Polarimetric imaging Radar: Analysis Tools and Applications

by

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March 1, 1989

1. Introduction

Several existing and future Earth and planetary radars will have multipolarization capability. For example, transmit and receive polarizations can be selected independently at major planetary radar facilities such as the National Astronomy and Ionosphere Center's Arecibo Observatory in Puerto Rico and the Jet Propulsion Laboratory's Goldstone Solar System Radar in California. In addition, the S-band (2.5 GHz) Synthetic Aperture Radar (SAR) on Magellan will provide backscatter cross section estimates over most of the Venusian surface with HH polarization. During the Extended Mission, the Magellan spacecraft will be turned so that VV polarized data may also be acquired. On the terrestrial side, there arc several imaging radar systems capable of acquiring multi parameter data. The Canadian Centre for Remote Sensing (CCRS) flew a multifrequency synthetic aperture radar (SAR) that operated at X-, C- and L- band from 1981-1984 and is currently upgrading the system to a digital C-band and X-band system that will acquire data at multiple polarizations (Goodenough and Livingston, 1986). The Jet propulsion Laboratory (JPL) developed and flew the first multipolarization SAR in which the received wave is decomposed into two orthogonally-polarized components, which independently feed two identical and coherent receiver channels, and in which reception polarization diversity is accompanied by transmission polarization diversity, so that an object's complete scattering matrix can be measured. Polarimetric radar data were acquired at L-band in Spring of 1985 using this airborne SAR. The Environmental Research Institute of Michigan (ERIM) developed an X-, C-, L-band polarimetric SAR (Kozma et al., 1986) which was completed in 1987 (see chapter by van Zyl and Zebker, in this volume for background on imaging radar polarimetry).

The Shuttle Imaging Radar (SIR-C), currently planned for flights in February 1992, March 1993, and September 1994 will acquire multifrequency (L- and C-band), multi-incidence angle, polarimetric SAR data over the Earth's surface between 57 degrees north and south latitude, and the Earth Observing System (Eos) SAR currently planned for the late-1990's will acquire comparable data sets over the entire Earth. In 1988, the NASA/JPL Aircraft SAR was rebuilt and upgraded to a C- and L-band system so that it provides a nearly exact prototype for the C-band and L-band channels of SIR-C and the Eos SAR. In addition, a longer wavelength P-band (440 MHz) channel was added which provides a prototype to the proposed Spaceborne P-band Imaging Radar Experiment (SPIRE), Multiparamctcr data sets have been acquired with thc NASA/JPL Aircraft SAR over several geologic and forested areas, grasslands and sca ice. These data arc being used in a variety of Earth Scicncc investigations and to develop software tools for analysis of polarimctric data from future sensors. Examples of how recently dcvclopcd tools have been used to analyze polarimctric radar images in two Earth Scicncc investigations, a geologic process and palcoclimatology study and a forest ecology study, are dcscribcd in the following sections.

11. Geologic Proccsscs and Palcoclimatology

A kcy element in understanding the nature and significance of contemporary global change is thc ability to reconstruct past climatic variables. This requires that surface proccsscs related to past climatic conditions bc identified and correlated over large regions, a task for which remote sensing is ideally suited. Kcy to deriving process signatures related to past climates is the dcvclopmcnt of physically based models of the relationship bctwccn the geophysical quantities being measured and geologic information.

Weathering and dcpositional processcs in dcscrts generally cause surfaces to smooth with agc while erosional proccsscs cause a roughening. The scales of these proccsscs are different and their rates vary with climate, rock typc, and geologic structure, however their effects can bc used to relatively date surfaces for studies of climate change and tectonic history. Rcccnt work has shown that relative ages of picdmont surfaces can bc mapped on the basis of surface roughness changes brought about by physical weathering and acolian deposition (e.g. Farr and Gillespie, 1984). In some cases, numerical ages have allowed preliminary derivations of the rates over time of some of these processcs. For example, radiomctric dates of lava flows at the Cima Volcanic Field, located approximately 120 km southwest of Las Vegas, Nevada in the Mojavc Desert of California have allowed the rate of acolian deposition on the flows to bc derived (Farr and Anderson, 1987). This region is composed of some 40 cinder cones and 60 associated basaltic lava flows that range in agc from 8 million years (my.) to 16,000 years (Dohrcnwcnd ct al., 1984; Dom, 1984; Turrin et al., 1984). Local relief on these flows ranges up to 5 m on younger flows but is less than 1 m on flows older than 0.25 my.

