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Observations of Temporary Plant Stress Induced by the Surface Shock of a 1-kt Underground Chemical Explosion

William L. Pickles

Abstract. *The Non-Proliferation Experiment (NPE) involved carefully monitoring a 1-kt chemical underground explosion using extensive seismological measurements and low-altitude overhead imagery. Lawrence Livermore National Laboratory has conducted a study to determine whether the multispectral overhead imagery acquired during the NPE can be combined with other techniques to locate the ground zero (GZ) of an underground nuclear explosion within the seismic error ellipse. This report describes the use of such overhead images to detect the changes in plant metabolisms, normally referred to as plant stress, that appear to have been induced by the surface accelerations caused by the NPE underground explosion.*

The metabolic condition of the plants on the surface above the explosion point was determined using a published plant stress measuring methodology to analyze the multispectral images taken from a low-flying aircraft. The surface areas that experienced accelerations greater than 0.2 g show measurable plant stress, within 56 hours of the underground explosion, in all of the plant species. The pattern of the plants' stress generally follows the pattern of the measured surface acceleration. Seven days after the explosion, the levels of apparent plant stress had relaxed to about one-third what they were 56 hours after the explosion, while the pattern of the apparent plant stress remained the same.

Introduction

One of the critical issues in creating international confidence in the ability to verify compliance with the Comprehensive Test-Ban Treaty (CTBT) being negotiated in Geneva is whether underground nuclear explosions can be detected, located, and distinguished from other seismic events, such as earthquakes, mine collapses,[1] or large chemical explosions. Chemical explosions with yields of 1-kt or more are used routinely in mining, quarrying, and civil engineering projects worldwide. Large commercial chemical explosions could provide a cover for a clandestine nuclear test. To look for seismological differences between an underground nuclear test and a similarly sized chemical explosion and to refine on-site inspection techniques for kiloton-sized explosions, Lawrence Livermore National Laboratory (LLNL) participated in the Non-Proliferation Experiment (NPE).[2] The NPE was detonated on September 22, 1993, in N tunnel under Rainier Mesa at the north end of the Nevada Test Site (Figure 1). The experiment was designed to measure the seismic, overhead imagery, effluent tracer gas, and possible electromagnetic signatures of the kiloton-sized chemical explosion. The explosion and measurements were successful and have been compared to similar measurements made during a nuclear test conducted in the same tunnel in 1992, a year earlier. However, no overhead imagery was acquired for the 1992 test.

LLNL added low-altitude overhead imagery acquisition and analysis to the NPE experiment. These images were acquired to provide the scientific data necessary to determine whether the low-altitude—and hence, high spatial resolution—overhead imagery would show some sign of disturbance that might help precisely locate underground explosions. Typically, 1-kt explosions that have been detected seismically have a location error ellipse that is larger than 40 km across.[3,4] Searching an area 40 km across for the potential location of an explosion is time-consuming. Overhead imagery has the potential to locate specific targets for intensive search within the seismic error ellipse.

The NPE was observed by representatives of public interest groups and by teams of official observers from many countries, including the United States. The representatives inspected all aspects of the explosive test. Much of the data collected and the results of preliminary analysis, including the infrared overhead imagery, were presented at an international conference sponsored by the Department of Energy during 1994.[2]

This report focuses on results discovered during subsequent analysis of the visible overhead imagery obtained during the NPE. These new results show that when the underground explosion shakes and lifts the surface of the ground above the explosion, many of the plants seem to be tempo-

rarily highly stressed. The plants alter their metabolisms in response to this stress in a way that is observable in visible light reflected from the leaves. We found that within 56 hours of the underground explosion, all the plant species located on the surface areas that experienced accelerations greater than 0.2 g do in fact show what appears to be measurable stress. The pattern of the amount of indicated stress in the plants generally follows the pattern of the measured surface acceleration caused by the underground explosion. Seven days after the explosion, the observed levels of plant stress relaxed to about one-third of levels observed 56 hours after the explosion. Seven days after NPE, the observed distribution and radial extent of the relaxing plant stress remained generally the same as the original distribution measured 56 hours after NPE.

NPE Overhead Imagery Data Collection

EG&G Remote Sensing Laboratory (RSL) at Nellis Air Force Base in Las Vegas acquired all of the overhead images for the NPE, using a Citation CE-550 twin engine jet. Flights were made on September 20, 21, 22, 24, 29, and 30, 1993. The predawn flights, to acquire the thermal infrared images, were done on September 21, 22, 24, and 29. The results of these thermal infrared predawn images are discussed in Ref. 2. The solar-noon flights, to acquire the visible and infrared images, were done on September 20, 22, 24, and 30. The weather conditions were ideal—dry and clear on all eight overflights. The NPE was exploded on September 22 at 12:01 a.m. Pacific Daylight Time, so the images taken at solar-noon on September 20 and at predawn on September 21 are the preexplosion reference images. The predawn images taken on September 22 were acquired 5 hours after the explosion. They were followed by the solar-noon images 5 hours later. Predawn and solar-noon images were then acquired on September 24, 29, and 30 to record longer-term changes or possible erasure of changes following the explosion.

