3.2 Ground, Aerial, and Satellite Photography for Geomorphology and Geomorphic Change

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Glossary

Change detection The use of repeat photography or images acquired at different time periods to detect and map changes on the landscape.

Colorimetry Science and technology used to describe physically, the human perception of color.

Film-return satellite An early generation of orbital satellites with onboard cameras whose film was ejected periodically by parachute return vehicle to be collected and developed.

Forward-looking, infrared radiometer (FLIR) A portable device to obtain thermal or temperature-based images of phenomena.

Gigapan technology Gigapixel-panorama technology using digital cameras for an aggregated single image that can be browsed and zoomed at multiple scales from macroscale to microscale.

Megageomorphology Geomorphology of large regions (regional geomorphology) enabled by space photography or satellite images that cover broad areas.

Photogrammetry Practice of determining geometric properties of objects from photographic images, in some cases with dimensionally accurate and precisely rectified aerial photography.

Spectrophotometry Quantitative measurement of the spectral reflectance or transmittance of an object as a function of wavelength.

Stereoscopy A technique for creating an illusion of depth by presenting two offset photographs or images to the left and right eye of the viewer.

Thermal imaging (thermography) Thermal imaging cameras detect radiation in the thermal infrared region of the electromagnetic spectrum and produce images of the emitted radiation as thermograms.

Time-lapse photography Individual picture frames of slowly moving or changing objects taken repeatedly from a fixed position over some intermittent time period, and then sequentially viewed to depict environmental change.

Videography The process of capturing sequential images that depict object or landscape change.

Abstract

Historically, repeat coverage enabled change detection and study of landscape evolution. Today, digital cameras and videography permit new capabilities in terms of producing ground, aerial, and space 'photography,' as geomorphologists still rely on spatial data collected from camera sensors that enable them to collect field data and document geomorphic events and environmental change. Active geomorphological research now involves the acquisition of digital photography/ imagery, videography, and the use of historical photography, as historical data must serve as baseline data that is compared to recently collected data for detecting and measuring geomorphic change. Digital camera technology has rapidly evolved,

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and scientists now use these sensors to record flooding, volcanic, mass movement, and other events. Movies and videos of geomorphic phenomena, especially transient processes such as landslides, debris flows, or time-lapse glacial activities are an essential research and teaching element. Finally, new gigapixel-panorama (gigapan) technology will provide new capabilities to assess multiscale geomorphic phenomena.

3.2.1 Introduction

Understanding surface processes and process–form relationships, and conveying that understanding requires conceptual, qualitative description, quantitative characterization, and graphic depiction. Several centuries ago, graphic depiction consisted solely of scientific illustrations, primarily artistic field sketches of greater or lesser capability and complexity (Merriam, 2009). Line drawings, sketches, or watercolors were commonly used in the field, and a well-trained young scientist, particularly in Europe, normally had some formal education in drawing to assist their field work. This useful manner of touristic, military, or scientific illustration was largely supplanted by widespread use of cameras by the early twentieth century, and the ability to make skillful field sketches and hand-drawn illustrations has been replaced with newer technologies, involving new platforms and sensor technologies for acquisition of various forms of photography.

The idea of using a camera for field documentation, however, is almost as old as the first cameras themselves. For example, in 1838–42, F. Catherwood used camera-lucida projections to make accurate drawings of Mayan ruins, while also documenting their weathered condition with daguerreotypes only shortly after the invention of that camera-film type (von Hagen, 1947). Malde (1973) noted that the camera 'sees' all of the intricate qualities of the terrain that might otherwise escape notice and never make it into the field notebook. Such things include weathering stains on outcrops, soil cracks and small rills on bare ground, plant species and growth patterns, and countless other features and environmental characteristics that are impossible to specifically map and describe by any other reasonable means.

The earliest known use of what is referred to by the military as an 'overhead platform' to observe the ground during the French Revolution in the late eighteenth century was when aerostiers, or balloonists took to the skies. In the nineteenth century, military photographs from balloons in the American Civil War were used to document enemy positions in landscapes, as well as to obtain high-angle views of the terrain. This capability from the air has undergone various stages of development over time that have proven quite useful to geomorphologists. For example over a century ago, G. Lawrence devised cameras weighing >453 kg (1000 lb) that took panoramic pictures as large as $1.4 \text{ m} \times 2.4 \text{ m}$ ($4.5 \text{ ft} \times 8 \text{ ft}$) from heights of >600 m from balloons and kites. Of relevance to geomorphology were his panoramas aloft of the results of the great San Francisco earthquake (Rosenberg et al., 1966). In the early twentieth century, shortly after the invention of the airplane, aerial cameras were beginning to be used for mapping, and between World War I (WWI) and World War II (WWII), aerial-survey techniques were extensively developed. Cameras in airplanes were flown for reconnaissance before WWI, but geomorphologic studies with them were not done at that time. This is thought in part to be because early conceptions of idealized and hypothetical terrain conditions and preconceived notions of geomorphic genesis through time were presented primarily as artistic block diagrams (Lobeck, 1958; Hayden, 1986).

Between the two world wars of the twentieth century, an enhanced development of aerial photography was undertaken and the photogrammetric principles of aerial photography for mapping were elucidated (Bagley, 1922; Lee, 1922; Reeves, 1927; Ashworth, 1937). Then with the advent of new aerial photography for WWI, extensive development of the use of aerial photographs occurred. Where direct overflights were possible, vertical aerial photographs prevailed, in which overlapping photographs along flight paths allowed stereography, wherein pseudo-three-dimensional (3-D) relief was possible to visualize. Commonly however, low-oblique aerial photographs (without the horizon), or high-oblique photos (with the horizon) had to be taken from a distance, and then projected into the vertical using the principles of photogrammetry in order to make a map. After the war, the systematic use of such postwar photography permitted detailed topographic mapping (Smith, 1943), thereby allowing this geomorphic research medium to achieve its apogee of technical formulation.

In the latter half of the twentieth century, the Cold-War drive to 'command the high ground' led to the race into space by the USA and the Soviet Union. This endeavor resulted in the development of a host of new technologies, including photographic and imaging sensors aboard a multitude of satellites.

Numerous sensing devices have moved from experimental to effectively operational, and from aerial to space-based, or from space-based to ground-based, such that new sensors for producing digital photography and imagery are commonplace. Many of these technologies overlap considerably in terms of data acquisition, manipulation, analysis, and geomorphic application. Therefore, the objective of this chapter is provide examples of the use of historical photography, as well as some newer technologies that are not be covered elsewhere in the Treatise on Geomorphology.

3.2.2 Data Acquisition

The first known photographs were daguerreotypes produced in 1839, and shortly thereafter the science of photogrammetry started, although the term 'photogrammetry' did not come into common usage until the mid-twentieth century (Whitmore and Thompson, 1966). In the mid-nineteenth century, photography began to be used to make topographic maps by combining surveying theodolites with cameras. In the latter half of the nineteenth century many early photographers of the new (to them) lands of the western USA, such as W.H. Jackson, A.J. Russell, and others, were led to document the exciting new landscapes that were being discovered. These professional photographs, and any number of more amateur attempts up to the present day, constitute a collection of photographs that are valuable for landform analysis as well as constituting historical documents. Consequently, much effort is being focused nowadays on electronic storage and computer analysis to generate digital presentations and animations of geomorphic change.

Cameras, of course, can be used in a variety of ways to permit accurate delineation and measurement of geomorphologic phenomena. It is not the purpose of this chapter, however, to relate the geometric or algebraic details of photogrammetry to enable quantitative geomorphic measurements because other sources do that in detail (e.g., Thompson, 1966; Malde, 1973; Graf, 1985; Lane et al., 1993). Nonetheless, it should be noted that major objectives of ground-based geomorphologic research are characterizing, measuring, and explaining surficial processes as they vary spatially and temporally across landscapes. Measuring dimensions of landforms is a standard method to make such observations, and the methods of photogrammetry using ground-based and aerial cameras enable many useful measures to be obtained.

In an interesting new usage of photography in documentation for later geomorphologic interpretation, J.P. MacCalpin has described what he terms as objective, 2-D photomosaic, and 3-D photogrammetric logging of exposed trench faces (*see* Chapter 14.12). These techniques (Coe et al., 1991; Fairer et al., 1989) are designed to capture all the essential details of sediment clast size, grain orientation, color, structure, and all other fine information to document exactly what a subsurface trench wall looks like so as to be best able to interpret past events in the stratigraphy relating to the formation of the landforms. Processes of ground rupture and sedimentation attendant to past earthquakes, slope failures, or karst subsidence may be much better understood and explained in this fashion in the investigation of the subsurface of fault scarps, landslides, or sinkholes.

Beginning in the late 1940s, the desire to monitor developments inside the Soviet Union and its satellite countries to prevent another 'Pearl Harbor' surprise attack led to a plethora of classified airborne and spaceborne platforms for photography of the Earth's surface. The reconnaissance versions of high-altitude bombers, especially the RB-26, RB-29, RB-50, RB-47, RB-57, RB-58, and the later purpose-built reconnaissance aircraft – the U-2 and the SR-71 – allowed photography during the Cold War, but little useful geomorphology is known to have ever been obtained from them.