The geomorphic evolution of the Cima flows has been described by Wells et al. (1985). Systematic changes in the flow surfaces were found to be caused by cyclic changes in the rates of aeolian deposition, soil formation, and fluvial erosion. These cycles were interpreted to be the result of changes in climate alternating between warmer, dryer interglacial and cooler, wetter glacial periods. Wells et al. (1985) made morphologic measurements on flows of different age in order to quantify the changes they observed. One of the most prominent and consistent changes observed and measured was the change in surface relief or roughness with lime. This is caused mainly by rubbling of flow projections and by filling in of flow depressions with wind-blown silt.

Changes in surface roughness with age in the Cima area were analyzed using L-band polarization signatures of the different units by Evans et al. (1988). The concept of the polarization signature of a scatterer was used by van Zyl et al. (1987) and Zebker et al. (1987) to plot the power of a return wave as a function of transmit and receive polarizations. In addition to the co- and cross-polarized polarization signatures for which both transmit and receive polarizations arc spccificd, Evans cl al. (1988) introduced polarized and unpolarized signatures which depict the relative power of the return wave for all transmit polarizations. These signatures taken together, represent a more complete description of the polarimetric scattering properties of a surface. Evans et al. (1988) noted that the unpolarized return was the most sensitive to the effects of age on lava flow surfaces and concluded that trends in the unpolarized signatures were consistent with a decrease in "pedestal height" (see van Zyl and Zebker, this volume) caused by decreasing roughness with age.

As described in Evans et al. (1988), knowledge of the Stokes vector of the received signal allows the decomposition of a partially polarize.d signal into completely polarized and completely unpolarized components, where the partially polarized signal may be regarded as the sum (e.g. Kraus, 1966):

$$\begin{pmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{pmatrix} = s_0 \begin{pmatrix} 1-d \\ 0 \\ 0 \\ 0 \end{pmatrix} + s_0 \begin{pmatrix} d \\ d\cos(2\chi)\cos(2\psi) \\ d\cos(2\chi)\sin(2\psi) \\ d\sin(2\chi) \end{pmatrix}$$

where:

$$\begin{pmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{pmatrix} =$$ Stokes vector of average **received** signal from a region

$$d = \sqrt{\frac{s_0^2 + s_1^2 + s_3^2}{s_0}}$$

$\chi =$ wave **ellipticity** angle

$\psi =$ wave orientation **angle**

$$\begin{pmatrix} d \\ d\cos(2\chi)\cos(2\psi) \\ d\cos(2\chi)\sin(2\psi) \\ d\sin(2\chi) \end{pmatrix} =$$ Stokes vector of completely polarized part of the average **received** signal from a region

Figure 1 is a total power L-band image image of the Cima Volcanic Field showing areas where unpolarized signatures have been extracted from lava flow units with three different ages. Figure 2 shows the C-, L- and P-band unpolarized signatures from these three units. Unit i_1 is dated at 0.14 million years (my.), Unit r2 at 0.7 my., and Unit p_1 at 0.6- 1.1 my. (Dohrenwend et al., 1984). Figure 2 shows that L-band unpolarized signatures decrease with age as noted in Evans et al. (1988). However, while the unpolarized C-band return decreases from Unit i_1 to Unit r_2, it increases from Unit r_2 to Unit p_1. In the P-band case, there is a continued increase in unpolarized return going from the youngest to (hc oldest units.

These trends can be explained by investigating the Wells et al. (1985) model in more detail. As mentioned, Wells et al. (1985) observed consistent changes in roughness with time caused mainly by rubbling of flow projections and by filling in of flow depressions with wind-blown silt. However, after approximately 1 my., drainages develop causing an apparent roughening of the surface. Models of these three representative stages of landscape evolution arc shown diagrammatically in Figure 3. The signatures in Figure 2 arc consistent with an overall smoothing from about 0.1 to 0.2-0.7 my. at roughness scales where L- and C-band arc sensitive, then an increase in roughness at C-band scales caused by rougher surfaces being exposed as drainages develop. It appears that the P-band may be penetrating the wind-blown silt that fills in flow depressions, resulting in increased multiple scattering with age.

The results presented here indicate that multi frequency polarization signatures provide a link between geologic processes and radar remote sensing data. Future work will emphasize the quantitative determination of the physical state of the surface which should allow direct comparison between different areas in terms of the absolute roughness of surfaces and the rate of modification under different conditions. Specifically, radar backscatter models and inversion techniques arc being developed that will allow backscatter data acquired at multiple angles, frequencies, and polarizations to be inverted to yield estimates of dielectric constant and surface roughness at scales from approximately 2 cm to 1 m. These estimates can then be used as measures of the amount and type of physical modification of a surface. Once the spatial distribution of these modification processes can be determined, it will be possible to relatively date surfaces for studies of climate change and tectonic history.

