# Photogrammetric Methods Applied to Surface Effects Mapping and Volumetric Studies at the Nevada Test Site, Nevada

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ABSTRACT: The Nevada Test Site is the proving ground for subsurface nuclear testing; over 607 announced tests have been conducted since 1958. Surface geologic features produced by the tests are termed surface effects. Common surface effects are concentric, radial, and linear fracture patterns and sinks, formed by the collapse of the ground surface above the nuclear detonation. Mapping of surface effects is important as they are often indicators of local stress fields and subsurface structure. Prior to 1981, surface effects were mapped in the field on pre-test aerial photographs shortly after detonation of the nuclear device. A photogrammetric procedure, developed in 1981, allows surface effects to be mapped using post-test aerial photographs. A computer-assisted photogrammetric mapping system has also been used to calculate volumes of the test-induced sinks. Safety hazards restrict field survey crews from entering the sink; as a result, field approximation of the sink dimensions are often oversimplified. A better interpretation of the sink dimensions can be made photogrammetrically. Both photogrammetric uses have been successful and are currently being used for surface effects mapping and volumetric calculations at the Nevada Test Site.

## INTRODUCTION

SINCE 1958, approximately 607 announced nuclear tests have been conducted on the Nevada Test Site (NTS), the proving ground for subsurface nuclear testing. Surface geologic features produced by the explosion are termed surface effects. These features occur in the form of concentric, radial, and(or) linear (aligned) fracture patterns and topographic depressions (sinks) formed above the nuclear test (Houser and Eckel, 1962). Surface effects produced by the explosions are possible indicators of local stress fields and subsurface structure. Areas of aberrant collapse behavior can also be detected by study of surface effects patterns. In the past, surface effects were field-mapped shortly after detonation using pre-test aerial photographs. Since 1981, the U.S. Geological Survey (USGS) has routinely mapped surface effects on post-test aerial photography utilizing a Kern PG-2 photogrammetric plotter*. Designed for topographic mapping, the PG-2 plotter has proven to be an excellent tool for surface effects mapping. The PG-2 provides a means of accurately plotting data on a base map by means of a high-quality stereoscopic viewing system and has been successfully adapted for surface effects studies (Dueholm and Pillmore, 1989).

The successful use of the plotter for mapping surface effects led to the use of a Computer-Assisted Photogrammetric Mapping System (CPMS) for measuring sink volumes. Volumes determined using this system were found to be more precise than those measured in the field. Detailed measurements of the sinks cannot be made in the field because of possible safety hazards; thus, field measurements are often simplified and ignore the sag zone, an area of minor subsidence that occurs just beyond the sink perimeter. The sag zone is not easily seen on the surface of the ground but, when present, may account for 5 to 20 percent of the total volume of the sink. Field measurements are also time consuming and may not be recorded until days or weeks after surface collapse. As the photogrammetric procedure relies on photographs taken as soon as possible after collapse and because the dimensions of the sink, including the sag zone, can be measured more precisely, a better interpretation of the effects of the explosion can be made.

## GEOLOGIC SETTING OF YUCCA FLAT

Yucca Flat, within the Nevada Test Site (Figure 1), has been an area of subsurface nuclear testing since 1958. Geologically,

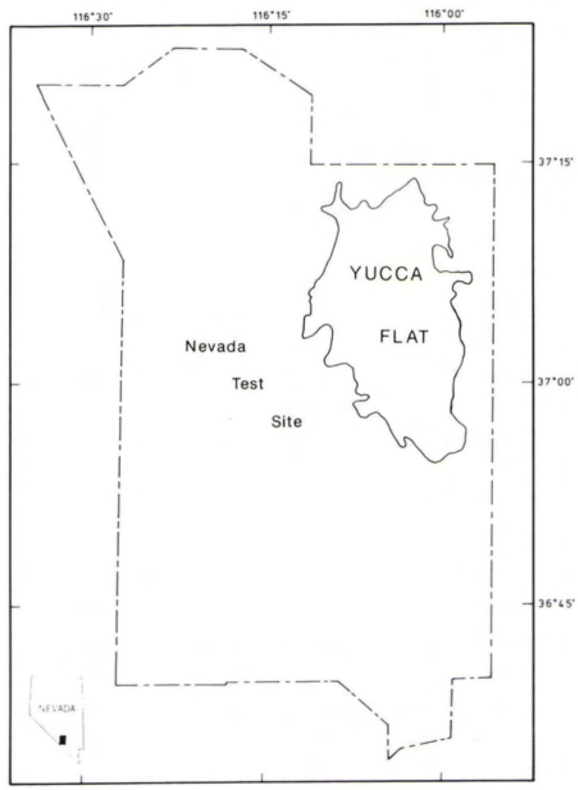


FIG. 1. Index map showing the State of Nevada and Yucca Flat on the Nevada Test Site.

