

DEM Manipulation and 3-D Terrain Visualization: Techniques Used by the U.S. National Park Service

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Abstract

Manipulating digital elevation model (DEM) surfaces, like pliable modelling clay, enhances the appearance and legibility of 3-D topography on maps. The U.S. National Park Service (NPS) uses the familiar image-editing tools in Adobe Photoshop to manipulate raster DEM data. Exporting modified DEM data with the help of freeware and shareware utilities allows subsequent rendering of final 3-D scenes in Corel Bryce. Techniques to be discussed include topographic substitution – a method for reverse engineering present-day landscapes into the past or projecting them into the future; selective vertical exaggeration; resolution bumping – a technique developed specifically for improving the legibility of high-mountain landscapes; painting and filtering effects; and, borrowing from the traditional masters of landform depiction, creating 3-D scenes that emulate the panoramas of Heinrich Berann and the spherical over-the-horizon views of Richard Edes Harrison by warping the projection plane of DEMs. The unique challenges of 3-D mountain mapping and the continuing pursuit of design excellence – a cornerstone of the NPS cartographic program – are overarching themes.

Introduction

This paper discusses the graphical techniques used by the U.S. National Park Service (NPS) in manipulating digital elevation models (DEMs) for the design and production of 3-D landscape visualizations. After discussing approaches to DEM manipulation (geographic information system versus graphical), an overview of raster-based DEM manipulation in Adobe Photoshop – my software of preference – is given. Next and most important, a discussion of specific techniques emphasizes how to produce 3-D landscape visualizations with modified DEMs. The techniques are not step-by-step tutorials. Considering the frenetic pace of software revisions, tutorials would soon be out of date (Photoshop

was updated twice since this article was first written). Instead the goal is to acquaint cartographers with just a few of the many beneficial manipulations that can be applied to DEMs, and encourage development of new techniques that will enable mountain landscapes to be visualized in unimagined ways.

Over the past five years, the NPS has increasingly relied on 3-D visualizations – static images, animations, and interactive scenes – to portray the natural and cultural resources of the 387 units in the NPS. Perhaps because they look more realistic, it is generally assumed by NPS staff that 3-D visualizations are more easily understood by casual visitors than abstract two-dimensional (2-D) maps and illustrations. The types of 3-D visualizations created by the NPS include geologic block diagrams, natural science illustrations, hiking maps, mountain panoramas, and bird's-eye views of cultural sites showing buildings, landscaping, and vegetation set on topographic models.

DEMs – the term is used generically here to describe all varieties of spatially arranged elevation data, regardless of format – comprise the digital foundation for all 3-D landscape visualizations. Despite the importance of DEMs, cartographers and GIS specialists generally hesitate to manipulate DEMs to enhance 3-D visualizations – in contrast to their willingness to modify vector data routinely to enhance 2-D maps. Manipulations of DEMs are usually made only to edit imperfect data, such as systematic banding and discrepancies in matching edges. This hands-off approach to DEMs may have several causes: the lingering belief that DEMs, like the landscapes they represent, are largely immutable; well-intentioned respect for maintaining the integrity of data created by others; and unfamiliarity with the necessary software applications and techniques, and the concept of DEM manipulation itself.

Why Manipulate DEMs?

Practical reasons abound for manipulating DEMs beyond routine editing of cosmetic data imperfections. As in all cartographic presentation, geographic reality and graphic reality are often at cross purposes. Just as vector data must be simplified to be legible on a 2-D map, DEMs must

be generalized at reduced scales to avoid creating topography that looks more like a noisy graphical texture than a 3-D landscape. This problem can be ameliorated with resolution bumping – a DEM manipulation technique that yields legible small-scale 3-D topography in rugged high mountains, such as the Alps, without sacrificing detail (Figure 5). On the other extreme, small topographic features whose importance is disproportionate to their size can be given greater emphasis by using selective vertical exaggeration. For example, Puu Oo volcano on the island of Hawaii has a surface area of only 10 hectares but has sheathed 105 square kilometres of Hawaii with lava since it began continually erupting in 1983. With selective vertical exaggeration, Puu Oo could be exaggerated in height and made more discernable next to its dominant neighbour, Mauna Loa, whose mass is greater than any other solitary mountain in the world.

The most remarkable DEM manipulation techniques may be those that depict geologic processes. Starting with a DEM of an existing landscape, the user can either reverse-engineer topography to portray an earlier stage of landscape development or project it into the future. Like virtual modelling clay, DEMs are malleable; they allow users to create an almost unlimited variety of derivative or even entirely new landscapes. The challenge when altering the topographic morphology of DEMs is to do so with the control and precision required for geographic visualization.

The main objective of DEM manipulation is not the manipulation of DEMs themselves, but the enhancement of 3-D visualizations generated from the altered data. DEM manipulation is simply another technique – not unlike linework generalization on vector maps, which cartographers may use for presenting complex spatial information to audiences in a more comprehensible form. DEM manipulation is not for everyone. It is a highly specialized endeavour that requires users to possess a deep understanding of landscapes, 3-D visualization, and expertise with the requisite software. Design sense and restraint are critically important.

Approaches to DEM Manipulation

The software used to manipulate DEMs can generally be categorized as either GIS or graphic. Although the applications in each category have similarities (such as their underlying algorithms), they are used by entirely different professional cultures to produce different products. GIS applications, as most readers of this text are well aware, appropriately emphasize spatial analysis and accuracy, but the relatively staid 3-D graphical capabilities of these applications provide few tools for creatively manipulating DEMs. By contrast, graphical 3-D software applications generally contain a plethora of tools, some with real-time interactivity, for manipulating elevation data to create eye-catching special effects. The landscapes yielded by graphical software are used mostly for entertainment (computer games and movie special effects), fine

art, and fantasy/science fiction pursuits. Despite these imaginative ends, graphical 3-D software tends to have limited DEM import capabilities. Imaginary fractally generated terrains, some stunningly realistic, are the landscape type of choice (Musgrave 1998). Geographic accuracy, if addressed at all, is often an inconvenient afterthought.

The NPS approach to DEMs manipulation bridges the gap between the cartographic/GIS and graphic 3-D cultures. Three-dimensional visualizations are created with Corel Bryce, a consumer-oriented, landscape rendering application most famous for its unconventional Kai Krause-inspired graphical user interface (<http://www.corel.com>). Because Bryce does not import geo-coded data, helper utilities and a workaround procedure are used to bring large-format DEMs into the program. However, once the DEM is imported, a powerful suite of 3-D special effects exists; the interface is easy to use, and the rendering engine yields exceptionally high-quality ray-traced output in the form of raster images, animations, or Quick-Time Virtual Reality scenes. Although Bryce contains a fascinating terrain editor, which allows DEMs to be manipulated interactively, its cramped interface and inability to edit precisely defined geographic areas limits effectiveness for making professional landscape visualizations (Webster 2001).

Manipulating DEMs in Photoshop

To overcome the shortcomings of Bryce's terrain editor, the NPS uses Adobe Photoshop (<http://www.adobe.com>), the popular image-editing application, to manipulate DEMs before importing them into Bryce. Because the NPS already uses Photoshop as a go-between application for importing large-format DEMs into Bryce, making DEM manipulations in Photoshop makes practical sense. Depending on their format, in some cases Photoshop can open DEMs directly as raw binary files (row and column dimensions must be known), or more easily with the help of intermediary freeware utilities such as MacDEM (<http://www.treeswallow.com>) or MicroDEM (<http://www.usna.edu/Users/oceano/pguth/website/microdem.htm>), on Macintosh and PC respectively. When opened in Photoshop, DEMs appear as 16-bit greyscale raster images containing 65,536 levels of height information. With 16-bit vertical resolution a user can depict topographic surfaces with near-perfect smoothness – in contrast with the 256 elevation levels available in 8-bit DEMs, which often yield topography with stair-stepped surfaces (Figure 1). To convert 16-bit greyscale DEMs from Photoshop format (.psd) to quadratic-sized files in portable greyscale map format (.pgm), which Bryce can then import, requires BSmooth (<http://www.bsmooth.de>), a Macintosh shareware utility, or pbm+, a Macintosh freeware Photoshop plug-in (<http://www.nacis.org/cp/cp28/resources.html>).