111. Forest Ecology

Another kcy clcmcnt in understanding global change is thc ability to quantify sources and sinks of greenhouse gases such as C02, CH4, and N_2O. For example, the magnitude of the carbon source and sink strength in forests depends largely on thc successional stage. In addition, forests arc being rapidly clcarcd for agriculture and pasture resulting in a rclativcly instantaneous (depending on whether the forest in burned or left to dccomposc) influx of C02 in the atmosphere. Information on (1) the biomass of the existing forests, (2) the area] extent of the clcarcd forests and (3) the successional stage of primary and secondary growth forests (and thus the carbon source/sink strength) arc all essential to understanding thc role of forests in the global carbon cycle.

Several studies have shown that radar may be an cffcctivc tool for analysis of deforestation and reforestation, and possibly determination of above-ground woody biomass and successional stage (Hoffcr et al., 1986; Richards ct al., 1987; Paris and Kwong, 1988; Sun and Simonctt, 1988 a,b). van Zyl (1989) dcscribcd an unsupervised classification tcchniquc which is uscful for interpreting scattering from forested areas and was used in Evans ct al. (1988) to map clear cut areas that were not discernablc in L-band HH and VV images.

Thc unsupervised algorithm described in van Zyl (1 989) classifies scatterers into onc of three types based on the relationship bctwccn the orientation angles and handedness of the transmit polarization to the corresponding parameters of thc rcccivc wave for each transmit polarization. The first class of scattering is single reflection. Using Rice's (195 1) rough-surface scattering model as cxtcndcd by Pcakc (1959) and Valcnzucla (1967), onc would expect that in the case of a slightly rough dielectric surface the incident wave would cxpcricncc little multiple scatter (Figure 4a). In this case, HH and VV signals arc in phase, and the orientation angle of the scattcrcd wave incrcascs as the orientation angle of the transmitted wave increases, and dccrcascs as the orientation angle of the transmitted wave dccrcascs. The handedness of the scattered wave, however, would be the opposite of that of thc transmitted wave polarization. That is, for example, a left-hand elliptically polarized wave would bc returned as a right-hand elliptically polarized wave.

The second class of scattering (Figure 4b) is from a dihedral corner reflector, and exhibits a double-bounce geometry, resulting in a 180 degree phase shift between HH and VV. In this case, the orientation angle of the scattered wave decreases as the orientation angle of the transmitted wave increases. The handedness of the scattered wave polarization is the same as that of the transmitted wave polarization so that the ellipticity angles for the transmitted and scattered waves have the same sign.

For the third class of scattering, a diffusely scattering area exhibiting multiple interactions, a different behavior occurs. Due to the multiple interactions, the highly varying HH to VV phase difference over the area exhibits a noise-like character. The resulting Stokes matrix elements imply that the orientation angle of the average scattered wave tracks that of the transmitted wave, a behavior similar to that observed for the single-bounce case. However, the handedness of the scattered wave is the same as that of the transmitted wave polarization which is more consistent with a double-bounce mechanism. Evans et al. (1988), and van Zyl (1989) noted that this behavior is generated by a class of "three-layer" vegetation models such as the one shown in Figure 4c and described in van Zyl (1985), Richards et al. (1987), Ulaby et al. (1988) and Durden et al. (1989).

As discussed in van Zyl (1989), in a three-layer forest model consisting of a slightly rough ground surface at the bottom, a layer of randomly oriented dielectric cylinders oriented statistically around the vertical direction that represents the tree trunks, and a layer of randomly oriented dielectric cylinders that represents the major limbs of the trees, one expects a number of scattering processes to be important. The most important ones at L-band are: 1) direct back scatter from the top layer of the canopy (single reflection), 2) double reflections from the ground surface to the tree trunk or limbs (two forward reflections), 3) direct backscatter from the ground (single reflection), and 4) direct backscatter from the tree trunks (single reflection). By varying the number of cylinders in the two vegetation layers, van Zyl (1989) observed that for very sparse canopies, direct backscatter from the ground dominates and the area is classified as dominated by an odd number of reflections. In somewhat thicker canopies, scattering is dominated by the ground/trunk double reflections, and the area is classified as being dominated by an even number of reflections. If the canopy density is further increased, direct backscatter from the branches and ground/trunk double reflections become comparable, and the area exhibits the characteristics described for the diffuse class. Finally, for very thick canopies, where direct backscatter from the branches dominates, the area is classified as being dominated by odd reflections, The exact points at which these transitions from one class to the other are functions of radar frequency, forest density and trunk water content (cylinder dielectric constant).

