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for a
STUDY OF CLOUD PATTERNS
as seen by
METEOROLOGICAL SATELLITES

OCTOBER 30, 1964

VOLUME I: CLOUD PATTERN CLASSIFICATION AND DISCRIMINATION

VOLUME II: CLOUD PATTERN ANALYSIS BY INTERPRETERS

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GREENBELT, MARYLAND

Final Report

on Contract NAS5-3461

for a Study of Cloud Patterns

as Seen by Meteorological Satellites

Submitted to

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland

by

Budd Information Sciences Center
McLean, Virginia

October 30, 1964

Volume I: Cloud Pattern Classification and Discrimination

and

Volume II: Cloud Pattern Analysis by Interpreters

FOREWORD

This *Final Report for a Study of Cloud Patterns as Seen by Meteorological Satellites* was prepared by the Information Sciences Center, The Budd Company, McLean, Virginia, for the Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, Maryland, under NASA Contract NAS5-3461. The contract period extended from July 1, 1963 through September 30, 1964.

Principal investigators on the study were Dr. Azriel Rosenfeld, project leader and specialist in image processing; Dr. Charles Fried, research experimental psychologist; and Mr. James N. Orton, electronic data processing systems analyst. Other contributors to the study were Messrs. Ernest Smith and Bernard Altschuler, computer programmers; Mr. James Prevel, psychological research assistant; and Mr. Andrew Pilipchuk, electronics engineer. Dr. R. M. Schotland of New York University served as meteorological consultant to the study. Mr. J. H. Conover of the Office of Aerospace Research, Air Force Cambridge Research Laboratories, Bedford, Massachusetts, provided assistance in the preparation of TIROS cloud picture nephanalyses.

The cooperation of the Goddard Space Flight Center and the Institute for Space Studies, NASA, in providing TIROS cloud pictures and related materials for the study is gratefully acknowledged.

VOLUME I

Cloud Pattern Classification and Discrimination

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ABSTRACT

This volume introduces and summarizes studies of TIROS cloud patterns performed under Contract NAS5-3461. Past approaches to cloud pattern classification are reviewed, and an approach proposed which appears to be compatible with automatic cloud picture analysis. The objective measurability of the basic classification parameters is briefly considered. Techniques for automatic discrimination of "solid" from "broken" cloud cover on cloud pictures are described. A bibliography of reports and papers on TIROS picture interpretation which appeared during the period January 1963 - June 1964 is also included.

VOLUME I

TABLE OF CONTENTS

VOLUME I

LIST OF FIGURES

1. General Introduction

1.1 Scope of this report

This Final Report describes studies of human and automatic interpretation of TIROS cloud cover pictures performed during the period 1 July 1963 through 30 September 1964.

The report consists of four volumes. The first volume contains a general introduction to the study program and a summary of its major accomplishments; a discussion of approaches to cloud cover classification and their suitability for automation; a description of a proposed approach to automatic discrimination among basic cloud cover types on TIROS pictures; an annotated bibliography on TIROS picture interpretation for 1963 through mid 1964; and a statement of the general conclusions which can be drawn from the results of the program, particularly as to the feasibility of automatic cloud picture interpretation.

The second volume describes a series of quantitative studies of TIROS picture annotation, cloud pattern discrimination and classification, and judgments of basic cloud pattern parameters by interpreters; these studies provide important information about the possibility of automatic cloud pattern discrimination, classification, and description.

The third volume contains detailed descriptions of two computer programs which were developed for analyzing the areas and shapes of connected regions on arbitrary pictures; and the results of applying these programs to digitized TIROS pictures and nephanalyses.

The fourth volume describes two computer programs which were developed for delineating the "solid" regions on arbitrary pictures, and the results of applying these programs to digitized TIROS pictures as a preliminary step toward automatic cloud cover discrimination and nephanalysis.

The four volumes are bound in two sections, Volumes I and II in the first section and Volumes III and IV in the second. Volumes I and II include the definition of logical and psychological concepts utilized in the development of the computer programs for cloud picture analysis described in Volumes III and IV.

1.2 Background of the program

From the earliest days of the TIROS program, much attention has been given to the possibility of automatically processing TIROS cloud pictures. When an operational network of cloud cover observation satellites becomes a reality, automation may become very important in achieving optimum data utilization.

The problem of TIROS picture processing has two aspects: geometrical and interpretational. Geometrical processing involves such tasks as rectification and determination of geographic location; it will not be discussed in this report. In interpretational processing, two tasks may be distinguished:

(a) The discrimination between cloud and non-cloud
(b) The meteorological interpretation of cloud cover patterns

The possibility of automatically discriminating between cloud and non-cloud on TIROS pictures has been discussed by Arking (1964) and others; this problem will not be discussed further in this report.

(It should be recognized, incidentally, that in many cases pattern and context also play a role in cloud/non-cloud discriminations by human observers.) In order to avoid having to cope with this problem in the studies described in this report, TIROS pictures without visible ground images were used.

The problem of interpreting cloud patterns as seen by TIROS has long been of interest to workers in the automatic pattern recognition field. Applications of automatic TIROS picture interpretation, if feasible include

(a) Automatic indexing and retrieval of TIROS pictures by content

(b) Automatic screening of TIROS pictures to single out those of probable meteorological significance for detailed analysis by humans

(c) Automatic on-board processing of TIROS video data so that only important information is transmitted

The application of automatic recognition techniques to TIROS pictures is currently being studied by the Rand Corporation under NASA sponsorship. In the Rand studies, numerical parameters which should provide important recognition clues are being computed for a collection of cloud cover samples selected from high-resolution TIROS pictures. These samples were chosen to contain only one type of cloud cover each; as a check on their adequacy for recognition purposes, it was verified that they could be correctly classified by human observers.

In order to apply the results of the Rand studies to the automatic analysis of entire TIROS pictures - specifically, to the production of nephanalyses or similar maps from such pictures - the size of the picture samples which are analyzed must be small enough to fit inside the regions on the maps. This condition may not be easily fulfilled; for example, there may exist important regions (such as long, thin cloud bands or streets) which are very small in one dimension. A sample size which is small enough to detect thin cloud bands will generally be too small to yield representative data on a region composed of large "cloud cells."

Another possible limitation on the applicability of the Rand studies to the processing of entire TIROS pictures is suggested by the fact that the identification of cloud patterns by human observers often depends on such factors as the overall shape of the region in which the pattern occurs and the context in which it appears. Admittedly, recognizability by human observers is neither a necessary nor a sufficient condition for recognizability by automatic means. Nevertheless, it seems reasonable to assume that regions which are correctly identifiable out of context by observers can probably be identified by a sufficiently detailed set of parameter measurements. Conversely, it is plausible that where context is necessary for human recognition, automatic recognition out of context may be impossible.

The considerations just stated suggest that the study of the applicability of automatic pattern recognition techniques to

TIROS pictures should be supplemented by descriptive studies of the pictures themselves and of the conditions under which the types of cloud cover contained in the pictures can be correctly identified by human observers. Specifically, it is of interest to determine

(a) What limitations on useful picture sample sizes are imposed by the dimensions of the regions on TIROS pictures which it is desired to identify

(b) Which of these regions are likely to be identifiable out of context, as suggested by the recognizability by interpreters.

The over-all goal of the study program which is the subject of this report is to obtain useful answers to these questions. Specific tasks which were undertaken in order to achieve this goal were

(a) Generation of criteria by which a TIROS picture can be divided into a small number of types of meteorologically significant regions

(b) Measurement of the dimensions of these regions, in order to determine bounds on the picture sample sizes which can be used for their automatic identification

(c) Analysis of the ability of human interpreters to recognize these regions in and out of context, in whole and in part, as an indication of the probable feasibility of their automatic identification.

The studies conducted under the program were not intended to support any specific automatic recognition technique; rather, they have provided general estimates of the input data available for and required by a wide class of such techniques. In addition, they have contributed to a better understanding of the problems involved in the quantitative description and interpretation of TIROS pictures by human observers.

1.3 Scope of the program

The subject program has been divided into three study phases as follows:

1.3.1 Phase I

In the first phase, objective criteria for describing meteorologically significant cloud cover regions on TIROS pictures have been investigated. These criteria are suggested by a general analysis of factors relevant to the "organization" of complex pictures into "uniform" regions. Explicit cloud cover classes based on these criteria have been defined.

1.3.2 Phase II

The classification system developed under Phase I has been applied to produce about fifty cloud cover maps corresponding to TIROS pictures. Under the second phase, computer programs for analyzing the sizes and shapes of the regions on these maps have been written. Using these programs, region size and shape information relevant to the design of automatic cloud cover mapping systems have been tabulated.

1.3.3 Phase III

In the third phase, the abilities of human observers to recognize pieces of cloud cover of the types defined in Phase I have been tested, using the pictures and maps of Phase II, as a function of such variables as piece size, piece shape, and context.