Each overflight acquired visible-light color photographs using the RC-30 large-format, forward-motion-compensated camera, and 11 wavelength bands of light from the blue to the thermal emission infrared using the Daedlus AADS1268 multispectral imaging scanner. Eight bands have wavelengths in visible light starting at 420 nanometers and ending at 1050 nanometers. The remaining three bands are the 85 - to 1250-nanometers infrared thermal emission band, and the 2080- to 2350-nanometers and the 1550- to 1750-nanometers infrared reflection bands. Sets of images were acquired from altitudes of 305 and 1525 meters (1000 and 5000 feet) above the top of Rainier Mesa at predawn and at solar noon on each day. Although the jet did not fly in a perfectly straight line, the images from different bands can be compared directly without georegistration because all 12 bands were acquired simultaneously during the flight pass.

Two areas were imaged each day (Figure 1). The first was a square area 4 kilometers on a side and centered on GZ. The surface elevation of Rainier Mesa is approximately 2195 meters (7200 feet) above sea level. This 4- by 4-kilometer area was imaged in 13 separate overflights by a jet traveling at a ground speed of 130 knots and an altitude of 305 meters (1000 feet). With this flight pattern, the Daedlus multispectral imagery had a spatial resolution not greater than 1 meter at the surface. The second image area was a rectangle that extended 5 kilometers north and south of GZ and was imaged from an altitude of 1525 meters (5000 feet) above the surface of the mesa.

Shock-Induced Plant Stress

The effects of underground nuclear explosions on the plant life on top of Rainier Mesa were studied extensively and reported on by Rhodes.[5] In that study, however, Rhodes limited the methods to physical inspection of the plants and ground features. For example, he studied the ratio of the number of plants that died after one year to the total of the same species as a function of their location with respect to GZ of kiloton-sized nuclear explosions. These explosions were done in N tunnel, the same tunnel used in the NPE.* However, Rhodes could not study temporary plant stress effects because data in that study were collected in surface surveys, and stressed plants would have returned to normal by the time people were allowed to walk through the area.

The NPE explosion offered the opportunity to study plant stress effects again, but this time using wide-area timely snapshots of the top of Rainier Mesa. I, personally, reentered the top of Rainier Mesa at dawn on September 24 and conducted a day-long search of the entire mesa for classical tell-

*Many effects were observed, and the extensive report is well worth reading for those who are interested in this type of work.