Figure 5 shows an L-band total power image of an area in Mt. Shasta in northern California, This area contains conifers and some hardwoods (Durden et al., 1989), According to Durden et al. (1989), the area at the lower left of this image is a burned area with somewhat smaller trees (35 meters versus 45 m for the unburned trees). Figure 6 shows classification results based on C-, L-, and P-band data of the same area. One can see in Figure 6a that much of the area is classified as dominated by single reflections at C-band, indicating that the canopy is dense enough to result in single reflections from the branches, and the clear cuts areas allow single reflections from the ground surface. At L-band, while the clear cut areas are still dominated by single reflections, there is a much more pervasive diffuse scattering by the canopy, in both the burned and unburned areas, and some double reflection. At P-band, the clear cuts are more visible and the burned area in the lower left of the image exhibits significantly more scattering caused by double reflections. This increase could either be caused by the difference in the size of the trees as noted above or some change in the canopy as a result of the fire that results in increased penetration into the burned area. According to Durden et al. (1989), there is also an decrease in the P-band unpolarized signature of the burned area relative to the unburned area. They conclude based on model results that this may be caused by a lower dielectric constant in the burned area, which would explain the increased canopy penetration seen here.

The results presented here indicate that multi frequency polarimetric radar data provides the ability to isolate the scattering pathway which interacts mostly with tree trunks and stems, which is key to extracting biophysical parameters such as woody biomass (i.e. height and diameter of tree trunks and stems) and possibly trunk water content. Thus, as in the case of geological process studies, future work will emphasize the development of radar backscatter models and model inversion algorithms which can be used to convert radar parameters to biogeophysical parameters directly.

IV. Summary

In this chapter, wc give examples of recently developed software tools that enable scientists 10 analyze polarization signatures of natural targets and to identify probable scattering mechanisms for each pixel in a radar image, and discuss how these tools have been used to analyze radar images for two Earth Science investigations. Thc results presented here for a geologic process and paleoclimatology example indicate that multifrequency polarization signatures provide a link between geologic processes related to past climatic conditions and radar remote sensing data. The results of a forest ecology example indicate that multifrequency polarimetric radar data provides the ability to isolate the scattering pathway which interacts mostly with tree trunks and stems, which is kcy to extracting biophysical parameters such as woody biomass (i.e. height and diameter of tree trunks and sterns) and possibly trunk water content. Derivation of process-related information and biogeophysical parameters from remote sensing data is key to our understanding the nature and significance of contemporary global change. Thus, future work will emphasize the quantitative determination of the physical state of the Earth's surface and cover through the development of radar backscatter models and model inversion algorithms which can be used to convert radar parameters to biogeophysical parameters directly.

Acknowledgements. This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration, We would like to thank the people in the Radar Science and Engineering Section at JPL who operated the imaging polarimeter and processed the data used in this manuscript.

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Figure 1. Total power L-band image image of the Cima Volcanic Field showing areas where unpolarized signatures have been extracted from lava flow units with three different ages.