*Use of brand names is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

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Yucca Flat is an intermontane basin formed relatively recently (10 to 13 Ma) during a phase of Basin and Range faulting (Zoback *et al.*, 1981; Eddington *et al.*, 1987). The basin is superimposed on and influenced by older (30 to 40 Ma) Basin and Range structures described by Carr (1984). The Yucca Flat basin is filled with thick upper Tertiary tuffs and Quaternary alluvial deposits and thin basalt flows. Structurally, the basin is characterized by gently step-faulted margins along which fault-blocks descend to a graben in the center, a characteristic feature of all basin valleys in the Great Basin (Stewart, 1971).

## EFFECTS OF UNDERGROUND NUCLEAR EXPLOSIONS

Test yields of recent subsurface nuclear explosions in Yucca Flat range from less than 1 kiloton to 150 kilotons. The tests are conducted in alluvium or tuff. The nuclear devices are emplaced in vertical drill holes at depths of 183 to 640 metres (Figure 2). The drill holes are filled and tamped following emplacement, and the nuclear device is detonated. The energy of the explosion is released in about a tenth of a microsecond, the temperature increases to several million degrees Kelvin, and the pressure increases to many kilobars. All material surrounding the device is vaporized and melted. The initial cavity produced by the explosion expands and the surrounding medium begins to act hydrodynamically. Shock energy begins to propagate in all directions, creating seismic waves. A slight upward bulge occurs at the ground surface and fractures begin to form (Figure 3a). As the cavity ceases to expand, the molten rock drains downward to form a pool, and the ground surface returns to a position near or above its pre-test level (Houser, 1970). Several seconds to hours later, the explosion cavity collapses to form a chimney (Figure 3b). If the test is very deep in alluvium or deep in competent rock, the chimney does not reach the ground surface. If the test is at moderate depth in alluvium or at moderate to shallow depth in competent rock, the collapse continues upward to the surface and forms a sink (Figure 3c).

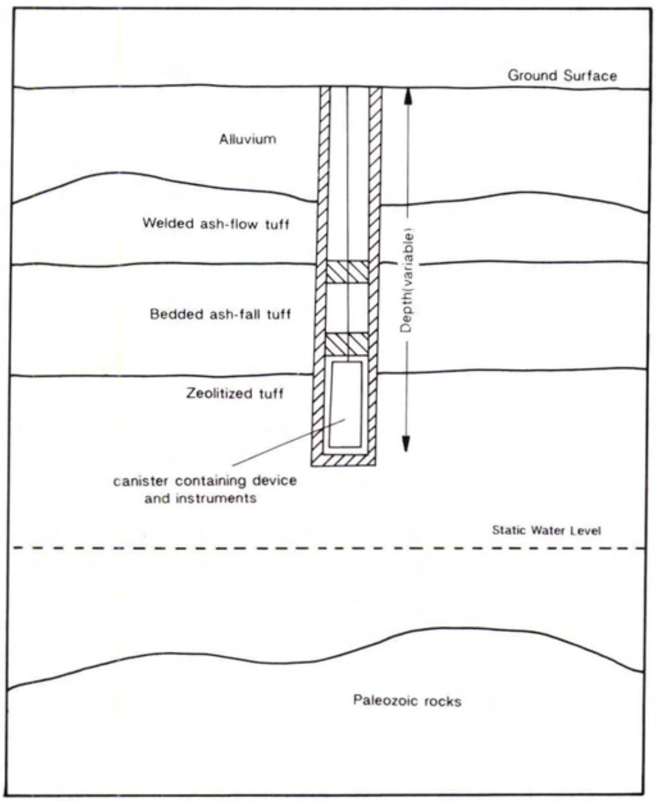


FIG. 2. Diagram showing a typical drill-hole emplacement of a nuclear test in Yucca Flat, Nevada Test Site.

## SURFACE EFFECTS

The formation of surface effects (sinks and fractures) is dependent on many factors: the test medium, the yield of the device, the depth of burial, and the integrity of the surface material. Surface effects provide valuable criteria to evaluate the geology around a subsurface nuclear test. Approximately 80 percent of the tests conducted in Yucca Flat have formed a sink. The collapse of material helps contain radioactive gases generated after a subsurface nuclear explosion (Houser and Eckel, 1962). Few of the sinks have the appearance of a perfect circle. The sinks formed on the NTS range form deep, steep-sided, flat-bottomed "cookie-cutters," to shallow, broad-sided, inverse cones. The dimensions of the sinks in Yucca Flat range from 3 to 345 metres in radius and 0.6 to 60 metres in depth. The larger sinks have volumes approaching 21 million cubic metres.