In addition, quantitative parameters useful for automatic cloud cover description have been derived by analyzing human observers' cloud cover descriptions.

1.4 Summary of accomplishments

The basic objectives of the program, as set forth in Section 1.2 above, have all been achieved. Specific accomplishments include the following:

(a) A system for classifying cloud cover in terms of quantitatively definable parameters has been developed (Section 2 of this volume).

(b) Programs for analyzing the sizes and shapes of connected regions on arbitrary pictures have been developed. These programs have been applied to sets of TIROS pictures and nephanalyses. They have been used in particular to analyze the dimensions of the regions on the nephanalyses and to determine upper bounds on the size of the picture samples which an automatic recognition system should analyze if it is to detect and identify given proportions of these regions (Volume III).

(c) An approach to the automatic annotation of TIROS pictures has been defined and initial stages of it tested (Section 3 of this volume and Volume IV).

(d) Studies of the abilities of interpreters to annotate, discriminate, and identify TIROS cloud patterns have been conducted. These studies have confirmed the plausibility of automatic cloud cover discrimination and classification. In particular, they have been used to establish a lower bound on the size of the picture samples which an automatic recognition system should analyze, on the reasonable assumption that automatic recognition is unlikely to succeed if a sample is too small to be identified by observers (Volume II, Sections 2-3).

(e) Quantitative definitions of basic cloud pattern description parameters have been derived from analyses of observers' judgments. These parameters are important to the design of future automatic cloud pattern recognition systems (Volume II, Section 4).

2. Cloud pattern classification

2.1 Need for objective classification

In investigating cloud pattern classification criteria suitable for application to automatic cloud cover mapping, a primary consideration is that the cloud cover maps which result must be meteorologically valid and must discriminate meteorologically significant cloud cover features as far as possible. However, since the production of the maps may ultimately be at least in part the task of a machine, the criteria used in defining mapping features must be machine-interpretable; in particular, they must be statable in objectively and quantitatively definable terms.

In past approaches to cloud cover mapping and nephanalysis, the cloud cover categories used have been selected by meteorologists. In general, the definitions of these categories have tended to be nonquantitative and relatively lacking in objectivity (for more detailed comments on specific past approaches, see Section 2.2 immediately following). The use of traditional cloud type names in such classifications can also lead to confusion with small-scale cloud cover terminology when the classifications are applied to satellite's-eye-view cloud pictures.

To fulfill the present goals, a cloud cover classification based on objective description is needed. Such a classification would in principle be meaningful to a hypothetical automatic cloud cover mapping system. In defining the needed classification, it is of course important to keep the requirements of meteorological validity and significance in constant view. Qualified meteorologists should review any proposed classification scheme, and the performance of trained observers should be used as a standard in determining quantitative parameters for the scheme. As a check on machine interpretability, however, the classification performances of trained and untrained observers should be compared.

An important principle in cloud cover mapping, whether human or automatic, is that it is not absolutely necessary to classify every portion of the given picture. Emphasis should be placed on the identification of those regions which are clearly classifiable and meteorologically significant. Other regions can be denoted as "ambiguous" or "unidentified" as appropriate. Cloud mapping systems which attempt to be exhaustive, often by default or by relying heavily (and conjecturally) on context, are not ideally suited for automation.

2.2 Past approaches to classification

The classification of cloud elements has developed along three avenues. The earliest concept that still has modern applicability was suggested by Howard (1803). His approach was to consider the form and appearance of the generating elements in a basic classification. Howell in his paper (1951) in the Compendium of Meteorology points out that the elements "cirrus", "cumulus", and "stratus" and the combined forms are recognizable in the present day International Cloud Atlas. Present classification methods follow three general approaches.

2.2.1 Form classification

This classification method is founded upon the form and appearances of clouds as seen by an observer located on the ground. The resulting organization and classification essentially reflects the small scale aspects of the cloud systems. If it is assumed that the upper level clouds are at an average altitude of 30,000 ft. and the significant viewing angle is a cone of 120 degrees, then the observation scale is of the order of ten miles. The resolving ability of the observer is an involved function of physiological factors as well as the physical properties of the cloud elements and their radiance background. A rough estimate based upon a 2 min. resolution capability yields a minimum detectable element size of the order of 50 ft. at distances of 5 miles. This value is of course subject to large upward variability. Both the observing range and the element resolution size of the human observer differ greatly from the equivalent properties of the satellite.

2.2.2 Physical classification

The physical classification of clouds is based upon the assumption that a suitable separation of cloud types may be made by noting the characteristics of the drop spectra of warm clouds and crystal types and spectra in ice clouds. Additional parameters would be included as knowledge of the microphysics of clouds progresses. One such classification has been proposed by Bergeron (1933).

It is apparent that the quantitites that would enter into such a classification approach cannot at present be measured by satellite instrumentation; consequently, this method will not be considered further here.

2.2.3. <u>Genetic classification</u>

The third classification approach considers the kinematic and thermodynamic fields which lead to the generation of various cloud formations. Some simplified typical factors entering into such a system are given by Douglas (1934) as:

(a) Slow general large scale vertical motion leading to stratiform clouds,

(b) Isolated air masses moving through the environment leading to cumuloform clouds and

(c) Clouds produced by "turbulent" air motion.

A number of other genetic classifications have been suggested which further subdivide the kinematic and thermodynamic fields so as to obtain greater detail, and to permit an association of these fields with meso- and macro-scale meteorological systems.

2.2.4 <u>Cloud classification for satellite observation</u>

The primary problem posed in classification of cloud elements observed from a satellite is one of resolution and scale. The distortion-free camera viewing angle for this system (typical of Camera 2, TIROS IV) is of the order of 60°, and the resolution for zero nadir angle approximates 2 km. Future systems postulate an increase by a factor of the order of two in angular coverage and three in resolution capability. It is apparent that the adoption of the International Cloud Atlas (1932), a combination of form and genetic classifications, will not be successful because those features that enter into this classification are not in the main measurable from satellite data.

Approaches to classification of cloud data obtained from satellite photography have been proposed by Glaser (1957), Erickson and Hubert (1961), and Conover (1962-3). These authors indicate that satellite pictures primarily show a larger scale of cloud organization. Typical of such groupings are cyclonic vortices, bands, streets and cumuloform clusters. In addition to shape organization, there exists scales of brightness and brightness variability which relate in some sense to liquid water content and solar angle. The distribution of texture and pattern is also significant.

The general philosophy of the above authors has been the deduction of conventional cloud data from the large scale patterns of brightness. As an example, Conover has formulated a detailed logical decision scheme in which an analyst performs a series of decision operations on classes which take into account form, pattern, texture, brightness, and size or spacing. This method may be considered to be a combination of both genetic and form classification. A major problem associated with the machine adaptation of this method is the lack of detailed specification of the nature of the classes. It is still necessary to pursue this aspect of the problem.

2.3 An objective cloud pattern description system

A black-and-white picture (in particular, a cloud cover picture) is often comprised of discernible pieces each appearing to have constant brightness-that is, a constant shade of gray. In the extreme case in which the picture consists of white "cloud cells" seen against a black (say deep sea) background, the pieces are the cloud cells and the intervening patches of black; in general, of course, neither the clouds nor the background will have constant brightness, and the problem of discriminating between them may be nontrivial.

Regions of "uniform" cloud cover type which are seen in a cloud cover picture generally arise as a result of some <u>regularity</u> or <u>repetitiveness</u> in the nature and arrangement of the constant-brightness pieces, and in particular of the pieces which appear to be cloud. Such regularities define <u>groupings</u> of the pieces. At small scales, uniformities in the groupings of the pieces correspond to uniformity in "visual texture"; at larger scales, to uniformity in "pattern." The variables or parameters with respect to which regularity is important include:

(a) brightness

(b) size and shape

(c) spacing and its directionality

Some specific shape "dimensions" which seem important in cloud type mapping are

(b1) Elongation: Cellular vs. bandlike

(b2) Curvature (degree): "Straight" vs. sharply curved

(b3) Curvature (regularity): Simply curved vs. irregular

Spacing and directionality are in a sense duals to size and shape and can be broken down into subparameters analogously; important parameters seem to be the existence of a "preferred direction" (in which the piece spacing is markedly smaller than in other directions) and its relationship to the directions of the long axes of elongated pieces (if any).

The approach to defining uniform "groupings" of "pieces" in a picture just discussed is basically <u>hierarchical</u>. The lowest level of "pieces" are the regions of constant brightness. At a higher level, the groupings defined by these lowest-level pieces in accordance with the above rules may be used as "superpieces" and combined into "supergroupings" using essentially the same rules. Such second-order groupings can also be important in cloud cover mapping. For example, a series of closely spaced cloud cells (first-order pieces) can define (broken) cloud bands (first-order groupings); but these bands themselves (as second-order pieces) may be part of a vortex system (second-order grouping).