A DEM opened in Photoshop appears as a ghosted greyscale image, similar to an X-ray, with light-coloured pixels representing high elevations and dark pixels low-

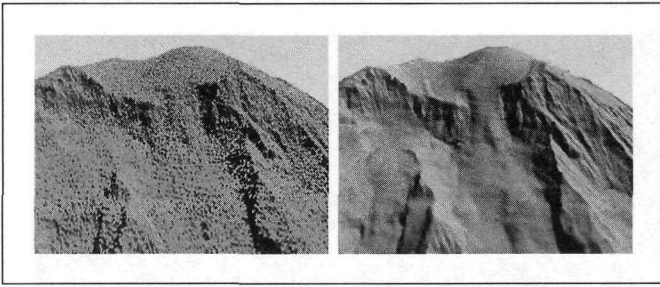


Figure 1. 3-D views of Mt. Rainier's summit generated from 8-bit (left) and 16-bit (right) DEM data.

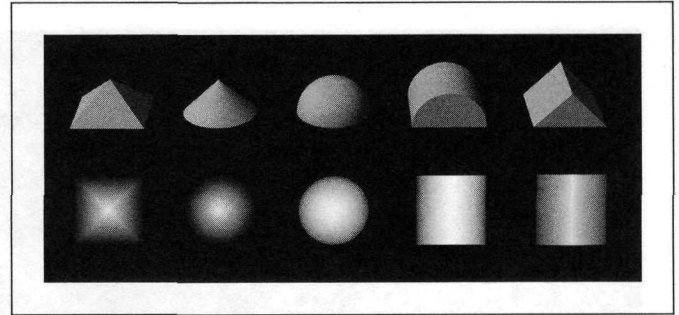


Figure 2. 3-D geometric objects (top row) look considerably different from the greyscale "DEMs" in Photoshop format (bottom row) from which they were extruded.

lands. Although a greyscale DEM in Photoshop looks nothing like the 3-D surface it will eventually become when rendered in Bryce (Figure 2), being able to see it in pictorial form at all is a huge benefit when making manipulations. Changes actually can be seen, in contrast to the original DEM – a text file of numbers that defies visualization.

Cartographers can use Photoshop's image-editing and selection tools, more or less, to edit a greyscale DEM just like any other image. Basic image transformations – cropping, downsampling (decreasing the resolution), rotating, and scaling – behave in the usual manner. Applying the Gaussian blur filter to a DEM results in a smooth generalized surface, while the noise filter adds roughness, and lightening or darkening the image either raises or lowers topography respectively – no surprises there. However, because they are data files, greyscale DEMs sometimes respond unexpectedly or detrimentally to Photoshop manipulations that we are accustomed to using with typical 2-D images. For example, the median filter, enormously useful for generalizing 2-D shaded relief (Patterson 2001a), when applied to a DEM yields terrain with a creased surface that looks like crinkled paper. The unsharp mask filter, another stalwart of 2-D shaded-relief editing, produces unsightly needle-like artifacts along prominent ridgelines and drainages.

There are notable disadvantages to manipulating DEMs in Photoshop. Previewing an edited DEM in 3-D involves exporting the DEM from Photoshop, importing it into Bryce, and then rendering the scene – a time-consuming process when making repeated subtle edits. More problematic is Photoshop's limited functionality when using 16-bit images as opposed to "normal" 8-bit images. Most items in the toolbar are disabled, as are most filters and the layers palette – 16-bit functionality is akin to going back to Photoshop version 1.0.

Despite Photoshop's diminished 16-bit functionality, it nevertheless contains all the tools needed to manipulate DEMs with the accuracy required for cartographic visualization. Clever workarounds, however, are often necessary to perform routine functions. For example, hard-edged and feathered selections can be used on 16-bit DEMs despite the fact that the magic wand and color range selection tools are disabled in 16-bit mode. Using

either of these selection tools requires duplicating a 16-bit DEM file and saving it as an 8-bit proxy to be used only for making selections. The selection boundaries can then be dragged and dropped from the 8-bit file to the 16-bit file. (Hint: temporarily inverting an interior selection allows it to be precisely registered to a corner when dragged into the 16-bit image.) Cartographers can use similar techniques to import selections from rasterized vector geo-data.

Photoshop's painting tools are also disabled in 16-bit mode. However, the rubber stamp tool, which is enabled, is an effective substitute for the airbrush tool for painting on DEM surfaces. Data can be sampled and cloned between two open 16-bit Photoshop files. By filling a proxy 16-bit file entirely with black or white and then using the rubber stamp with a soft brush and setting the blending opacity to a low value, black or white tones can be subtly transferred from the proxy image onto the DEM, lowering or raising elevations respectively.

Photoshop can be used in innumerable ways to manipulate DEMs to enhance 3-D landscape visualization. The following examples emphasize creating static images of 3-D landscapes to show some practical techniques used by the NPS. Although 3-D illustrations of terrain are used to depict the results of the techniques, readers need to remember that the techniques are exclusively about the manipulation of raw DEM data (in greyscale format) rather than post-rendering touch-ups to illustrations.

Generalization

Downsampling means decreasing the resolution or size via the Image Size dialog. Downsampling greyscale DEMs in Photoshop results in more generalized landscape surfaces. For example, a DEM downsampled from 1024×1024 pixels to 512×512 pixels will have a quarter as much detail as the original and a smoother appearance. In the Preferences dialog, Photoshop offers three interpolation methods for calculating pixel values when downsampling or otherwise transforming images. In general, bicubic interpolation (the default) works best for straight downsampling. If the DEM were also to be ro-

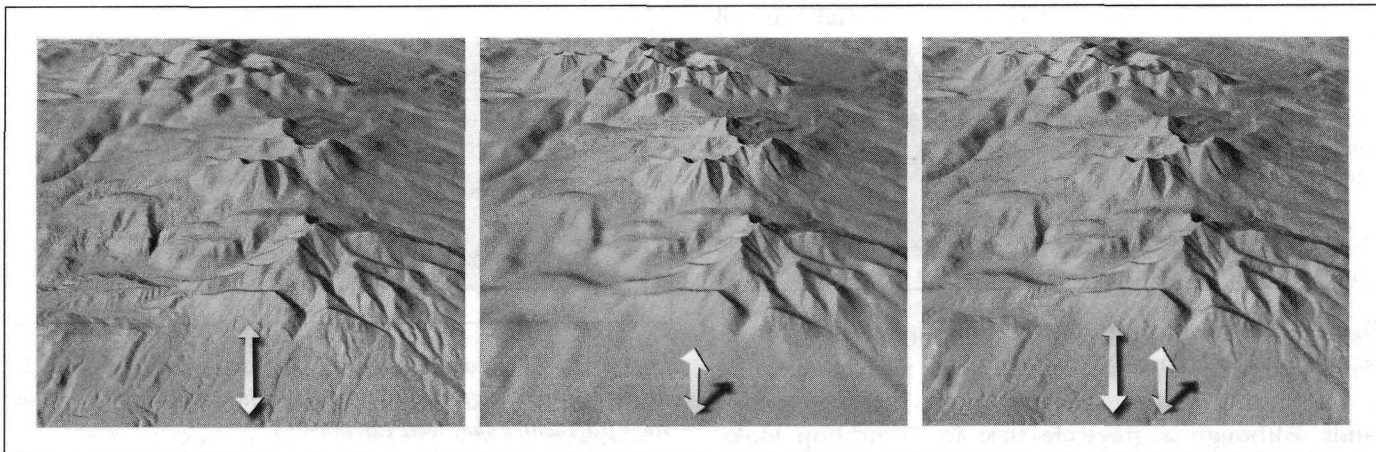


Figure 3. Intra-DEM resolution variation, La Sal Mountains, Utah: (Left) Resolution gradually decreases fivefold from front to back within the scene. (Middle) Resolution decreases fivefold from highlands to lowlands. (Right) Combination: resolution decreases from front to back and from highlands to lowlands.

tated, however, Nearest Neighbor interpolation would be a better choice, because this faster interpolation eschews anti-aliasing, thus preserving crisp-edged pixels at the margins of the DEM. Regardless of which interpolation method is used, upsampling – the procedure opposite to downsampling – which adds pixels to an image, should generally be avoided. Upsampling only increases the file size without increasing discernable detail.

Alternatively, applying the Gaussian blur filter to a DEM, a method that does not decrease the file size, achieves extremely smooth generalization. The smoothing effects of Gaussian blur filtering are different from those of downsampling; experimentation is required to achieve comparable levels of generalization between the two techniques.

Although generalization is most often applied globally throughout a DEM, it can also be applied in graduated amounts to achieve subtle visual effects. For example, increasing generalization from foreground to background on a DEM creates the optical illusion of depth when it is viewed in 3-D (Figure 3). Foreground to background generalization also hastens rendering time – an important consideration when creating interactive environments (Moore 1999). Graduated generalization can also be applied to the vertical axis of a DEM, creating scenes with more visible detail at higher elevations than at lower elevations. This technique mimics the aerial perspective effect, a visualization technique pioneered by Eduard Imhof, which accounts for the veiling effects of atmospheric haze. When aerial perspective is employed, highlands, which are theoretically closer to the viewer, are depicted with greater detail and contrast than the lowlands further away, enhancing three-dimensionality (Imhof 1982).

