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RECOMMENDATIONS REGARDING THE USE OF TEXTURES FOR CUING SURFACE SLANT AND SHAPE IN FLIGHT SIMULATION

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Most surface textures convey useful information about the slant, curvature, and depth of the surface, as geometric consequences of perspective projection (primarily foreshortening and scaling). For the visual system to correctly interpret two-dimensional (2D) evidence of foreshortening and differential scaling as suggesting three-dimensional (3D) slant and depth, certain assumptions must hold regarding the regularity or homogeneity of the physical texture as well as its statistical isotropy. Recommendations are given regarding the selection of textures for flight simulation which match the perceptual assumptions and thereby permit 3D percepts.

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PREFACE

This research effort was supported by the University of Dayton Research Institute (UDRI) under Contract F33615-90-C-0005, in conjunction with Work Unit No. 1123-03-85, Flying Training Research Support. The laboratory contract monitor was Ms Patricia A. Spears; the project scientist was Dr Elizabeth L. Martin.

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RECOMMENDATIONS REGARDING THE USE OF TEXTURES FOR CUING SURFACE SLANT AND SHAPE IN FLIGHT SIMULATION

INTRODUCTION

It is generally recognized that texture mapping (or cell texturing) yields several benefits for flight simulation: It provides the visual grist for optic flow, which is an important cue to direction of travel; to altitude change; and to speed (shape from motion). It also provides information that allows one to instantaneously perceive the local slant and shape of the terrain (shape from texture).

Recent research into the perception of shape from texture can provide the theoretical basis for some recommendations regarding the optimal choice of textures for these purposes. That research is briefly summarized here as it applies to flight simulation. Also, the relative effectiveness of actual cell textures used in flight simulation are compared in a series of demonstrations.

One can effectively derive 3D information from the systematic effects of foreshortening and perspective on surface texture. A perspective view of a field is a familiar example: As one scans from the foreground towards the horizon, the image size of rocks or bushes diminishes with distance, and their density increases with distance. Continuous changes in texture size and density across an image, known as texture gradients, effectively provide 3D information about the slant, distance, and 3D shape of the viewed surface.

Gibson (1950a, 1950b) proposed that the perception of visual space is reducible to the perception of visual surfaces, specifically, to qualities such as the slant, distance, shape-at-a-given-slant and size-at-a-given-distance at locations across a visual surface. He further suggested that these 3D qualities are directly related to specific stimulus variables, placing particular emphasis on texture density. Hypothesizing that the spatial properties of phenomenal surfaces are in correspondence with variables of retinal stimulation, Gibson proposed that:

> Distance may be given by the relative density of texture, the finer the density the greater being the distance. Slant at any point may be given by the rate of increase of density of the texture at that point. Perspective, in this theory, reduces to the

increasing condensation of the projected elements of the physical environment - a gradient of density along a meridian of the retina (Gibson, 1950b, emphasis his).

Those proposals were mathematical oversimplifications, as they did not take into consideration the problem of isolating the effects of perspective from those of foreshortening on texture density, as will be discussed. Nonetheless, Gibson's ideas about the representation of visual surfaces in terms of local spatial properties have been influential. For example, subsequent studies of texture gradients generally have assumed that the observer derives apparent local surface orientation or depth from the textured image, either from texture density or some local measure of texture compression or foreshortening.

Three Visual Percepts: Orientation, Curvature, and Distance

A basic visual ability when viewing a textured surface is judging the orientation of the surface, which entails estimating the 2 deg of freedom of the spatial orientation, measured relative to the observer. These are usually described as the slant and tilt of the surface (Stevens 1979, 1983a, 1983b). Slant relates to foreshortening and is measured by the angle between the normal to the surface and the line of sight. A surface patch of zero slant is one seen perpendicularly (straight on, where the surface normal aligns with the line of sight) and one of 90 deg slant is completely foreshortened such that the line of sight grazes the surface. The direction of slant, termed the tilt of the surface, varies through 360 deg. This is usually defined to correspond to the direction of the distance gradient in the vicinity of the surface patch or equivalently, the image direction in which the surface normal points. Most theories of 3D perception from texture presume that the results are the recovery of local surface orientation.

Given surface stimuli with sufficiently rich 3D cues, both the direction and magnitude of surface orientation can be judged with admirable precision. Standard deviations in apparent tilt can be as little as a few degrees when viewing monocular stimuli (Stevens 1983a), and the slant of a surface can be matched to within a few degrees (Stevens 1983b). The subjects' ability to estimate orientation depends on whether the stimulus surfaces present sufficient information to support the perceptual task -- most textures do.

Cutting and Millard (1984) examined the relative contributions of different types of texture gradient (gradients of texture density versus size or foreshortening -- see below) towards different perceptual judgments. They concluded that the visual system directly extracts curvature from texture (see discussion in Cutting 1984, Stevens 1984). There are two strategies for perceiving surface curvature: from image measures that vary directly with surface curvature; and indirectly, by first deriving local surface orientation from measures that vary directly with slant. Both are likely to be involved in human vision. In everyday judgments of the planarity of an extended surface, it is necessary to integrate slant information across different visual directions. A familiar example is effect of visual direction, since perspective projection will cause slants to vary relative to the line of sight (recall that the visual slant of a floor varies from zero at your feet to 45 deg at a distance of one eye height away from your feet). Human vision demonstrably incorporates such knowledge in its ability to judge planarity and curvature.

Texture gradients also produce the impression of distance, which is often characterized as the computation of a range map -- a pointwise representation of distance from the observer to the surface as a function of visual direction. A distinct type of distance information is depth (i.e., differences in absolute distance -- such as across a surface or between two points). Depth is related to surface relief, or the amplitude of a surface as it extends towards the observer, and is often expected to be represented in a pointwise manner, as a so-called depth map.

Humans have some ability to convert slant information into depth information. To demonstrate this, Stevens and Brookes (1987) used a binocular depth probe to measure subjects' apparent depth in monocular surface stimuli. The pictorially represented surfaces were presented to one eye and a binocular probe point was momentarily superimposed. A 2AFC experimental paradigm revealed apparent depth at points across the monocular surface, even for stimuli drawn in orthographic projection. This conversion among three forms of information, slant, curvature, and depth (and perhaps a fourth, which is distance), makes it difficult to support strong assertions as to the form of the end percept of 3D texture perception. The question of an end percept is perhaps not well founded: If surface perception involves processes that map to an association area (depending on the particular pattern of inputs), then the association area might connect all perceptual knowledge of the surface. No single form of 3D information need be primary. Regardless, it is valuable to think in terms of these various forms of 3D information when attempting to account for which qualities of image texture effectively carry 3D information.

Two Effects of Projection on Texture: Compression and Scaling

Fundamental to any 3D perception from texture is the task of inferring (or estimating) 3D shape on the basis of image measurements. There are two consequences of the perspective projection that affect the imaging of physical surface texture into image texture. The visual system must make measurements (or, in other terminology, register or be selectively sensitive to) of these effects. The effects are foreshortening (the anisotropic compression of texture in the direction the surface is slanted away from the observer) and scaling (the isotropic diminution of texture image size as a function of distance from the observer. A planar surface is subject to both effects: Its texture gets progressively smaller and foreshortened in the distance. All perceptual effects in 3D texture perception can be traced to these two factors: foreshortening and scaling. If the visual system can make measurements that are related to these effects, then it can infer, or estimate, slant and distance.

The sorts of measurements that have been proposed include texture element density, texture element size or area, texture element width. All of these measurements presume discrete, countable texture elements with measurable image area and dimensions (see below). Also proposed are more continuous measurements such as spatial frequency content. Additionally, some proposals amount to measuring the distortion to the silhouette shape of individual texture elements. Generally, the 3D interpretation of such measurements requires an assumption that the corresponding physical dimensions and properties are constant (or regular, or isotropic, etc.) on the surface, so that the measurements reflect the consequences of the projection process and not some independent, and misleading, variation. For instance, if texture size is presumed constant, then variations in size can be related to distance (see below).

The 3D perception of surface slant and distance from image texture must ultimately be based on some a priori assumptions, because 3D information is lost in the process of projecting to a 2D image. A photograph which shows a slanted textured surface, is of course producing an illusion. It is difficult to suppress the 3D interpretation of texture variations in order to see the markings on the emulsion of the photograph veridically. At best we see the surface of the glossy photograph correctly, and while aware that the markings within the photograph lie on that emulsion surface, they also strongly represent some other 3D surface. This point is crucial to the designer of synthetic textures. Textures are compelling inducers of three-dimensionality. Not all surface textures should be expected to be equally effective in inducing these percepts, however. It is therefore important to determine which texture qualities are most salient.

Distance from Texture Density

Perspective projection affects texture density, as Gibson (1950 a, b) observed. Texture density increases towards the horizon because each patch of unit surface area is projected in the image with decreasing scale according to its distance, and with increasing compression with its foreshortening. This also increases with distance for a plane extending towards the horizon.

While both effects act in the same direction, the mathematical relationship between distance and image density is tractable for the restricted case of viewing a horizontal planar surface (Bajcsy & Liebermann, 1976; Cutting & Millard, 1984; Purdy, 1960; Rosinski, 1974). Jau and Chin (1990), for instance, show an approximate solution for surface orientation by fitting a plane to measured variations in texture density. This assumes that all the variation is due to perspective; that the surface is a plane; and, as usual, that the texture density is uniform across the surface. Aloimonos (1988) shows a more general solution, but one that again assumes the surface is planar.

Distance from Texture Size

In contrast to the problems presented in interpreting texture density, projected size provides, in principle, a straightforward cue to distance. In this case, the validity of using apparent size to infer distance rests on the assumed uniformity of the corresponding physical sizes. Thus, for example, if across a dry river bed the size of stones is graded from large in one region to small in another, that systematic variation in apparent size may be misinterpreted from certain vantage points as being a result of perspective. Accepting the necessity to assume the physical texture size is uniform, how might image texture size be measured?

Apparent size is usually attributed to individual objects. The apparent size (width and height) of a discrete texture element, such as a rock, is measured as a subtended angle. The height is subject to foreshortening, such as a flat pebble viewed obliquely. The width, on the other hand, corresponds to the angular measurement which is least likely to be foreshortened. Hence it will vary directly with actual width and inversely with distance. The width measurement is usually made horizontally, as in the familiar view of objects on a slanted horizontal plane extending in the distance. In general, however, to determine the width dimension requires analysis, either of the apparent direction in which elements are foreshortened, or of the apparent direction of the depth gradient.

In the case of viewing a smooth slanted surface patch, the path across the surface along which distance, relative to the observer, changes most rapidly corresponds to the direction of the distance gradient. The magnitude of the distance gradient is trigonometrically related to the slant angle; the angle between the surface normal and the view vector. For an extended surface, a field of gradient vectors is defined, each indicating locally the direction and angle in which the surface slants away from the observer. The direction of the distance gradient can readily be determined from the texture gradient since the two gradients are aligned. Distance varies most rapidly in the direction that element size, foreshortening or density also varies most rapidly. Perpendicular to the direction of the gradient of any of these quantities is a direction which corresponds to a path on the surface which is parallel to the image plane. That is, image measurements taken in that direction correspond to physical lengths that are parallel to the image plane (i.e., unforeshortened).

Since the direction of the gradient is orthogonal to the direction of least variation, there are two ways, in principle, to establish the orientation of the distance gradient. Distance locally varies most rapidly in the direction of the texture gradient (e.g., measured by density) and perpendicular to the direction of least texture variation. Of the two, determining the local image direction in which the texture is most uniform provides a more robust and accurate estimate of the gradient direction, compared to measuring the direction of greatest change in texture (Stevens, 1981a).

While apparent size or width measurements are usually associated with individual discrete elements, there have been proposals to measure size indirectly (e.g., on the basis of a prominent peak in spatial frequency from a local Fourier analysis [Bajcsy & Liebermann, 1976]). Shifts in that peak across the image would presumably correspond to shifts in projected texture scale. Jau and Chin (1990), mentioned earlier, use a related Wigner distribution for measuring spatial frequency.