In the studies reported below, emphasis has been placed on regions defined by first-order grouping of first-order pieces. This restriction is useful for two reasons:

(a) First-order groupings correspond to smaller scale meteorological features than do higher-order groupings. There is thus much more detailed information of this type on a typical cloud picture than there is higher-order information (such as the presence of vortices). The mapping of this more detailed information is more tedious and hence more important to automate.

(b) Groupings which are low in the hierarchy are necessarily easier to identify automatically than are higher-order groupings.

A "decision tree" summarizing the classification factors suggested above is shown as Figure 1. The following remarks provide further explanation:

(a) Brightness: It is assumed here that cloud/non-cloud discrimination can be made on the basis of measured picture element brightness, perhaps normalized relative to the mean brightness of the picture. This assumption is not too implausible if consideration is restricted to cloud cover over the open ice-free ocean in the absence of sun glitter. In any case

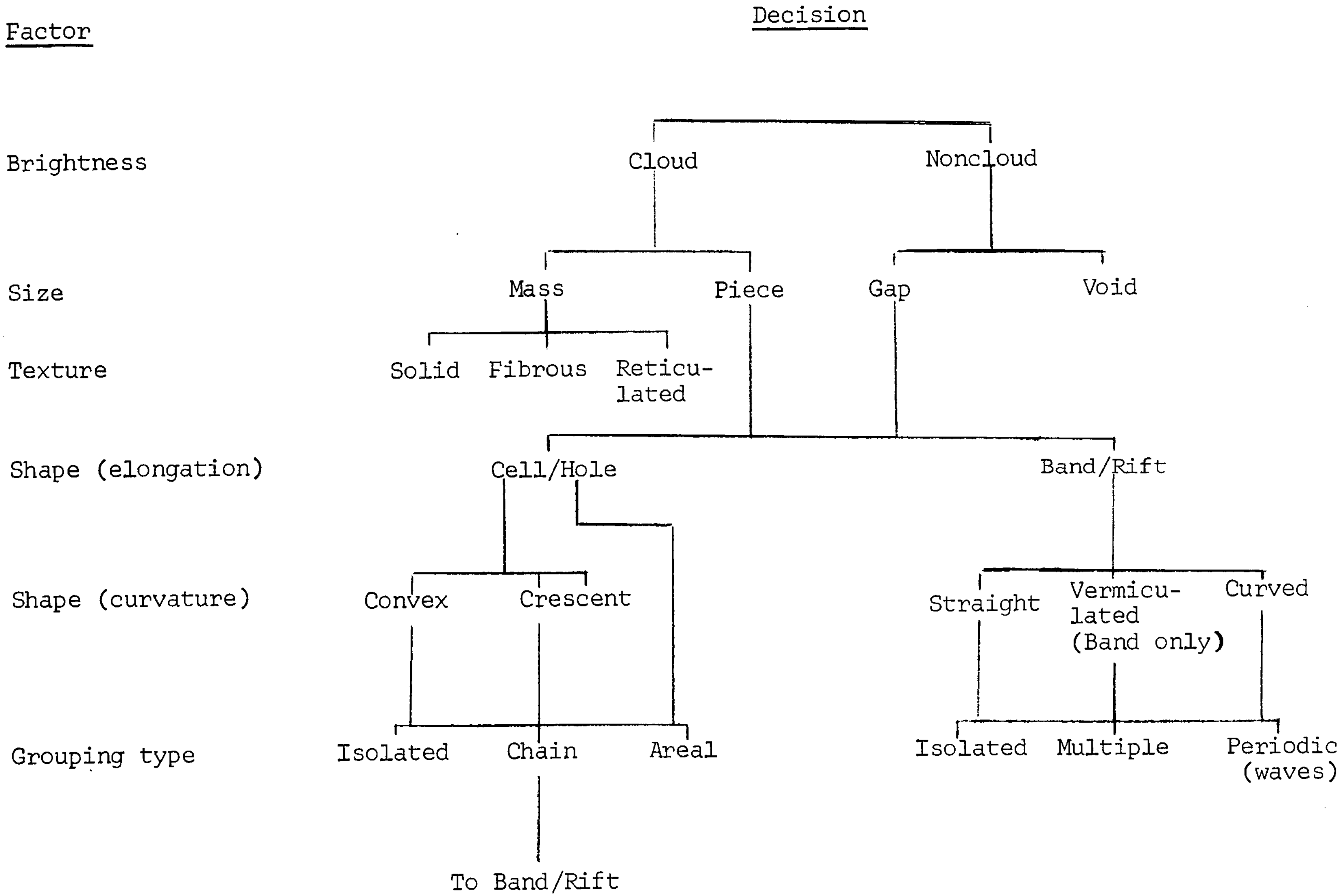

Figure 1

Cloud Cover Classification Decision Tree the emphasis in this program is on the spatial factors (discussed below) which characterize cloud cover types, since the quantification of these factors presents a highly challenging problem to the analyst.

(b) Size: From the point of view of physical meteorology, the absolute size of a cloud formation (or gap between clouds) is significant for interpretation. From the picture organization viewpoint, the size of formations relative to one another and to the picture as a whole can significantly affect the determination of important groupings. Since the present classification scheme is based on an analysis of a set of near-vertical TIROS pictures having approximately constant scale, the requirements of the two viewpoints do not come into serious conflict.

(c) Texture: Experience indicates that it is unnecessary to discriminate textures for small "pieces" of cloud. For large cloud masses, on the other hand, there are at least three important types of "texture" which should be discriminated:

(1) Solid. Relatively bright, featureless

(2) Fibrous. Dimmer, "wispy", filamentary

(3) Reticulated. A "network" of "lacy" cloud enclosing "hollow cells".

(d) Shape (elongation). For both cloud and noncloud it is useful to distinguish between elongated ("bandlike") and less elongated ("cellular") pieces. The terms "cell" and "band" apply to cloud pieces; "hole" and "rift", to gaps in cloud cover.

(e) Shape (curvature). In the case of cloud pieces, a finer discrimination is useful as regards both the elongated and nonelongated cases. Convex ("solid") cells may be distinguished from crescent-shaped, concave cells. Similarly, a distinction may be made among relatively straight, irregular ("vermiculated") and markedly curved bands. The analogous discriminations for holes and rifts can also be made.

(f) Grouping type. As discussed above, individual small "picture pieces" can combine to form groupings which are important to picture organization. On the other hand, a "piece" which is isolated from others of its kind (for example, a cloud band which has no other cloud nearby, or which is surrounded by large cloud masses) may become important by virtue of its isolation. Cells, holes, bands, and rifts can all be significant in isolation. In the case of bands (and equivalently, of rifts), there is one other grouping type which is of special importance - namely, the case of the periodic, parallel, "wave-like" band/rift formation. As regards cells and holes, an important distinction can be made between "chainlike" groupings in which there is a natural direction of "lineup", and isotropic, "areal" groupings. In the former case, the cells form a <u>broken band</u> (or the holes a <u>broken rift</u>, respectively.) This band (or rift) can then be treated as a new "super-piece" of (or "supergap in") the cloud cover, as described above. In particular, it is appropriate to classify it as straight or curved (but not vermiculated) and to distinguish isolated occurrences from regular, periodic broken band/rift formations.

2.4 Objective measurement of cloud pattern parameters

The cloud pattern parameters discussed in Section 2.3 are intuitively basic, but it is a far from trivial matter to define most of them quantitatively. (<u>Brightness</u> has an immediate objective definition, but as mentioned in Section 2.1, cloud/non-cloud discrimination is not always possible on the basis of brightness or albedo alone.) <u>Size</u>, for example, might be defined in terms of area, of diameter, or of some combination of the two; studies reported in Volume II, Section 4.3 indicate that area is the most important correlate of the judged size. Approximate objective correlates of other basic cloud pattern parameters are suggested by other studies reported in Section 4 of Volume II. For cloud masses which are not highly elongated and sharply curved, <u>elongation</u> can be defined in terms of a maximum diameter to minimum diameter ratio. A completely general definition, however, is much less trivial to formulate. Consider, for example, the problem of defining "elongation" in such a way as to correctly rank the shapes shown in Figure 2. Intuitively, shapes (a), (b), and (e) are non-elongated: (c) and (f) are somewhat elongated; and (d) is very elongated. The elongation of a shape thus cannot be measured by its diameter (=greatest distance between two of its points), since this would rank (d) as low as (a, b, e). On the other hand, elongation cannot be measuredby perimeter, since this would rank (b) too high.

A novel method shape description has been proposed in an unpublished paper by Mr. Harry Blum of United States Air Force Cambridge Research Laboratory. The key ideas underlying this method may be very briefly stated as follows:

(a) The given shape is caused to "propagate" over the plane in the manner of a wave disturbance (the instantaneous direction of propagation at any point is normal to the wave front through the point, unless no unique normal exists at the point).