Finally, greater amounts of resolution can be applied selectively to small but otherwise important topographic features on a DEM, such as Puu Oo, Hawaii, mentioned earlier. Detailed objects tend to attract the viewer's atten-

tion more readily than generalized objects (Garfield 1970), a phenomenon that can be exploited beneficially for 3-D landscape visualization (Figure 4).

Resolution Bumping

Resolution bumping is a generalization technique for manipulating Global 30 Arc Second Elevation Data Set (GTOPO30) and other small-scale DEMs. The technique alters digital elevation surfaces so that rugged, high mountains are more legible and look more natural as compared to unmodified data (Figure 5).

When used for 3-D visualizations, unmodified GTOPO30 data typically produce mountains with a choppy appearance. Vertical exaggeration, which is a graphical necessity when making small-scale landscape visualizations, exacerbates the choppiness. Especially problematic are glaciated northern mountains comprising tightly packed ridges and valleys – for example, the coast ranges of British Columbia, Canada, and the Alps – which often appear as an irregular texture rather than as recognizable topography. Solitary high peaks with small surface areas, such as Mt. Shasta or the Matterhorn, spike upwards like the Eiffel Tower. Used in combination, topographic detail, vertical exaggeration, and small-scale presentation are the enemies of legible mountain depiction.

Downsampling GTOPO30 data to a sparser resolution alleviates the problems outlined above. Generalized data are better for depicting patterns within mountain ranges and are more tolerant of vertical exaggeration. Downsampling elevation data, however, introduces new problems that arguably are worse than the now-corrected original problems. Knife-edged mountain ridges appear excessively rounded, like the vacuum-formed plastic relief maps used in schools, and simplified valley bottoms are prone to misregistration with drainages.

The idea behind resolution bumping is simple: merging low-resolution and high-resolution GTOPO30 data of the same area produces hybrid data that combine the

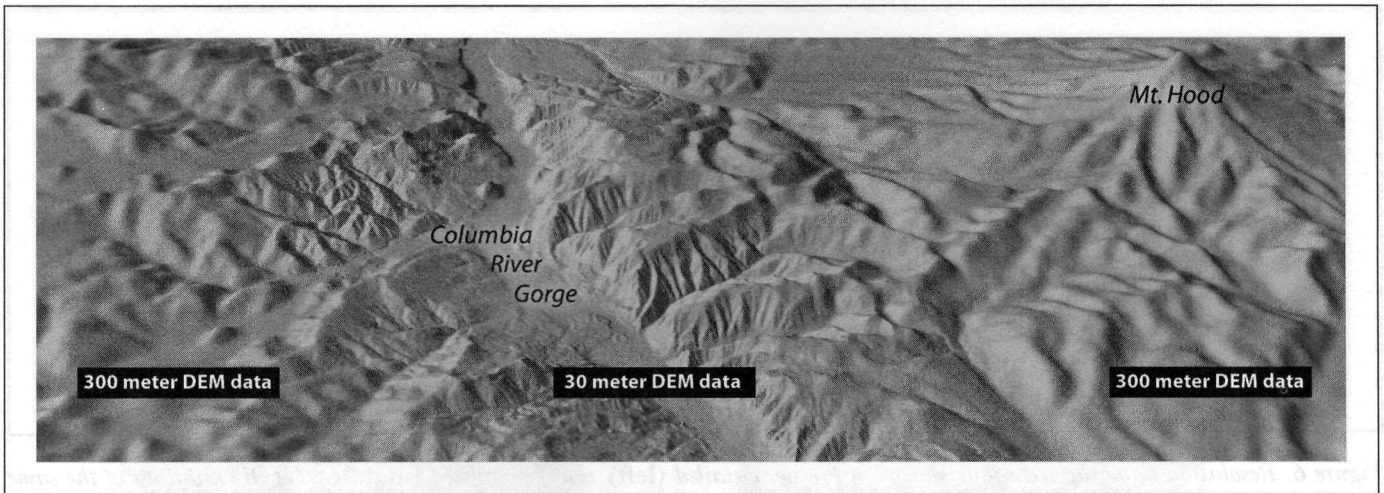


Figure 4. Columbia River Gorge, Oregon, looking east. Topographic detail generated from higher-resolution DEM data directs the viewer's attention to the gorge despite the looming presence of nearby Mt. Hood.

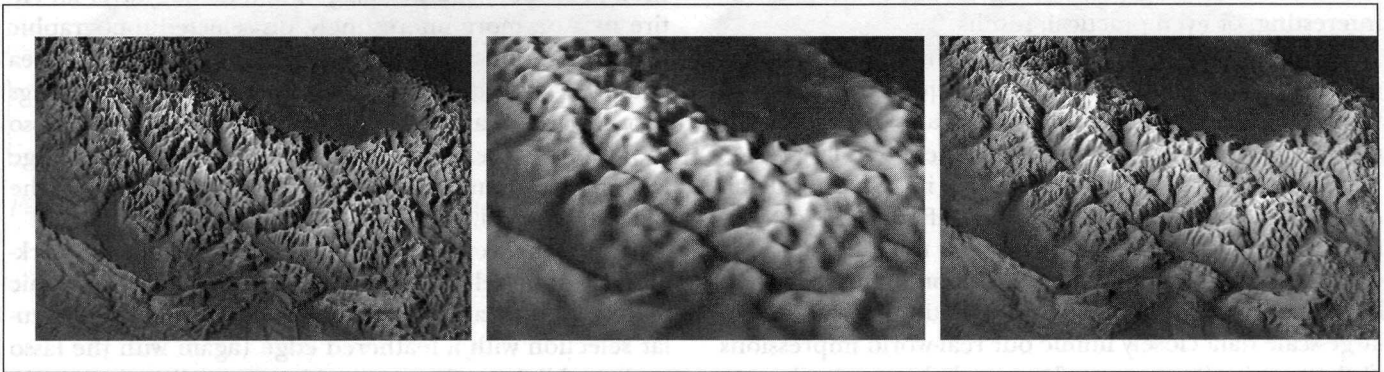


Figure 5. Resolution bumping: (Left) A 3-D scene of the western Alps created from 1-km GTOPO30 elevation data. The detailed terrain appears choppy when vertical exaggeration is applied. (Middle) Downsampling the data to 8-km resolution, although excessively generalized, gives major landforms a more distinct appearance. (Right) A scene created from 1-km and 8-km elevation data blended at a 4:6 ratio. This treatment etches a hint of topographic detail onto generalized major landforms.

best characteristics and minimize the problems found in the originals. Two copies of a GTOPO30 file are used, one high-resolution and the other downsampled to a lower resolution. These files can then be blended in Photoshop by a proportional amount that is controlled by the user. This technique yields a new greyscale DEM that, if merged in the right proportions, combines the readability of the downsampled data with all the detail one expects to find in mountainous terrain – without the graphical noise. Resolution bumping in effect “bumps” or etches a suggestion of topographical detail onto generalized topographic surfaces (Figure 6). The resolution-bumped data create an elevated base in mountainous regions, upon which individual mountains, with diminished vertical scaling, project upwards (Patterson 2001b).

The look of resolution-bumped GTOPO30 is dependent on the resolution of the downsampled host data and the percentage of blending with original high-resolution

data. The best results, I find, are achieved with drastically downsampled host data (10% to 20% of original resolution) blended at a 40:60 ratio with the high-resolution data. When too little downsampling is used, or when the blending opacity is high, the resolution-bumped data do not appear to be appreciably different from unmodified data. At the other extreme, data that have been downsampled by a large amount and blended lightly with high-resolution data yield topography that tends to look peculiar.