Surface Orientation from Local Gradients

The gradient operator, or grad, is mathematically $\nabla = \partial/\partial x + \partial/\partial y$, the sum of two first derivatives of a continuous function taken in two (arbitrary but orthogonal) image directions x and y. The grad operator has been proposed to be a useful operation to perform on texture, as it leads to simple relationships between slant and some texture measure such as density or size. As discussed, the direction of the gradient corresponds to the surface tilt t (i.e., the direction of the gradient distance relative to the observer). Generally ignoring the question of regularizing the image, in order that density or size might be effectively treated as a continuous variable, slant angle s is related to the local gradient of texture density r by

$$\tan \sigma = p/3p$$

where the density gradient is normalized by the magnitude of the density at each location (Purdy, 1960; Stevens, 1979). Similar expressions relate slant and other texture variables. It is significant that these direct computations of slant do not require globally uniform texture.

Surface Orientation from Back projection

A similarly orientation-dependent measure is texture foreshortening. The familiar, but unrealistic, illustration of foreshortening involves circular surface markings which, on a slanted surface, project as ellipses. The predictable manner in which a circle compresses into an ellipse provides the basis for the recovery of the slant (e.g., as the arc cosine of the ratio of projected height to width [Flock, 1964]). Note that the width and height measurements of each projected marking would be made perpendicular and parallel to the local distance gradient. This somewhat contrived example of foreshortening illustrates a more general problem of back projection: finding that surface slant which maximally accounts for the projection of the original unforeshortened shape into the given image shape.

Witkin (1981) showed that a general solution to the back projection problem for foreshortening is in terms of the systematic effect of slant angle on tangent direction. Slant compresses texture anisotropically, biasing the distribution of contour tangents to cluster around the orientation perpendicular to the direction of the depth gradient. The tangents to the surface markings are preferentially flattened about one axis, an effect that is illustrated by the familiar ellipse-as-slanted-circle. And yet this is more general, in that it applies to virtually any pattern of texture contours. The solution to the back projection problem is to find that slant which accounts maximally for the variation in tangent directions in the image texture. This method assumes that the original distribution of tangent directions is unbiased (i.e., isotropic, as are the tangents around a circle). But generality comes from the fact that the tangent measurements need not arise from the boundaries of connected forms: A random scattering of oriented bars (e.g., an image of rice kernels or straw scattered on the floor, results in a biased distribution of orientations which carries sufficient evidence for foreshortening to estimate the slant of the underlying plane [Vorhees & Poggio, 1989]). Blake and Marinos (1989) show uniqueness and convergence results for an iterative algorithm that solves the texture orientation back projection problem.

Two recent studies bring closure to the theoretical analysis of texture foreshortening (Gårding, 1991; Malik & Rosenholtz, 1993). Gårding has shown how slant and tilt can be derived from local gradient measures such as provided by the Gabor filter. This method requires texture that is isotropic. On the other hand, Malik and Rosenholtz show how to derive orientation by treating the image texture locally as a texture distortion due to perspective, and to recover orientation from an analysis of the changes in texture across the image as an affine transform between image patches. In their analysis, the texture need only be uniform, not necessarily isometric. These two analyses, representative of several more (e.g., Super & Bovik, 1991) show two possible computational strategies for the interpretation of texture.

EMPIRICAL OBSERVATIONS

Slant Underestimation

Gibson relied largely on texture gradient studies to provide empirical evidence for theory of direct perception (Gibson, 1950a, 1950b; Purdy, 1960). As initially stated, there should be a direct psychophysical correspondence between texture variables and 3D percepts. But that hypothesis was not borne out by the psychophysical experiments that followed. Apparent slant (usually measured by matching the visual impression of slant with that of a palm board) is often underestimated; it does not vary in direct correspondence with that specified by the texture gradient (see review by Epstein & Park, 1964). That cast doubt on the strict interpretation of Gibson's above hypotheses, prompting his revised notion of affordances (Gibson, 1979).

Underestimation of apparent slant is now a familiar effect, often observed in viewing a stimulus that presents only a single 3D cue, such as a texture gradient. This effect, regression to the frontal plane, varies with exposure time (Beck, 1960; Freeman,1965; Gibson, 1950b; Purdy, 1960; Smith & Smith, 1957) and varies considerably with the quality of the stimulus. For example, much less underestimation is observed for textures that contain linear perspective (i.e., converging lines in the image that appear parallel in 3D [Clarke, Smith, & Rabe, 1956]).

The Efficacy of Texture Density

It was discussed that the distribution of texture density across an image, in and of itself, does not provide adequate constraint on the 3D interpretation of the underlying surface, unless overly restrictive assumptions are imposed. In principle, if one assumes the surface is planar, or furthermore horizontal, one can solve the orientation and distance parameters from the image texture. But since surfaces are not so constrained, it is thus not surprising that texture density gradients, in isolation, have been found to convey little effective 3D information. By presenting random dot patterns as stimuli, varying local dot density would arguably allow isolation of the density cue from size, foreshortening, and other texture gradient cues. Many such studies have shown that density in such displays is an ineffective cue to 3D shape and distance (Braunstein, 1966, 1968; Braunstein & Payne, 1969; Cutting & Millard, 1984; Smith & Smith, 1957; Stevens, 1981a). If dot density increases from bottom to top according to a slanted plane viewed in perspective, it is possible to interpret the increasing density as suggesting increasing distance. But that depth impression is not compelling: The same display might suggest curvature, as if viewing a cylinder, or the dots may also simply appear to lie flat in the image plane, the obvious density gradient notwithstanding. There may be an interaction between density and other 3D cues, however, such as a weakening of the impression of slant when uniform image density is placed in conflict with the slant information provided by other texture gradients (Cutting & Millard, 1984), as discussed below.

Texture Size

It is well known that apparent size is a strong cue to distance in accordance with perspective (Hochberg, 1971). The tendency to relate apparent size and apparent distance may play a substantial contribution to the impression of depth in texture gradients, but not be restricted to the case of features that lie across a common surface. Stevens (1981a) showed that elements that are similar except for size, tend to appear distributed in depth with relative distances varying inversely by their size, independent of their pattern of distribution. That is, size gives rise to distance independent of whether the elements are arranged as spatially continuous gradients defining a continuous plane, or a random arrangement, as if the elements were scattered through a volume of space. Sensitivity to the size-distance relationship in general, therefore, may be responsible for much of the appearance of depth and slant specifically in texture gradient images where discrete elements present a continuous size gradient. Obviously, when viewing stimuli as simple as circles of different image diameters, to infer differences in distance the visual system must assume the corresponding 3D objects have equal diameter but different distances from the observer. This is one of the central assumptions underlying the interpretation of texture gradients, to which we now turn.

UNDERLYING ASSUMPTIONS ABOUT THE PHYSICAL TEXTURE

Geometric Requirements

To be useful sources of 3D information, physical texture must obey several restrictions:

spatial homogeneity. To be a valid cue to distance, the physical texture statistics must be invariant across the surface. In particular, a gradual variation in size would, in the absence of other information, erroneously suggest variation in distance.

distinguishable size. To be a valid cue to distance, a sufficiently narrow range of element sizes must be present in any vicinity, so that projected sizes at different localities are comparable.

isotropy. To be a valid cue to slant, the physical texture must, according to most theories of human perception, be isotropic, at least not systematically mimic foreshortening. In particular, the surface features should provide contours with random correlation between tangent direction and curvature.

The requirement for homogeneity is all too easily met in the simulator: Memory restrictions for texture mapping usually result in repetitious textures, often to the detriment of the overall appearance. The second requirement, distinguishable size, is more difficult. Some granular textures present, within a given neighborhood, at least an order of magnitude of element sizes. If the distribution of sizes is broad or nearly flat, then the visual system has difficulty distinguishing a statistical difference in texture projected size across the image. On the other hand, a very narrow range of sizes would appear artificial and improbable. Although the effect of the scatter of texture size on the accuracy of 3D judgments has not been studied by formal psychophysical experiments, it appears that the visual system tolerates a wide distribution of sizes provided there is a sharp peak in the distribution which, given spatial homogeneity, is constant across the surface.

Isotropy is required to derive slant from foreshortening. The visual system is sufficiently robust to often ignore the erroneous information about slant from anisotropic textures. For example, in flight simulation, texture is often projected or mapped downward onto the slopes of the terrain (not normally to the polygons). The result is that texture is stretched in the direction of the gradient of altitude, and the texture on steeply sloping terrain looks like streaks. This effect is widespread in texture mapping, and yields an incorrect cue to slant. Of course, if the texture does appear streaked or stretched, that correct perception derives from other cues than texture. Of concern are cases where the orientation of the textured surface is misperceived based on the erroneous assumption that the surface is isotropically textured.

In addition to homogeneity and isotropy, the luminance contrast with the texture is also important in order to extract reliable contour foreshortening information. An indeterminate blotchy texture, devoid of high spatial frequency components, is very ineffective as a source of slant information.

Highly salient cues to changes in surface tangent are linear contours that lie across the surface (Stevens, 1981b, 1983c). Curvature of the 2D contour in an image provides information about the curvature of the corresponding 3D contour across the surface. In the limit, a sharp discontinuity in tangent in the 2D contour is a local cue to a surface crease. These creases often arise as artifacts of texture mapping algorithms (along the borders of the cell textures where they abut a repeating cell), but despite the unrealistic appearance, these linear features are highly salient sources of information about creases.

Illustrations Using Texture Mapped Cell Textures

To examine the relative efficacy of actual cell textures, six photographs of actual cell textures were provided in order to generate the series of demonstrations shown below. In some of the original photographs the wallpaper-like tiling of the cell texture was apparent (see Figures 1a-f, illustrating Textures A-F). The six textures were scanned and digitally cropped as necessary. Then they were texture mapped onto a variety of stimulus surfaces using software especially written for this task. The goal was to provide a series of still photographs of representative cell textures in controlled viewing circumstances, including perspective versus orthographic projection; planar versus curved; creases; occlusion; and different magnifications. Note that the cell texture samples have undergone a long series of image processing transformations: The simulator's cell texture originated as a photograph (e.g., of an acoustic ceiling tile, such as was the source of Texture B), which was then scanned in at the Armstrong Laboratory facility (at Mesa, AZ), and used as a cell texture. For this study, the cell textures were first photographed on a computer monitor at the Armstrong Laboratory facility and then enlarged and printed. At the University of Oregon lab, the glossy photos were scanned to return them to digital form so that the cell textures could be mapped onto a digital surface. To produce the final illustrations, textures were projected onto a computer monitor, photographed, then sent to the Armstrong Laboratory facility for publication. It was therefore understandably not possible to preserve the precise grey level distributions of the cell textures; nonetheless, their characteristic geometries are apparent and yield different results.

Texture A, while resembling an aerial photograph of actual terrain, is not promising as a texture gradient cue. It is quite inhomogeneous and composed of elements of a broad range of sizes, and furthermore is anisotropic. Texture density varies considerably across the figure in that some regions are predominantly light. Others are predominantly dark. Moreover, the blotches in each locality vary over a very large range of scales, making it difficult to correlate size and distance. Finally, while the texture blotches are individually fairly isotropic, there are short striations in different orientations. In contrast, Texture B, originally a photograph of acoustic ceiling tile, is quite homogeneous, presents high-contrast, has convex elements of distinguishable size, and is quite isotropic. Texture C is moderately homogeneous, but presents a large range of element scales with indistinct borders and often low contrast. That texture is fairly isotropic. Note that Texture C shows four repetitions of the basic texture tiled together. Texture D, showing an obvious pattern of four-by-four tiles, is a rather miserable texture with inhomogeneous density, a motley collection of blotches of indeterminate size, and a diagonal bias which falsely suggests foreshortening, even in this unslanted view. Texture E, a four-by-four tiling, is quite homogeneous. It is rather distinct in size and is slightly anisotropic. Finally, Texture F presents large irregular white blotches, stark contrast, inhomogeneous density, yet isotropy. How do these six textures compare as sources of 3D information? Textures B and E should be effective given their density homogeneity and distinguishable element size. Texture F might present good foreshortening cues based on its isotropic distribution of high-contrast contour tangents.

