualization of the topography when mapped onto Google Earth scenes. These systems complement each other and both belong to the geologists’ toolbox for mapping and analysis.

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Figure 9. Oblique photograph looking northwest along the Kimbell Anticline from location of the scanner in the study area. Note the windmills. Location at the center: 540828.10m E, 3855525.86m N, UTM zone 14S.

Figure 10. Several laser scan point clouds from a single site seen in Fig. 9, color coded, but seen from above using Polyworks to display the gaps in the data due to shadowing (blockage of the scanning).

Figure 11. Closeup of merged scans of modeled area (looking west) using Polyworks. Note the prominent resistant ledges typical in the Slick Hills.
Figure 12. Flow chart of procedure for three-dimensional (3D) photorealistic mapping with laser scanners. The outcrop is scanned and global positioning system control is established. In the postprocessing of the data, the point cloud is edited, and then a triangulated mesh is created (and edited). Four common points are picked on both the model and the photos. Transformations relate the model to global coordinates and then the photo pixels are also transformed onto the model to map (not “draped”), resulting in a 3D photorealistic model. 3DLT—three-dimensional laser tool.
Figure 13. Procedure shown in flow chart results in these stages of three-dimensional (3D) virtual mapping with terrestrial laser scanner (TLS) and digital photography as shown in the area of Fig. 9.

Figure 14. Digitization with cursor along top and bottom of layers using Polyworks. Image below shows just the digitization. Note that we are almost looking down the strike of the geology as shown in the area of Fig. 13.

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Figure 15. Demonstration of defining a surface fit for contacts, in this case a layer. The surface was produced by importing the digitized data into 3DLT (three-dimensional laser tool) and generating the surfaces as shown in the area of Fig. 14.

Figure 16. (A) Additional surface fits defining strike/dips on 3D photorealistic model of Slick Hills, Oklahoma, converted from captured points using 3DLT (three-dimensional laser tool) as shown in the area of Fig. 13. (B) Planes fitted to original data points shown as line elements in (A).

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