The blending modes in Photoshop behave differently when merging raw elevation data, when compared to the graphical images we are accustomed to editing. Normal blending mode works best for resolution bumping elevation data. Normal blending mode etches both positive (peaks) and negative (canyons) topographic detail on the downsampled host data below. By comparison, multiply mode only intensifies the darker negative values, ignoring positive topography. The inverse is true for

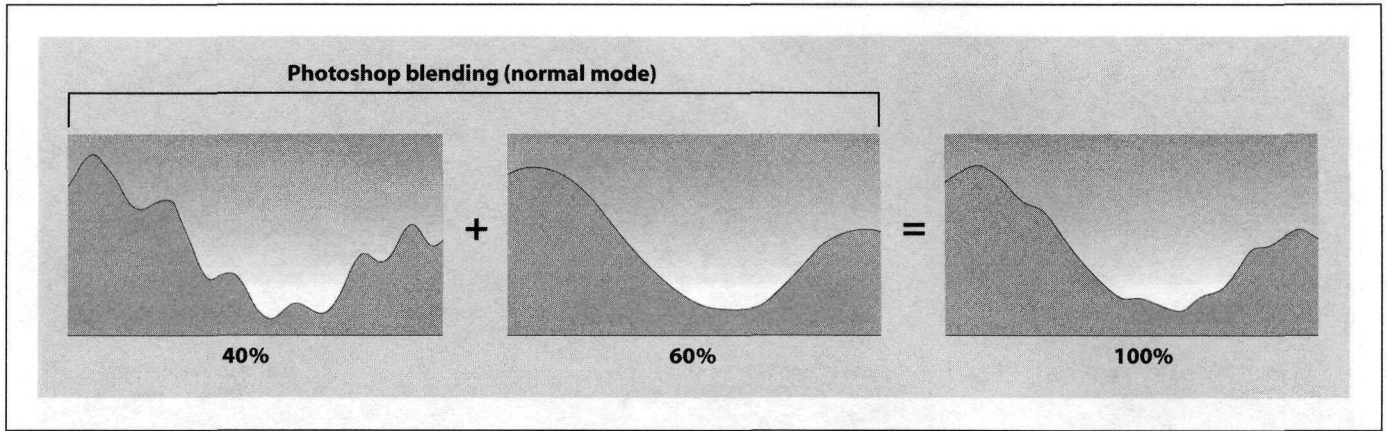


Figure 6. Resolution bumping technique shown in profile. Detailed (left) and generalized (middle) GTOPO30 data of the same geographic area are blended in Photoshop. Varying the blending opacity determines the amount of topographic generalization.

lighten blending mode. Additional experimentation with Photoshop's other blending modes could produce interesting, or even practical, results.

Resolution bumping is not a panacea for all DEM generalization situations. The technique does not work well with large-scale elevation data and maps. Unlike GTOPO30, showing rich topographic detail on large-scale maps is usually not a problem. Rather, it is a lack of detail that is of greater concern. The simplified small-scale topography in GTOPO30 is much more tolerant of exotic data manipulation, such as resolution bumping, than large-scale DEMs – landscape visualizations created from large-scale data closely mimic our real-world impressions of the terrain. By contrast, few people have actually seen the Alps, for example, at 1:2,000,000-scale. Even at small scale, not all landscapes are suitable for resolution bumping. Most non-mountain topographic features (eroded drainages, tablelands, escarpments, foothills) appear quite nicely without data manipulation, even when large amounts of vertical exaggeration are used. Moreover, mountains that already have simplified forms, such as the fault-blocked Sierra Nevada in the United States, may not benefit from resolution-bumping.

One last caveat must be considered. When resolution bumping is applied to a small-scale DEM containing rugged mountains, the effect is also applied to adjacent lowlands, disproportionately generalizing the already modest topography in these areas. Showing full lowland detail in conjunction with resolution-bumped topography in the mountains is sometimes the more desirable presentation outcome. This effect can be accomplished by rubber-stamping resolution-bumped data with a soft-edged brush to an unmodified DEM only to mountainous areas in need of generalization.

Height Manipulation

Lightening or darkening a DEM with Photoshop's image adjustment tools (levels, curves, brightness/contrast) raises or lowers surfaces respectively when the DEM is lat-

er rendered in 3-D. This adjustment technique can be used to modify vertical exaggeration globally over an entire DEM or, more interestingly, on selected topographic features. For example, a mountain hosting a ski area could be exaggerated in height above its surroundings (for ski area maps, bigger is better) by using the lasso tool to draw a selection boundary with a feathered edge around the mountain and lightening the area within the space (Figure 7).

Going one step further, applying lightening and darkening within selections can create simple topographic features. To create a volcanic cinder cone, draw a circular selection with a feathered edge (again with the lasso tool) and lighten the area inside – extruding the DEM in 3-D forms a cone-shaped hill. Drawing the circular selection with a slightly irregular shape avoids excessive symmetry and gives the cone a more realistic appearance. Last, contracting the initial circular selection by several pixels and applying a smaller amount of darkening, depresses the summit (see Figure 11, left image).

Glaciers can be depicted by manipulating elevation on a duplicated DEM, positioned precisely below the original unaltered DEM in Bryce. In Photoshop, on the bottom DEM an imported selection boundary representing the glacier's extent is drawn or imported and filled with lighter pixels. Using a feathered selection boundary creates a domed effect when the glacier is extruded in Bryce. By increasing the bottom DEM's vertical exaggeration and lowering its position in Bryce, the virtual glacier will protrude through the top DEM, neatly intersecting the valley walls (Figure 8).

Taking elevation manipulations to the extreme, the user can apply solid black on a DEM to form block diagrams and cutaway views. Black represents the lowest elevation value. When applied to a selected portion of a greyscale DEM it flattens and lowers the topography to base level – the digital equivalent of a peneplain. The bottommost elevation data can then be clipped from a DEM when rendered in 3-D. This technique allows select-

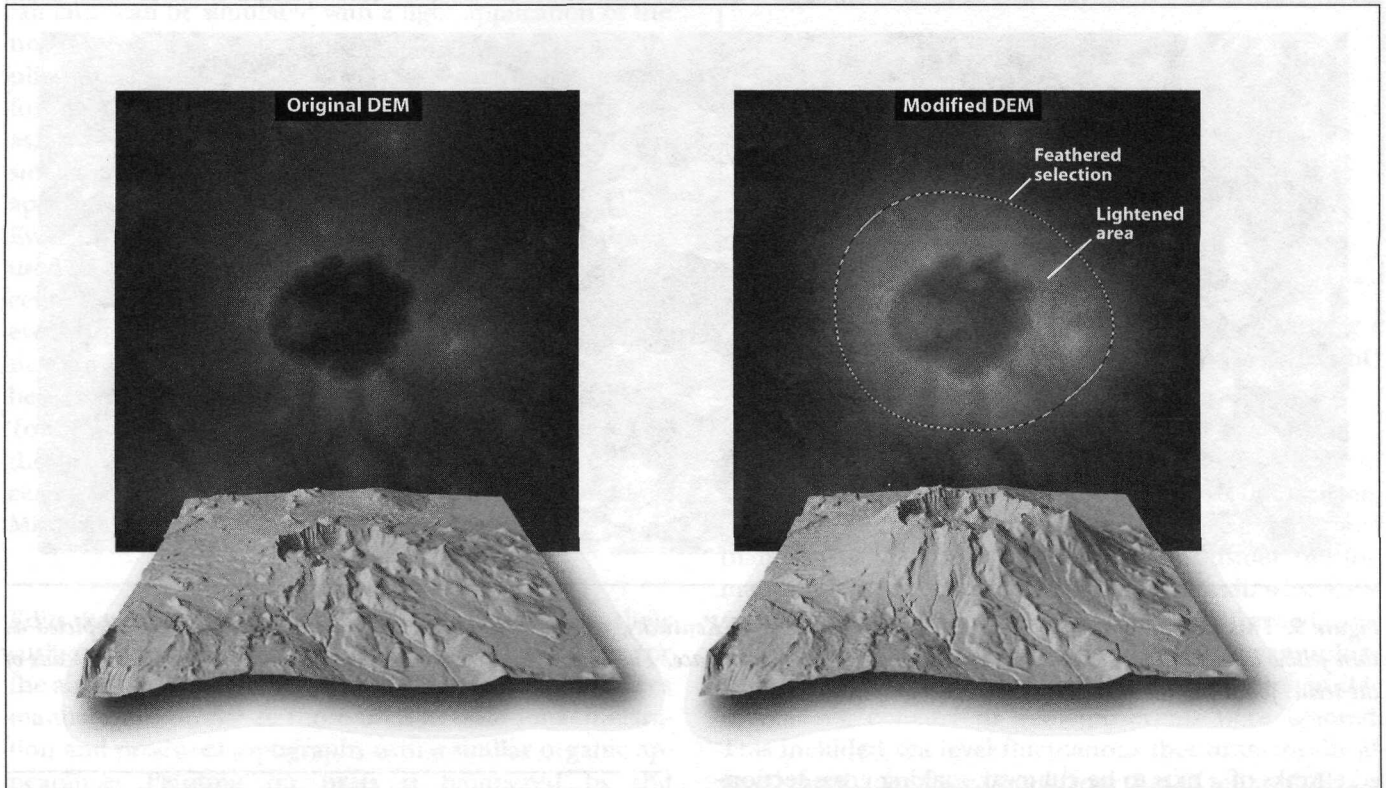


Figure 7. Selective vertical exaggeration applied to a DEM of Crater Lake, Oregon.