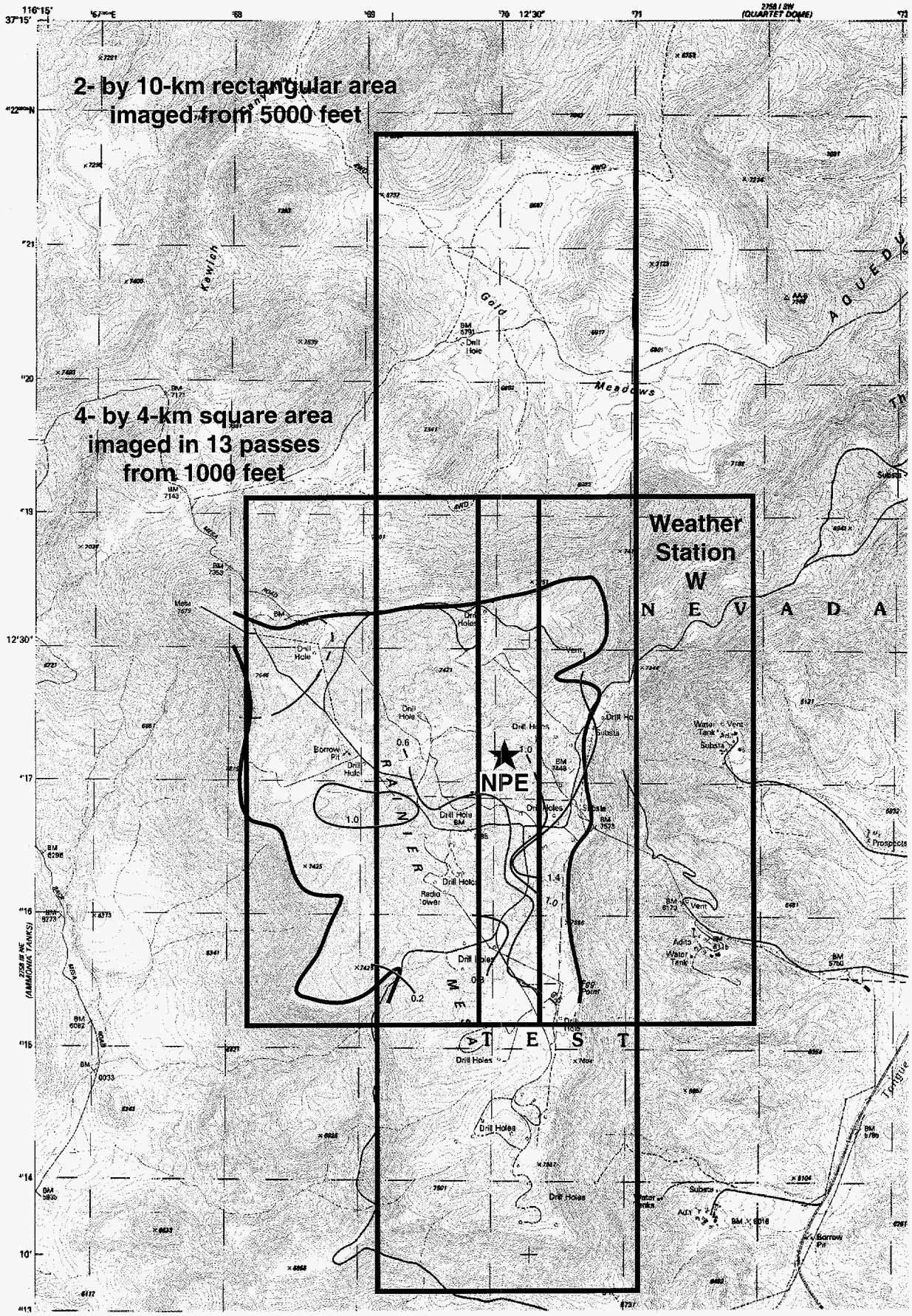

Figure 1. U.S. Geological Survey map of Rainier Mesa with the areas imaged during NPE and the location of GZ superimposed. The 4- by 4-kilometer area was imaged from an altitude of 305 meters (1000 feet) above the mesa surface. The spatial resolution of these images is 0.7 meters for all bands acquired. The larger rectangular region was imaged from an altitude of 1525 meters (5000 feet) above the mesa surface, with a spatial resolution of 3.5 meters. Red contours are the maximum acceleration in g (see also Figure 5).

tale signs of changes to plants or other changes that might have been caused by the NPE explosion. I did not discern such changes as openings or cracks in the soil, power poles that had shifted, new rock slides, or visible damage to the plants. However, the oak trees on top of Rainier Mesa showed an early and particularly intense onset of senescence, which is the change to fall colors. Although senescence is a common, usually annual event for plants, its early onset is one form of plant stress that has been studied extensively.[6,7] Many conditions will induce stress in plants, causing them to alter their metabolic processes. Such stress agents include drought, disease, exposure to saltwater or pesticide, and overfertilization.[6,7] The spectacular senescence of the oaks was also observed independently and reported to me by the members of the other reentry parties whom I interviewed. It was this serendipitous observation of senescence that led to my investigation of the shock-induced plant stress and to the results reported in this paper.

Plant Stress Analysis Method

The method used in this study was adapted directly from that used by Gregory Carter.[6,7] Carter conducted extensive investigations using remote-sensing techniques to identify stress in several plant species. He studied plants that were assaulted by seven common agents, or conditions, such as saltwater, drought, pesticide, and disease. One of the stress conditions he studied was senescence, and one of the species was oak trees. Carter's results were particularly significant to this imaging study because the oak trees within 2 kilometers of GZ on Rainier Mesa had undergone rapid senescence.

According to Carter,[7] the ratio of light reflected by the plant leaves with a wavelength of 690 nanometers to that with a wavelength of 420 nanometers is the single most sensitive measure of plant stress in all of the species he studied. Figure 2 shows the wavelength spectrum of visible