Before the declassification in 1995 of the historic photographs taken by the generations of spy satellites, the few available photographs of the Earth's terrain from space in the early days were those taken by orbiting US astronauts. At first in the manned space programs in the 1960s, handheld camera photographs by the astronauts through porthole windows in space capsules were only barely possible, and their use in geomorphology has been rather limited. The four Mercury orbital missions primarily used the Swedish-made precision Hassleblad cameras, but it was only on the last two missions, MA-8 and MA-9, that systematic terrain photography was a formal experiment (Lowman, 1996). Astronauts W.M. Schirra and L.G. Cooper took photographs that received widespread publicity.

The follow-after Gemini program (Underwood, 1967; Lowman and Tiedemann, 1971) had a Synoptic Terrain Photography Experiment (S005) that produced some 1300 usable 70 mm color pictures of Earth's terrain (**Figure 1**). Some resulting Gemini photographs were published in Life, National Geographic, and many newspapers to engage the public's interest. It was only later that the progressive diminutions of Lake Chad in Africa and the Aral Sea in Central Asia were documented through repeat photography that the values of such data were realized for change detection. Photography obtained from the Gemini astronaut program was the stimulus to what ultimately became the Landsat series of fairly standardized acquisition of satellite multispectral imagery. In 1966, the US Geological Survey had proposed an Earth Resources Observation Satellite (EROS), whose name was later changed to Earth Resources Technology Satellite (ERTS), and finally, Landsat. Early satellite imagery was low resolution that showed only broad areas at small scale, but even so this enabled views of megageomorphology (wherein huge areas of the Earth's crust could be viewed collectively to gain understandings of regional geomorphology).

Well before astronaut photographs entered the public domain, several series of satellites were acquiring greater than 860 000 detailed photographs of many parts of the Earth's surface, but the photos were unavailable for general scientific or geomorphologic use. After declassification by the Clinton–Gore executive branch of government in 1995, geomorphologists were able to access the treasure trove of available espionage-satellite data for the first time (**Figure 2**). In spite of the unavailability of some critical photogrammetric documentation and deficient metadata that impedes some usages, the historical data from widely dispersed parts of the world are an unusual source of information that can be used in any number of change detection or other studies in geomorphology.

Figure 1 Astronaut photograph from the Gemini 4 mission of 1966 showing the delta of the Nile River in the foreground and center, with the Suez Canal area in the middle ground and the Red Sea, Gulf of Aqaba, and Dead Sea in the background. Courtesy of US Government.

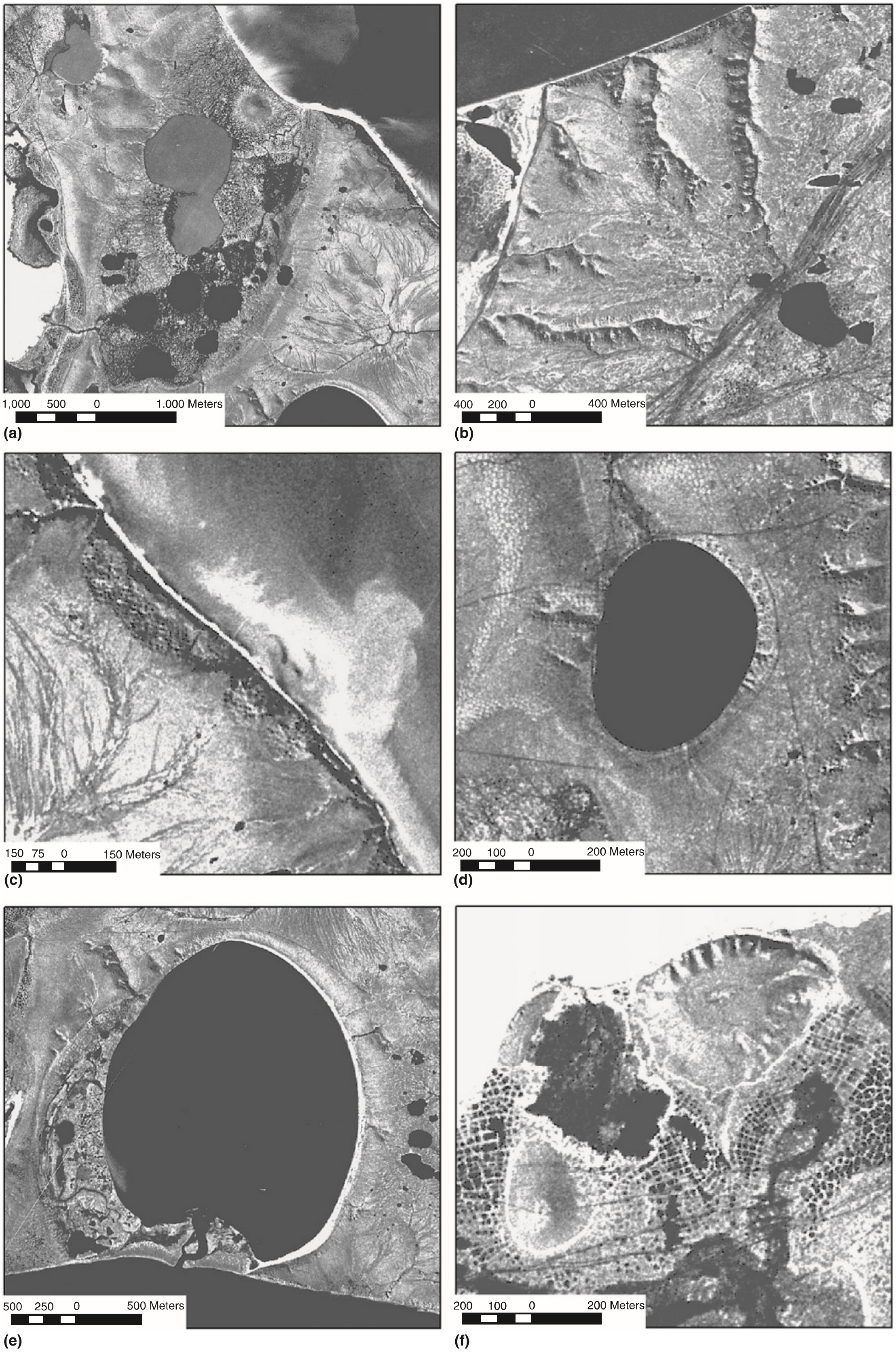


Figure 2 Periglacial geomorphological features on the Bykovsky Penninsula of the northeast Siberian coast identified from Corona photographs of July 1969. Courtesy of US Government.

Table 1 Early generations of espionage satellites with film return by ejected canister in the Keyhole program whose large number of declassified photographs can be accessed from the US Geologic Survey's EROS Data Center for change detection and other studies in geomorphology. Each satellite number may represent multiple satellite systems as 144 satellites alone were launched in the Corona program

Satellite number	*Satellite name*	*Resolution (m)*	*System operation*
KH-1	Corona	~7.5 m	1960–72
KH-3	Corona	~7.5 m	
KH-4	Corona	~7.5 m	
KH-4A	Corona	~2.75 m	
KH-4B	Corona	~1.8 m	
KH-7	Gambit	~48 cm	1963–67
KH-8	Gambit	~10 cm	1966–84
KH-9	Octagon	~15 cm	1971–86

The US National Reconnaissance Office (NRO) has operated satellites for the national intelligence community for some time. Beginning in June of 1959 the NRO launched and operated a number of Earth-observation satellites. Only the early film-return satellites are discussed here (**Table 1**); imagery from later satellites has not been declassified. In general the film-return CORONA, ARGON, and LANYARD satellites were in elliptical orbits ranging from a low of ~280 km to a high of ~1006 km above the Earth's surface. Each satellite passed over its assigned observation target on the ground approximately twice a day. At appropriate times, canisters of exposed films were ejected over oceans, made reentry and deployed parachutes at lower altitudes, where most were successfully caught by US aircraft, although some floated for a time until the US Navy could intercept them. Others that were not recovered quickly were designed to sink to deny them to other espionage agencies. A large number (144) of satellites were launched under the CORONA program and 102 returned usable data.

Many of the now-declassified scenes were acquired in stereographic mode from forward and aft-pointed cameras (relative to the direction of motion of the satellites). Some stereo viewing of the ground surface is possible, although spatial distortions caused by forward camera motion, scan time, and imaging of a 'bow–tie' shaped area of the ground that was compressed into a rectangular image frame in the Corona system makes such viewing rather difficult (Casana and Cothren, 2008). Distortions in the Corona images can be corrected using a rigorous model (e.g., Schenk et al., 2003; Sohn et al., 2004), or a simple photogrammetric frame model (Altmaier and Kany, 2002). The distortions can be further removed using ground-control points for geometrically correcting the data.