(b) A point through which the wave front has passed becomes "refractory" (that is, resistant to

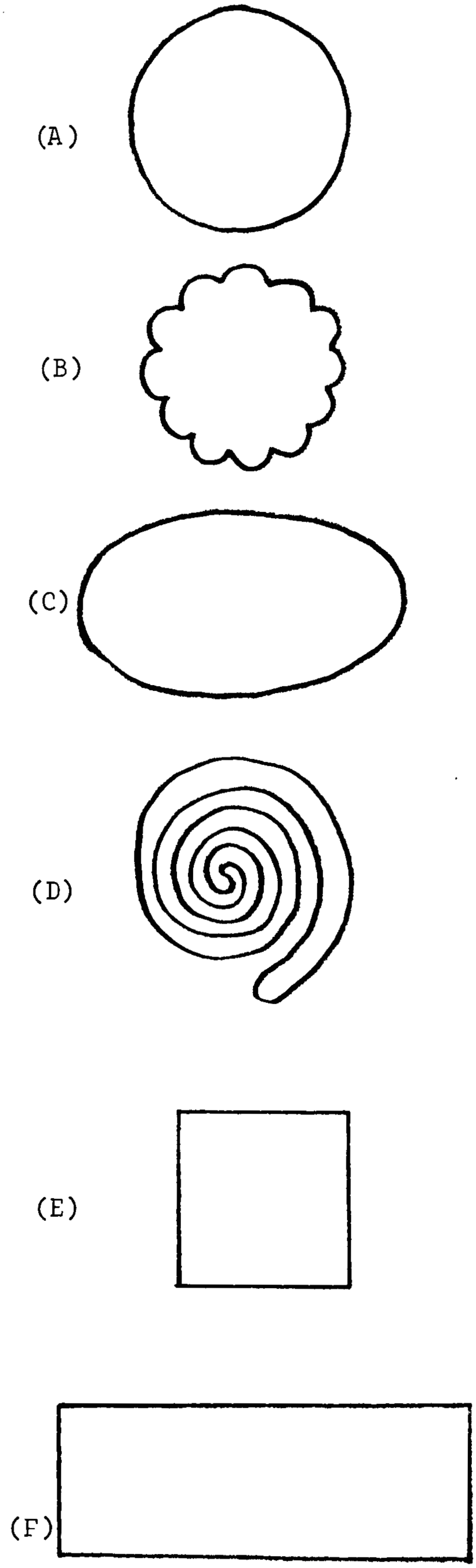

Figure 2

<u>Shapes Which Differ In Elongation</u>

further passage) for some time. In consequence, when two segments of the wave front intersect they produce a resultant in the direction of the vector sum of their velocities, and a magnitude essentially that of their resultant "phase velocity".

(c) The wave front arc length as a function of time, and the locus of wave front selfintersections, provide important information about the shape of the given contour.

The problem of elongation measurement can be solved in terms of the Blum selfintersection locus. Figure 3 shows, for each of the shapes of Figure 2, the locus of wave front selfintersection points at which the propagation velocity changes. It can be seen that a very reasonable definition of elongation can be given for these shapes in terms of the connected length of this locus.

The Blum propagation process resembles certain discrete processes which are believed to occur in certain types of neural networks. This discrete version of the process is easy to simulate digitally. The Blum method of shape description is potentially a valuable tool for the analysis of cloud patterns and the like, in which basic (but hard to define) shape parameters play important roles. The use of the method in future automatic cloud cover mapping systems deserves serious consideration.

2.5 Limitations on objective cloud pattern classification

The cloud cover classification system described in Section

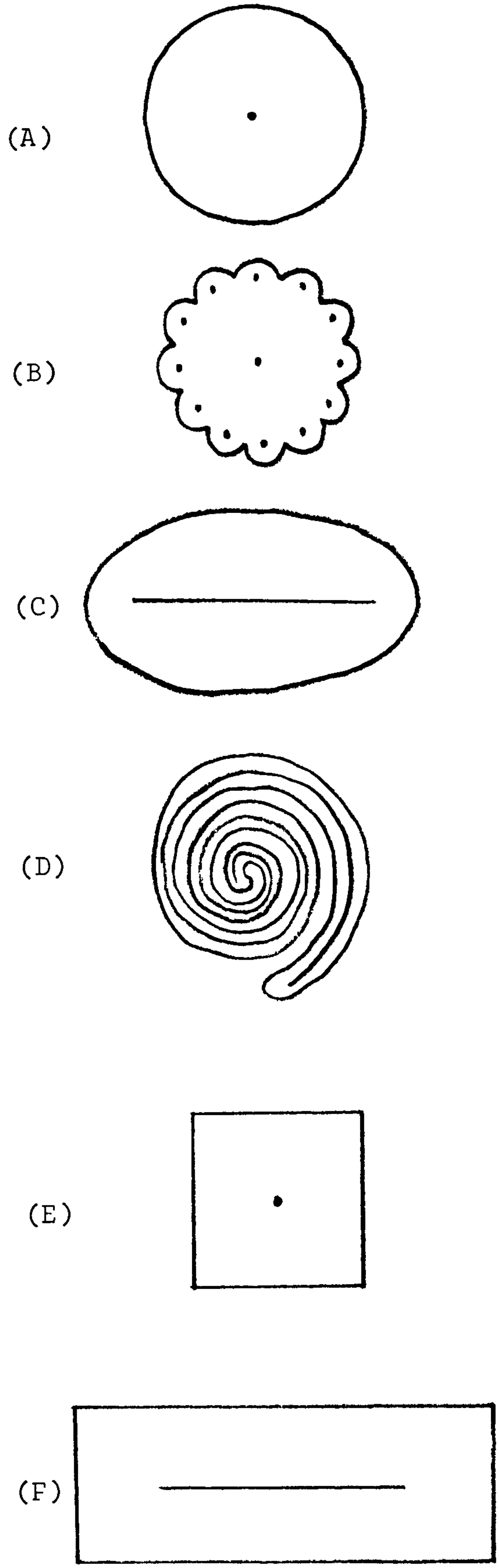

Figure 3

Elongation and the Self Intersection Locus

2.3 is somewhat idealized, since it relates to cloud cover which consists primarily of discrete, disconnected masses and pieces. This observation implies that a practical automatic cloud mapping system based on this type of classification must begin by "idealizing" the observed cloud cover, namely breaking it up into clearcut, disconnected cloud pieces and masses.

A more important limitation on the classification system described above is its emphasis on "distinctive" types of cloud cover - specifically, on types defined by strongly characteristic textures or regular groupings of cloud pieces. This emphasis is entirely reasonable, since these types have been found to be meteorologically as well as geometrically "distinctive."[1] As even a cursory examination of quantities of TIROS imagery reveals, however, most cloud pictures simply do not contain examples of the distinctive cloud cover types. In terms of the classification system, most observed cloud cover consists of large, irregular solid masses and voids or of "groupings" of one or two pieces or gaps.

In spite of the nondistinctiveness, or even nondescriptness, of most cloud cover with respect to the classification scheme, it has been demonstrated (Volume II, Section 2.1) that even naive

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1. It is certainly plausible that geometrical distinctiveness on a cloud cover picture results from the operation of some special physical mechanism, which in turn implies probable meteorological significance. It should of course be realized that there may exist many other meteorologically significant features of cloud cover which have escaped notice because they lack geometrical (and hence perceptual) distinctiveness.

observers can consistently subdivide arbitrary cloud cover pictures into regions. For nondescript cloud cover, this subdivision is certainly not based on the observers' discrimination of the regions as being of "labelable" types. Such discrimination without accompanying "labelability" must involve relatively basic "perceptual" performance on the part of the observers.

An analysis of the factors which influence cloud pattern discrimination, and preliminary results of an approach to automatic cloud picture subdivision, are presented in Section 3 of this volume and Volume IV.

3. Cloud pattern discrimination

3.1 Approach

Over the past three years, the factors which influence the perception of complex pictures as subdivided into "uniform" regions have been studied extensively by The Budd Company, with the partial support of the Directorate of Information Sciences, United States Air Force Office of Scientific Research. These studies have led to the definition of basic "visual texture" parameters on which the perception of picture subdivision is largely based. Perceived visual texture, in the broad sense of the term intended here, is in general a complex, multilevel hierarchical phenomenon. However, it appears that picture subdivision perception performance in a great majority of situations can be accounted for in terms of a few very primitive textural parameters. These situations include, in particular, the cases in which the given picture is "nondescript" in the sense of being free of distinctive patterns.