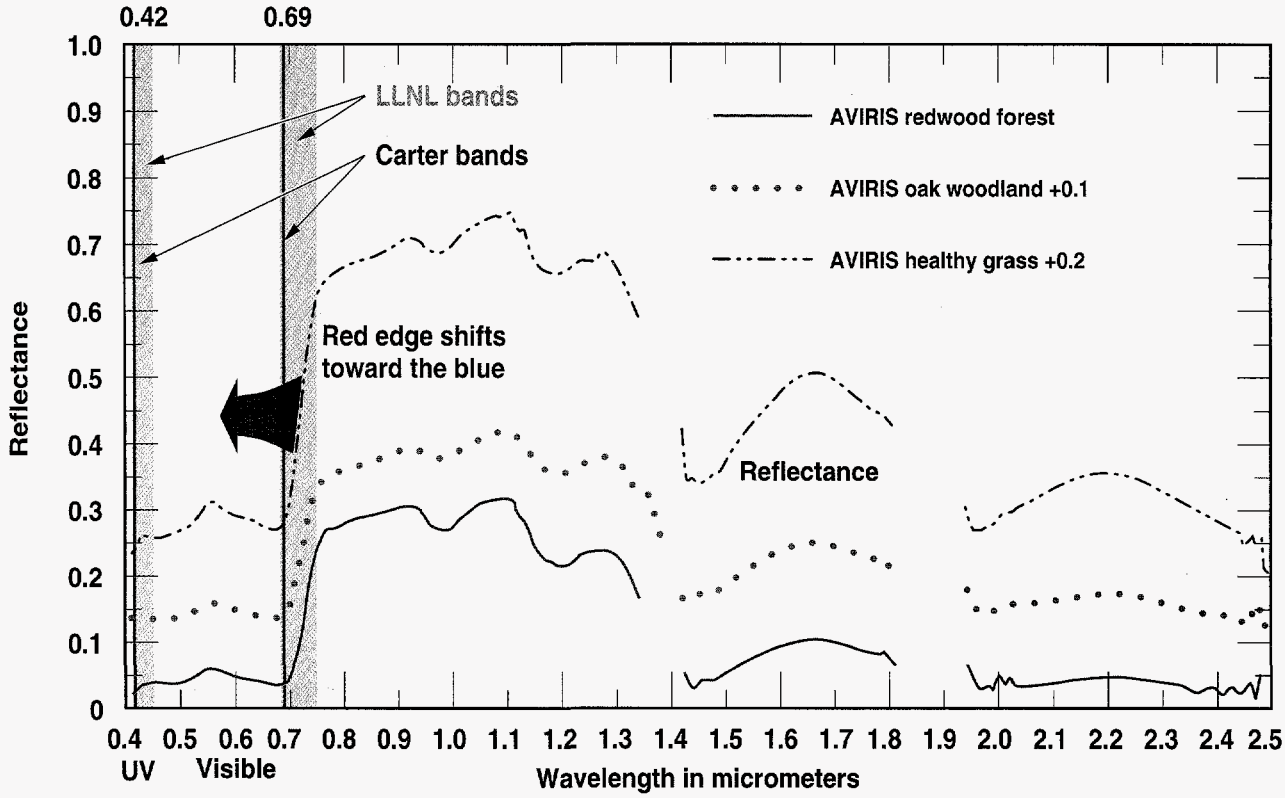

Figure 2. The Carter and LLNL bands at 0.42 and 0.69 micrometers (420 and 690 nanometers) that were used to form the plant stress ratios shown superimposed on the wavelength spectrum of expressed leaf water as measured by Green and Roberts. The LLNL bands are 30 and 50 nanometers wide. Carter's bands are 2 nanometers wide. The widening of the red chlorophyll peak into the bands at 0.69 micrometers that occurs when the plants are stressed is shown schematically by the large arrow. Note: Bands are shown in micrometers because of space constraints.

and infrared light reflected from three types of plants as measured by Green and Roberts.[8] Figure 2 shows the locations of the wavelength bands Carter used. Carter's conclusions about the uniform applicability of the 690- to 420-nanometer ratio[7] were the basis for this study.

As shown in Figure 2, Carter used very narrow wavelength bands about 1 to 2 nanometers wide centered at 690 and 420 nanometers to produce the most sensitive detection of plant stress. The wavelength bands acquired by the Daedlus AADS1268 during the NPE overflights were 50 nanometers wide. However, these relatively wide bands do not prevent using Carter's ratio technique. The ratio of 690- to 420-nanometer reflected light is increased by a subtle widening of the highly saturated chlorophyll reflectance peak into the 690-nanometer band compared to the relatively constant amount of reflectance in the 420-nanometer band. This chlorophyll reflectance peak has a steep edge almost exactly at 690 nanometers (Figure 2), so a slight shift of the large peak into the edge of a band that is at 690 nanometers will rapidly increase the brightness observed. On the other hand, 420 nanometers is in the near ultraviolet region of the visible light spectrum. Ultraviolet images formed using 420-nanometer light have very indistinct shadows and generally low contrast. Also, as shown in Figure 2, reflectance from leaf water measured by Green and Roberts[8] shows little variation with wavelength in the 420-nanometer region. Any reflectance shifts in this region would result in very little change in observed brightness. In any case, phenomenologically, the brightness in the 420-nanometer region does appear to be insensitive to plant stress conditions.

The lower edge of band 6 of the Daedlus AADS1268 is exactly at 690 nanometers. Therefore, our band 6 includes the 695-nanometer region, which is the most sensitive region for plant stress measurement determined by Carter.[6,7] The lower edge of band 1 is at 420 nanometers and is about 30 nanometers wide. Although the Daedlus band 1 is wider than that used by Carter, it can still be used as the reference reflectance in the observed images.