A 2D Gaussian produces a smooth hill shape for our purposes. Viewed in perspective the hill is apparent not only because of the texture gradient cue, but because the crest of the hill occludes the more distant background (Figure 2). For comparison, Figure 2 shows Texture A mapped over this surface. The scale of the texture relative to the hill was arbitrarily chosen (scale is examined below).

Figure 3 shows Texture A on the same surface, but in orthographic projection rather than perspective. The primary difference is the removal of the trapezoidal outline cue to 3D orientation.

Figure 4 substitutes Texture B for A, holding other factors constant. Note how the foreshortening of the dark blotches varies quite distinctly according to the slope of the hill, yet the occlusion cue along the crest of the hill is less apparent.

Despite the theoretical expectation that Texture B (Figure 4) should be more effective than Texture A (Figure 3), that actual advantage, if any, is not impressive. On the contrary, the greater texture density and the fortuitous position of the dark patch in Figure 3 makes the hill stand out relative against the background. The robustness of human vision is apparent here: It is difficult to factor out the contribution of shading from that due to texture.

To factor out shading, the terrain next consists of two planes, one horizontal, one sloped, that meet along a sharp horizontal crease (a smoothly curved join would be far more difficult to detect). This approximates an important visual task for low level flight; the detection of differences in ground slope ahead of the aircraft. Texture differences might reveal the slope change, if not a visually distinct crease itself. Each of the six textures were mapped over the creased surface, and projected so that the crease is horizontal and viewed from a perspective resembling that ahead of an aircraft, with a 20 deg angle of depression. The crease was not subtle, consisting of an up-slope of 0.12 or 6.8 deg. The six textures are shown in Figures 5a-f. While the crease is difficult to discern in all cases, in Texture C (Figure 5c) the unintentional contrast edge across the border of the tile shows a discontinuity in tangent, a cue to the underlying surface crease. Thus the linear edges associated with cell texture borders, while unrealistic, may be useful in the simulator. Nonetheless, some scrutiny is still required to interpret the figure in 3D.

Figure 6 shows the six textures in orthographic rather than perspective projection. Without the perspective splay in the foreground, the figures look far less three-dimensional. The task is now simply to judge how discernible is the discontinuity in texture between the bottom and top portions of the image. In Figure 6b (Texture B) the foreshortening is noticeably greater below the crease than above, but in Figure 6c (Texture C) the vertical edge artifact just to the right of center is more apparent than the horizontal crease (cf. Texture C in perspective, Figure 5c).

The detectability of the crease depends on the scale of the figure, as can be noted by observing them at different viewing distances. Two effects, which work in opposite directions, can then be noted. Compression gradients are more apparent as the texture scale is reduced, so that more blotches fall in a given visual area, within limits. On the other hand, to detect foreshortening or compression, the individual blotches must be discernible, and that improves with increasing scale. Figure 7 shows different scales or magnifications (1x, 2x, 4x, 8x) of the corresponding displays in Figure 6; as before, the horizontal crease is approximately 40% up the figure.

Finally, while the formal psychophysics are not in the literature, it would appear that the detectability of differential foreshortening is a function of the overall slant. Figures 6 and 7 correspond to a 20 deg angle of depression or a slant of 70 deg (angle between the line of sight and the surface normal for the lower surface, the plane below the crease). Increasing the slant to 80 deg (Figure 8) makes the differential foreshortening much more apparent.

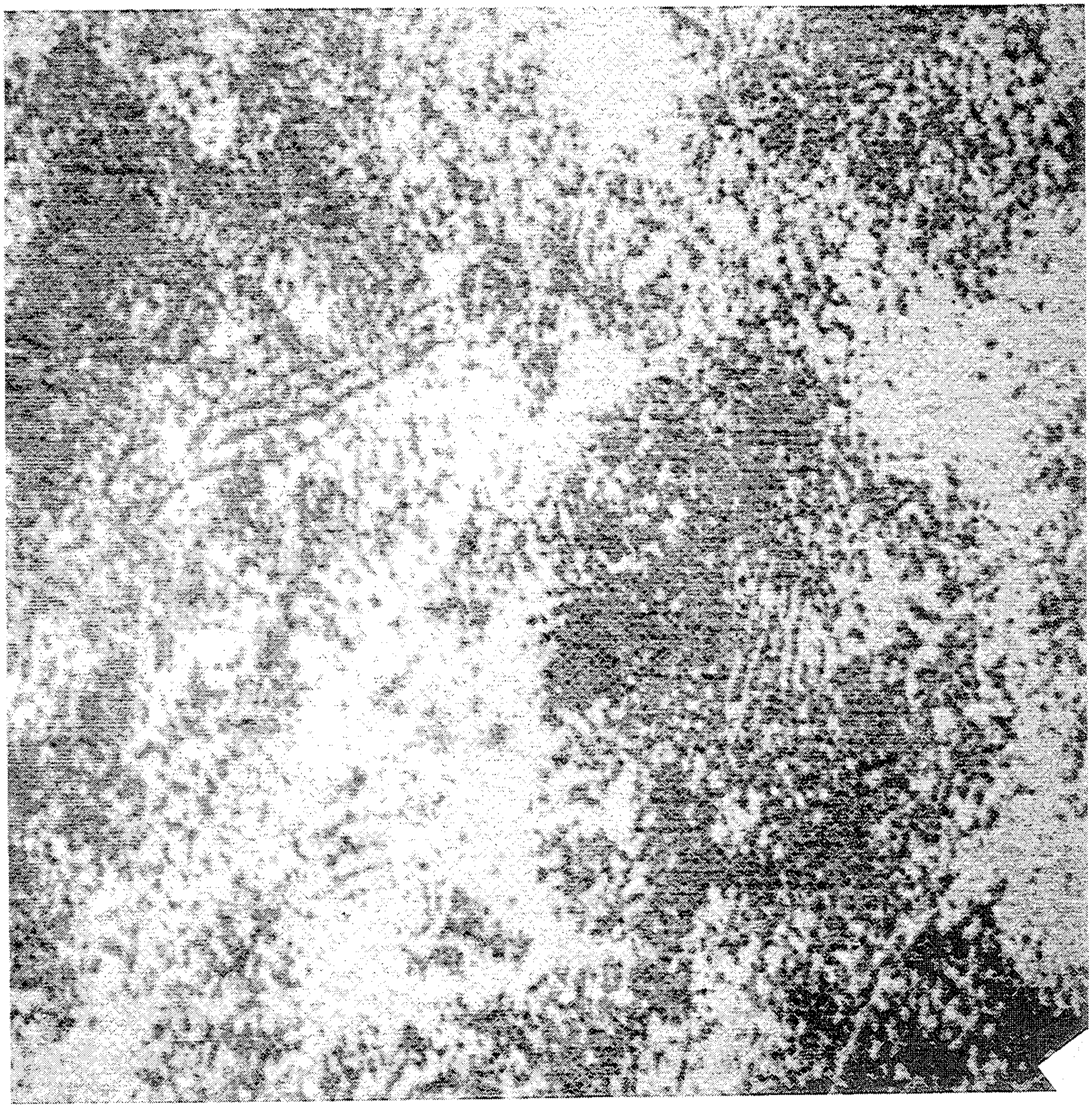

Figure 1a.
Six photographs of actual flight simulator cell textures. Their relative ability to indicate surface shape, slant and creases will be compared. The textures in a-f will be referred to as textures A-F.

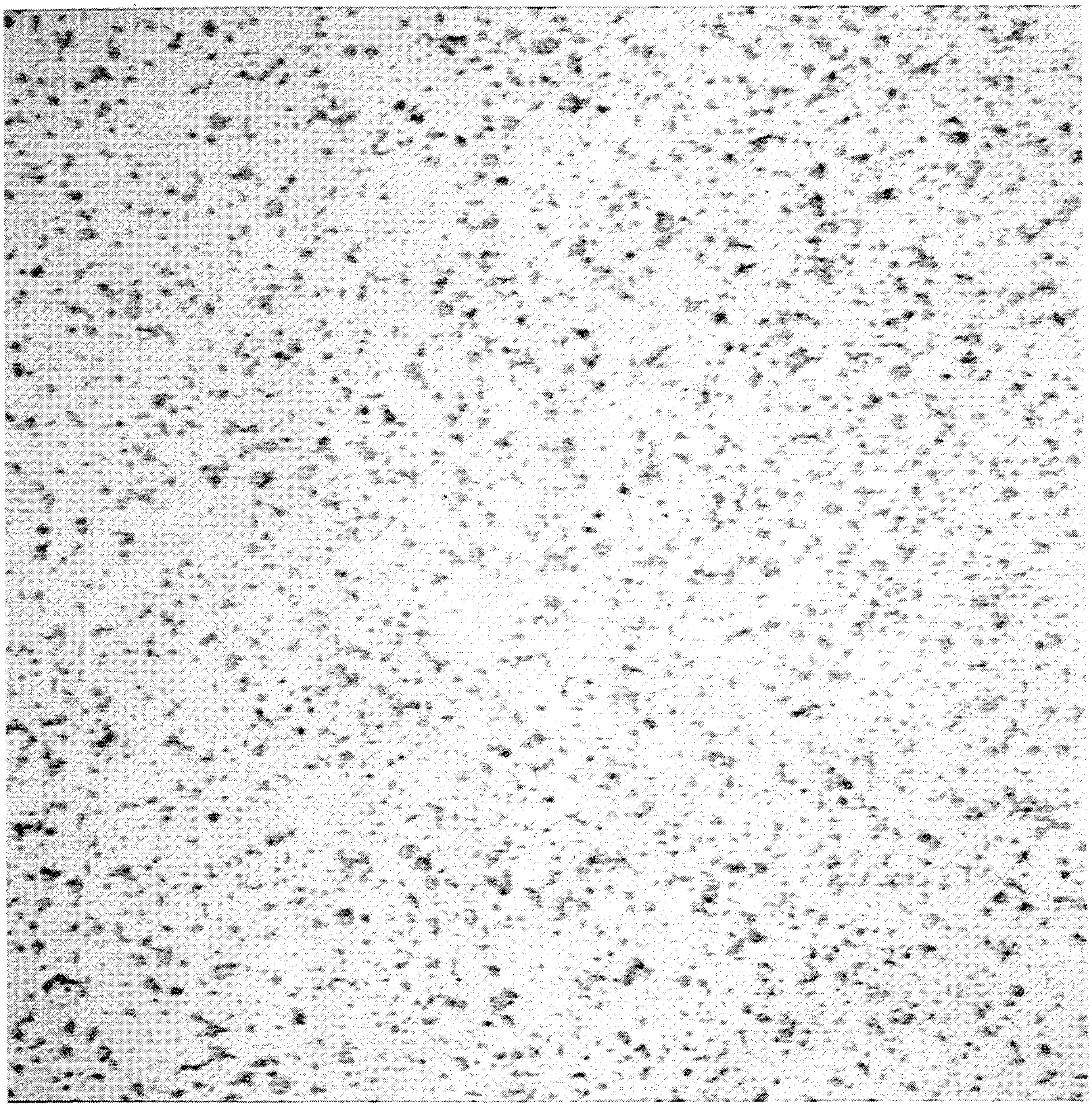

Figure 1b.