In practice, one might have expected such declassified data to have been used much more in geomorphology. For example, in the Global Land Ice Measurements from Space (GLIMS) project begun in the late 1990s that was designed to monitor the world ice masses, researchers have used declassified satellite data to identify the terminus positions of glaciers in the Hindu Kush and the Himalaya (Bishop et al., 2004; Kargel et al., 2005), and stereoscopic mapping of rockslide denudation there as well (Shroder et al., 2010). Rao (2009) used declassified satellite data to map beach ridges on the Godavari delta in India, and Grosse et al. (2005) were able to map a wide variety of periglacial geomorphology (thermokarst depressions, lakes, and lagoons; thermoerosional cirques and valleys; pingos) in northeast Siberia with the imagery (**Figure 2**).

The US Geological Survey maintains these images at its EROS Data Center, in Sioux Falls, SD, and beginning in 2005 began distributing images scanned directly from the original film strips at resolutions of up to 7 μm, which produces much crisper images than the previous contact prints provided (Casana and Cothren, 2008). Inasmuch as over 800 000 of these images were acquired and the collection of Corona material alone included 2.1 million ft of film in 39 000 cans, the terrain information contained in these sources is enormous and can be used to facilitate geomorphological research.

Other official NASA campaigns of terrain photography were also undertaken (Robinson et al., 2002). These include data acquisition during the Earth-orbiting Apollo missions (Colwell, 1971), the Apollo–Soyuz mission (El-Baz, 1977; El-Baz and Warner, 1979), Skylab (NASA, 1974; Wilmarth et al., 1977), some Shuttle missions (Jones et al., 1996), and the Shuttle–Mir missions (Evans et al., 2000). As of 30 September 1999, some 378 461 photo frames had been included in the database (Office of Earth Sciences, 2000), but approximately 50% have been deemed not useful for remote sensing applications, which leaves some 190 911 possibly suitable for Earth science related studies (Robinson et al., 2002).

With the large number available, astronaut photographs can be an excellent source of data for different studies, and the best case resolutions are similar to Landsat or SPOT imagery with pixel resolutions down to <10 m (Robinson et al., 2002). As public domain information, costs are minimal to nothing, and these images can be quite useful in filling in time-series gaps where other imagery are not available. Access to the complete and available database of astronaut photographs, including low-spatial-resolution browse images, is available via the web (Office of Earth Sciences, 2000). Such images posted on the web are of low quality, but high-quality images can be obtained on request for no cost (Robinson et al., 2002).

In recognition of the great advances made in visualizing the geomorphology of the Earth's surface from space, NASA produced a large volume with copious pictures that represent an atlas of regional landforms (Short and Blair, 1986). This atlas has as its core, 237 color or black and white plates, each of which consists of a space image with accompanying commentaries, explanations, together with three or four informative and enhancing aerial and/or ground photographs (Lattman, 1987). Astronaut photographs, Landsat images, radar, and thermal images are included as well. Twelve extensively illustrated chapters on regional, tectonic, and global geomorphology are included, as well as detailed information regarding process types and geomorphological mapping.

3.2.2.1 Photographic Scale

The mere existence of historical photography does not mean that the data are suitable for specific geomorphological studies. In addition to the typical problems of cloud cover, vegetation cover, and differential illumination causing extensive shadowing, the issue of photographic scale must be accounted for. This is especially the case for process-based versus mapping-based studies, as photographic scale in relation to the spatial complexity of the landscape, and the phenomena of interest, dictates photographic-scale requirements. In general, large-scale photography can be used for detailed geomorphological mapping, although aerial coverage is limited and requires the mosaicking of photographs. Medium scale photography addresses this issue as long as the landforms or features can be detected and differentiated from other objects. Regional geomorphological mapping can be facilitated by medium- and small-scale photography although the level of detail progressively worsens. These issues have been extensively addressed in the past and readers are directed to manuals and textbooks, especially those published by the American Society for Photogrammetry and Remote Sensing.

3.2.2.2 Temporal Coverage

Two types of repeat photography or repeat imagery can be recognized: (1) obtaining historical ground or aerial photographs for modern replication and (2) establishment of photographic or videographic monitoring stations that are meant to be replicated in the future for various purposes. Sources of historical photography are varied and commonly obscure enough that Graf (1985) recognized a convergence of interest between the geomorphologist, historian, and even the detective to ferret out locations of known historical photographs, as well as to find out whether photographs exist at all for certain important areas. Government agencies are obvious sources of a plethora of photographs, and local historical societies are another major source. Postcard collections in antique shops and the popular parlor stereopticon pictures of the nineteenth century provide useful historical photographs as well. A major problem in all searches for useful photographs to use in rephotography studies is that indexes are generally not at all relevant, and the search for photographs to use in repeat photography forces the researcher to use visual inspection of historical photographs, one photo at a time. In some cases somewhat fortuitous photographs have given geomorphologists the ability to 'see' long-term processes in action. For example, Stephenson et al. (Chapter 10.11 in this volume) and Shepard and Kuhn (1983) used historical photographs to document the evolutionary development of coastal sea caves on peninsulas into arches by wave erosion.

Historical photographs of any area in the world may or may not be difficult to acquire, although by far the most difficult job once the photograph has been obtained, is to reestablish the original standpoint in the target photograph. In some cases, only a reasonable approximation is possible, whether because the original standpoint was on a boat on a body of water, or was inundated subsequently, or is covered with new or growing vegetation, or might be too hard to find or to get to (A. Byers, oral communication, 2007; B. Molnia, oral communication, 2009). In order to facilitate finding difficult locations, Hanks (2006) for example, has engaged in 'virtual repeat photography' wherein digital aerial photographic data are draped over a digital elevation model (DEM) to locate past camera stations that would have been difficult or impossible to find otherwise.

In terms of temporal coverage where historical photographs were not available, R. McInnes of the Isle of Wight consultancy, Coastal and Geotechnical Services in the UK, compiled an array of more than 1000 sketches, prints, watercolors, and oil paintings of the Isle of Wight off the southern coast of England and the adjacent Hampshire coast that record the changes and landform evolution there since 1770 (Johnson, 2009a). He and his colleagues developed a ranking system of the art based on up to five factors for accuracy determinations that enabled useful comparison for delineation of change over time. In general, the watercolors of the nineteenth century were the most accurate because they were designed to record the actual landscape, especially as tourists or military artists wanted to record information to explain their travels and observations (**Figure 3**).

The capture of photographs of geomorphic processes in action have been obtained over the years by people with movie or video cameras at the right place and time in the field, or in wind tunnel or flume experiments, and other such laboratory manipulations (**Table 2**). For example, videos of landslides have been taken, such as the famous quick-clay failure in Rissa, Norway, in April 1978, as well as a wide variety of other slope failures, or rapid wet debris flows (**Video 1**) in various parts of the world (California, Japan, China, Afghanistan, and Pakistan). Many of these videos are available online through You Tube, Flickr, and other media outlets. Other processes that have been captured using videography include saltating sand grains, river meandering, flow and flooding (Gough, 2007), action of waves in eroding landforms and transporting coastal sediment, as well as a wide variety of volcanic processes including catastrophic eruptions, lava flows, formation of pillow lavas underwater, and so forth.

Figure 3 Wash sketch of rocks displaced by mass movement and an erosional residual pillar in Sinjao Nullah (gulley) a few km west of Herat Afghanistan, painted in 1885 by Edward Law Durand of the Afghan Frontier Commission during the border delineations of the country. Such sketches could be quite accurate delineations of landscapes in the 18th and 19th centuries when cameras were unavailable or quite rare. Print purchased from India Office Library, 1979; identification India Office, British Library, Prints and Drawings, shelfmark WD427. Copyright © The British Library Board.