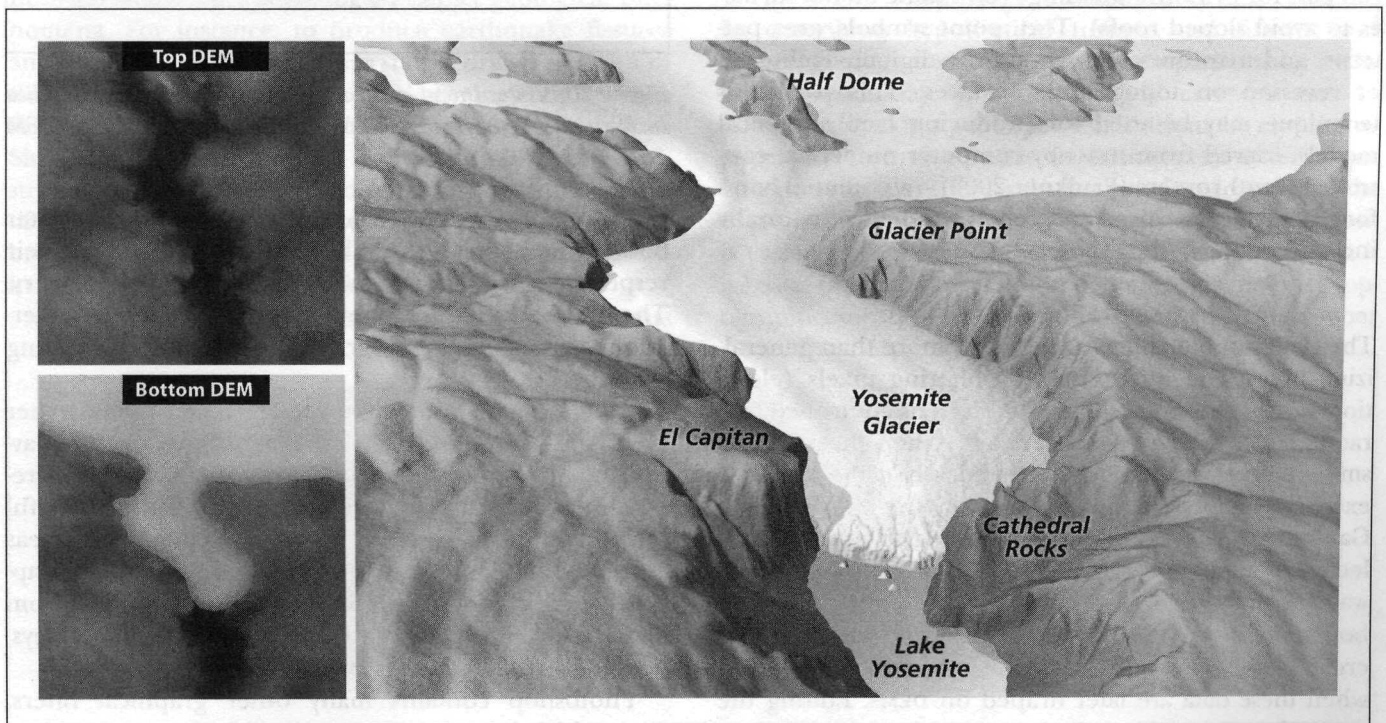


Figure 8. (Right) Yosemite Valley ca. 20,000 B.P. Placing two DEMs (left), one on top of the other in Bryce, created the glacier by extruding the bottom DEM containing the glacier bulge through the top DEM of today's landscape.

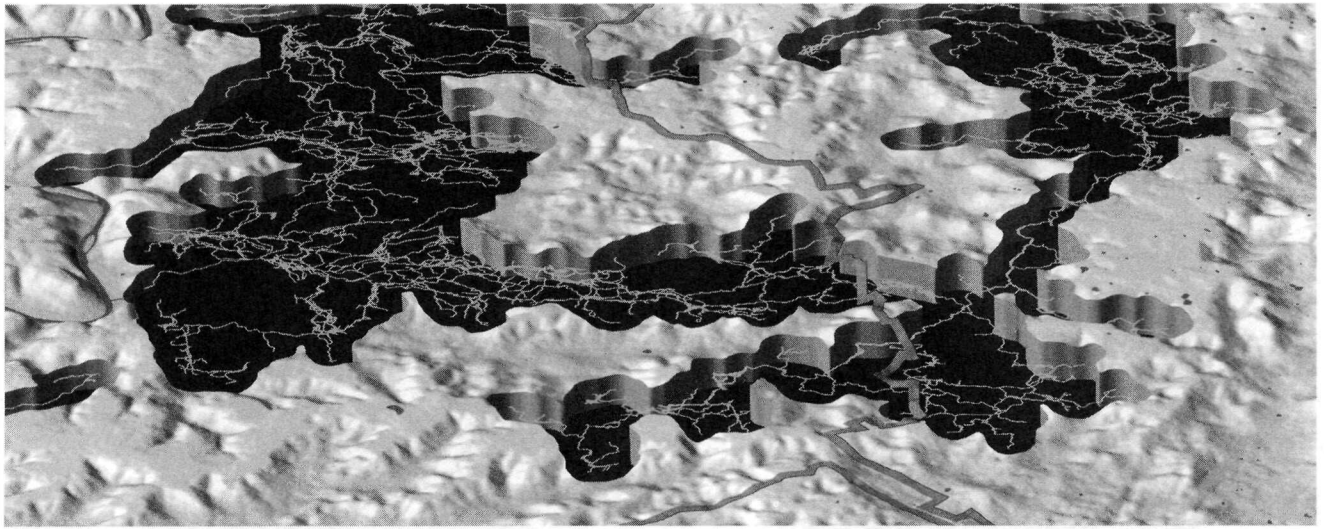


Figure 9. This portion of a cutaway view of Mammoth Cave, Kentucky, reveals some of the 563 kilometres of passages, depicted as thin yellow lines, that would otherwise be hidden beneath the surface. The park boundary crosses the cave cutaway on the right side of the scene, following the invisible surface topography.

ed chunks of a DEM to be cut away, making cross-sectional views or revealing hidden features beneath the surface (Figure 9).

Conversely, filling portions of DEM with white abruptly elevates these areas above their surroundings. On a large-scale DEM, filling small rectangular selections with white creates blocky shapes that, when extruded in 3-D, can pass for primitive buildings (best done on flat surfaces to avoid sloped roofs). Text, point symbols, area patterns, and map linework can also be digitally embossed or recessed on topographic surfaces. This particular technique may be used for producing tactile physical models, carved from DEMs by computer numerical controlled (CNC) routers (Faulkner 2002) – a potential boon for the visually impaired and general audiences naturally inclined to touch objects on display.

Filtering

The Gaussian blur filter is useful for more than generalizing DEMs. The filter works by filtering pixels (elevations) through a mathematical “soft” lens controlled by a radius slider, which removes detail. When the radius is small, the DEM is merely smoothed; when the radius is excessive and/or applied repeatedly, the DEM flattens. Gaussian blur flattening, when applied to imported selection boundaries, yields benefits. For example, land/water boundaries on DEMs often do not match the same boundaries on imagery or vector linework. This problem creates unsightly misregistration near the shorelines when these data are later draped on DEMs. Editing the DEM solves the problem. By importing a selection of water bodies taken from the geo-imagery or rasterized vectors (using the drag-and-drop technique described

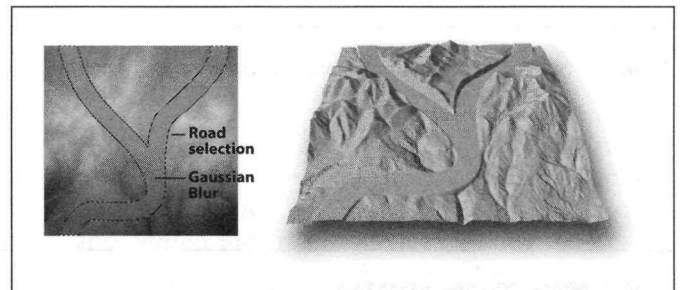


Figure 10. Virtual road grading: (Left) Gaussian blur applied to a road selection on a DEM. (Right) The modified DEM extruded in 3-D.

previously) and applying maximum Gaussian blur, water body surfaces on the DEM become perfectly flat at their respective elevations in concert with the draped imagery. The drawback to this technique is the occasional obliteration of distinctive topography immediately bounding water bodies.