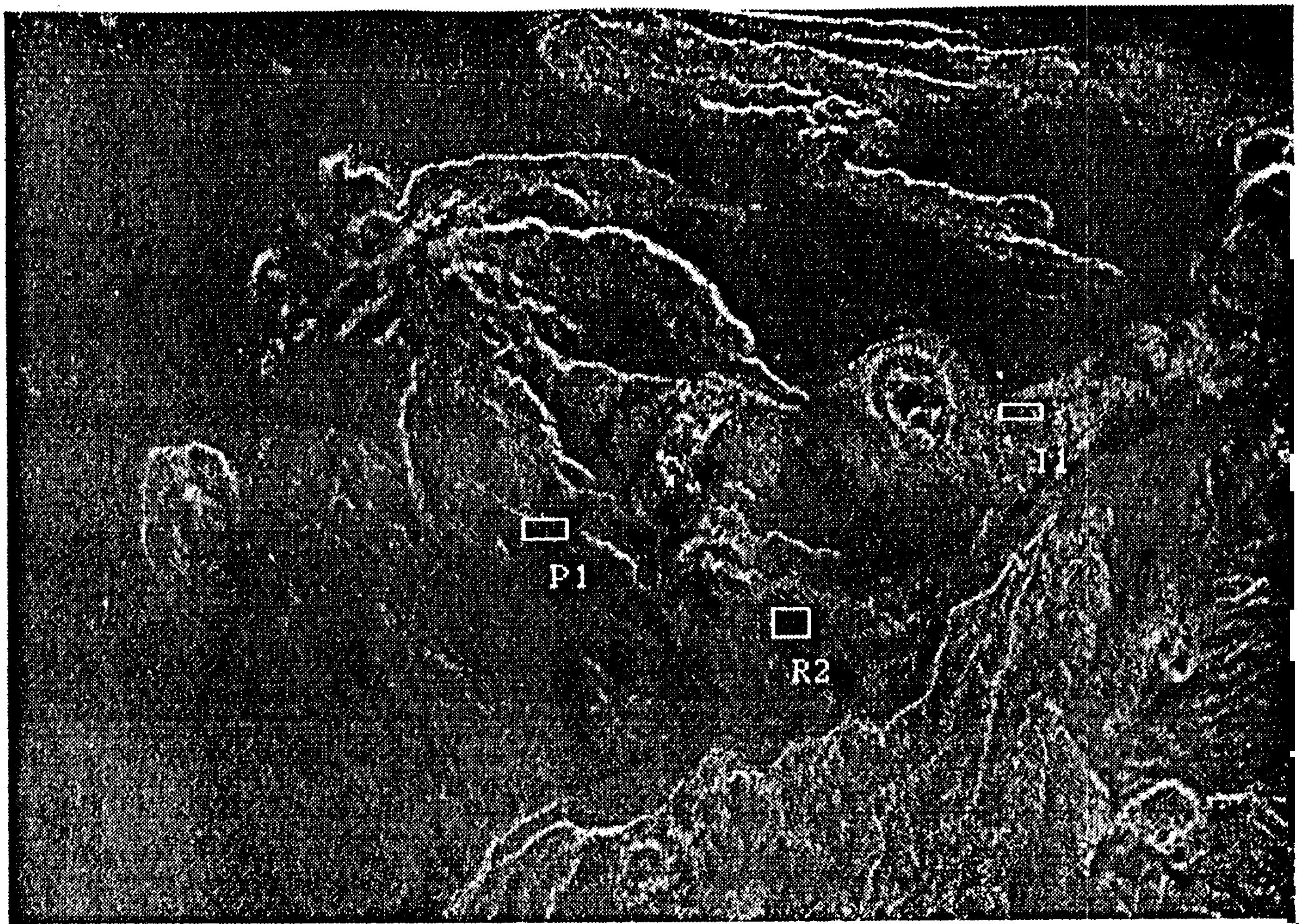
Figure 2. C-, L- and P-band unpolarized signatures from Unit i 1 (0.14 m.y.), Unit r2 (0.7 my.), and Unit P1 (0.6- 1.1 my.), Note that L-band unpolarized signatures decrease with age. However, while the unpolarized C-band return decreases from Unit i1 to Unit r2 , it increases from Unit r2 to Unit P1. In the P-band case, 'there is a continued increase in unpolarized return going from the youngest to the oldest units.

Figure 3. Models of these three representative stages of landscape evolution (modified from Wells et al., 1985).

Figure 4. Geometry for a) single (odd) reflection, b) double (even) reflection, c) diffuse reflection. (1) represents direct backscatter fromthe canopy, (2) represents signals that were scttered twice, (3) represents direct backscatter from the ground surface, and (4) represents direct backscatter from the tree trunks.

Figure 5. Total power L-band image image of of an area near Mt. Shasta, CA.

Figure 6. Classification results based on a) C-, b) L-, and c) P-band data of the Shasta area. Pixels classified in red arc consistent with a double reflection, in blue, with a single reflection and in green with a diffuse reflection.