The band-6 image acquired on September 24, about 56 hours after NPE, was much brighter than the band-6 images taken on the other days before and after NPE. This result is consistent with the brightening of band 6 being caused by plant metabolic changes. The natural time constant for most plants to show stress or to return to normal after the stress is removed is about 48 hours. Since a real signal seems to be present, a Carter-type ratio technique to display plant stress has been performed using the NPE images. The ratio of brightness in band 6 to that in band 1, in the same pixel location in the two images, was used as the measure of the degree of plant stress in that pixel. The ratio of band 6 to band 1 was formed on each of the days for which data were acquired. Because all of the bands were acquired simultaneously, a pixel location in the band-6 image and the same location in the band-1 image during each flight pass are the reflected brightness, at the different wavelengths, of exactly the same 0.7-meter square on the surface. This detail is critically important because when the ratio of band 6 to band 1 is formed, the band-6 pixel and the band-1 pixel used must represent exactly the same area on the ground. It was also critically important that, prior to forming the ratio between the bands, none of the images was subjected to geo-registration, warping, or another enhancement operation, because such operations move pixels and mix the values in adjacent pixels. Care was taken to force the analysis program not to perform a smoothing or substitution operation during the internal computations.

The result is that the ratio of band 6 to band 1 formed from the data taken on September 24, 56 hours after NPE, has many individual pixels with large ratio values. Carter established a ratio of 4 as being most representative of highly stressed plants.[9] As discussed previously, the NPE wavelength bands are somewhat wider than Carter's but are fortuitously placed so that the expected ratio values should be only somewhat less that Carter's. The wider bands use all of the signal that Carter's bands would be using, but the noise or background values will be somewhat larger because the bands are wider. In the analysis reported here, 3.75 was chosen as the indicator of highly stressed plants, but this assumption must be studied further.

The September 24 ratio images have many pixels with values greater than 3.75. In contrast, no pixels in the ratio images formed from data taken on other days have ratio values above 3.75. In addition, the centroid of the frequency distribution of the pixel values is much larger on September 24 than on September 20, and it is somewhat larger than that observed on September 29 (Figure 3). This result is consistent with the conclusion that the plant stress observed in the ratio image from September 24 could have been induced by the violent shaking from the explosion and that the plants were then recovering by September 29.