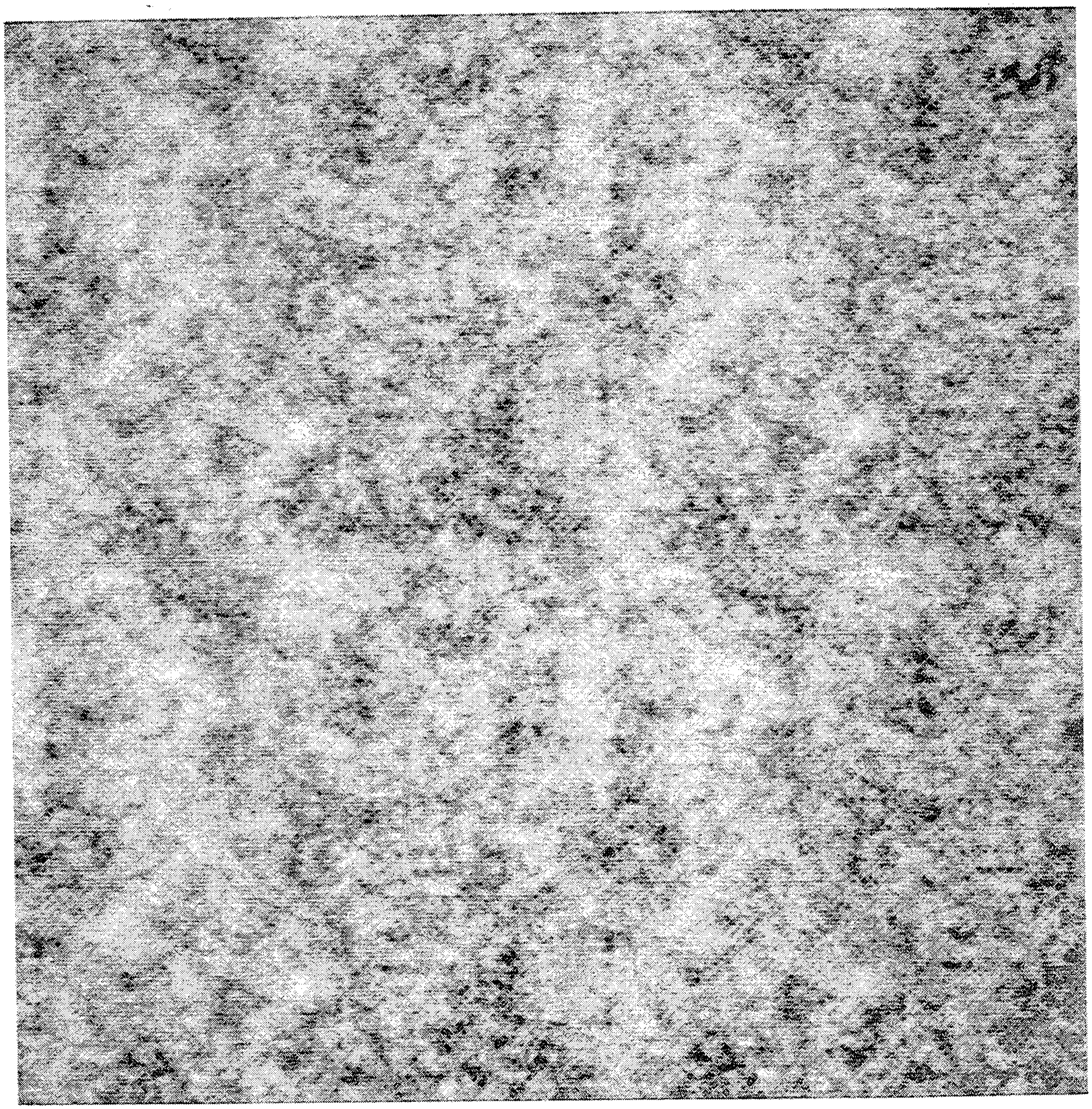

Figure 1c.

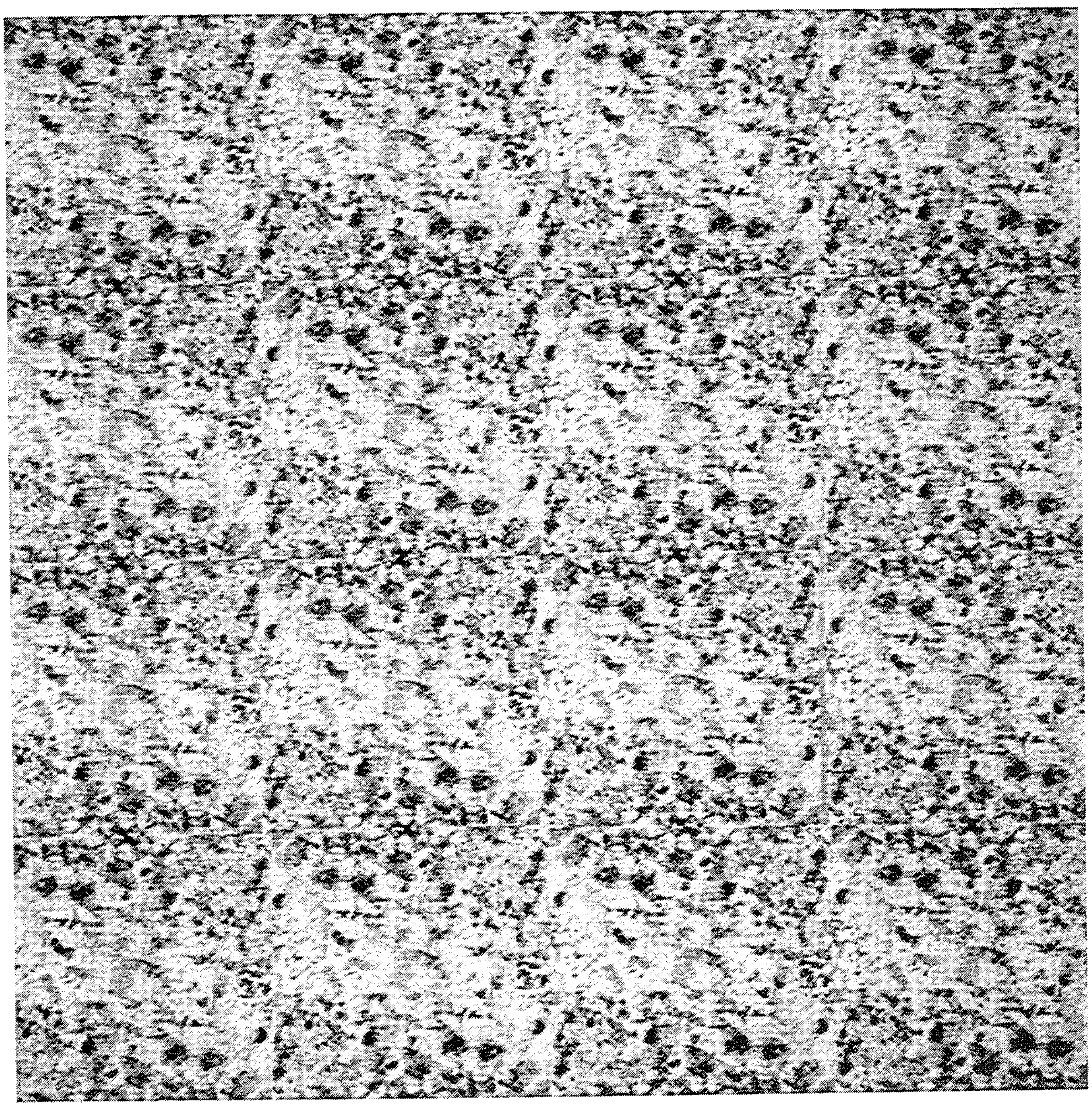

Figure 1d.

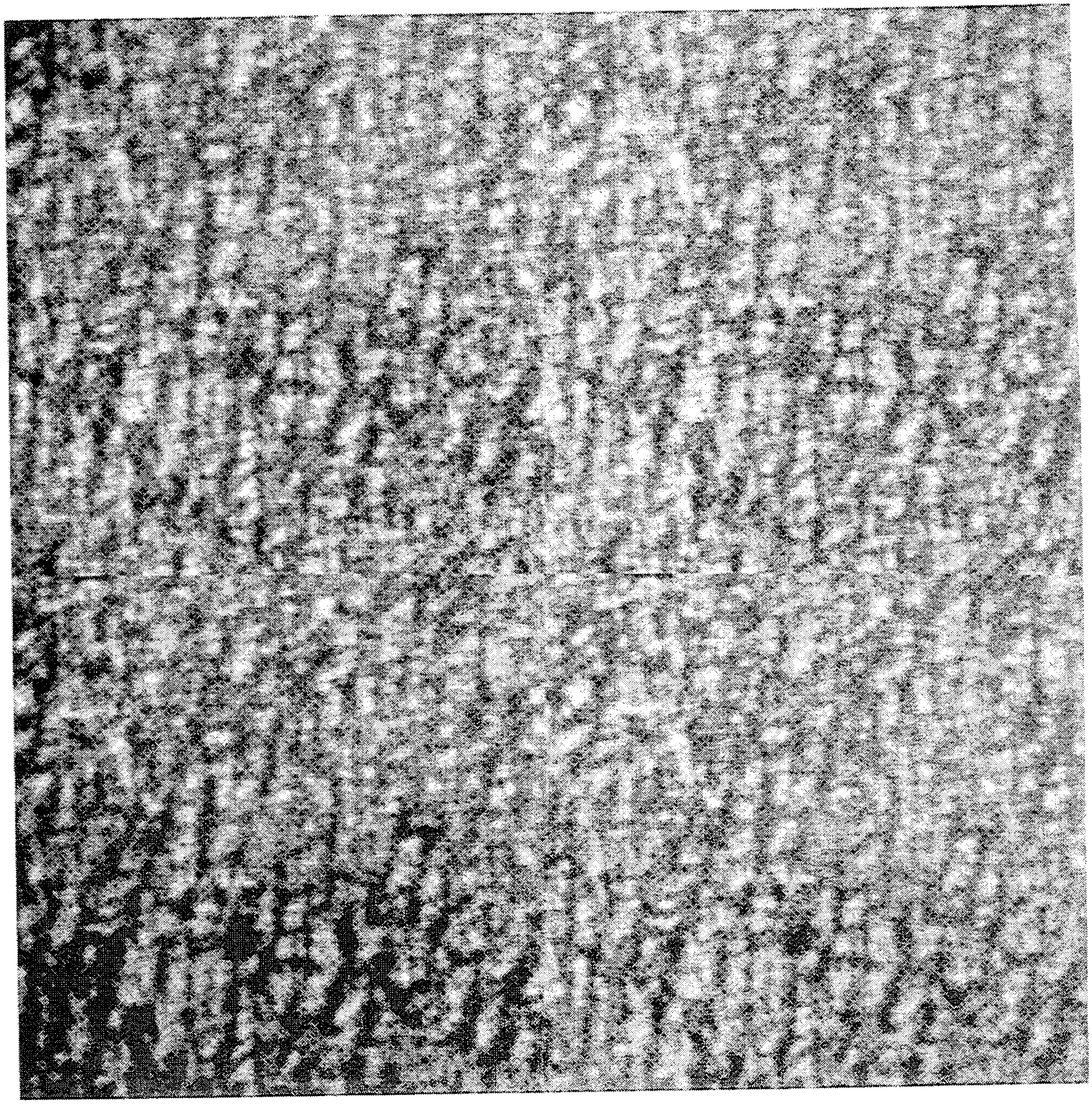

Figure 1e.