Gaussian blur used in moderate amounts has other uses. Applied to a selected area on a slope, elevation-averaging produces terraces uncannily similar to those created by actual earth-moving equipment. This is a useful technique on large-scale DEMs to depict level areas around buildings. Moreover, moderate Gaussian blur applied to road selections removes excess height data from elevated protuberances and adds data to bisected valleys, creating virtual road cuts and fills (Figure 10).

Photoshop contains many other graphical filters, some which have practical application for DEM manipulation, particularly for the creation of landcover textures. For example, aa lava (a variety of rough-surfaced Hawai-

ian lava) can be simulated with a light application of the noise filter. Median and/or Gaussian blur filtering applied in addition to the noise filter creates a hummocky forest-like canopy. Rock texturing in high-mountain areas, as a replacement for hand-drawn rock hachuring on small-scale maps (the impressionistic results would be inappropriate at larger scales), is another potential use. Even filters that operate only with 8-bit data could be used in this endeavour – the coarseness would only accentuate the frost-shattered alpine environment. Whatever the type of landcover texture created by filtering DEMs in Photoshop, the application of these filters must be extremely light to produce a mere hint of a texture. Too much filtering permanently alters the character of the underlying elevation data. Backup copies are a necessity because the technique requires experimentation. Mistakes will invariably occur.

Painting

Edits may be made to DEMs by painting directly on their surfaces (using the rubber stamp tool as a substitute for the airbrush tool on 16-bit DEMs). DEM painting requires manual skills similar to those used in traditional illustration and produces topography with a similar organic appearance. Painting on DEMs is hampered by the disconnect between the appearance of the 2-D greyscale DEM (the surface that is painted) and 3-D model it will eventually become (see Figure 1). The problem is especially acute when painting subtle tones that can be difficult to see on the monochromatic surface of the DEM. Nevertheless, with practice the user can learn to paint DEMs effectively in Photoshop to depict geological phenomena. For instance, to produce earthquake fissures and glacial crevasses a user may simply draw a network of thin dark lines with tapered ends – an unsteady hand is, for once, a benefit. Stream erosion is another application. Sinuous dark tones applied with multiple light brush strokes, moving in an uphill direction, mimic the growth of drainage basins over time. If a progressively larger brush size with soft edge is used, drainage basins expand in volume to simulate natural erosion (Figure 11).

Painting on a DEM to depict temporal geologic events

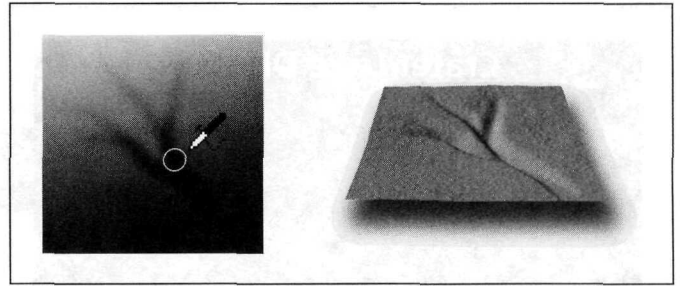


Figure 11. (Left) A greyscale DEM in Photoshop showing a dendritic stream drainage painted on a flat tilted slope. (Right) The DEM extruded and rendered in 3-D.

as an image sequence or animation requires decisions about generalization that are more difficult than for single-image views. Nature is often much more complicated than can be illustrated conveniently. Consider the formation of Haleakala Crater on Maui, Hawaii, which, despite its name, is an erosional feature formed over 900,000 years by coalescing amphitheatre stream valleys (Figure 12). To keep this visualization comprehensible to readers, concurrent geologic events were ignored. This included sea level fluctuations that dramatically altered the shape of the island from that of today; differential erosion rates on the windward and leeward shores; post-erosional volcanic events that repeatedly filled valleys with lava; and the gradual lowering of the summit elevation by about 600 metres. In a geologic visualization, less is often more.

Topographic Substitution

In describing hypothetical former and future landscapes, geology texts often make comparisons to analogous present-day landscapes. This concept can be applied to making geologic visualizations by cloning topography from one DEM to another in a technique known as topographic substitution. Providing that the user obtains appropriate DEMs, topographic substitution is easier than DEM painting from scratch and, because it is based on actual DEMs, looks convincingly realistic. Topographic substitution is accomplished with the rubber

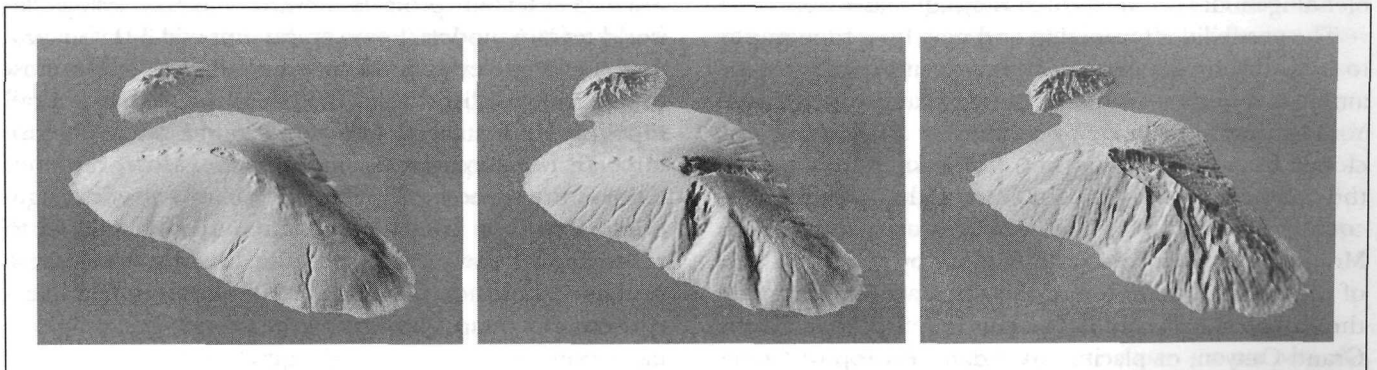


Figure 12. DEM painting used to depict nascent stream erosion on ancestral Haleakala (left and middle), a dormant 3056-metre shield volcano that dominates present-day Maui, Hawaii (right).

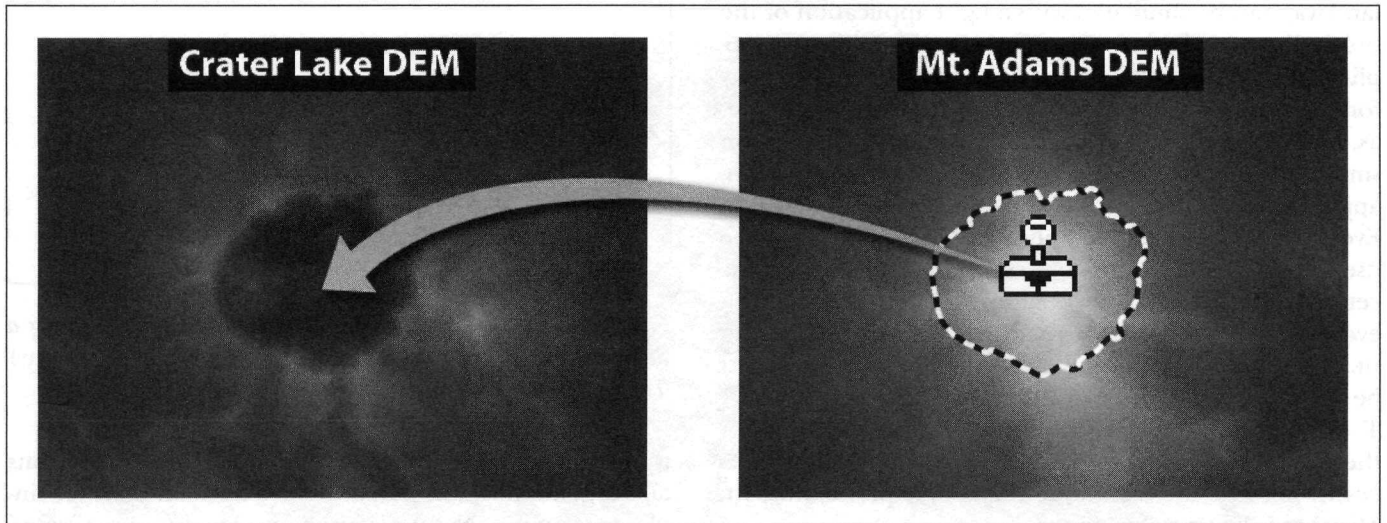


Figure 13. Cloning topography between DEMs in Photoshop.