The strongest factor which influences the perception of subdivisions in "nondescript" pictures seems to be the discrimination of differences in average brightness; the "next strongest" factor, the perception of differences in average "coarseness of detail".[2] The analysis of a given picture with respect to these factors is by no means a trivial task; the crux of the problem is that the size of the "neighborhood" over which the averages are computed must somehow be specified. This neighborhood size is not an absolute constant; the choice of neighborhood size is tantamount to the choice of a "level of scrutiny" at which the picture is to be examined. Thus, very close examination of a picture by an observer might lead him to subdivide it into a large number of only slightly differing regions; this would essentially be a subdivision based on averaging over very small neighborhoods. Conversely, a more superficial examination and resulting coarse subdivision of the same picture would correspond to application of the averaging process over larger neighborhoods. Furthermore, there may exist "natural" neighborhood sizes for a given portion of a picture; these are related to the coarseness of the detail in the given portions. Coarse detail requires a relatively large neighborhood for a "meaningful" average, while fine detail or lack of detail permit the use of smaller neighborhoods. Similarly, there is a well-known relationship between the ability of observers

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2. Many measures of "coarseness of detail" have been proposed, among them:

(a) Spacing between points of high brightness gradient
(b) Size of constant-brightness patches
(c) Rate of falloff of autocorrelation function
(d) Spatial power spectrum
(e) Probability of brightness change between adjacent points
(f) Brightness variance or standard deviation

In the discussion below, it will be convenient to use the first of these measures.

to discriminate brightness differences and the local degree of detail; when detail is present, observers become much less sensitive to slight differences in brightness. This implies that a smaller neighborhood size must be used to compute the desired averages in the absence of detail.

These considerations suggest the following general approach to automatic picture subdivision:

(1) The picture is analyzed for large areas of essentially constant brightness (=areas free of high contrast detail). Since the observers can easily discriminate small brightness differences in such detail-free regions, these regions themselves are important subdivisions; they correspond to subdivisions on the basis of brightness averaged over small neighborhoods.

(2) The remainder of the picture consists of <u>small</u> pieces of roughly constant brightness. This part of the picture can now be subdivided on the basis of differences in brightness averaged over relatively large neighborhoods (representing some reasonable fraction of the size of the picture). It may also be possible to binary-quantize this part of the picture in brightness before performing the averaging process without much loss in the accuracy of the resulting subdivision.

The procedure just outlined, applied to "nondescript" cloud cover pictures, should produce subdivisions resembling those drawn by a consensus of human annotators, and corresponding to a relatively coarse "level of scrutiny". If applied to arbitrary cloud cover pictures, which may contain distinctive regularities of texture or pattern, the procedure will be somewhat less reliable. However, it represents a key preliminary step in the analysis of such pictures. The techniques for cloud cover recognition now under investigation by the Rand Corporation and others are virtually powerless unless they are applied to portions of pictures which show single types of cloud cover exclusively. The suggested subdivision procedure should in a great majority of cases subdivide a given picture into such portions, even though it cannot identify their contents. It is thus a highly essential complement to the cloud pattern recognition techniques which are being investigated by others.

3.2 Feasibility

As suggested in Section 3.1, a first reasonable step toward automatic cloud pattern discrimination is the identification of large detail-free regions. In implementing this step, it is important to recognize that these cannot simply be connected regions. A connected region of essentially constant brightness can still have a very high level of detail; for example, a reticulated cloud pattern may be completely connected and yet highly "broken." It is necessary here to develop an objective method of identifying large "unbroken" cloud masses.

Two computer programs identifying and demarcating large "solid" masses on digitized pictures have been developed and tested. Detailed descriptions of these programs, designated SORD (="SOlid" Region Delineator) -1 and -2, and examples of their application to cloud cover pictures, are presented in Volume IV of this report.

4. New Technology

Careful consideration was given to the possibility of reportable new technology having been accomplished in each of the following specified disciplines:

mathematics

statistics

programming

image processing

optics

experimental psychology

meteorology

In all of these fields, the technical effort on the subject program has required application of state-of-the-art techniques but has not in all cases led to new developments or innovations.

We have reported as new technology, the set of digital computer programs which were written as aids to the analysis of cloud cover pictures and maps. Fully detailed descriptions of these programs are given in Volumes III and IV of this report. They can be applied to an arbitrary digitized image to determine the number sizes, and shapes of connected regions defined by given ranges of densities in the image. There is a strong possibility that these computer programs can be usefully applied to the analysis of other types of images, such as terrestrial (as opposed to satellite cloud cover imagery) aerial photography of sea ice or of certain simple terrain types and the like.

5. Conclusions and Recommendations

As summarized in Section 1.4 and detailed in the body of this report, the results of this study program constitute important steps toward the ultimate goal of automatically interpreting the cloud patterns seen by meteorological satellites. Specific conclusions resulting from the program are as follows:

(a) Cloud cover as seen by TIROS can and should be described in terms of objectively definable parameters (Volume I, Section 2).

(b) Quantitative definitions of basic cloud pattern description parameters can be derived by analyzing observers' estimates and judgments (Volume II, Section 4).

(c) The success of cloud cover annotation, discrimination and identification experiments using small picture samples viewed out of context by inexperienced observers makes the feasibility of automatic cloud picture interpretation, based on the analysis of such samples, highly plausible (Volume II, Sections 2-3).

(d) The optimum sample or "window" size which an automatic interpretation system should analyze should be about one-sixth of the picture size (measured between "corner" fiducial marks) on a side (Volume III, Section 5, in combination with Volume II, Section 3.3).

An approach to automatic TIROS picture annotation and interpretation is outlined in Volume I, Section 3. Tests of the initial steps in this approach have been successfully completed

(Volume IV). Because of the importance of this work to the ultimate objectives of this study program, the reasoning underlying the approach and its implementation is briefly recapitulated below.

(a) Approach

In general a TIROS picture shows several different types of cloud cover which occupy different regions on the picture. The automatic interpretation of the picture requires the localization and identification of the cloud patterns in each of these regions. Even if only a classification of the entire picture is desired (e.g., as to whether or not it contains a specific type of cloud formation, such as a vortex), it is still in general necessary to analyze every portion of the picture individually. If analytical tests are applied only to the picture as a whole, it is very likely that the pattern or formation of interest will be missed, since the portions of the picture which do not contain it will contribute negatively to the results of the tests, and the positive contribution made by the portion (if any) which does contain it may pass unnoticed.[3]

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3. When automatic cloud picture interpretation is being performed by a Perception or similar "trainable" device, it may appear as through the device is "looking" at the picture as a whole. Actually, however, the device is applying tests in parallel to every part of the picture. When it has been trained to make correct classifications, say into "contains vortex" and "does not contain "vortex", it is in effect testing every part of the picture for "vorticity" and producing the "contains vortex" response if and only if at least one of these local tests yields positive results. It will thus have implicitly determined the location(s) of the vortex pattern(s); however, its limited output capability makes it unable to indicate these locations, so that it can only produce the overall classification of the picture as output.

These considerations suggest the following general approach to automatic TIROS picture interpretation. The picture is inspected through a "window" which shows only a portion of it at a time. This portion is analyzed and if possible classified as to cloud type. This process is repeated for all possible positions of the window within the picture. Assuming that adequate analytical tests can be devised, this procedure should correctly identify the cloud cover type which shows through the window whenever the window is in a position such that primarily only one type is visible. The aggregate of these local identifications constitutes the interpretation of the picture.

(b) Feasibility

The feasibility of the "window" approach to automatic cloud picture interpretation depends on the following assumptions:

(1) The window size used must be large enough for it to be possible to recognize cloud cover types by analyzing window-sized samples out of context.

(2) The window size used must be small enough for the window to fit inside the regions in which the cloud cover types to be recognized occur.

The studies successfully completed under this contract and described in Volumes II-IV of this Final Report have demonstrated that these conditions can in fact be satisfied simultaneously.

(c) Implementation

To implement an automatic interpretation system of the "window" type, it is necessary to specify:

(1) The size(s) of window to be used.

(2) The tests to be applied to the cloud patterns which show through the window in order to identify them.

Just as it will almost certainly be necessary to apply more than one type of test in order to be able to identify all of the cloud cover types of interest, so it may be desirable to use more than one window size. For example, it can be seen that recognition of "solid" cloud cover ("overcast") or of "solid" non-cloud ("clear") requires a relatively small window, whereas recognition of the various types of broken cloud cover ("cells", "bands", etc.) may require a considerably larger window, since a small window will not in general show enough of such cloud cover types to represent their defining characteristics.

In designing a practical window-type interpretation system, it is desirable to begin by applying simple tests which discriminate among the most basic cloud pattern types. Experimental studies of the discriminability of cloud cover types on TIROS pictures by human observers (see Volume II) indicate that the most fundamental discrimination is that between the "solid" types and the "broken" types. Identification of these types as a first step can also simplify the analysis of the broken types on subsequent steps, since the "solid" regions, once identified, can be eliminated from the picture so that they do not interfere with the broken region analysis where they overlap the window.

(d) Preliminary studies

The recommended first analysis step, in which "solid" and "broken" regions are discriminated, has been implemented experimentally. Two digital computer programs for performing this discrimination have been written and successfully tested as described in Volume IV of this Report.

(e) Further studies

The first-level problem of subdividing a picture into solid and broken regions is now essentially solved. The next step to be taken involves writing computer programs for further subdividing the solid and broken regions into subregions having optimum differences with respect to such basic parameters as mean brightness. The regions resulting from this second step should resemble quite closely those on nephanalyses produced by human analysts. Subsequent steps would then primarily involve applying further tests to these regions in order to identify the cloud cover which they contain, and would only rarely lead to further subdivision of the regions.