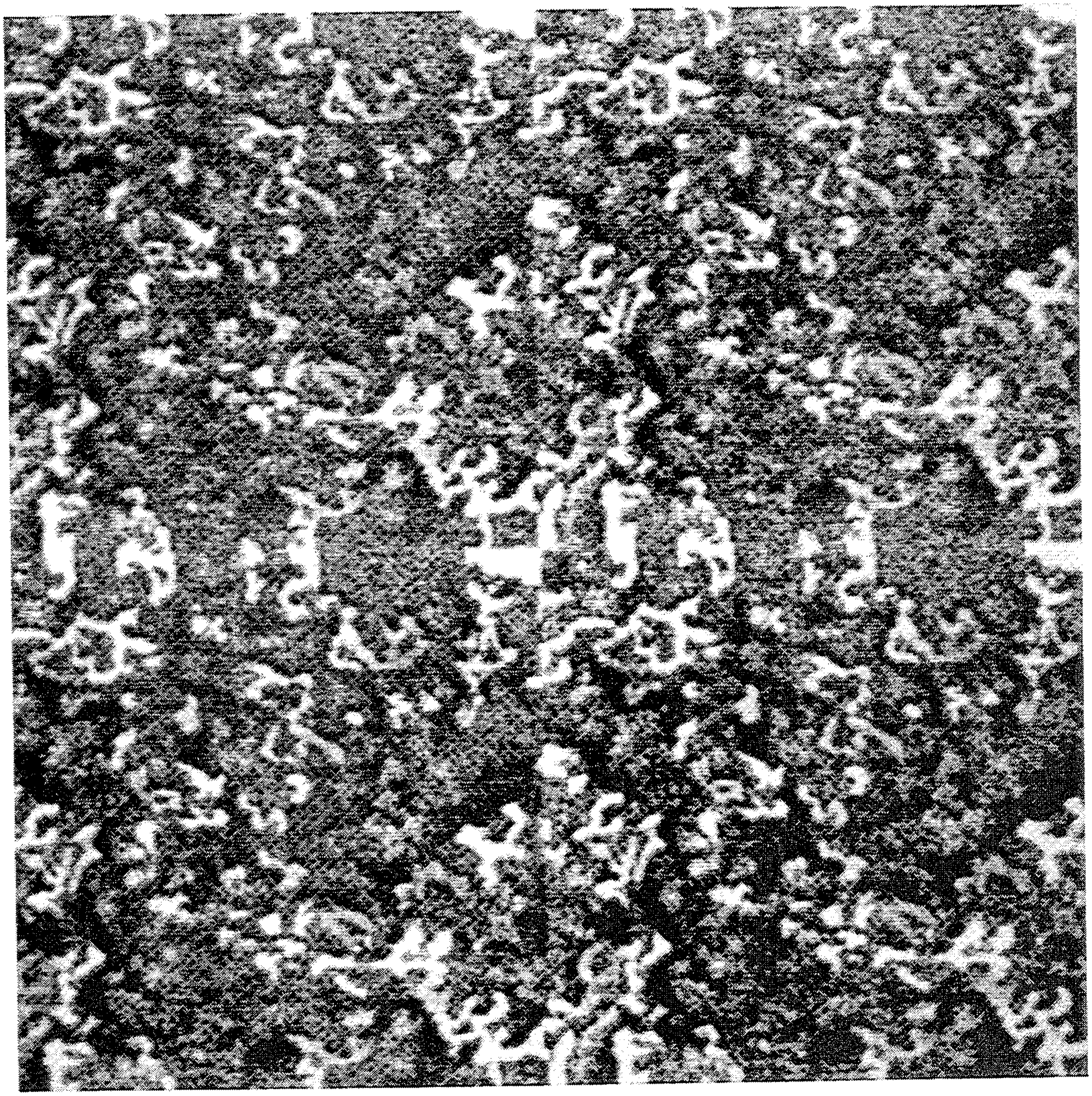

Figure 1f.

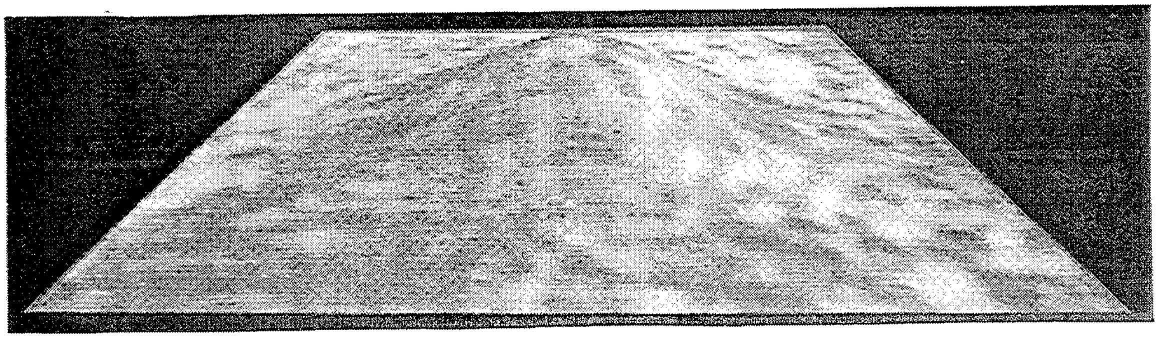

Figure 2.
Texture A (see Figure 1a) texture mapped over a gaussian-shaped hill, seen in perspective.

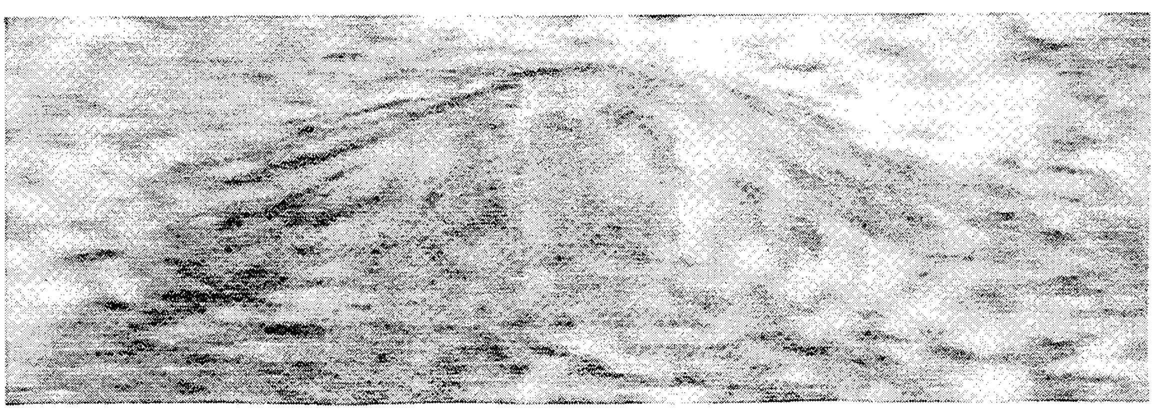

Figure 3.
Same as Figure 2, but in orthographic versus perspective projection. The trapezoidal outline cue is no longer present, thus further isolating the contribution of texture to 3D shape.

Figure 4.
Same as Figure 3, but with Texture B substituted for Texture A.

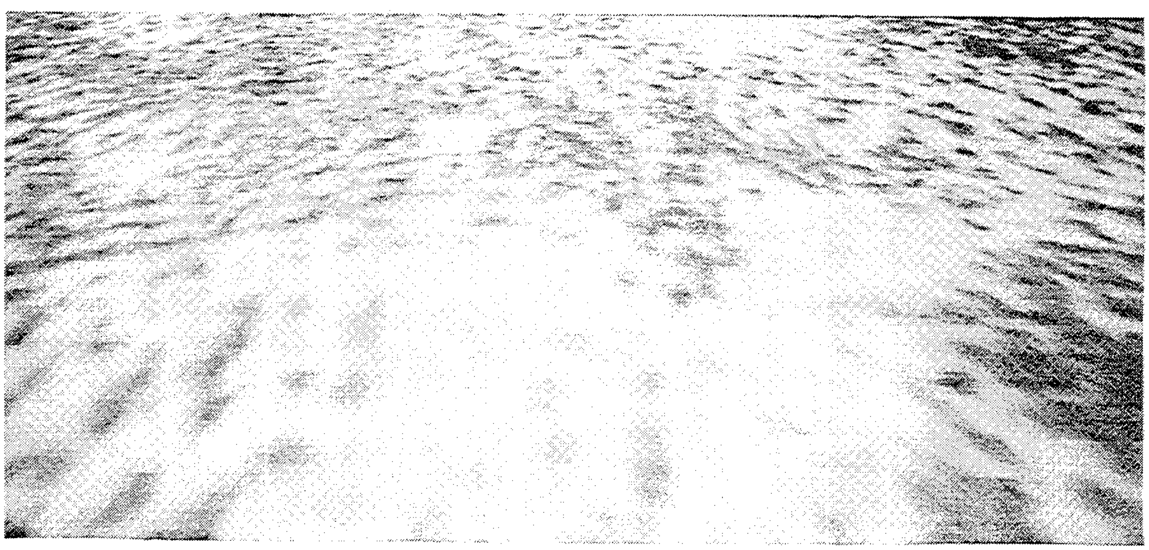

Figure 5a.
A creased surface is viewed in perspective for textures A-F.

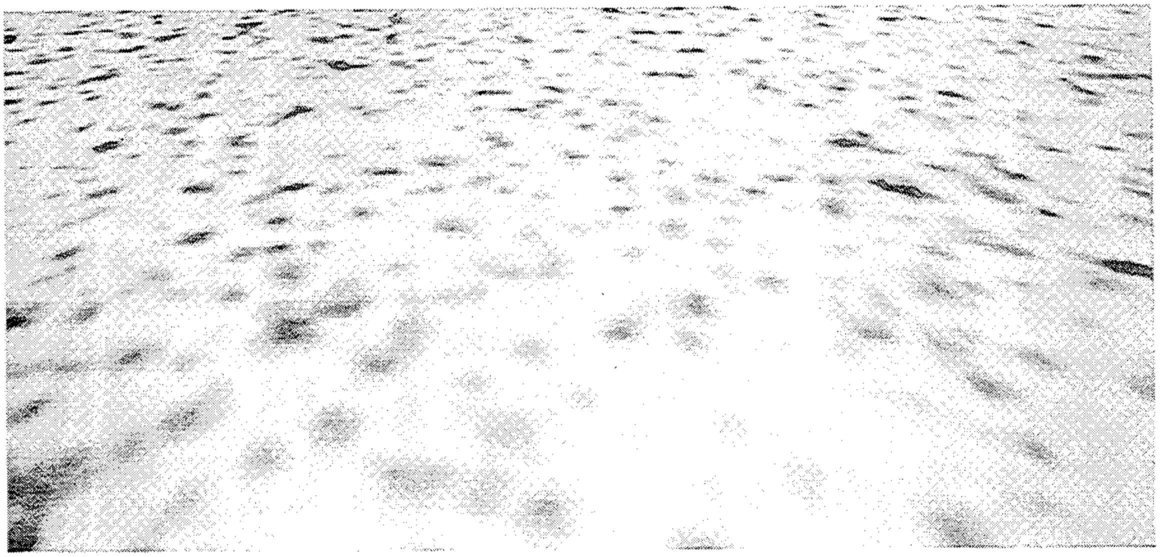

Figure 5b.

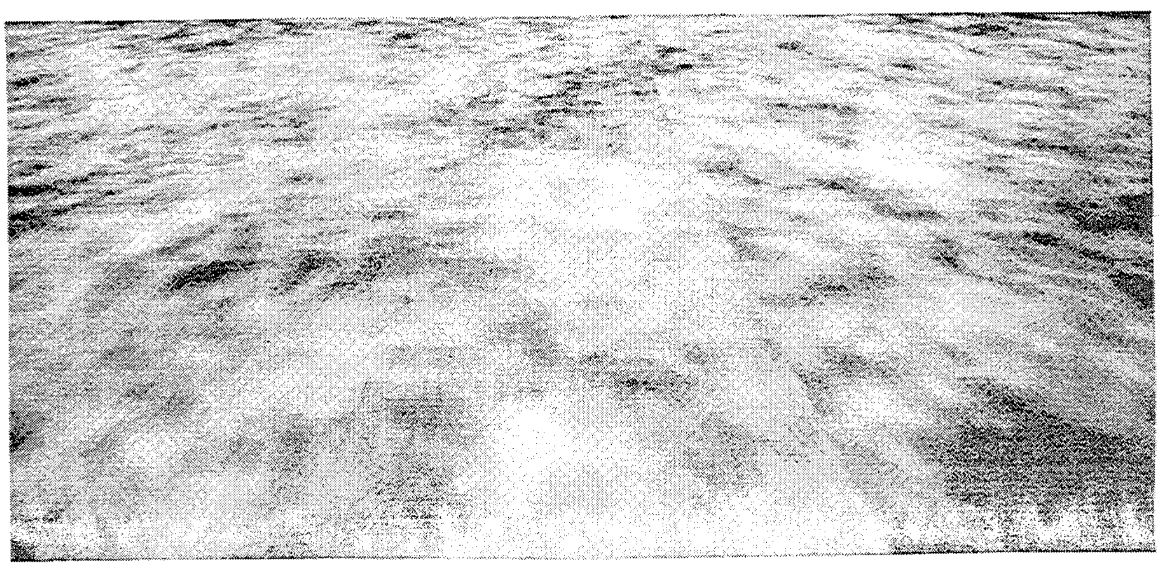

Figure 5c.