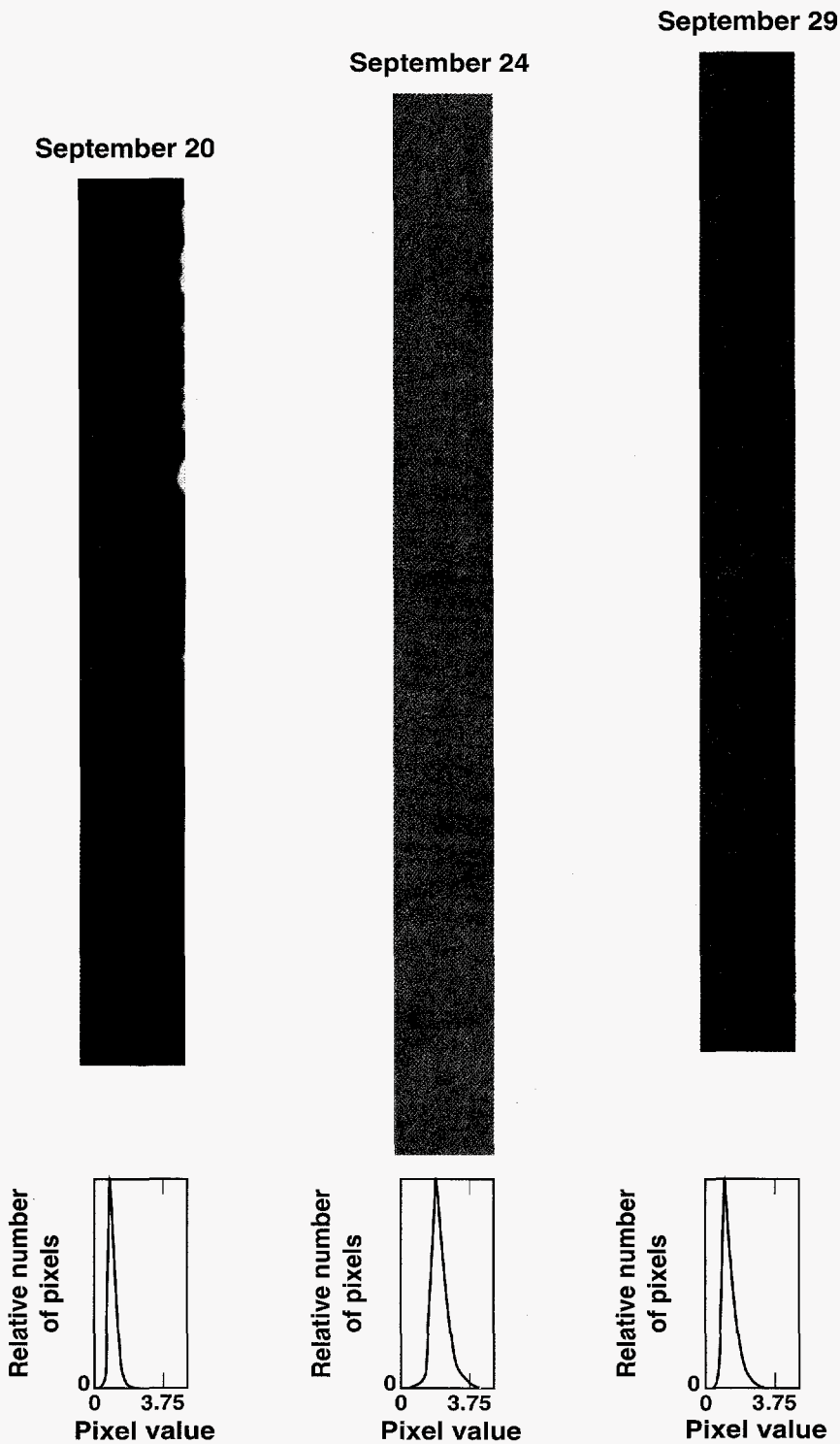

Figure 3. The pseudo-color rendering of the ratio images for the flight line over GZ on September 20, 24, and 29, and the frequency distribution of pixel values in the ratio image for each day. Red is the largest numerical value, and blue is the smallest. The same scale of pseudo-colors is used in all three images. The September 24 image (middle) is very bright and has many pixels with values greater than 3.75, in contrast to the day before or the week after the NPE. Also, the centroid of the frequency distribution of the pixel values is much larger on September 24 than on September 20 and somewhat larger than that on September 29.