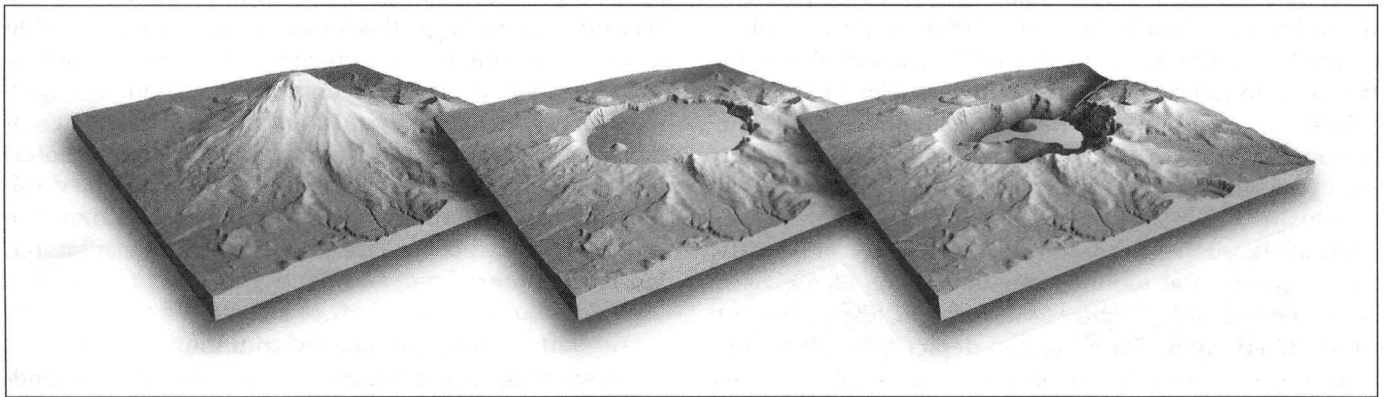


Figure 14. Crater Lake geologic evolution: (Left) Ancient Mt. Mazama created by cloning a DEM of present-day Mt. Adams, an analogous strato volcano in the Cascade Range of Washington state, onto a DEM of present-day Crater Lake (middle) upwards from the rim. (Right) A cloned DEM of today's Aniakchak Caldera, Alaska, depicts the breached caldera wall – the fate of many caldera lakes.

stamp tool by cloning data between simultaneously opened 16-bit DEMs (Figure 13). All of Photoshop's blending modes can be used at varying opacities.

The possibilities for mixing and matching topography to create hybrid landscapes are nearly unlimited. For example, a depiction of the primordial landscape of New York City could be made by combining a strato volcano, cloned from a present-day DEM of Alaska, onto a DEM of the bayou country of Louisiana. Other applications could include showing the weather-worn Appalachian Mountains in their former lofty glory by grafting a DEM of today's Rockies on top of the Appalachians; merging the Kaibab and Coconino Plateaus together to in-fill the Grand Canyon; or placing Mt. Adams on top of Crater Lake to depict ancient Mt. Mazama before it erupted and imploded to form today's caldera lake (Figures 13 and 14).

Projection Plane Warping

The projection plane of DEMs – the digital datum upon which 3-D terrain projects upwards – is flat. Using flat-world terrain models, however, can impede 3-D visualization. On low-elevation views the landscape looks most dramatically realistic when the horizon is visible, but tall topographic features in the foreground often obscure important features deeper in the scene. Moreover, even if the entire scene were visible, the oblique viewing angle renders surface information difficult or impossible to read. Raising the viewing elevation usually solves these problems, but then the landscape looks too much like a conventional map, eliminating the advantages of 3-D visualization.

A better solution is to emulate the view as seen from an aircraft. From high above the Earth the horizon is always visible, yet when you shift your eyes downward the

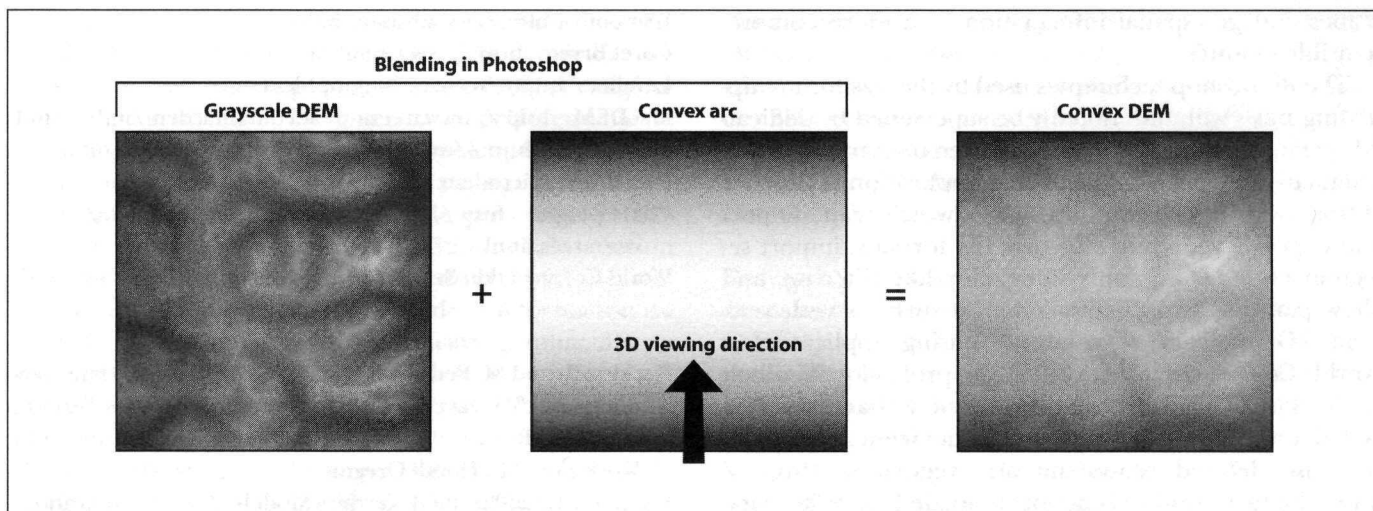


Figure 15. Merging a grayscale DEM (left) with a gradient representing an arc (middle) produces a convex DEM (right). 3-D scenes created from convex DEMs can be viewed only from a direction perpendicular to the convexity, which in this case would be from top to bottom or from bottom to top.

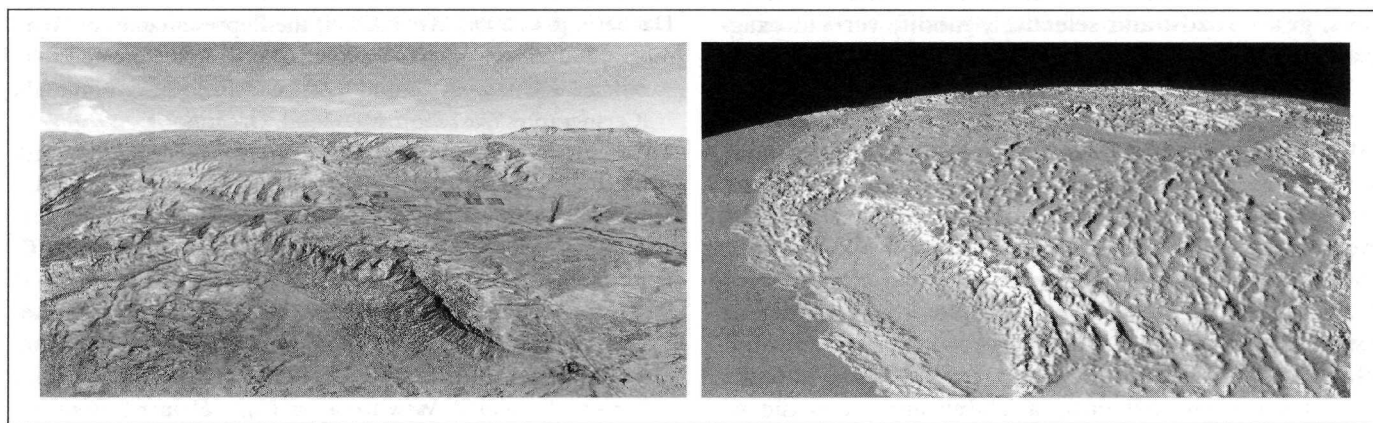


Figure 16. (Left) Pipe Spring National Monument, Arizona. Warping the projection plane of the DEM on a convex arc that tilts toward the viewer created the scene's map-like foreground and receding horizon. (Right) California and the western U.S. Warping DEM data on a sphere yields a domed topographic surface.

view gradually becomes less oblique and more planimetric. This effect can be brought to 3-D landscape visualization by adding convex curvature to the DEM in Photoshop and aligning the axis of convexity perpendicular to the 3-D viewing direction (Figure 15). The practical result is a 3-D scene that combines the best of both worlds: the foreground and middleground (where the important information resides) appear map-like, while the background appears realistic, complete with a horizon and sky (Figure 16, left). The technique borrows from Heinrich Berann, the renowned traditional panoramist and classical painter from Austria, who died in late 1999 (Patterson 2000). A variant of this technique, merging a small-scale DEM with a sphere in Photoshop, yields a domed landscape (Figure 16, right) reminiscent of the popular over-the-horizon maps created by Richard Edes Harrison for *Fortune* magazine during the post-World War II years (Schulten 1998).