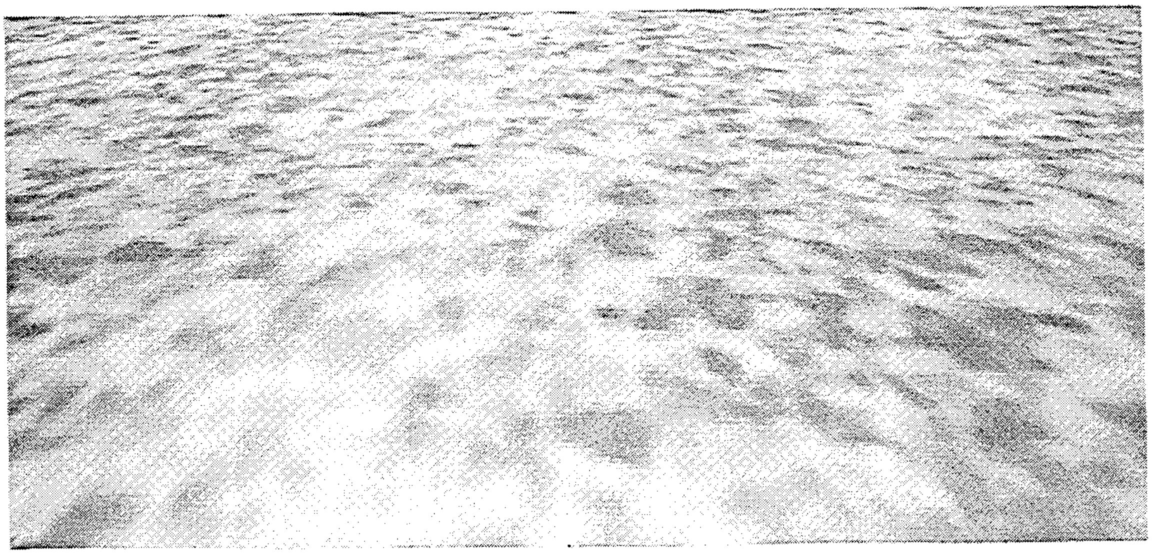

Figure 5d.

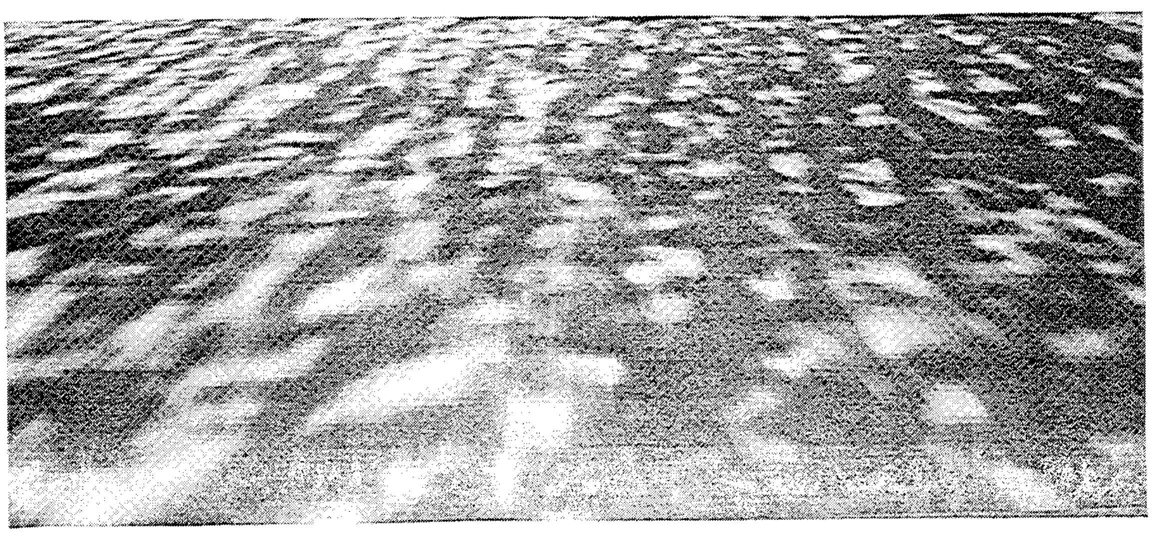

Figure 5e.

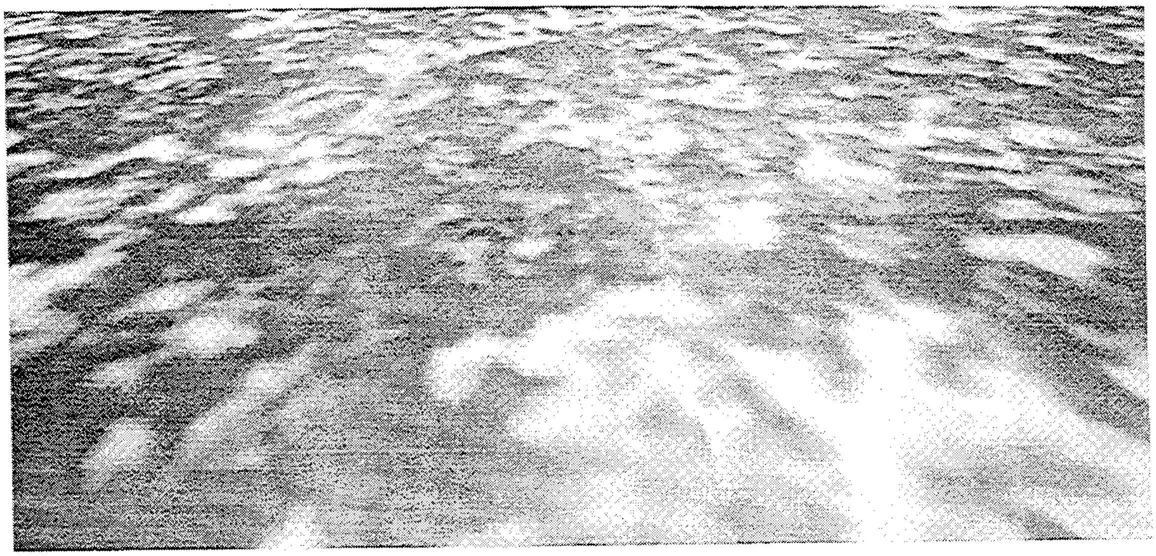

Figure 5f.

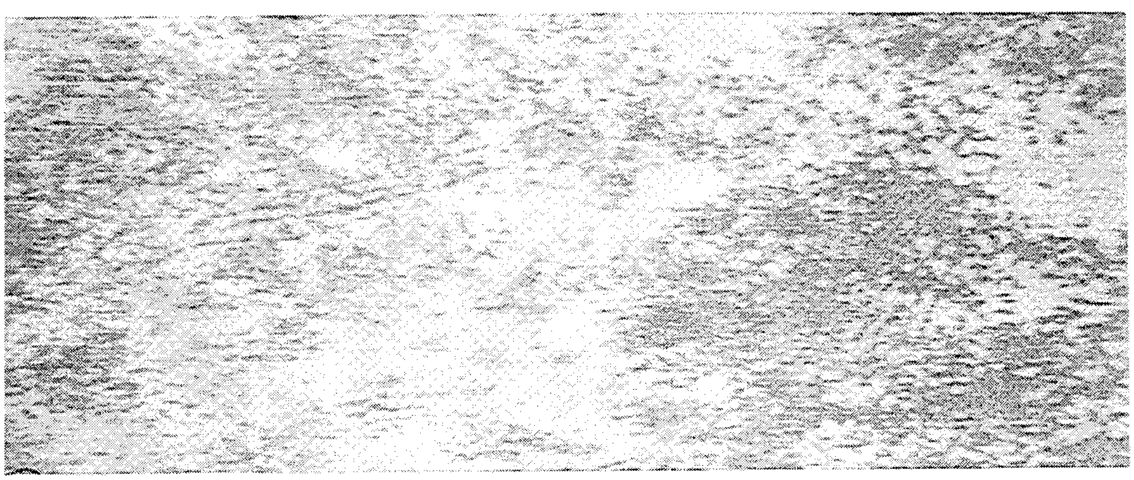

Figure 6a.
Same as Figure 5, but in orthographic projection.

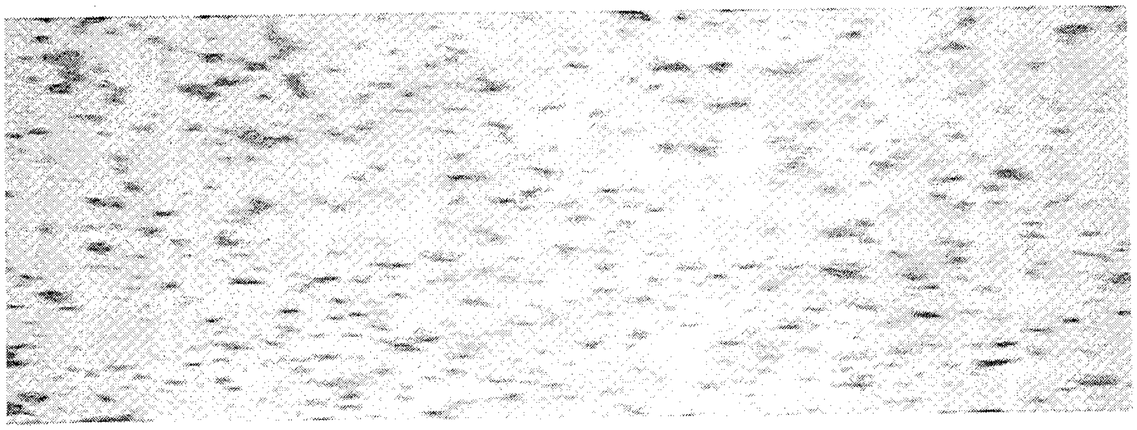

Figure 6b.

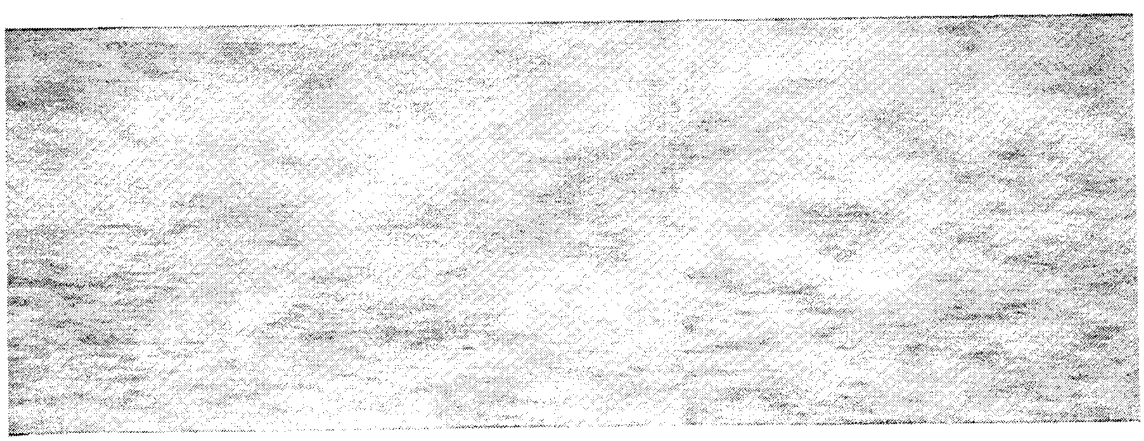

Figure 6c.