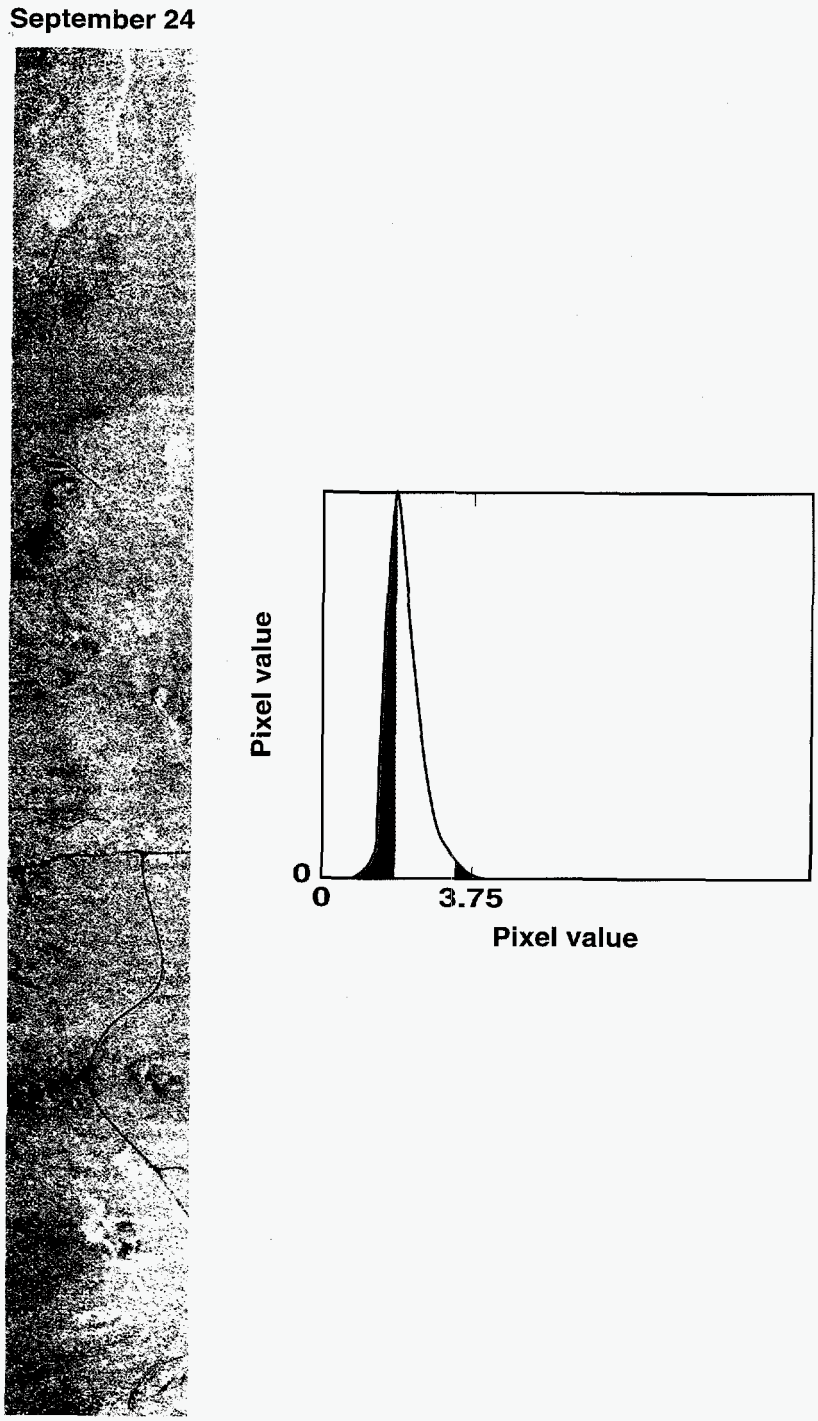

Figure 4. A pseudo-color ratio image from the flight line passing through GZ taken on September 24. This image is tailored to expose the pattern of plant stress observed (red) with respect to the roads and major geological features (blue). All pixels with ratio values below 1 appear as shades of blue; those with values above 3.75 are shades of red; and those with values between 1 and 3.75 are white.

To verify that the pixels with the high ratios, between 2 and 5, are in fact from plants, I walked or drove through the entire image area. This phase of the study was facilitated by Rainier Mesa being an arid high desert with distinct clumps of plants. Incidentally, during this inspection, I observed that man-made objects seem to have ratio values of 0.2 and below, which makes distinguishing man-made objects from natural objects rather trivial.

Figure 3 shows the pseudo-color rendering of the ratio images for the flight line over GZ on September 20, 24, and 29. In this figure, pseudo-color displays give a color to the ratio of band 6 to band 1 in each pixel. On the color scale, red is the highest, and blue is the lowest. The same scale of pseudo-colors is used in all three images. Histograms that show the relative frequency distribution of pixel values in each ratio image are also included. All of the plant species on Rainier Mesa appear to be strongly stressed by the NPE explosion. Figure 4 shows a different pseudo-color rendering of the image that is in the center of Figure 3. This image is the ratio image of the line passing through GZ taken on September 24, 56 hours after the explosion. In this figure, pixels with ratios below 1 appear as shades of blue, those with ratios above 3.75 are shades of red, and those with ratios between 1 and 3.75 are white.

Close study of Figure 4 reveals the distribution pattern of the plants with high ratio values, which are thus asserted to be highly stressed. The pattern generally is more concentrated around GZ and the area that runs off to the north–northeast or slightly to the left top of the image. This trend is reflected in the pattern of measured maximum accelerations plotted on top of the Rainier Mesa map shown in Figure 5. Although not shown, investigation of the other 13 strip images taken on September 24 show that strong apparent plant stress does indeed appear to be concentrated to the north–northeast and extends out several kilometers. The degree of correspondence between the measured peak acceleration patterns and the concentration and degree of plant stress will be studied in FY 1996. Interestingly, the areas observed to be the most stressed are also reported by Rhodes as having anomalously greater long-term plant damage because of similarly sized nuclear explosions done in N tunnel.[5]

Conclusions

Widespread and intense temporary stress of plants on Rainier Mesa around GZ following the NPE appears to have been observed using low-altitude, high-spatial-resolution images and an analysis technique that uses the ratio of reflectance at 690 nanometers to that at 420 nanometers. The apparent plant stress is not present before NPE, is very intense 56 hours after the test, and is almost gone 7 days after it. The most extreme plant stress is concentrated around GZ and extends out at least 2 kilometers. This distance roughly corresponds to the area that suffered surface shocks of greater than 0.2 g measured by the seismic arrays deployed around GZ. The pattern of the plants' stress generally follows the pattern of the measured surface acceleration. All of the plant species on Rainier Mesa were strongly stressed by the explosion. The bright pixels in the September 24 ratio image were verified to be caused by plants as opposed to some other source.

The results of this study seem to confirm that multispectral images taken from a low-flying aircraft can be analyzed using a reflected light ratio technique for measuring plant stress. However, this is only one experiment, and many questions remain. Ground truth experiments are needed to explore all the various plant-stress factors. Laboratory experiments under controlled conditions will help confirm the accuracy of these findings. Also, shock-induced plant stress must be studied in environments other than a high desert to determine whether this technique can be transported to other areas. In addition, by improving the sensor design, it may be possible to simplify the observation of shock-induced plant stress from smaller platforms such as small aircraft, the new generation of unmanned aerial vehicles, and possibly even small satellites.