Fractures occur in the alluvium overlying the site of an explosion regardless of whether or not a sink forms (Figure 4). Fractures not only occur in radial and concentric patterns, but are also commonly aligned along certain preferential directions. These preferentially aligned fracture trends form two groups: those that show a spatial relationship to major faults in the basin and those that do not. The fracture trends unrelated to faults are parallel to joint trends observed in the bedrock at the edge of the basin; the most conspicuous fracture trends in the alluvium appear to parallel closely spaced fractures in the bedrock. Fractures generated by explosions detonated in tuff beneath Yucca Flat show a greater degree of preferred orientation than those caused by explosions detonated in alluvium (Barosh, 1968).

## MAPPING TECHNIQUES

Surface effects are important to understanding to mechanics of containment (no release of radioactivity into the atmosphere); they may reveal buried geologic structures and contribute to the understanding of aberrant surface collapse behavior. Accurate documentation of surface effects is an important and necessary activity for site selection and structural studies.

### FIELD MAPPING METHODS

From 1958 to 1981, surface effects of tests were mapped in the field on pre-test aerial photographs shortly after detonation of the test. If delays in mapping occurred, surface effects could be obliteracted by weather and/or construction activities. The field method was effective, but involved three major problems. First, accurate field mapping at the NTS is difficult because the geography of the area is constantly changing: within a week datum points such as roads, vegetation, drilling pads, or trailers may appear or disappear, making it difficult to accurately locate field stations or control points on the aerial photographs. Second, the pre-test aerial photographs are of representative fraction (RF), commonly 1:2,400 or 1:4,800, and many provide an inadequate number of control points to properly annotate the photographs. Third, not all of the disturbed area is accessible for mapping after an explosion, because of possible safety hazards. In addition, field mapping is performed by numerous geologists, which introduces varying degrees of interpretation to the data. These problems indicated the need for a faster and more accurate and uniform method.

### PHOTOGRAMMETRIC MAPPING METHODS

The U.S. Geological Survey devised a method for mapping surface effects utilizing the Kern PG-2 photogrammetric plotter. A discussion of the PG-2 plotter and its applicability for geologic studies can be found in Pillmore (1979), Pillmore *et al.* (1981), Dueholm and Pillmore (1989), and Van de Werken (1983).