Table 2 List of geomorphology videos that are available online at http://serc.carleton.edu/NAGTWorkshops/geomorph/visualizations.html (accessed 10 February 2011). Each of these topics listed in the original website opens onto a plethora of animations, images, and videos that show geomorphic processes at work in real field situations, or contrived laboratory ones

- River Geomorphology Videos – Videos of geomorphic process at work in rivers and river beds.
- Chemical Weathering – Animations and images dealing with chemical weathering.
- Coastal Wave Mechanics (in ocean systems) – Animations and movies depicting how waves and water molecules act along the shore and in deep water settings.
- Cryosphere – Visualizations dealing with the cryosphere as a whole.
- Deltas and Plumes – Images and animations that illustrate both modern and ancient delta systems. Photos and 3-D animations depict the development of deltas at various spatial and temporal scales.
- Dunes: Process and Form – Animations describing conditions necessary for producing form variations in sand dunes.
- Examples of Deglaciation – Animations of the deglaciation of North America and the removal of ice from the Bering Strait.
- Glacial Landforms Resulting from Erosion and Deposition – Animations presenting how depositional landforms like moraines and outwash plains form.
- Glacier Physics – Animations, images, and movies revealing how a glacier forms, moves, retreats, and in the case of tidewater glaciers, calving.
- Longshore Drift and Depositional Landforms – Animations and images showing a variety of depositional landforms resulting from longshore drift and the impact of river and coastal engineering projects on sediment transport processes.
- Mass Wasting/Landslides – Animations showing different types of landslides like slumps, slides, and falls in a variety of environments.
- Mountain Uplift and Erosion (in structural geology) – Visualizations illustrating the physical processes interacting to create mountain uplift and erosion.
- Physical Weathering – Animations and images dealing with physical weathering.
- Processes of River Erosion, Transport and Deposition – Animations showing processes of river erosion, transport and deposition.
- River Systems: Process and Form (in sedimentary geology) – Visualizations and supporting material that can be used effectively to teach students about physical processes acting in rivers and their floodplains.
- Rocky Coastlines and Erosional Landforms – Animations and images related to erosional landforms such as cliffs, arches, sea stacks and other morphological features.
- Soil Erosion – Animations of soil erosion, images of soils, and audio files about the Dust Bowl.
- Soil Horizons – Animations illustrating the development of soil horizons and their characteristics.
- Soil Orders – Animations showing distinct soil orders.
- Soils Physical Properties – Animations about the physical properties of soil.
- Waterfall Formation/Nick Point Migration – Animations showing how waterfalls are created; examples of spectacular waterfalls from around the world, and how falling water is used in hydroelectric power.

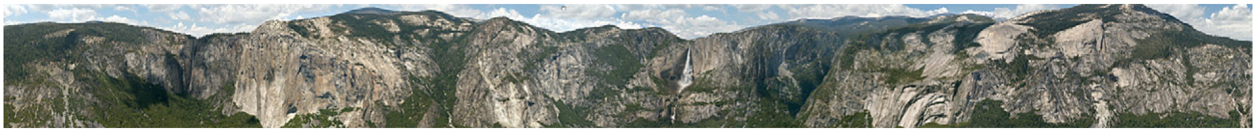


Figure 4 Extreme panoramic Gigpan picture of the north wall of Yosemite National Park. On the website, 14 snapshots can be selected and then zoomed in and out from one to another, showing fine details, such as climbers on walls, details of the rock and water, individual people, and other features. Interactive version available on http://www.xrez.com/, with permission from xRez Studio.

The online version of this chapter contains a Video with an **Animation 1**. The online version can be found at doi:10.1016/B978-0-12-374739-6.00041-5

Some largely imperceptible processes such as the slow ice flow of glaciers, or terminus retreat and calving are best captured by time-lapse photography in which individual picture frames are taken automatically once an hour or day, or some other time period. These data can then be used together to depict the movement of the phenomena that provides insights into process and mechanism. Where this is done by film production companies, they produce a product that provides for a relatively seamless transition, and maintain lighting conditions. In the real world of science given logistics, such conditions are not usually obtained. Instead, cameras are set to run automatically with batteries or solar power regardless of lighting conditions or processes velocities, which generally produces a jumpy, light-flickering, time-lapse series of images. Even so, and depending on the results captured, this can produce quite dramatic footage. For instance, the Extreme Ice Survey (EIS) is an example of recent ($\sim$2008) expedition work that Balog (2009) has done for glacier advance, retreat, and extreme calving for glaciers in Alaska, Greenland, Iceland, the Alps, and Andes, as part of the attempt to capture major cryospheric-change visuals for public presentation.

3.2.2.3 Digital Cameras and Videography

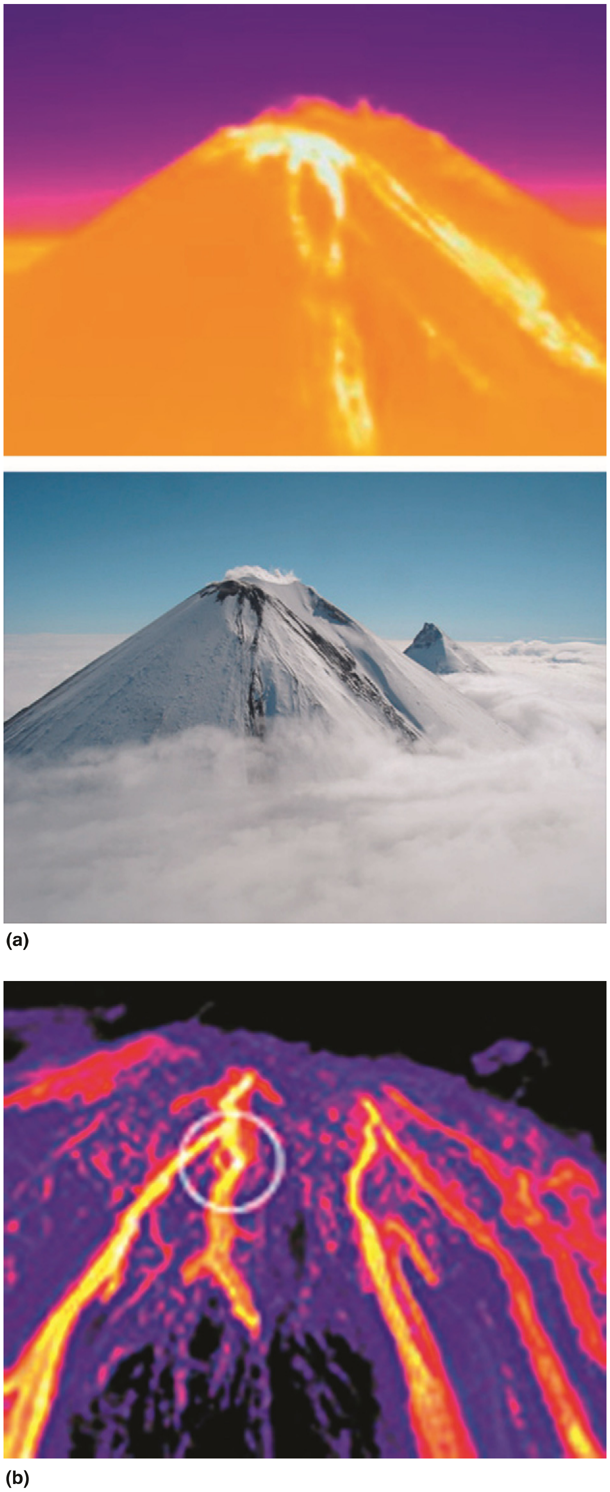
The transition from film to digital photography is a collision of interests and debate that goes deeply into arguments of feature resolution with random silver halide crystals of various sizes in film, versus pixel resolution and radiometric sensitivity (Galer and Horvat, 2005; Rand et al., 2005). In addition, digital sensor geometry is arranged in a rectangular grid pattern, which makes images susceptible to moiré interference-pattern artifacts, whereas the random orientation of film grains precludes this problem. In general, to approach 35 mm film quality with digital cameras requires at least 6 million pixels, but such an oversimplified statement needs to be amended very much on what one wishes to do subsequently with the acquired image (enlargement, publication, etc.). Part of the issue is also the dynamic range one is interested in capturing in the image, which is the amount of detail that can be seen in the shadows before the bright areas start to lose texture. In general one needs uncompressed file sizes >30 MB to come close to film when making enlargements. At the outset, many digital cameras were not as capable as film for capturing the level of detail that geomorphologists generally needed, although that is no longer the case. A number of digital cameras now exhibit a huge dynamic range, compared to either print or slide film, and film production companies are gradually ceasing to produce film for use anymore, as it becomes progressively more obsolete.

In addition, the line between 'still' and video digital cameras has become blurred, if not quite nonexistent, and digital camera technology is one of explosive growth and sudden collapse. For example, the once quite popular Flip video cameras, introduced in the spring of 2006, ended production in spring of 2011, as 'still' cameras increased onboard storage to the point that significant lengths of video imagery could be recorded. Cameras suitable for ground-based acquisition of instructional or simple photographs are in many smart phones and tablet computers. A profusion of more complex 'viewfinder' or digital single-lens reflex cameras suitable for very detailed studies are available for less than $1500, and prices are continuing to fall. Photogrammetric quality cameras, being more complex and less popular, are rarer and more expensive. Because of the variety of new cameras available in this growing field, expert advice should be sought before investing in a new digital camera for collecting field data.

3.2.2.3.1 Gigapan technology

Gigapan or gigapixel-panorama technology is a new system using digital cameras for acquiring composite pictures composed of billions of picture elements (pixels). The system produces extremely high-resolution panoramic images that are capable of resolutions from macropanoramas from a considerable distance away, zooming down without leaving the scene to microresolutions of rock thin sections (Johnson, 2009b). The goal of gigapan technology is to facilitate acquisition and presentation of data as a single image that can be stored efficiently on the web, and that can be examined and displayed at multiple scales. The system is established as single or multiple robotic cameras set to full zoom with automated image acquisition of multiple individual pictures arranged across a grid. The motorized camera system then automatically moves, taking hundreds to thousands of slightly overlapping scenes until an entire scene or viewscape is captured. Such images are then downloaded to a personal computer and software 'stitches' the individual pictures into one large explorable, gigapixel-sized, super-image, or gigapan.