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Douglas, C.K.M., The Physical Processes of Cloud Formation, Quart. J. R. Meteor. Soc. 60, 1934

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Glaser, A.H., Meteorological Utilization of Images of the Earth's Surface Transmitted from a Satellite Vehicle, Blue Hill Meteorological Observatory, Oct. 1957

Giraytys, J., Investigations of the Quantitative Interpretation of Brightness on TIROS I Film, S.M. Thesis, Pennsylvania State University, Sept. 1962

Howard, L., On the Modifications of Clouds and on the Principles of Their Production, Suspension and Destruction, Phil. Mag. 16, 1803, 97-107, 344-357

Howell, W.E., The Classification of Cloud Forms, Compendium of Meteorology, Amer. Meteor. Soc., 1951

Appendix: Interpretation of TIROS Pictures - An Annotated Bibliography (January, 1963 - June, 1964)

A comprehensive annotated Bibliography on Satellite Meteorology (1952-1962), prepared by the American Meteorological Society, was published by the United States Weather Bureau in April, 1963. The bibliography presented on the following pages supplements this by listing a number of important papers and reports which have appeared during 1963 and 1964, primarily on the subject of TIROS picture interpretation. A few items omitted from the Weather Bureau Bibliography are also included.

Arking, A.: Latitudinal distribution of cloud cover from TIROS III photographs, Science 143, 1964, pp. 569-572

Automatic analysis of digitized pictures, basing cloud-background discrimination on brightness difference.

Baliles, M.D., and H. Neiss: Conference on satellite ice studies. Meteorological Sat. Lab. Rept. No. 20, U.S.W.B., June 1963

Blankenship, J.R.: An approach to objective nephanalysis from an earth-oriented satellite. J. Appl. Met. Vol. 1, 1962 pp. 581-2 (See also Comments by C.P. Wood, and author's Reply, ibid, Vol. 2, 1963, pp. 808-9)

Approach is based on availability of accurate, reliable, radiometer data.

Boucher, R. J., et al: Synoptic interpretation of cloud vortex patterns as observed by meteorological satellites. Final report on Contract Cwb-10630, November 1963.

Detailed statistical analyses and development of interpretation keys based on 78 tropical and 106 extratropical cases. Includes review of prior literature.

Bristor, C. L., and W. M. Callicott: Meteorological products from digitized satellite vidicon cloud pictures. Meteorol. Sat. Lab. Rept. No. 26, U.S.W.B., March 1964.

Digital processing includes mesoscale grid summarization of cloud amount, brightness, and brightness "anomalies".

Brodrick, H.J., Jr.: TIROS cloud pattern morphology of some mid-latitude weather systems. Meteorol. Sat. Lab. Rept. No. 24, U.S.W.B., January 1964.

Association of cloudiness with positive vorticity advection at 500 mb.

Clapp, P.F.: Global cloud cover for seasons using TIROS nephanalyses. Monthly Weath.Rev. 92, 1964, in press

Conover, J.H.: Cloud and terrestrial albedo determinations from TIROS satellite pictures. Presented at the National Conference on the Physics and Dynamics of Clouds, Chicago, Ill., 26 March 1964.

Radiance determinations from TIROS VII pictures did not compare well with those obtained from a calibrated camera flown simultaneously on a U-2 aircraft.

Conover, J.H.: Lee wave clouds photographed from an aircraft and a satellite. Weather 19, 1964, pp. 79-85, 92.

Cramer, W.P.: An investigation of time changes in clouds observed over the Gulf of Mexico and Caribbean Sea during the period 18-23 July 1961. S. M. Thesis, A&M College of Texas, May 1963.

Analyses using conventional data and TIROS III data were used to identify cloud systems formed when an easterly wave crossed the Caribbean Sea into the Gulf and combined with an upper trough of polar origin moving eastward through the lower United States.

Cramer, W.P. and A. H. Thompson: Time changes in clouds as shown by TIROS observations over the Gulf of Mexico and Caribbean Sea during the period 18-23 July 1961. Scientific Report on Contract AF 19(604)-8450, 1 January 1964.

Cronin, J.F.: Terrestrial features of the United States as viewed by TIROS. Scientific Report on Contract AF 19(628)-2471, 1 July 1963.

A map has been completed portraying the United States as its surface features appear in TIROS pictures.

Cronin, J. G., et al: Special satellite cloud photographs catalogue. Final Report on Contract Cwb 10628, November 1963.

Analyses of 20 cases taken from TIROS IV, V, and VI coverage, showing bands, masses, lines, streets and vortices.

Defence Research Board (Canada): Project TIREC preliminary report by the Canadian participating agencies. Ottawa, February, 1963.

Interpretations of ice conditions from satellite photography can provide reasonably reliable information, particularly in regard to the distribution of ice and the position of ice boundaries.

Epstein, E.S., and J. Leese: An investigation of convective transfer processes based on satellite photographs. Final Report on Contracts Cwb-10062 and Cwb-10062-1, February 1963.

Contains (1) Application of two-dimensional spectral analysis to the quantification of satellite cloud photographs and (2) The nature of physical parameters affecting convective transfer processes.

Fett, R. W.: Some characteristics of the formative stage of typhoon development: A satellite study. Presented at the National Conference on the Physics and Dynamics of Clouds, Chicago, Ill., 26 March 1964.

Establishment of the anticyclone aloft is very apparent in the satellite pictures as revealed by cirrus striations diverging parallel to the upper winds in the outflow layer of the storm.

Fritz S., et al: Satellite measurements of reflected solar energy and the energy received at the ground, J. Atmos. Sci. 21, 1964

Problems associated with albedo measurements from satellites and their comparison with aircraft measurements and ground observations.

Fujita, T.: Use of TIROS pictures for studies of the internal structure of tropical storms. Research Paper No. 25, Mesometeorology Project, University of Chicago, October, 1963.

Three orientations of clouds "in line" were ascribed to
(a) The direction of the low level winds along which small cumuli align as a cloud street
(b) The "hurricane rainband", which probably represents a streak line when large convective towers originate at a fixed ground source.
(c) The plumes of cirrus from high convective towers

Fujita, T., and J. Arnold: The decaying stage of Hurricane Anna of July 1961 as portrayed by TIROS cloud photographs and infra-red radiation from the top of the storm. Research Paper No. 28, Mesometeorology Project, University of Chicago. Presented at the Third Technical Conference on Hurricanes and Tropical Meteorology, Mexico City, June 6-12, 1963.

Giraytys, J., et al: Investigations into the variation and distribution of relative brightness on TIROS I photographs. Final Report on Contract Cwb-10037, April 1962.

Brightness variance spectra used to define "structured" and "nonstructured" clouds did not reliably discriminate cumuliform and stratiform types.

Hadfield, R.G., et al: Meteorological interpretations of satellite cloud pictures. Final Report on Contract Cwb 10481, January 1964.

A series of TIROS III orbits over the North Atlantic during 7-16 September 1961 was analyzed. The cloud cover enabled recognition of major frontal bands, post-frontal areas, large scale vortices and well developed ridges or high cells, and location of the jet stream to some degree

Hansen, J.: Satellite photography as a means of evaluating the equations of vertical motion. S.M. Thesis, A&M College of Texas, May 1963.

Continuation of Scientific Report on Contract AF 19 (604)-8450 by the author and A. H. Thompson

Hansen, J., and A. H. Thompson: Vertical motion calculations and satellite cloud observations over the western and central United States. Scientific Report on Contract AF 19(604)-8450, 2 January 1963.

Results of comparisons between conventional and satellite data showed only moderate agreement.

Henry, W.K., and A.H. Thompson: The Texas dew point front as seen by TIROS I. Scientific Report on Contract AF 19(604)-8450, 1 February 1963

Examples generally showed good agreement between the dew point front and the cloud pattern seen by the satellite.

Hiser, H.W., et al: Meso-scale synoptic analysis of radar and satellite meteorological data. Interim report on Contract Cwb 10242, November, 1962. Final Report, October 1963.

TIROS III pictures analyzed for 16 and 26 August 1961 were found to be primarily useful in showing the geographic distribution of clouds as related to land masses and weather systems. Other case studies include TIROS I, 3 June 1960; TIROS III, 14 and 17 July 1961.

Huang, S., et al: Meteorological satellite system analysis. Final Report on Contract AF 19 (604)-5582, 30 June 1962.

Includes: (a)Can TIROS see jet streams?
(b) TIROS-revealed African disturbances related to Atlantic hurricanes (c) Some information-theoretic considerations and measurements concerning the efficient processing of satellite cloud pictures

[Joseph, R.D., et al:] Cloud pattern interpretation. Final Report on Contract NASw-609, August 1963.