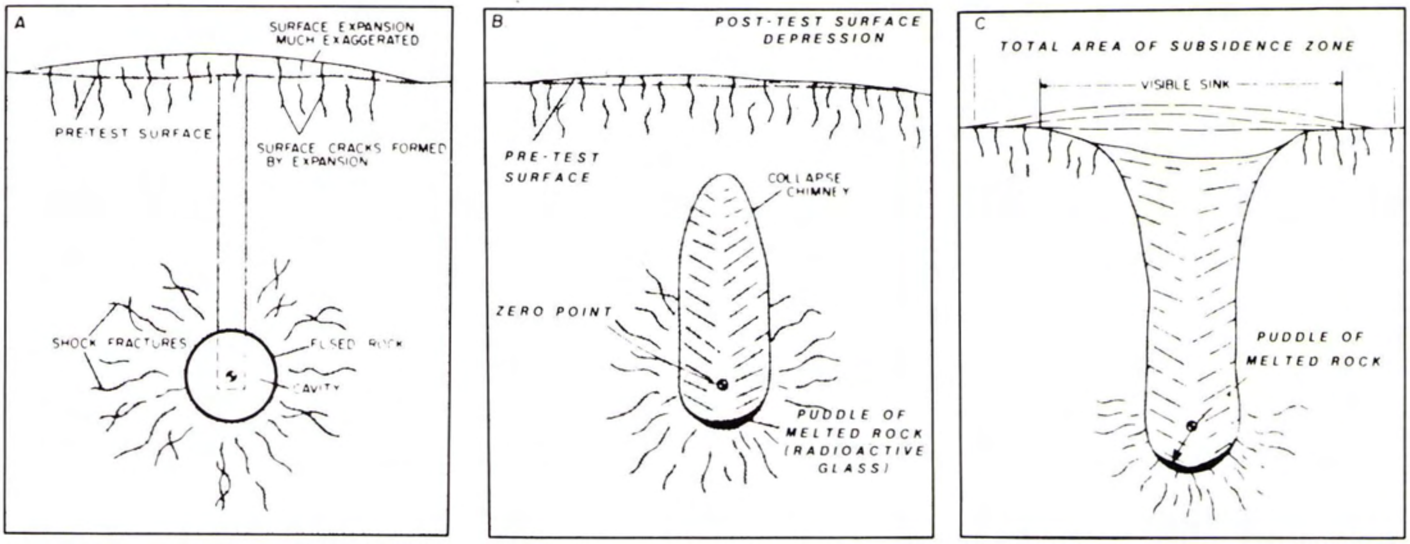


FIG. 3. Formation of a sink, cross-section view, not to scale (modified from Houser (1970)). (a) Generalized early reaction of rock medium to a nuclear explosion. (b) Generalized collapse of explosion cavity and formation of chimney. (c) Generalized collapse of surface chimney.

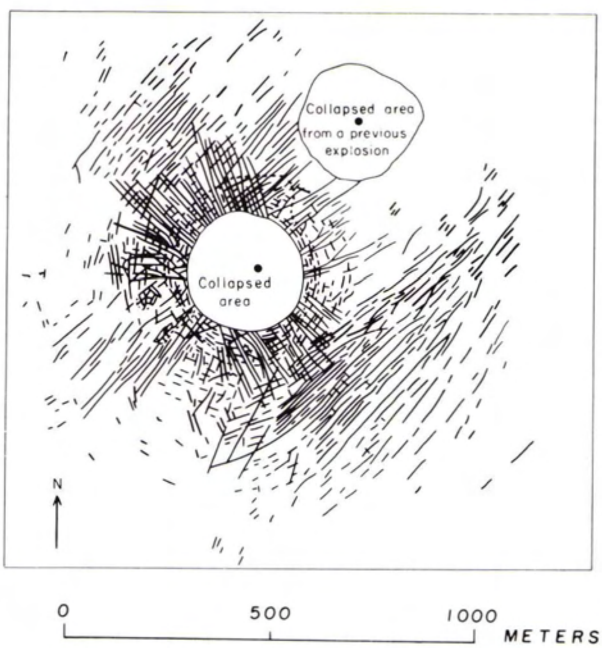


FIG. 4. Fractures in alluvium produced above an underground nuclear explosion, Yucca Flat (mapping by T. L. Prather, in Barosh (1968)).

Although initially designed for topographic mapping, the PG-2 plotter has been successfully used for surface effects mapping, because it provides a means of accurately plotting data on a base map from photograph stereo pairs and offers a high-quality viewing system for stereoscopic inspection.

The plotter method, functional since 1981, is successful primarily because the photos used in the field are set into the plotter, and additional data are observed directly in the stereoscopic model and compiled onto a map. This method also allows a large map area to be checked for surface effects rapidly, and sinks and fractures inaccessible in the field can be recognized and accurately mapped and measured.

During early use of the photogrammetric method, the quality and coverage of aerial photographs proved inadequate. A sufficient number of control points to properly orient the photographs to a map base were not available, and distortions along the borders of the paper photographic prints caused orientation problems, especially in areas of high topographic relief. To correct these problems, new control points were placed on the ground surface to the east and north of the event site to provide two control points. New aerial photographs were then obtained that showed the additional control points. Use of scale-stable diapositive transparencies rather than paper prints in the plotter also greatly improved the image quality and eliminated distortion problems.

The mapping of surface effects on the plotter has not completely eliminated field mapping. A pilot study conducted by Van de Werken (1983) recognized that, although surface effects mapping is more accurate when done photogrammetrically, field mapping is important in providing close-up visual descriptions of the surface effects. Currently, surface effects at the NTS are mapped using both field and photogrammetric mapping methods.

## VOLUMETRIC STUDIES

Sinks at the NTS can be divided into five distinct morphological zones (Houser, 1970) (Figure 5). The zones range from zone 1, the central part of the sink where the greatest amount of subsidence occurs, to zone 5, where no obvious deformation occurs. The sinks can be further systematically classified based on similarities among depth of emplacement, yield of the explosion, and characteristics of the testing medium (T.D. Kunkle, Los Alamos National Laboratory, written commun., 1984). The recognition of the characteristics of each sink and the accurate measurement of its dimensions, particularly volumes, are important to the planning of future tests.