Numerous examples of gigapan use in geomorphology are available, from full-gigapixel anaglyph (red/blue 3-D images)


(a)

(b)

Figure 5 Photographs of the following: (a) Russia's Klyuchevskoy volcano showing a thermal image (upper), and a photograph of the volcano (lower image. Reproduced from http://news.nationalgeographic.com/news/bigphotos/3626065.html). (b) Italy's Stomboli Island volcano showing a thermal image of openings of a new fracture vent in the middle of a flowfield along the Sciara del Fuoco, which is the hillside from which the lava flows to the sea. A curtain of smoke and gas emissions obscured the view in visible-light but not this infrared.

Table 3 List of geomorphology picture libraries that are available online with numerous photographs available of landforms and geomorphic processes. Many of these photographs are free (F) but some require payment ($)

Lisa Wells Geomorphology Images – http://geoimages.berkeley.edu/GeoImages/Wells/wells.html	(F)
Geomorphology from Space (NASA) – http://disc.sci.gsfc.nasa.gov/geomorphology	(F)
Gallery of Landform Images – http://www.geomorph.org/gal/mslattery/world.html	(F)
Ediafocus Stock Photos (Geomorphology) – http://www.mediafocus.com/image-search/geomorphology-stock-photos.html	($)
About.Com: Geology (Landform Picture Gallery) – http://geology.about.com/library/bl/images/bllandformindex.htm	(F)
Overview of Geomorphology Sites – http://www.falw.vu/~balr/geomorphology.htm	(F)

of sea stacks and uplifted wave-cut terraces in Sonoma County, CA (Johnson, 2009b) that can be viewed stereoscopically, to the Extreme Resolution Panoramic Imaging Project (ERPIP) in Yosemite National Park, where comprehensive assessment and mapping of rockfall hazards was required (**Figure 4**). Because the Yosemite Valley undergoes numerous large rock falls every year, with >600 recorded since 1850, evaluating, mapping, and quantifying the geomorphic hazard was deemed a major goal of the ERPIP activities. Thus high-resolution imagery of the precipitous valley walls was needed to establish a baseline datum for before-and-after comparisons. With establishment of a collaboration between the National Park Service and xRez Studios of Los Angeles, >10 000 concurrent images of the >25 km of granite walls in Yosemite were obtained at the same time on 9 May 2010 to ensure the same lighting and atmospheric conditions.

The basic technology included ground-based, gigapixel panoramic photography, light detecting and ranging (LiDAR) data acquisition from the air (plane and hang glider), and 3-D computer rendering. Twenty photo-shooting teams totaling 70 photographers between them ascended a total of ~11 000 vertical meters of trail. At each vantage point >500 overlapping shots were obtained, which when merged and printed at magazine-quality, 300 dpi resolution, the photos extended uninterrupted for >12 m (Madrigal, 2008). All 20 gigapixel panoramas were projected onto a 1-m resolution DEM using Maya 3-D animation software, unifying the 25 km of Yosemite walls into two single vertical orthographic (undistorted) views, which yielded a unique, nonperspective elevational view of the valley walls, which is a first in landscape photography.

In other future studies, obtaining such high-resolution imagery can be used to establish baseline conditions for before-and-after comparisons of geomorphic phenomena. Evaluation, mapping, and quantification of process rates, geomorphic hazard, and other useful measures of geomorphic change could be obtained in this way.

3.2.2.4 Thermal Imaging Technology and Geomorphology

A thermal imaging camera (TIC) records emitted thermal radiation and can be used to assess thermal properties and surface temperature, which is a useful for monitoring volcanic activity, especially in remote areas from the air, or where dangerous eruptions threaten and some distance needs to be maintained. Low resolution (1 km pixel^{-1}) satellites such as the Advanced Spaceborne Thermal Emission and reflection Radiometer (ASTER) on board the Terra satellite produce thermal imagery that can be compared to portable thermal camera systems. An example of a portable system is the forward-looking infrared radiometer (FLIR) that can then be used for generating high-resolution thermal images, such as from a helicopter hovering near a volcano (**Figure 5**), or a fixed camera position to record thermal change through time as lavas are emplaced (**Video 2**).

The online version of this chapter contains a Video with an **Animation 2**. The online version can be found at doi:10.1016/B978-0-12-374739-6.00041-5

Such instruments enable scientists to assess volcanic hazards more accurately because they can not only be used to assess surface temperatures, but they can also measure the presence of phenomena in the sky above the ground, such as ash or steam. From such data, calculations of emitted volumes of gas, rock, ice, water, ash, sulfur dioxide, and lava are possible. For example, in this sort of work on Erebus volcano in Antarctica in 2004, radiative heat outputs calculated for the Ray (~1400 m^2) and Werner (~1000–1200 m^2) lava lakes were 30–35 and 20 MW, respectively (Calkins et al., 2008). The estimated magma flux necessary to sustain the combined heat loss was ~250–710 kg s^{-1}, the minimum volume of the magma reservoir underground was ~2 km^3, and the radius of the conduit feeding the Ray Lava Lake was ~2 m.

3.2.3 Image Interpretation

Human interpretation of photography and imagery is a standard approach for information extraction that has been used for teaching and research for almost as long as the discipline of geomorphology has been practiced. Photo interpretation is based on the fundamental photographic or image information elements that include the following: (1) tone, or the relative brightness and color of landforms, soils and other surface features that make up the landscape; (2) texture, the local spatial variability in tone caused by variations in the surface structure or morphology of the landscape or feature; (3) size, both absolute and relative, that may be important with respect to classification; (4) shape, which is related to morphology and may be distinctive for specific landform features; (5) shadow, that reflects the shape and the nature of the object and topographic relief; (6) pattern, in which the spatial arrangements of landforms may be significant with respect to repetition, layout, and ordering; and (7) site, the topographic position of landforms on the landscape (Lillesand and Kiefer, 1994).

Collectively these elements constitute the basic information that can be extracted and synthesized via human visualization and analytical reasoning. When combined with *a-priori* experience, geographic-, and discipline-domain knowledge, effective analysis and information can be produced. Computer-assisted analysis that attempts to mimic the human interpretation process and information production can be utilized with digital 'photography,' although quantitative formalization of human interpretation still remains an active research area.

Human interpretation of the landscape and landforms is relatively more accurate under complex landscape scenarios, although great progress is being made in quantitative landform analysis and mapping from digital data (Bishop et al., 2011).

A number of web sites provide pictures of landscape and landforms that can be used most effectively in education (**Table 3**). Commonly ignored as an important means of doing research or making effective presentations, the ability to obtain field photography and images, and interpreting field data is an important skill that needs to be thought about carefully involving a fair degree of competence. This skill is not generally taught in graduate school or field camps, although it is an essential part of any project in geomorphology. Practical exercises in such landform analysis occur in some older texts, such as Miller (1961), Wanless (1986), and Way (1973), and the aforementioned manuals from the American Society of Photogrammetry and Remote Sensing. The Remote Sensing Tutorial, by Dr. Nicholas Short, contains several sections of interest to geomorphologists desiring further instruction in image interpretation, and is available at multiple web sites.

3.2.3.1 Change Detection

The elementary, although significant aspect of acquiring repeat photographs and images from marked locations seems to have been first used in Europe in the 1880s to monitor glacier changes, and then in 1896 in the USA by Israel Russell (1898), who used the technique to monitor and measure the terminus of the Nisqually Glacier on Mount Rainier. After a hiatus of approximately five decades, the technique of change detection using photography was finally taken up again with more attention and utilized by a number of people looking for other geologic change (Shepard and Grant, 1947; Phillips, 1963; Veatch, 1969; Baars and Molenaar, 1971). This flurry of interest by a number of people led to more general recognition of the potential of repeat photography to provide important new information, with the result that the United States Geological Survey (USGS) decided to utilize its vast historical collections of photographs to accomplish major efforts in change detection by trying to reoccupy many remote locations. The early expeditions by the USGS into the western USA in the 1860s and 1870s had resulted in thousands of photographs by such renowned photographers as W.H. Jackson, T. O'Sullivan, J.K. Hillers, and A.J. Russell that were envisioned in the USGS as ripe for rephotography. In the late 1970s then, the USGS began a second phase of taking new photographs at the same date and time of day in the same places as an experiment in repeat photography. A third phase of this repeat photography began in 1997 (Klett, 2004) (**Figures 6** and **7**).