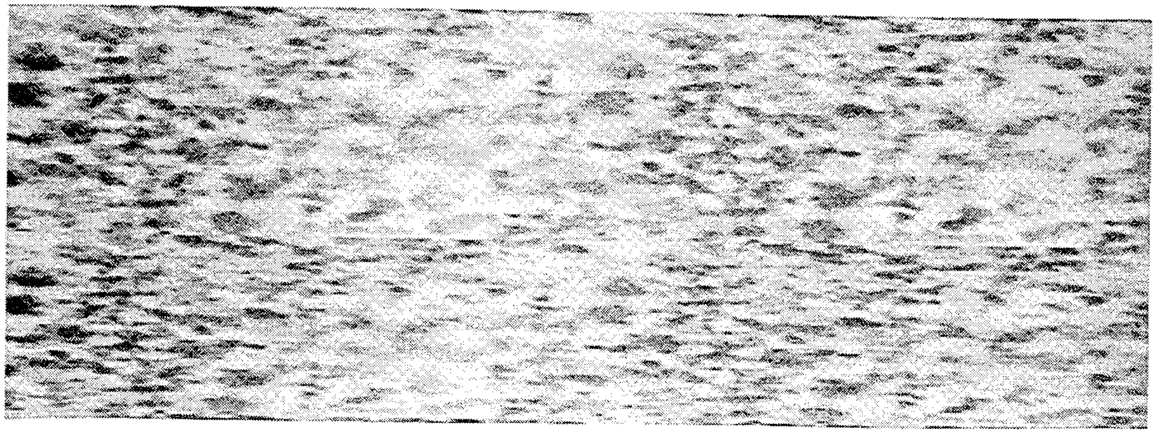

Figure 6d.

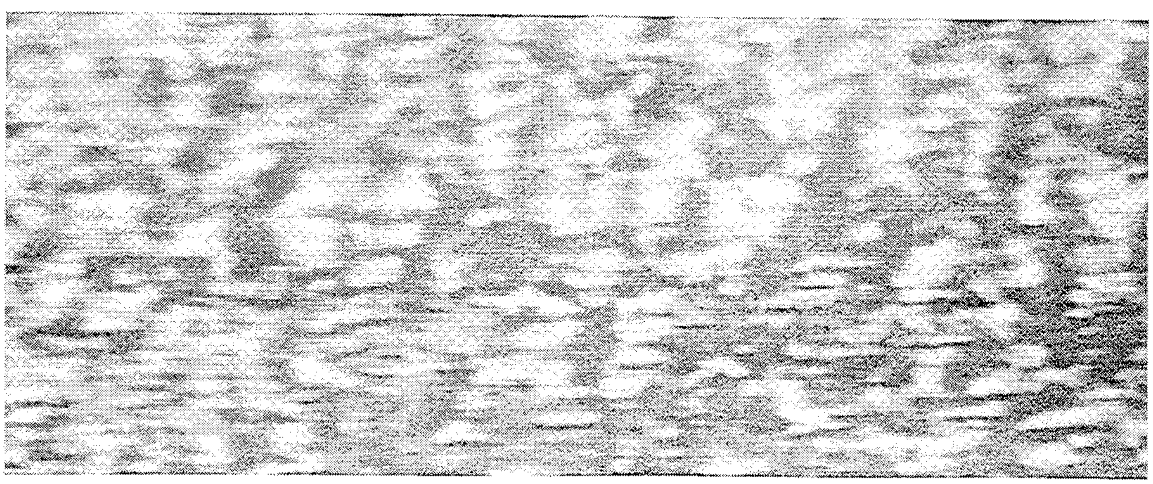

Figure 6e.

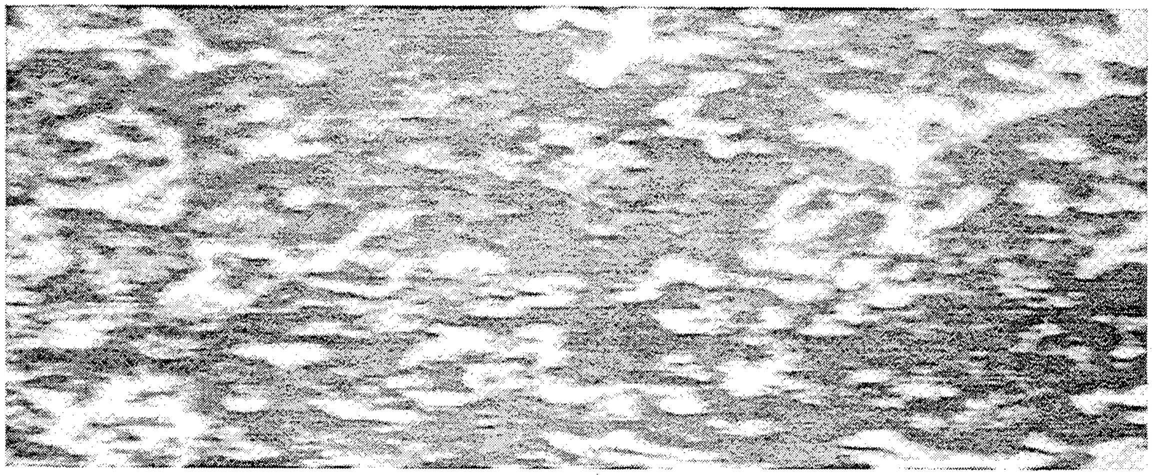

Figure 6f.

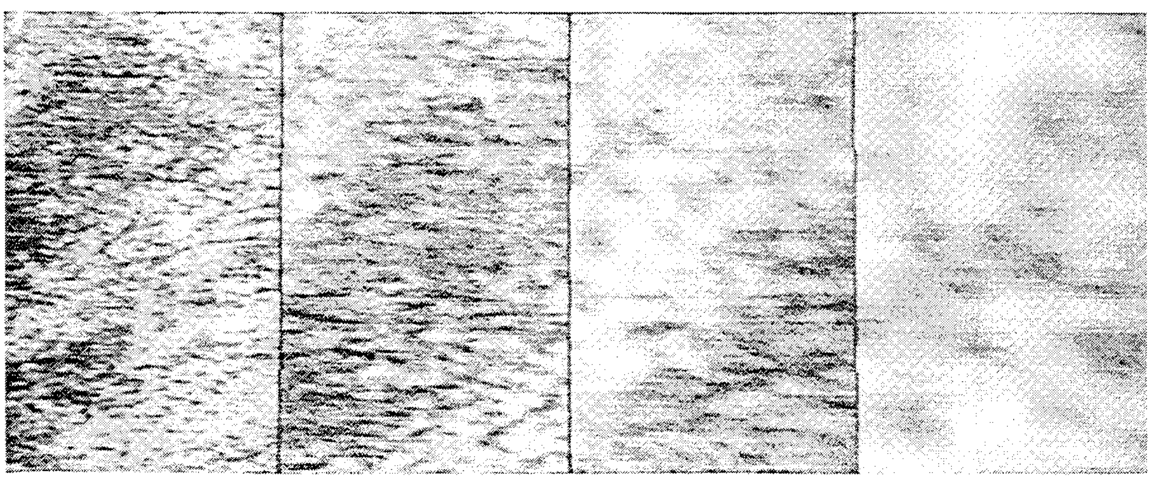

Figure 7a.
Examining the effect of magnification (1x, 2x, 4x, 8x from left to right).

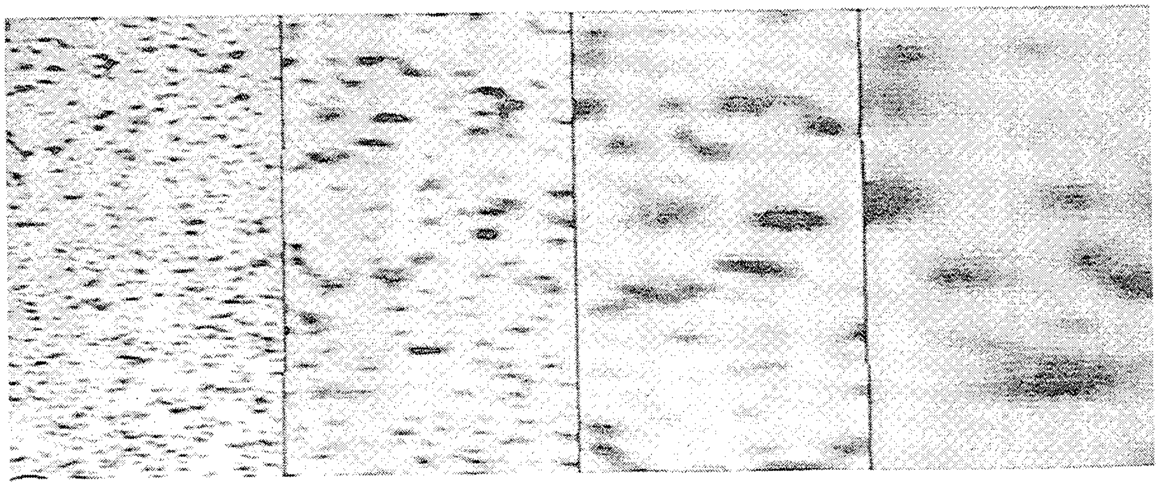

Figure 7b.

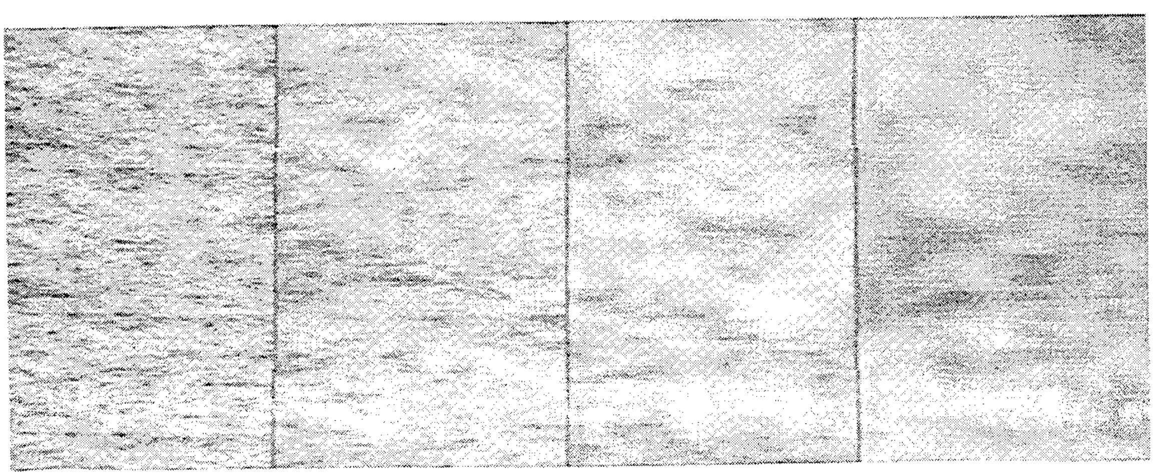

Figure 7c.

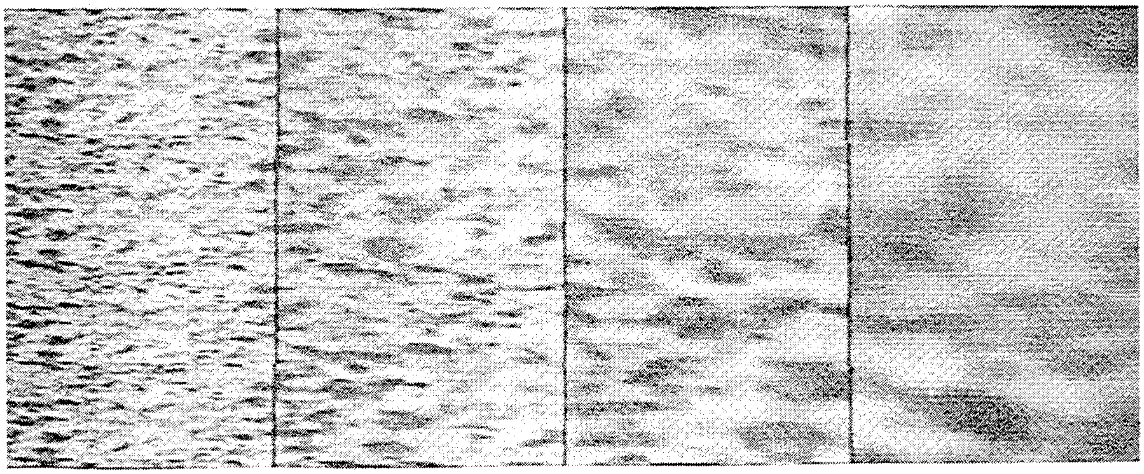

Figure 7d.