P1
R2
I1

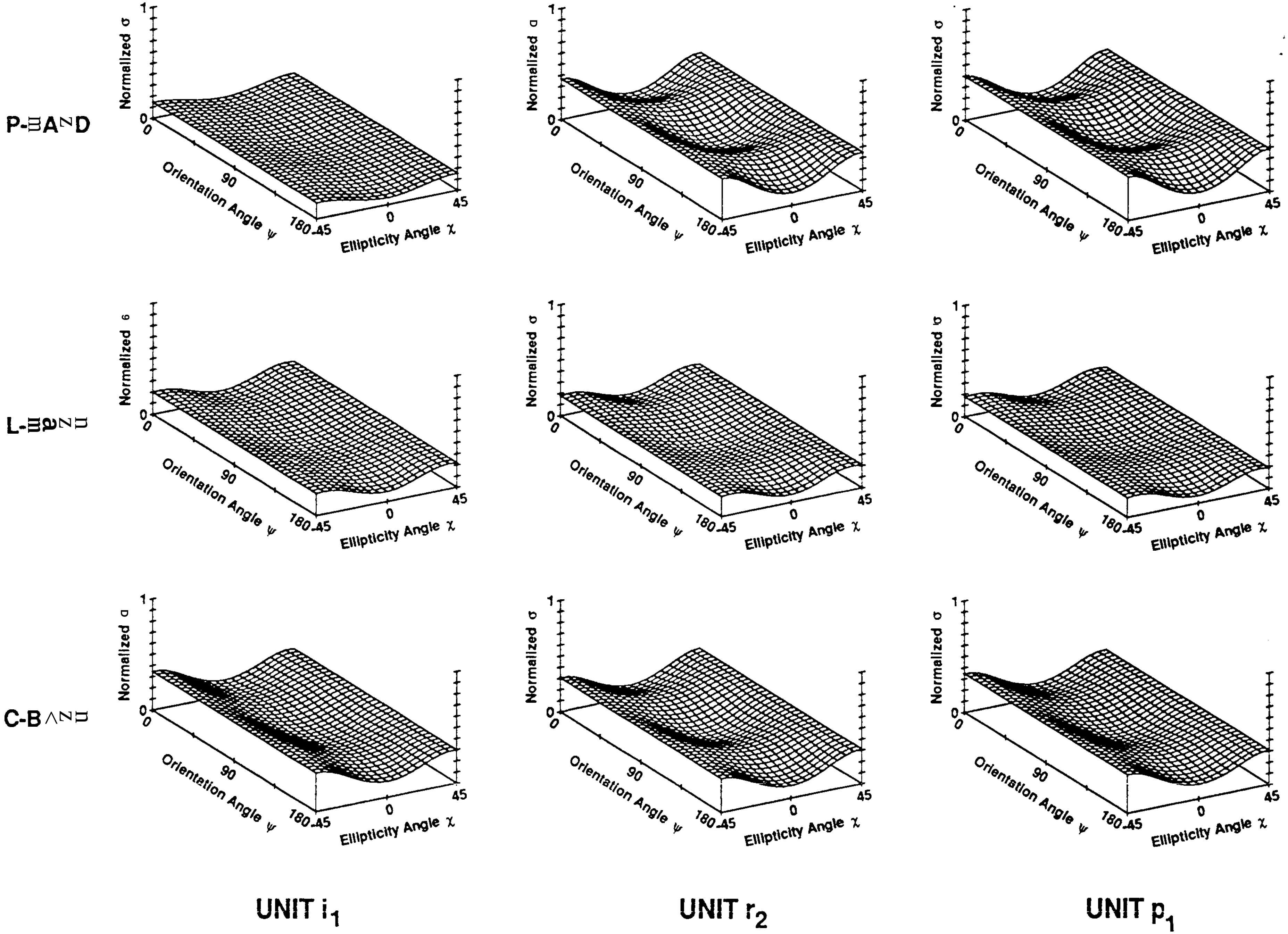
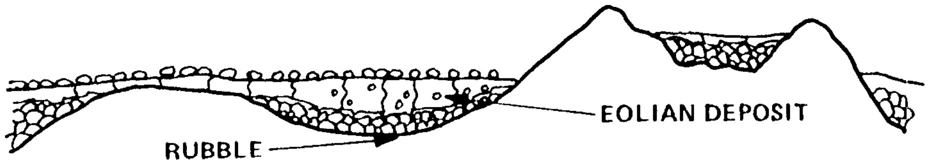

P-BAND
L-BAND
C-BAND
Normalized σ
Orientation Angle ψ
Ellipticity Angle χ
0
90
180
-45
0
45
1
UNIT i_1
UNIT r_2
UNIT p_1

Figure 2.

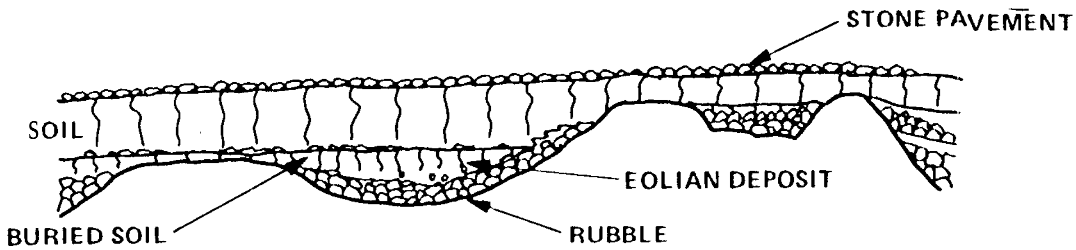
LATE PLEISTOCENE UNIT: i, (0.06-0.14 my.)