At this time, remote observation of plant stress is a potentially powerful tool for narrowing the initial inspection region for on-site inspection conducted as part of the Comprehensive Test Ban Treaty currently being negotiated in Geneva. In addition, since the ground motion associated with earthquakes can be 0.2 to 0.4 g or even greater, this technique may also be useful in studying damage patterns associated with large earthquakes.[10,11] However, the most important result of this work is probably the creation of a powerful methodology for wide-area, timely remote sensing of induced plant metabolic changes caused by environmental factors. These techniques should help improve the quality and breadth of environmental studies that involve the impact of one ecological system on another.

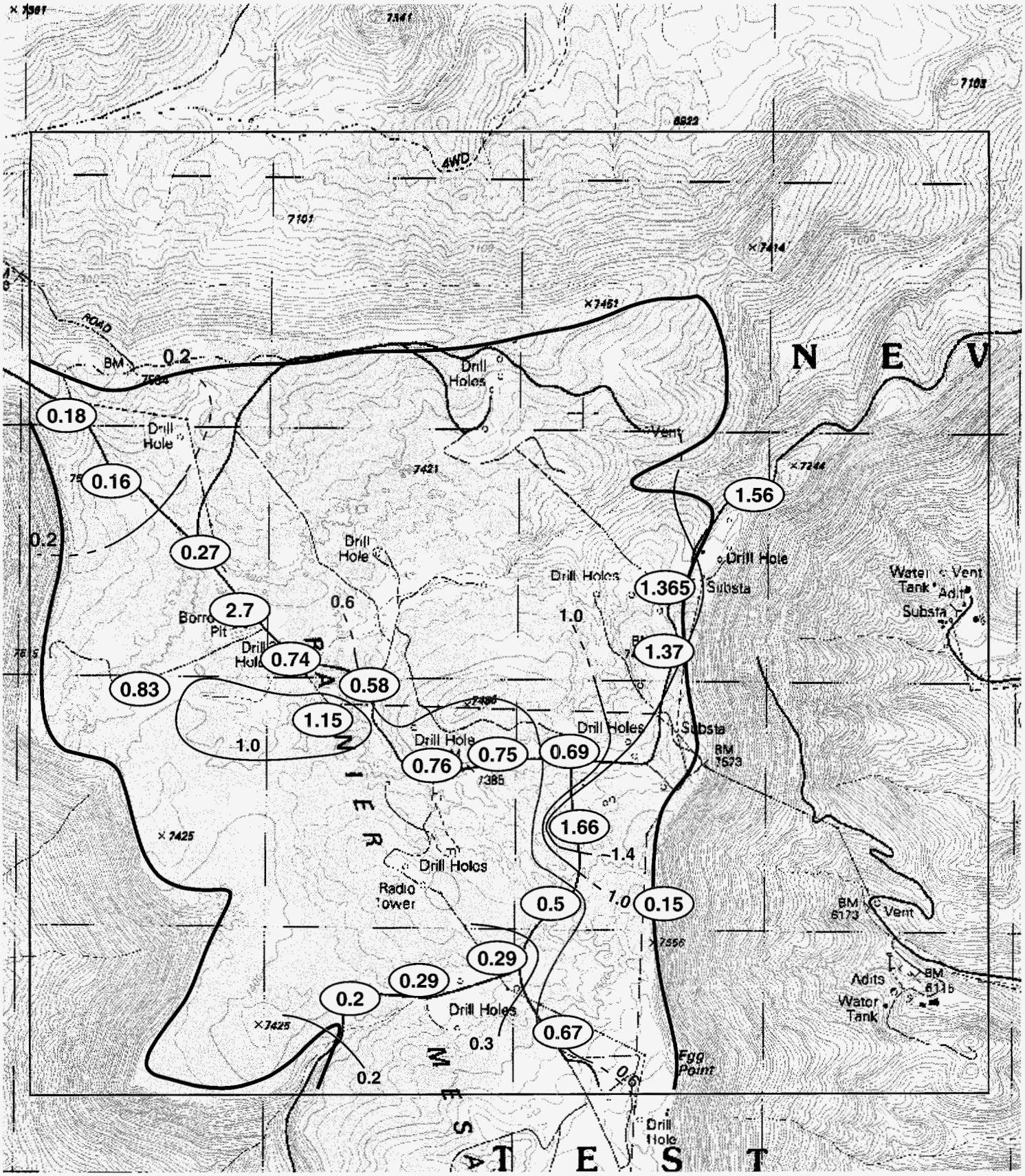

Figure 5. The actual peak or maximum surface accelerations produced by the NPE explosion, superimposed on the U.S. Geological Survey topographic map of Rainier Mesa. The contour lines are hand drawn and serve only to guide the eye; they should not be taken as data. The distribution pattern of the peak accelerations is complex and generally corresponds to the observed plant stress distribution. This pattern suggests that a detailed comparison with all 13 images should be done.

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