Self organizing system had limited success at vortex recognition

Kerr, R.E., et al: The use of meteorological satellite cloud photographs in silent area forecasting. Final Report on Contract N189(188)55464A, 20 August 1963.

Includes an objective method of classifying cloud patterns seen by satellites.

Leese, J.A.: Quantitative interpretation of low-level cumuliform cloud patterns as seen on meteorological satellite videographs (Preliminary results). Final Report on Contract Cwb-10564, February 1964.

Application of discriminant analysis techniques to determine synoptic parameters which contribute to these patterns in semi-permanent oceanic anticyclones.

Leese, J.A., and E. S. Epstein: Application of two-dimensional spectral analysis to the quantification of satellite cloud photographs. J. Appl. Met. Vol 2, 1963, pp. 629-644.

Two dimensional power spectrum analysis of TIROS photographs has revealed patterns which tended to be obscured by more dominant features in addition to patterns which were obvious in the original pictures.

Lester, P.F., et al: An investigation of tone variations in a subtropical jetstream and the associated cloud patterns as shown by TIROS I. Scientific Report on Contract AF 19(604)-8450, 1 February 1964.

Case study for 5-9 April 1960

Marggraf, W.A.: Weather satellite data processing. Final Report on Contract AF 19(604)-8861, January 1964.

Includes algorithms for describing cloud patterns (amount, variance, power spectrum, etc.) in digitized images.

Merritt, E.S.: An analysis of stratiform cloud patterns in the Canary Islands region. Scientific Report on Contract AF 19(628)320, 1 July 1963

Variations in cloud distribution in the cases analyzed seem to be related to variations in the direction of the low level wind.

Merritt, E.S: Fleet applications, meteorological operational satellites (Antarctic area). Final Report on Contract N189(188)56507A, 15 August 1963.

Techniques for extracting the following operationally useful meteorological information from satellite-observed cloud patterns have been developed:
(a) Field of motion of the lower and upper troposphere
(b) Cyclonic vortex intensity, development and direction of future motion
(c) Differentiation of cloud from snow and snow-covered ice.

Merritt, E.S.: Fleet applications, meteorological operational satellites (Tropics - easterly waves). Final Report on Contract N189(188)56897A, December, 1963.

Five distinctly different linear and vortical cloud distributions occur in association with tropical perturbations in the Atlantic region.

Nagle, R.E., and R.H. Blackmer, Jr.: The use of synoptic-scale weather radar observations in the interpretation of satellite cloud observations. Final Report on Contract AF 19 (628)-284, December 1962.

No characteristics of TIROS I picture data were found that allowed specific determination of precipitating clouds.

Randerson, D., and A. H. Thompson: Investigation of a TIROS III photograph of the Florida peninsula taken on 14 July 1961. Scientific Report on Contract AF 19(604)8450, 1 January 1964.

Ruzecki, M. A.: The use of satellite cloud photographs in numerical weather prediction. Meteorol. Sat. Lab. Rept. No. 23, U.S.W.B., December 1963.

Use of TIROS pictures and nephanalyses in sparse data areas to modify the stream function field obtained by objective analysis resulted in some improvement in the 36 hour forecast.

Serebreny, S.M., and J.E. Alder: The synoptic climatology of cloud-free areas. Final Report and Scientific Report on Contract AF 19(628)-2363, January 1964.

The synoptic patterns and air mass characteristics associated with high northern latitude clear areas of 1/2 million square nautical miles or more were investigated.

Serebreny, S.M., and R. H. Blackmer, Jr.: Cloud research data. Final Report on Contract AF 19(604)-7312, February 1963.

Cloud cover statistics derived in part from TIROS data.

Serebreny, S.M., and E. J. Wiegman: The distribution of clear air turbulence reports and cloud patterns as seen in satellite photographs. Final Report on Contract Cwb-10481, January 1964.

Satellite photographs of low pressure vortices may provide a useful supplemental tool in establishing the areal distribution of clear air turbulence risk during various stages of cyclone development.

Taylor, R.C.: The utilization of TIROS pictures to some selected studies of tropical meteorology. Final Report on Contract AF 19 (604)-6156, April 1964.

Summarizes Scientific Reports issued under the Contract including: (a) Sadler, J. C.: Tropical cyclones of the Eastern North Pacific as revealed by TIROS observations, May 1963 and (b) ibid. : TIROS observations of the summer circulation and weather patterns of the eastern North Pacific, October 1963.

[Tepper, M.D., et al:] Weather satellite systems. Astronautics and Aerospace Engineering, Vol. 1, No. 3, April 1963 (Special Issue)

Thompson, A.H.: Studies of satellite meteorological data for lower middle latitude weather situations. Final Report on Contract AF 19(604)-8450, 1 February 1964.

Summary of the Scientific Reports on the contract.

Ting, L.: Vortical cloud patterns on the leeward side of islands. Final Report on Grant WBG-12, November 1963.

A theory of these patterns as observed by TIROS is advanced.

Whitney, L.F., Jr.,: Severe storm clouds as seen from TIROS. J. Appl. Met., Vol. 2, 1963, pp.501-7.

In the cases investigated, the cloud patterns producing severe weather are medium scale systems characterized by strong brightness and well defined borders and are either isolated from other clouds or separated by a break in the cloudiness at the periphery.

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VOLUME II

Cloud Pattern Analysis by Interpreters

ABSTRACT

This volume describes a series of quantitative studies of the abilities of human interpreters to analyze and describe cloud patterns in pictures obtained by TIROS. The experimental tasks include cloud picture annotations; cloud pattern discrimination and classification; and judgments of specific parameters which are usefully descriptive of cloud cover.

VOLUME II

TABLE OF CONTENTS

VOLUME II

LIST OF FIGURES

Figure		Following Page
23	Analysis of Variance for Effect of Increasing Context	15
24	Cloud Cover Samples Used in Fibrosity Study	19
25	Results of Fibrosity Study	20
26	Cloud Cover Samples Used in "Brokenness" Scaling Study	21
27	Results of Brokenness Scaling Study	23
28	Typical Stimuli for "Largeness" Scaling Experiment	26
29	Judged "Largeness" as a Function of Increasing Area	26
30	Report of a Figure as Elongated as a Function of Increasing Length of one of Its Sides	27
31	Report of a Figure as Elongated as a Function of Increasing Length of one of Its Sides	27
32	Cloud Outlines Used in Regularity Study	27
33	Results of Regularity Study	27
34	Cloud Outlines Used in Straightness Study	28
35	Results of Straightness Study	28
36	Cloud Outlines Used in Convexity Study	28
37	Results of Convexity Study	28

1. Introduction

This volume describes a series of experimental studies of human performance in the description and analysis of TIROS cloud cover pictures. These studies constitute an important source of quantitative information on human interpretation of TIROS pictures. Primarily, however, they were performed in order to provide a basis for solving certain basic problems relating to the possibility of interpreting TIROS pictures automatically.

An approach to automatic interpretation which shows promise of feasibility involves the identification of the cloud cover which can be seen through a "window" as the window scans over the given picture. From a set of such piecewise identifications, a nephanalysis of the entire picture can often be constructed. This approach is quite plausible if it can be established that the discrimination of basic cloud cover types by observers

(a) Can be explained in terms of their perception of a limited number of primitive properties of cloud patterns which can be defined quantitatively

(b) Does not strongly depend on contextual cues

(c) Does not strongly depend on special meteorological knowledge.

Indeed, if any of these assertions were false, it would appear highly unlikely that an automatic system, lacking meteorological training, restricted to observing the cloud cover "through a window," and capable of making only simple quantitative measurements, could succeed in analyzing TIROS pictures.

The studies described in this volume demonstrate that

(1) Novices and experts perform comparably in cloud cover discrimination tasks involving cloud picture annotation (Section 2)

(2) Basic cloud cover types can be correctly classified when seen through a relatively small "window." Classification performance is not significantly affected by window shape or by the presence of context and can be performed by novices with a minimum of briefing (Section 3)

(3) Judgments of basic cloud pattern parameters by observers can be used to define these parameters quantitatively (Section 4)

2. Cloud pattern discrimination

2.1 Annotation

A set of twenty-eight TIROS pictures (Volume III, Figure 13a) was used in a comparative study of cloud picture annotation. In Figures 1-6 three independent sets of annotations are shown for the first six of these pictures. In these figures, the dotted-line overlay is a consensus of annotations by three Budd Company employees who had no significant degree of prior experience with such pictures; the dashed-line overlay is a similar consensus for three Goddard Space Flight Center employees who had considerable prior experience; and the solid-line overlay was made by a consultant analyst in a manner consistent with the objective cloud cover description system described in Volume I of this report.