RUBBLING OF ORIGINAL SURFACE, ACCUMULATION OF EOLIAN FINES IN TOPOGRAPHIC LOWS, AND DEVELOPMENT OF STONE PAVEMENTS AND STAGE I SOILS



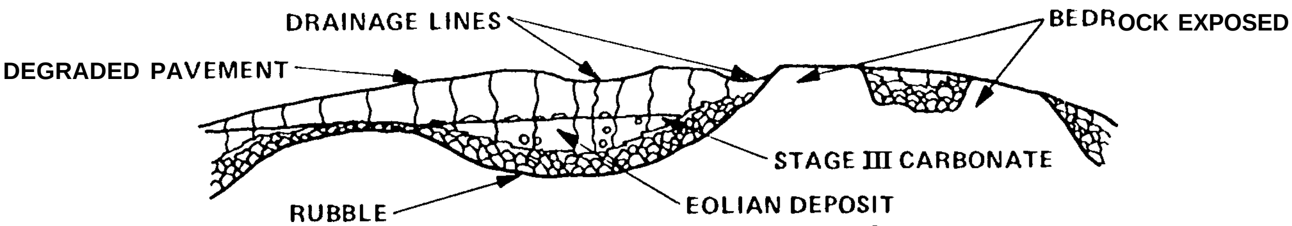
MIDDLE PLEISTOCENE UNIT: r_2 (0.20-0.70 my.)

RENEWED EOLIAN DEPOSITION, POST DEPOSITIONAL STABILITY, AND PEDOGENESIS



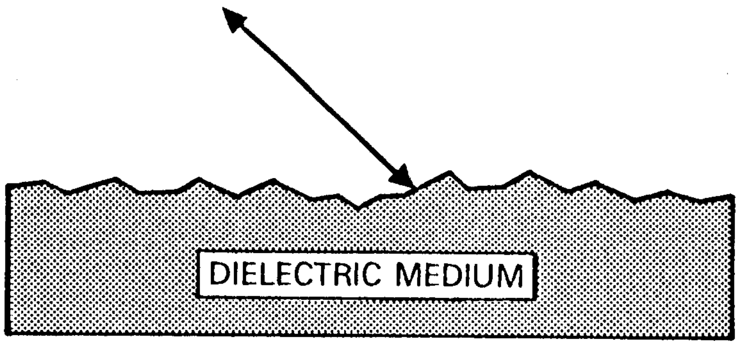
EARLY PLEISTOCENE AND PLIOCENE UNIT: PI (0.60-1.1 O my.)

PLUGGING OF SOIL WITH CARBONATE AND CLAY, INCREASED RUNOFF, STRIPPING OF PAVEMENT AND MANTLE

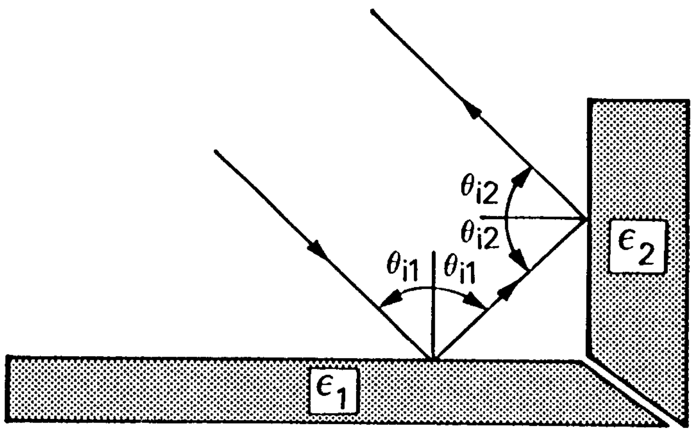


MODIFIED FROM WELLS et al, 19 B5, GSA BULL. V.96, P. 1518.

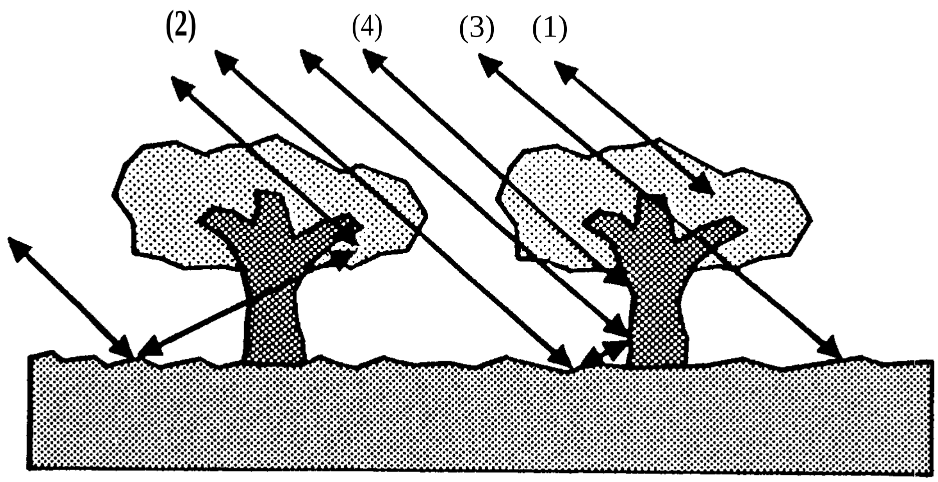
Figure 3.