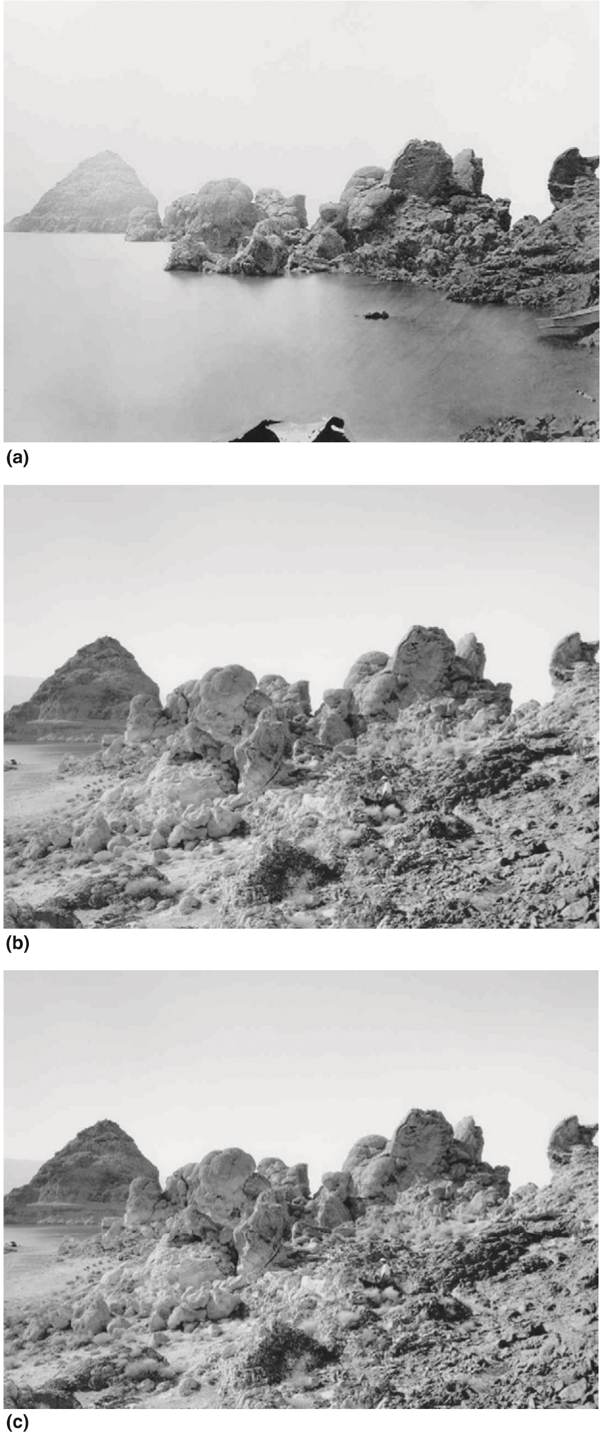


Figure 6 Tufa knobs, Pyramid Lake, NV: (a) Photograph by T. O'Sullivan for the USGS, 1867. (b) Photograph by M. Klett for the Rephotographic Survey Project, 1979. (c) Photograph by M. Klett and B. Wolfe for the Third View Project, 2000. Such tufa deposits are a characteristic of many playa lakes that were active in the late Pleistocene and some of the Holocene in the western USA but the progressive abstraction of ever more water from these sites for irrigation and other human uses indicates their progressive degradation thereafter. Such photographic documentation enables measurement of former water depths and potential erosional and depositional effects above and below the former water line through time. Courtesy of US Government.

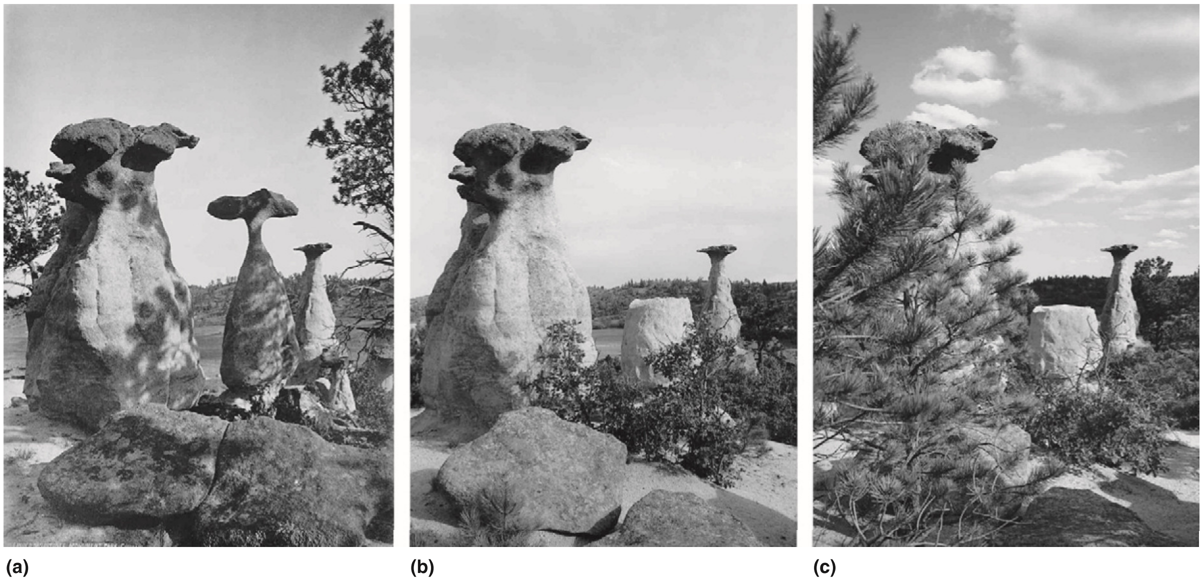


Figure 7 Eroded sandstones in Monument Park area of Colorado Springs, CO: (a) Photograph by W.H. Jackson for the USGS, 1873. (b) Photograph by J. Verburg for the Rephotographic Survey Project, 1977. (c) Photograph by M. Klett, B. Wolfe, T. Ueshina, K. Bajakian for the Third View Project, 1997. The prominent changes due to rock erosion between scenes allow some calculation of episodic erosion rate. Courtesy of US Government.

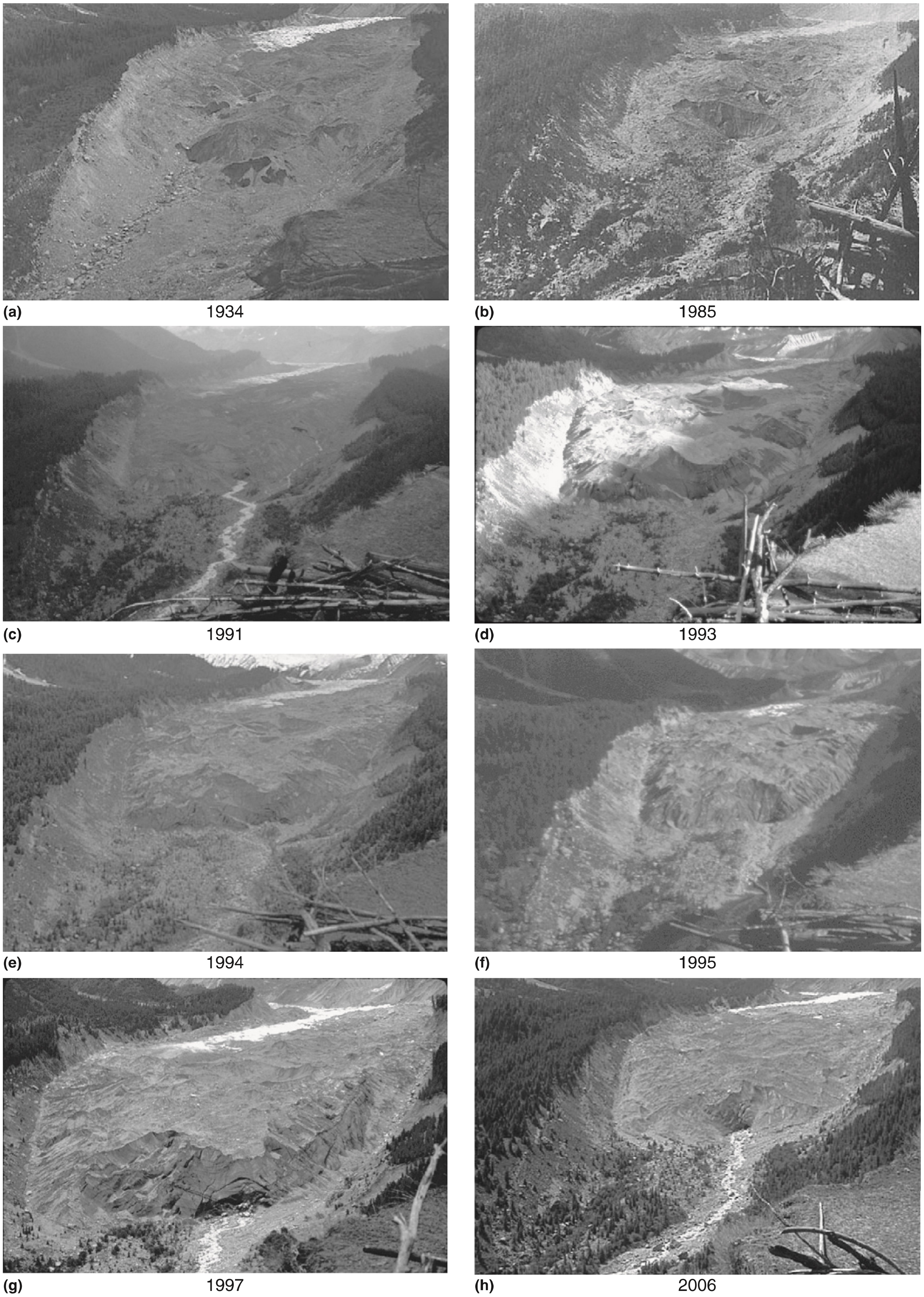
In other cases, commercial interests in developing the American West also eventually provided opportunity for repeat photography, as when in 1889–90 R.B. Stanton took photographs every few km along the bottom of the Grand Canyon in connection with a railroad that was planned close to the water level but that was never constructed. A century later, Webb (1996), a USGS hydrologist investigating debris flows in the Canyon, was able to replicate all 445 of Stanton's photographs. As with so many rephotography projects, the changes in vegetation were most obvious, but also apparent were changes exerted by the newer Glen Canyon Dam upstream so that eroded sand bars, aggraded debris fans, and new marshes have resulted from this anthropogenic–geomorphic interference with the natural river flows. The experience gained in this project enabled Webb et al. (2010) to write a text on the history, techniques, and applications of repeat photography that other geomorphologists may find quite useful.