Whether one is merging a DEM with a convex arc or sphere, a peculiarity of the technique is that vertical exaggeration of topography and projection-plane convexity cannot be adjusted independently. Increase vertical exaggeration on a convex DEM, and the projection plane will bow upward proportional to the height of the mountains. To ensure design options and to avoid production backtracking, I recommend exporting several convex DEMs that merge elevation and projection plane data by varying amounts, choosing the DEM that "looks right" when vertical exaggeration is applied in final 3-D production.

Conclusion

Using Photoshop to manipulate DEMs – a purpose for which the software is not specifically intended – has enabled the NPS to enhance 3-D visualizations economically, ultimately benefiting park visitors by presenting land-

scapes and geo-spatial information in a more comprehensible manner.

The Photoshop techniques used by the NPS for manipulating DEMs will undoubtedly be superseded by dedicated terrain applications that allow geo-data to be edited interactively. One such promising application is Leveller (<http://www.daylongraphics.com>), which can import and export a wide range of DEM file formats, import selection boundaries, apply Photoshop-like filtering, and allow painting and cloning on DEM surfaces with real-time 3-D feedback. Another promising application is World Construction Set (WCS), a professional, albeit challenging, 3-D landscape application that uses geo-coded data to render photo-realistic scenes complete with user-defined ecosystems and vegetation (<http://www.3dnature.com>). Using DEMs loaded into its database, WCS calculates varying amounts of topographic detail on-the-fly to depict background areas with less detail than the foreground, enhancing 3-D depth and speeding rendering times. WCS also uses imported vectors, called TerrafactorsTM to etch drainages onto DEM surfaces, grade roads, and selectively modify vertical exaggeration.

In addition to emerging software applications, new varieties of DEM data show promise for 3-D terrain presentation. DEMs derived from LIDAR (light detection and ranging) data sets, for example, show subtle surface details such as tree canopies, road cuts, and cliffs (Buckley and Renslow 2002). These data, when used with restraint and in conjunction with generalized DEMs, have the potential to represent topography (including a veneer of textured landcover) in a highly realistic fashion. On the other hand, critical data limitations still remain. The various DEM formats currently available are incapable of modelling vertical surfaces and overhanging topography. Some of the world's unique landscapes – Arches National Park, Utah; Mammoth Cave National Park, Kentucky; and the vertical climbing walls of El Capitan, Yosemite National Park, California, are beyond the representational limits of DEMs. Perhaps future cartographers will have at their disposal a "DEM-Plus" format that can adequately depict these features.

The design and production of 3-D maps in general, and the representation of 3-D terrain in particular, is a relatively unknown field to the mainstream (2-D) cartographic community. The rules and conventions that have guided cartographers for centuries largely do not apply to 3-D mapping, despite its growing popularity and the need for design standards (Haeberling 2002). As cartographers begin to embrace 3-D mapping using new software applications and data formats, the DEM manipulation techniques discussed here will, I hope, contribute to our understanding of 3-D terrain presentation and serve as a benchmark for further visual exploration.

Software

Adobe Photoshop <http://www.adobe.com>

BSmooth <http://www.bsmooth.de>

Corel Bryce <http://www.corel.com>

Leveller <http://www.daylongraphics.com>

MacDEM <http://www.treeswallow.com/macdem/index.html>

MicroDEM <http://www.usna.edu/Users/oceano/pguth/website/microdem.htm>

PBM+ plug-in <http://http://www.nacis.org/cp/cp28/resources.html>

World Construction Set <http://www.3dnature.com>

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Résumé La manipulation des surfaces d'un Modèle Numérique de Terrain (MNT) à la manière d'une pâte à modeler permet une amélioration notable de l'apparence et de la lisibilité de la topographie 3D des cartes. Le National Park Service (NPS) américain utilise le programme d'édition d'images *Photoshop* pour manipuler les données MNT. L'exportation de données MNT retravaillées à l'aide de logiciels (freeware) et de logiciels (shareware) permet ensuite une modification ultérieure de scènes finales 3D dans Corel *Bryce*. Parmi les tech-

niques présentées se trouvent : la substitution topographique, une méthode permettant la projection de paysages actuels dans le passé ou dans le futur ; l'exagération verticale sélective ; l'augmentation préférentielle de résolution, une technique développée spécifiquement pour améliorer la lisibilité des paysages de haute montagne ; les effets de filtres et de peintures ; et empruntée aux maîtres paysagistes traditionnels, la création de scènes 3D imitant les panoramas de Heinrich Berann ou les vues sphériques de Richard Edes (déformation du plan de projection du MNT). La cartographie 3D de montagne, ainsi qu'un design parfait sont les pierres angulaires du programme cartographique du NPS.

Zusammenfassung Indem man Digitale Höhenmodelle (DHM) – wie beispielsweise die Modellierung von geschmeidigem Ton – manipuliert, beeinflusst man das Erscheinungsbild und die Lesbarkeit der 3D-Topographie auf Karten. Das U.S. National Park Service (NPS) verwendet die bekannten Zeichnungswerkzeuge in Adobe Photoshop, um gerasterte DHM-Daten zu manipulieren. Das Exportieren der modifizierten DHM-Daten mit Hilfe von Freeware und Shareware-Software ermöglicht die Darstellung von 3D-Szenen in Corel Bryce. Die zu diskutierenden Techniken beinhalten topographischen Ersatz, eine Methode zum Nachbauen gegenwärtiger Landschaften in die Vergangenheit oder in die Zukunft; Selektive vertikale Überhöhung; Das Erzeugen auflösungsbezogener Unebenheiten, eine Technik, die speziell zur Verbesserung der Lesbarkeit von Hochgebirgslandschaften entwickelt wurde; Zeichen- und Filtereffekte; und, indem man vom traditionellen Meister der Landschaftsbeschreibung das Erstellen von 3D-Szenen übernimmt, ahnt man die Panoramen von Heinrich Be-

rann, sowie die kugelförmigen, Vogelschaubilder von Richard Edes Harrison nach, indem sie die Projektionsflächen verformen. Die einmaligen Herausforderungen der 3D-Gebirgskartenerstellung und das fortlaufende Bestreben nach ausgezeichnetem Design – ein Eckpfeiler des kartographischen NPS-Programms – sind die allumfassenden Themen der NPS-Kartographie.

Resumen El tratamiento de superficies generadas con modelos digitales de elevaciones (Digital Elevation Model DEM), al igual que la utilización de modelos flexibles de arcilla, permite mejorar la apariencia y legibilidad de la información sobre el relieve de los mapas. El U.S. National Park Service (NPS) utiliza las herramientas de edición de imágenes incluidas en Adobe *Photoshop* para manipular los datos raster de modelos digitales de elevaciones. Estos datos se exportan, con la ayuda de herramientas de uso gratuito, y permiten la generación de escenas 3D en Corel *Bryce* utilizando técnicas de "rendering". Las técnicas descritas incluyen la sustitución topográfica, un método que permite cambiar los paisajes actuales por los paisajes pasados o futuros; la exageración vertical selectiva; la resolución "bumping", una técnica desarrollada específicamente para mejorar la legibilidad de paisajes de alta montaña; los efectos de pintura y filtraje; y, continuando la tradición de los maestros de representación del paisaje, la creación de escenas 3D que emulan los panoramas de Heinrich Berann y las vistas esféricas sobre el horizonte de Richard Edes Harrison deformando la proyección plana de los modelos digitales del terreno. Los desafíos en la representación de cartografía 3D de montaña y la búsqueda continua de un diseño de calidad son la piedra angular del programa cartográfico del NPS.