DIELECTRIC MEDIUM

(a)


θ_{i2}
θ_{i2}
θ_{i1}
θ_{i1}
ϵ_2
ϵ_1

(b)


(2)
(4)
(3)
(1)

(c)

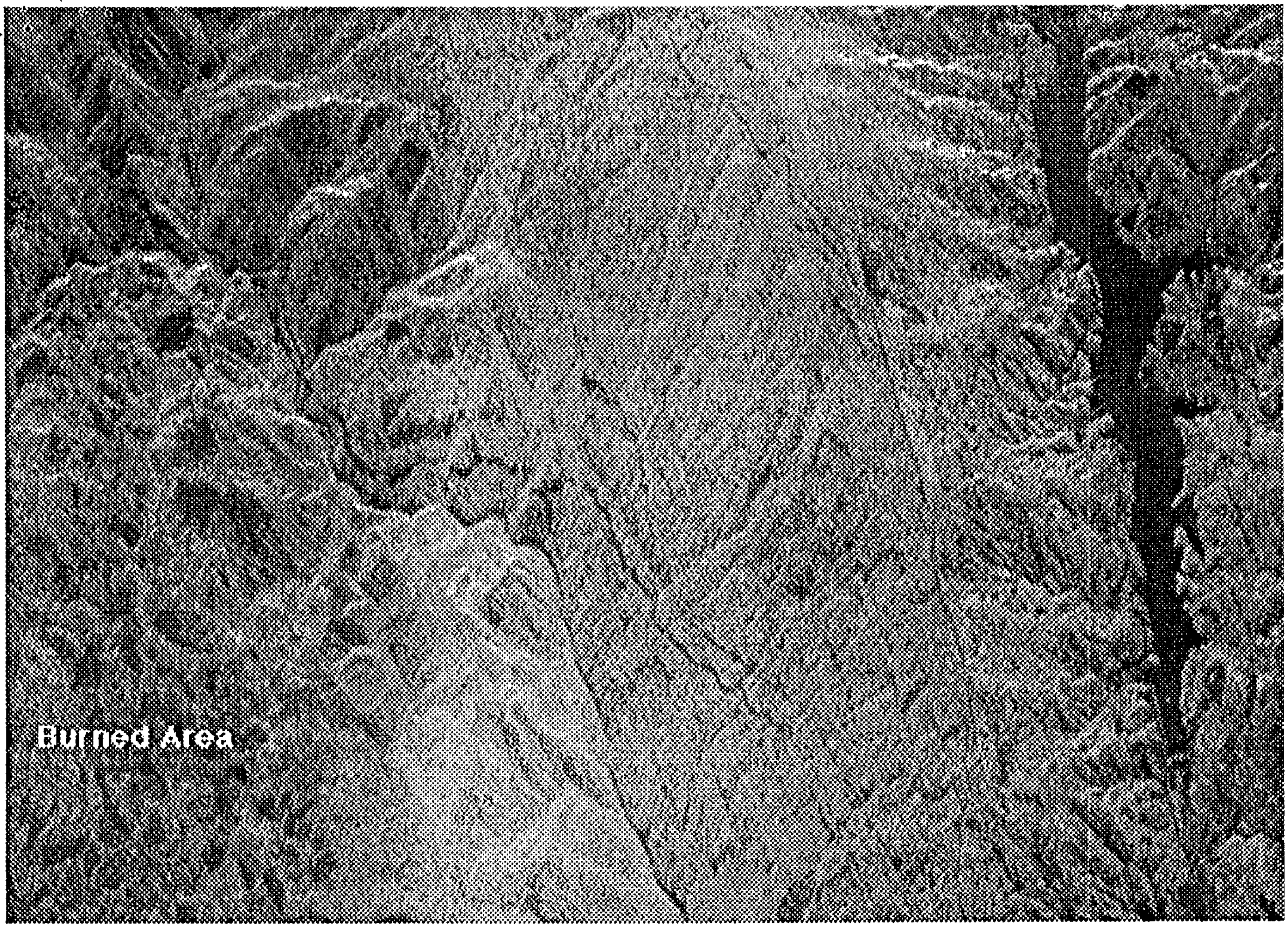


Figure 5.

(a) (b) (c)