Similarly, P. Bierman set about to replicate as many old photographs in the state of Vermont as he could find, with the result that he was able to document major landscape change in the state, especially as the clear-cutting of old growth forest in the nineteenth century led to extensive soil erosion, mass movement, debris-fan growth, and flooding exacerbated by denuded watersheds. Subsequently in the twentieth century, as farm fields were abandoned wholesale back to second-growth forests, dirt roads were paved, and major new interstate routes were constructed, the anthropogenic forcings of geomorphic change resulted in major changes in sedimentation and slope and river-valley changes. White and Hart (2007) did a similar rephotography project for the Canadian Rockies, which was dominantly about vegetation change, but also included change in some glaciers and other landform features.

Some landscapes in the Himalaya, such as those documented by R. Finsterwalder in the 1930s on Nanga Parbat, were so well photographed as major parts of their large-scale photogrammetry-based mapping, that it became desirable to see what changes have occurred there in the intervening decades. With the exception of the later German (Schmidt and Nüsser, 2009) and other rephotographic work on Nanga Parbat (**Figure 8**) in the western Himalaya, however, rephotography has been predominantly confined to the eastern Himalaya where so many iconic mountains, valleys, and glaciers occur. For example in the 1950s, several Austrian and Swiss scientists traversed the terrain in Nepal thoroughly and made extensive photographic records that A. Byers rephotographed in 2007 (**Figure 9**). In the western Himalaya, however, many of the superb high-altitude panoramas of the Karakoram Himalaya taken by Sella (De Filippi, 1912) on the expedition with the Duke of Abruzzi in 1909, remain to be rephotographed, although Diolaiuti et al. (2003) have reproduced some.

In other areas multitemporal photographs of glaciers have proven useful in geomorphologic change detection. This includes the glaciers of Alaska by B. Molnia after many other original photographers (**Figure 10**), or in a more restricted area such as Glacier National Park – those by D. Fagre after many other photographers (**Figure 11**). Many other areas of interest make ground-based, repeat photography very useful to understand geomorphic (and ecologic) change through time, especially with the rapidly changing and labile ice masses of the world. Although commonly hard to do, ancillary quantitative measurements from the photographs are possible as well.

Repeat aerial photography has also allowed a number of special geomorphologic applications. For instance, geomorphic change can be captured and better understood by limited extrapolation between successive scenes, as for example, where a sequence of migrating river meanders can reasonably be constructed between scenes and linked into an animation – **Video 3** (Gough, 2007). In another example, an



(a) 1934
(b) 1985
(c) 1991
(d) 1993
(e) 1994
(f) 1995
(g) 1997
(h) 2006

Figure 8 Pictures of the terminus of Raikot (Rakhiot) Glacier on the north face of Nanga Parbat, western Himalaya, Pakistan that were taken from the same standpoint at the northeast end of Fairy Meadows. In part after Schmidt, S., Nüsser, M., 2009. Fluctuations of Raikot Glacier during the last 70 years – a case study from the Nanga Parbat massif, northern Pakistan. Journal of Glaciology 55(194), 949–959. (a) Photograph by R. Finsterwalder, 1934. (b) Photograph by J. Gardner, 1985. (c) Photogaph by J. Shroder in 1992. (d) Photograph by M. Nüsser in 1994. (e) Photogaph by J. Shroder in 1996. (f) Photograph by M. Nüsser in 2006. Such variation allows determination of the highly labile nature of glacier geomorphology.

(a) Late 1950s

(b) 2007

Figure 9 Taboche (6367 m) in center, Jobo Lapstan, the peak leaning to the right, and Khumbu Valley from the east near Mount Everest (Sagamatha) in the eastern Himalaya of Nepal: (a) ca. 1955 photograph by Erwin Schneider, courtesy of the Association for Comparative Alpine Research, Munich. Archives of Alton C. Byers, The Mountain Institute. (b) Photograph by A. Byers, The Mountain Institute, 2007. The clean, debris-free ice below the summit of Taboche has been reduced considerably, as have the size of many small glaciers. Tsholo Tso is the moraine-dammed lake at the base of Jobo Lapstan and the moraine dam can be seen to have been more active half a century ago, whereas the lake was higher in 2007.

intermittently active landslide in the Slovakian Carpathian mountains was photographed at large scale from the air four times at ~decadal intervals and used to construct a detailed DEM that enabled calculation of the net vertical and horizontal, mass-flux volumes through the system – **Figure 12** (Prokešová et al., 2010). Similarly Chandler (1989) and Chandler and Brunsden (2006) applied analytical photogrammetry to archival photographs of five epochs of movement between 1946 and 1988 of the Black Venn landslide in Dorset, England (**Figure 13**). Digital terrain models were produced to assess slope changes through time.

The online version of this chapter contains a Video with an **Animation 3**. The online version can be found at doi:10.1016/B978-0-12-374739-6.00041-5

In an unusual application of repeat photography to geomorphic process, albeit of an anthropogenic nature, the Limestone Project in Oxford, England, was designed to assess the catastrophic decay of building limestone with a wide variety of tools (Meneely et al., 2008). Chief among these techniques is rephotography (Thornbush and Viles, 2005, 2007; Thornbush, 2010) wherein Adobe Photoshop$^{\text{TM}}$ was used as image-processing software to obtain histogram-based measurements of soiling and weathering of the building stone. Results showed that photographs could be used to measure and quantify change using integrated digital photos and image-processing techniques calibrated by photographic incorporation of a grayscale and spectrophotometry. In addition to the digital photography used in these analyses, comprehensive studies were also done using colorimetry, permeability, ground penetrating radar, thermography, X-ray fluorescence, and stone-condition surveys. Such detailed analyses devoted to buildings can also be applied to landforms in the natural rather than anthropogenic world.

Photomonitoring of sites is thus increasingly recognized as scientifically advantageous, especially in vegetation studies, range management, or ecological analysis (Rasmusson and Voth, 2001), and assessment of geomorphological conditions could be done in more locations. Equipment required to get started is minimal, and includes a camera, film or camera computer chips, a photo-information board, a reference-scale pole, evaluation forms, and a notebook or field computer in which to record the relevant information. The reference pole, which is particularly important in the background of the photograph for range managers to assess long-term health of vegetation, would be less essential for many geomorphologic situations, but might be relevant in gauging such things as ripple and dune size and character, badland topography, erosional scarps, depositional moraines, and such.

Most essential in setting up the picture for long-term monitoring is to make absolutely sure that a distinctive and

(a) 1941

(b) 1950

(c) 2004

Figure 10 Muir and Riggs glaciers, Glacier Bay National Monument, AL: (a) Photograph in August 1941 after nearly two centuries of retreat. (b) Photograph in August 1950. (c) Photograph in August 2004 by B. Molnia. Muir Glacier has retreated out of the field of view and is now nearly 8 km to the northwest. Riggs Glacier is still in view but has retreated as much as 610 m and thinned or downwasted as much as 250 m.

(a) 1913

(b) 2005

Figure 11 Shepard Glacier in Glacier National Park, MT: (a) Photograph in 1913 by W. Alden. (b) Photograph by B. Reardon. The highly labile nature of glacier ice is obvious.

permanent landmark occurs in the background or on the skyline. One must make sure that the camera frame includes the skyline, and that there are distinctive rock outcrops, mountain slopes, or other geologic or geomorphic features that will remain over long periods of human history so that the site can be found again and again. A secondary, but also important feature is the photoboard set up in the foreground that has the data and location of the monitoring site. Both the photoboard and the skyline or landmarks need to be quite visible in the photograph. Finally, a plan for preservation and long-term storage of the photographic images and written records is critical if they are to ever be of real scientific use to anyone in the future. This can be a problem if a geomorphologist has not had time to put things in order before retirement, or who has left inadequate documentation at death. Special efforts should be exerted by older geomorphologists who have had well published careers to see that their field photographs and mapped materials are not lost to science after their retirement. Film slides and photographs should be digitized at high resolution and stored in well indexed electronic media.