Although field measurements of the sinks are made, safety restrictions at the NTS prevent field mapping personnel from entering the sinks. Precise ground surface measurement, therefore, cannot be made, and the sink dimensions are, as a result, often oversimplified. Additionally, the peripheral sag zone associated with subsidence, Houser's zone 4, is often unmeasured. Houser (1970) indicates that zone 4 is not only an integral

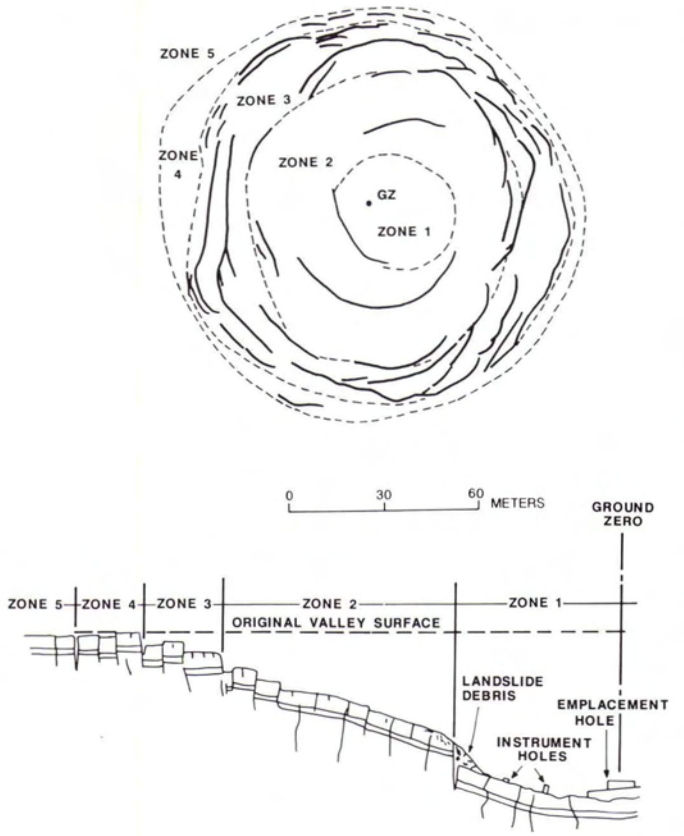


FIG. 5. Generalized plan view and cross section of morphologic zones of a typical sink, Yucca Flat (modified from Houser (1970)).

part of the subsidence process, but may be a more accurate measure of the degree of subsidence than the topographic sink edge. The calculated volume from this sag zone accounts for 5 to 20 percent of the total volume of the sink.

In addition to field measurements, sink volumes were also determined by measuring the dimensions of the sink graphically from post-test aerial photographs and then calculating the volume. These final volume calculations were in error because they assumed the sink was conical (Jones, 1979). With advances in photogrammetric technology, a procedure has been devised to precisely map sink dimensions, and therefore, to calculate more accurate volumes. The procedure utilizes the Computer-Assisted Photogrammetric Mapping System (CPMS) (Dueholm, 1979; Pillmore *et al.*, 1981; Dueholm and Pillmore, 1989). The procedure relies on large RF photographs (1:4,800) taken of the site of the test following collapse at the surface. The large-scale (1:4,800) photographs provide sufficient data to map all topographic features of the sink, including the sag zone. The CPMS allows the operator to accurately map the morphology of the sink by constructing topographic contours sufficient to adequately represent the configuration of the walls of the sink. The contour interval varies and is dependent on the size and shape of the sink. The computer then calculates the volume of the irregularly shaped space between two contours and a total volume of the sink. Advantages of using the CPMS volumetric method are that a three-dimensional view of the sink is used to determine the volume, significant irregularities observed on the sides and bottom of the sink can be noted and accounted for, little or no time is required in the field, and results are easily obtained and corrected.

A study by Garcia (1987) compared CPMS-calculated volume measurements with volume measurements calculated from field-surveyed data. The comparison of results indicated a difference of 10 to 15 percent between volumes calculated using the two different methods. Differences were attributed to the calculations of the irregularities of the sink walls observed by the photogrammetric method. Because field mappers cannot enter the sink to measure these irregularities, field measurements are, at best, estimates. The operator using the CPMS volumetric method, however, can depict a finite number of contours, and thus map irregularities that cannot be measured in the field.

## DISCUSSION

The photogrammetric surface effects mapping method and CPMS volumetric method used by the U.S. Geological Survey have been successful. Problems with both methods have mainly been the result of poor-quality photographs. Better quality photographs that provide a sufficient number of control points allow better orientation of the site to a base map and the use of high-quality photographic transparencies increases the resolution. Because both problems have been corrected, current mapping results are considered to be of acceptable accuracy. The above described methods are presently in use, and development of new photogrammetric methods are being actively pursued.

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