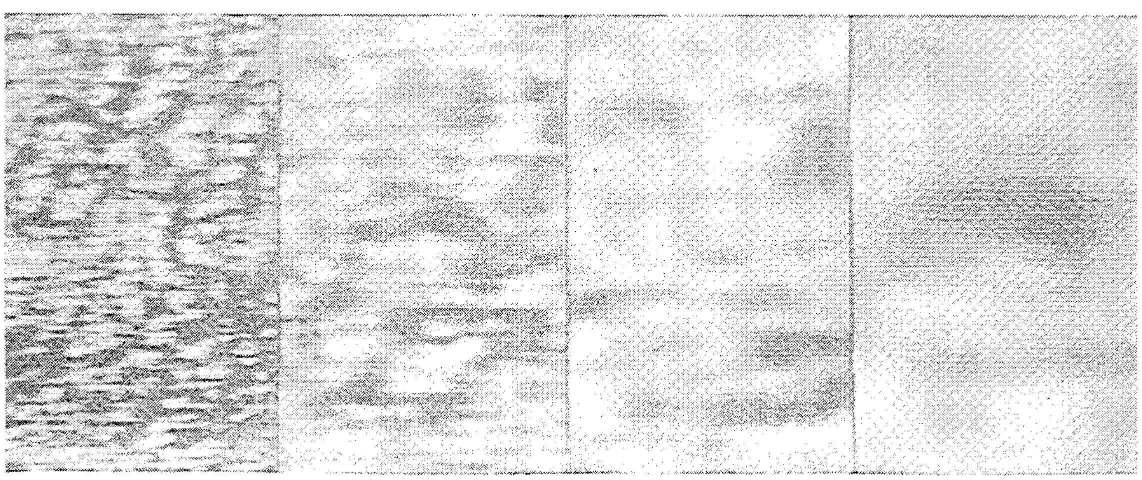

Figure 7e.

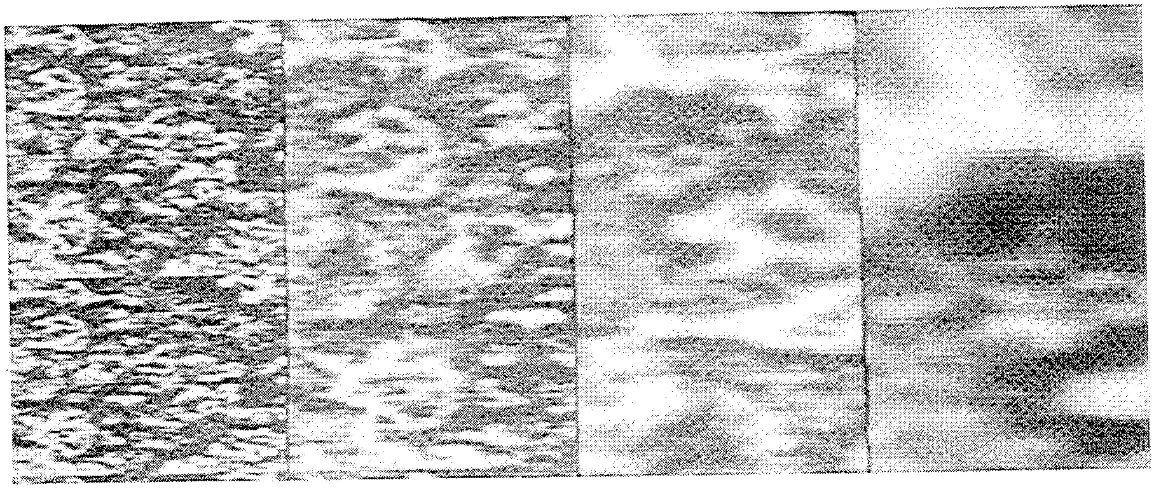

Figure 7f.

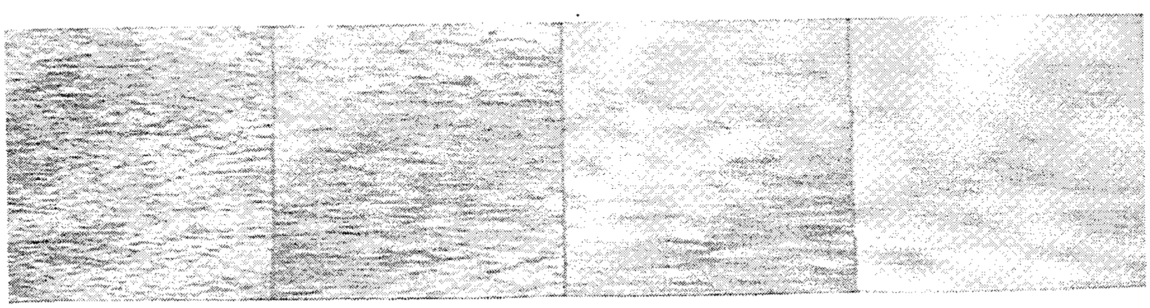

Figure 8a.
Same as Figure 7, but the slant is increased for 70 deg to 80 deg.

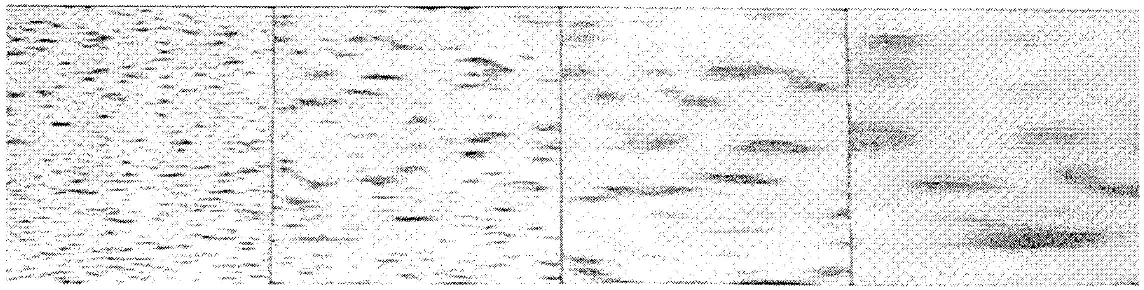

Figure 8b.

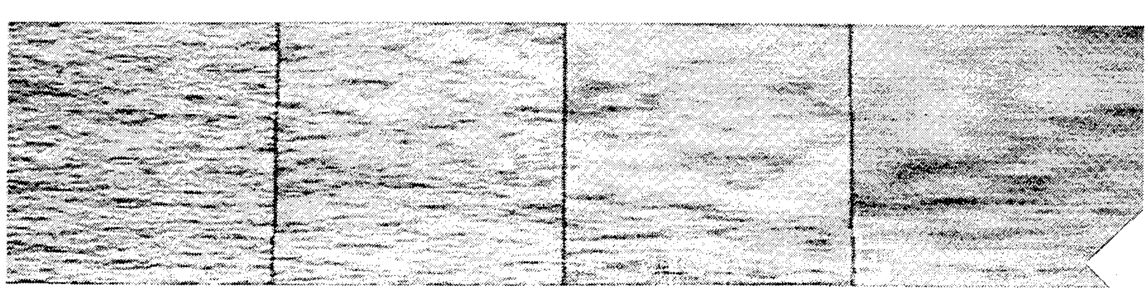

Figure 8c.

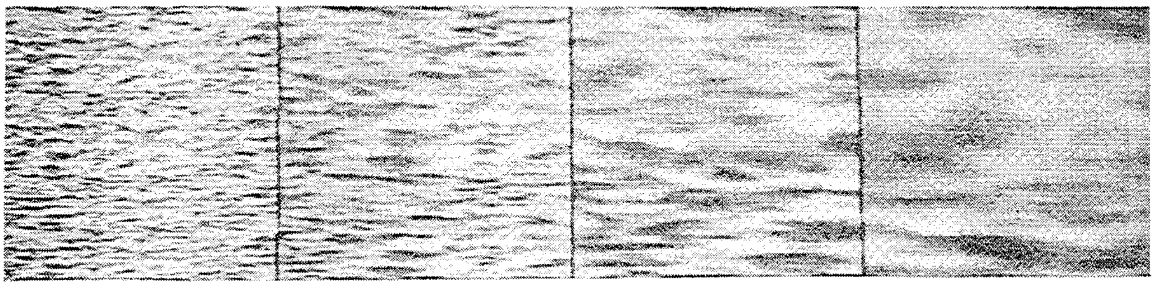

Figure 8d.

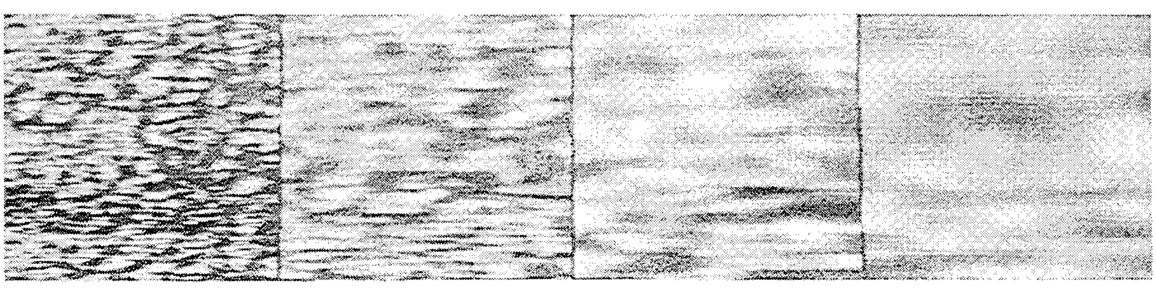

Figure 8e.

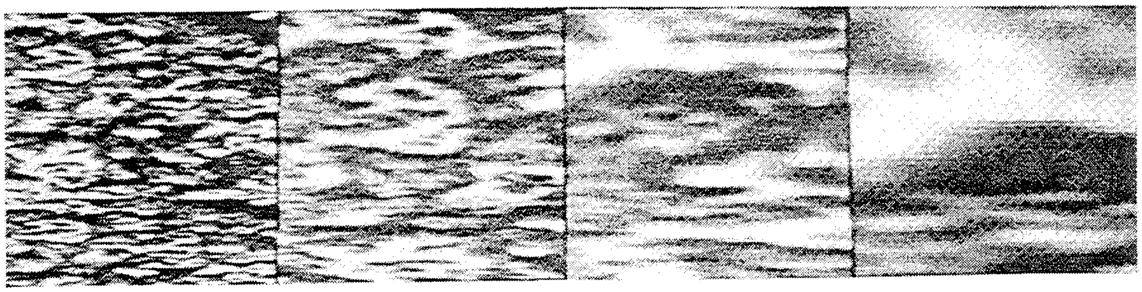

Figure 8f.

CONCLUSIONS

The 3D information in texture is carried in part by cues associated with collections of texture elements, such as the texture density, and in part by the properties of individual elements, such as foreshortening. The former cues require homogeneity and a uniform, distinguishable size; the latter require isotropy. The cell texture samples we examined varied in quality along these properties. Texture B appeared particularly high quality in terms of homogeneity and size uniformity; Texture F provided a rich and isotropic pattern of high contrast contours. The corresponding demonstrations qualitatively reflect these advantages.

In short, the two alternatives examined are to have large-scale isotropic blotches with moderate contrast, or to have small, discrete, homogeneous-sized features. The prediction would be that an optimal texture, robust over a large range of scales, would be one that combines the two: one with large-scale blotches that viewed normally to the surface, appear random in contour tangent direction; and superimposed on this, a pattern of discernible markings resembling those in Texture B.

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