3.2.4 Conclusions

The uses of photography as a primary data-collection and information-recording tool, as well as a device for obtaining some quantitative information about landforms and processes, has been established in geomorphology for some time. These qualitative as well as quantitative procedures can be used to aid geomorphologists in studying landscape dynamics and for geomorphological mapping. Most geomorphology papers use photographs of surface processes or landforms as a means to illustrate important aspects of the landscape or vital concepts.

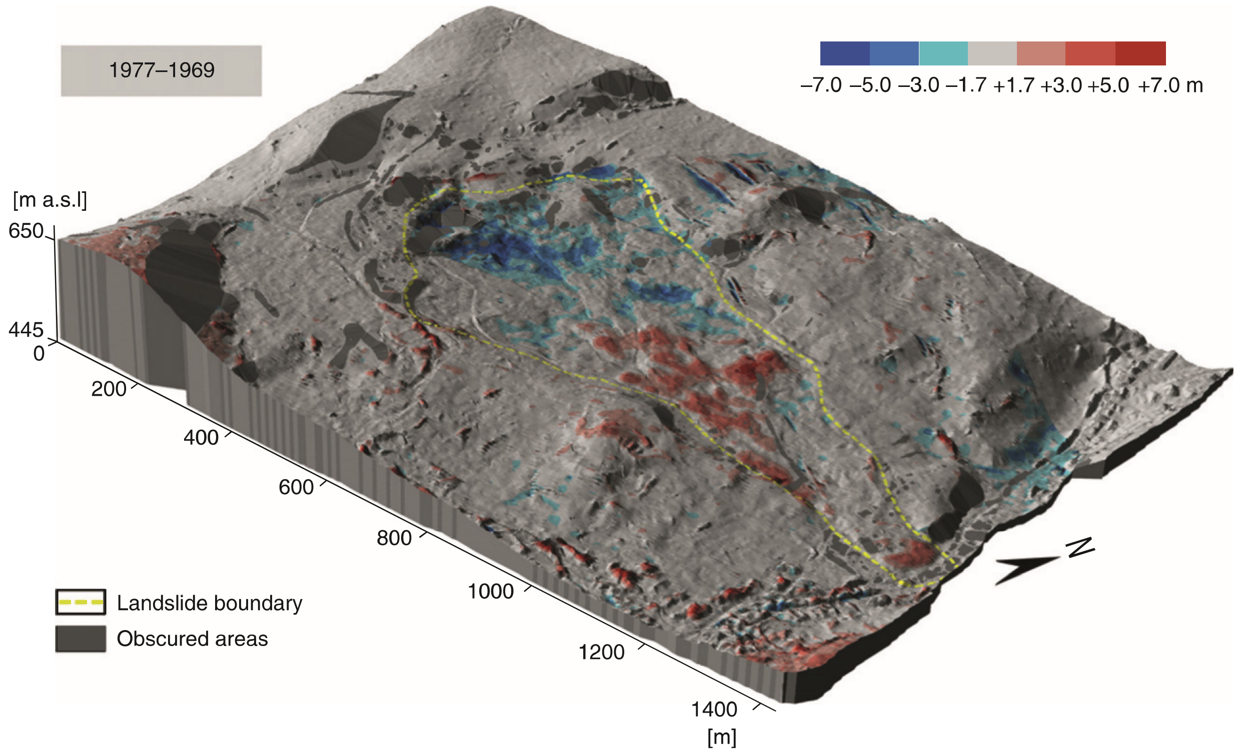


Figure 12 Differential image of the Ľubietová landslide in the western Carpathian Mountains of Slovakia that is draped over a 1977 DEM that shows the removal (blue) and accumulation of transported slope debris (red) measured from four sets of stereographic aerial photographs during the 1969–77 period. Reproduced from Prokešová, R., Kardoš, M., Medveďova, A., 2010. Landslide dynamics from high-resolution aerial photographs: a case study from the Western Carpathians, Slovakia. Geomorphology 115, 90–101.

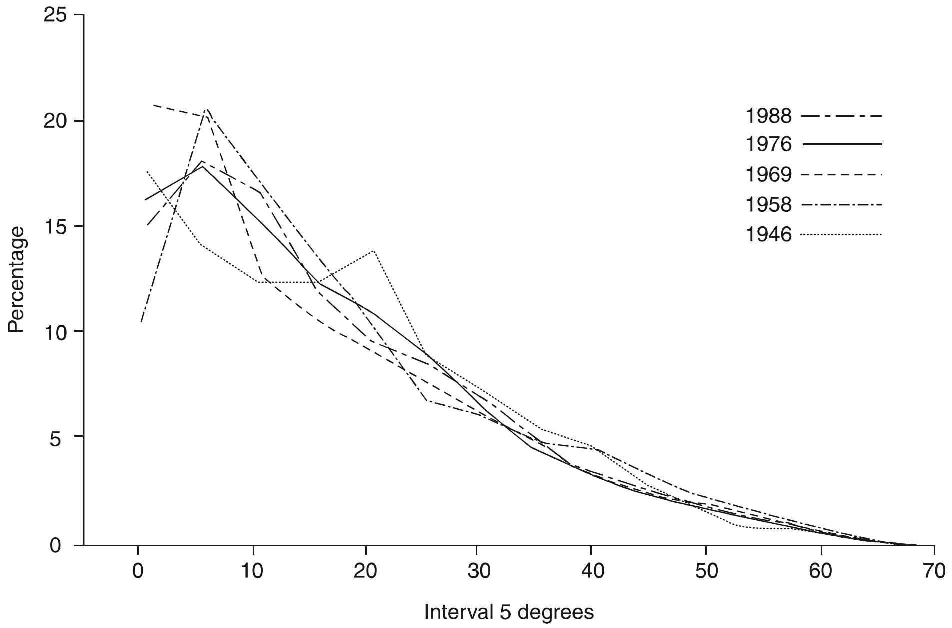


Figure 13 Percentages of changing slope angles of the Black Venn landslide measured from aerial photographs acquired in 1946, 1958, 1969, 1976, and 1988. Reproduced from Chandler, J.H., 1989. The acquisition of spatial data from archival photographs and their application to geomorphology. Ph.D. thesis, The City University, London, England, 300 pp., unpublished, and Lane, S.N., Richards, K.S., Chandler, J.H., 1993. Developments in photogrammetry; the geomorphological potential. Progress in Physical Geography 17(3), 306–328, with permission from Sage.

The great diversity of general photographs of the surface of Earth is a vast collection scattered in various places that has only been accessed and used in a limited way. Thus the discipline of geomorphology over the past century has produced large collections of still photographs of landforms, as well as hosts of movies and videos that show geomorphic processes in action. On top of the plethora of ground photographs, the huge amounts of aerial and space-based photos taken worldwide in the past 40 years are also tremendous sources that could be processed and stored in databases so that they could be used better than they have been. Stereographic aerial photographs are a long-term staple of geomorphologic research, and with the addition of photos from astronauts and film-return satellites, the potential data sources have grown ever larger over time. A problem is that with the millions of potentially rewarding and available historical photographic materials, a certain amount of time and energy is necessary to access, review, and store the scattered sources. This effort can put off busy people so that they do not make effective use of the materials of which they are unaware, or for which they lack the requisite skills to access effectively. The addition of new LiDAR and gigapan technologies and thermal sensor technologies add to the photographic disciplinary diversity as well.

New research using photographic techniques could certainly include greater use of the enormous store of Corona film returned from space, as well as the many historical photographs preserved unused in the many historical societies in towns and cities all across the world where such photo data are kept. Any number of quantitative or qualitative change-detection studies remain to be done with permafrost, glaciers, mass movement, fluvial, aeolian or coastal environments. The common availability of video cameras of various types, even in some cases only low resolution cell phones, sometimes have captured rare geomorphic phenomena in action, which can be useful in analysis. Different velocities, viscosities, and grain sizes of such unusual complex debris-flow continua are being caught increasingly. Eventually, such features as the high speed and enigmatic mass movements, such as long runout zone landslides or slow debris flows may be captured in motion photographically and assessed for better understanding of mechanics of their motion. Many other somewhat enigmatic processes may be similarly assessed in the future with these techniques.

In sum, the use of photographs is an essential and central part of almost all geomorphologic research, and the ubiquity and availability of so many old and new cameras and photographic techniques enhances geomorphological investigations. Attention to the details of making or obtaining good digital photographic-image coverage of any particular geomorphologic problem is viewed as an important, even essential part of the modern discipline that should be taught in some fashion in the more advanced graduate programs.

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