The instructions to the annotators were as follows:

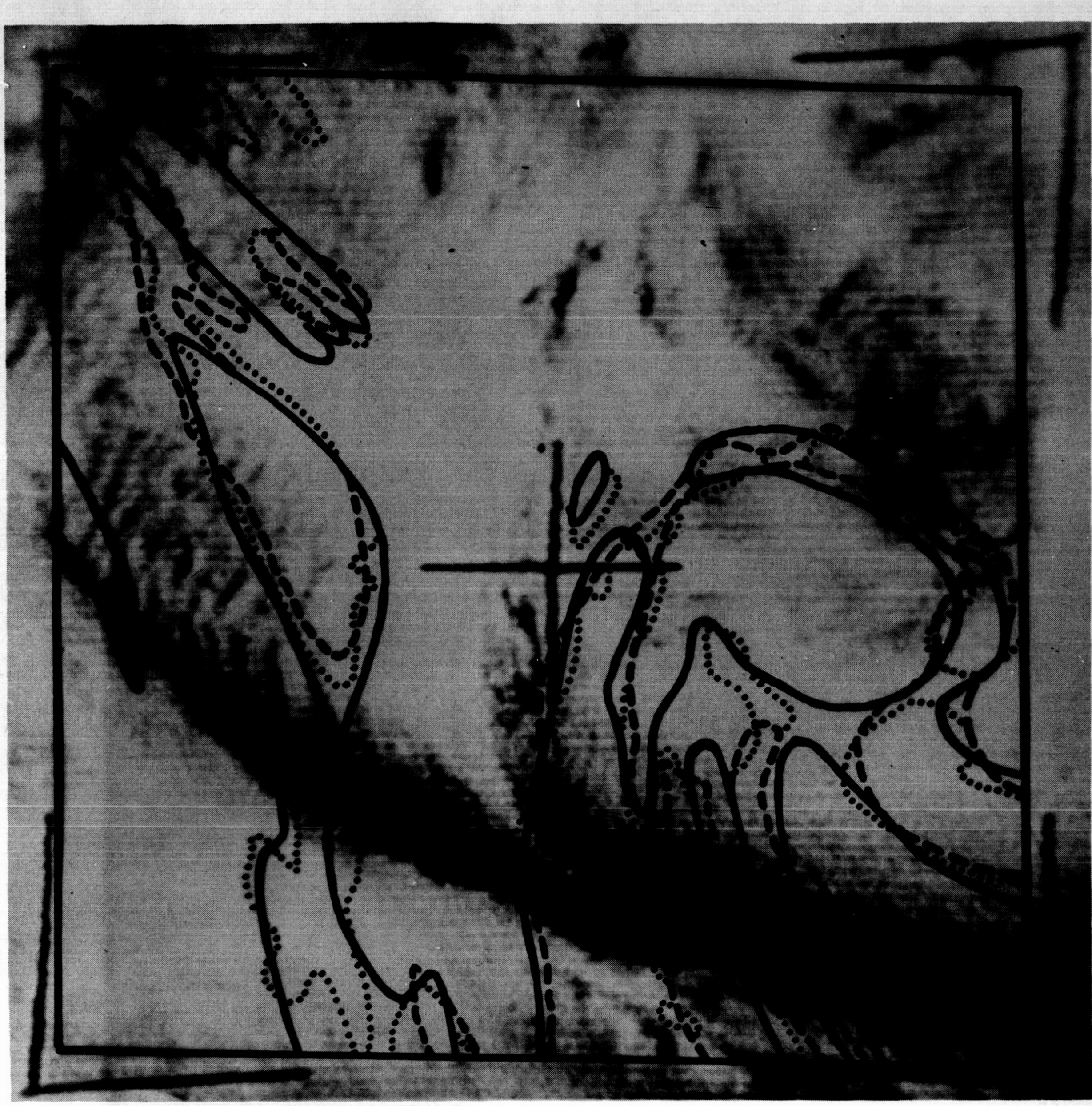
"I will show you a number of typical TIROS photographs. Place a plastic overlay over each of the photos and indicate the photograph number and the fiducial marks on the overlay with the grease pencil. Then outline the areas of meteorological significance on the overlay with the grease pencil. I will show you two examples of photographs that have already been annotated. Are there any questions about what you have to do?"

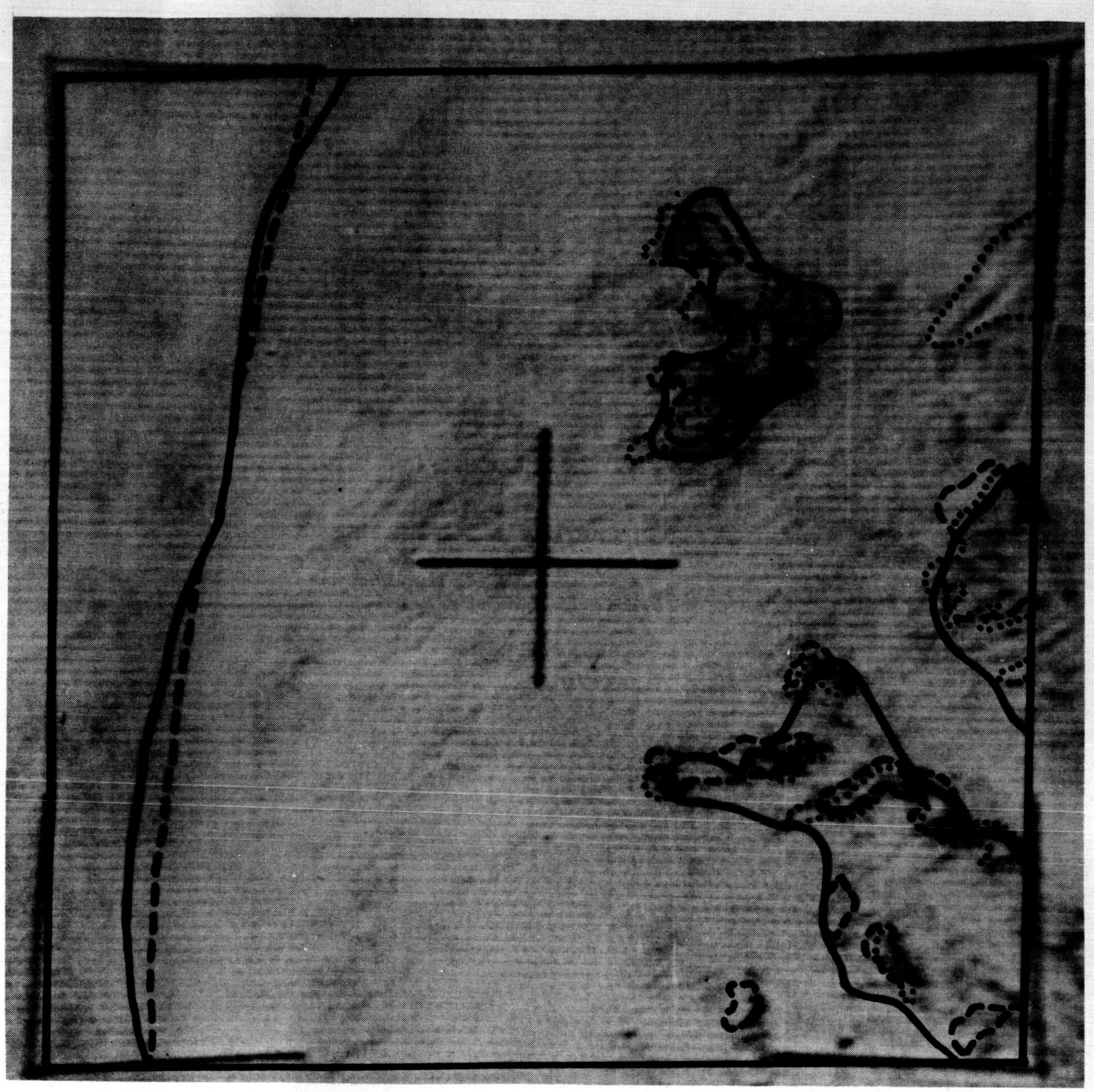
The following rules were used in consolidating the"consensus" annotations:

(1) All regions must be bounded by closed curves;

Figures 1-6

<u>Comparison of Annotations by Naive and Experienced Interpreters</u>





6

even the narrowest regions can not be indicated by single arcs. Broken curves or arcs used by the annotators were completed into closed curves.

(2) Annotations which agreed on part of a region boundary were combined only if they appeared to refer to the same region on the same side of the boundary.

(3) Regions were marked on the consensuses if they were agreed upon by a majority of the annotators. If no majority existed for a region but the selections of either all or some part of a region added up to a majority, it was considered that a majority had chosen the part (but not the whole).

The strong consistency among the annotations in Figures 1-6 indicates that experience is not a major factor in discrimination among basic cloud cover types. The agreement is worst for the "featureless" pictures (particularly Figure 4) in which the lack of clearly discriminable differences makes disagreement almost inevitable.

2.2 Pair comparison

As a preliminary to the extensive cloud pattern classification studies described in Section 3, a pair comparison experiment was performed using two samples each of five basic cloud cover types as shown in Figure 7. In this experiment each sample

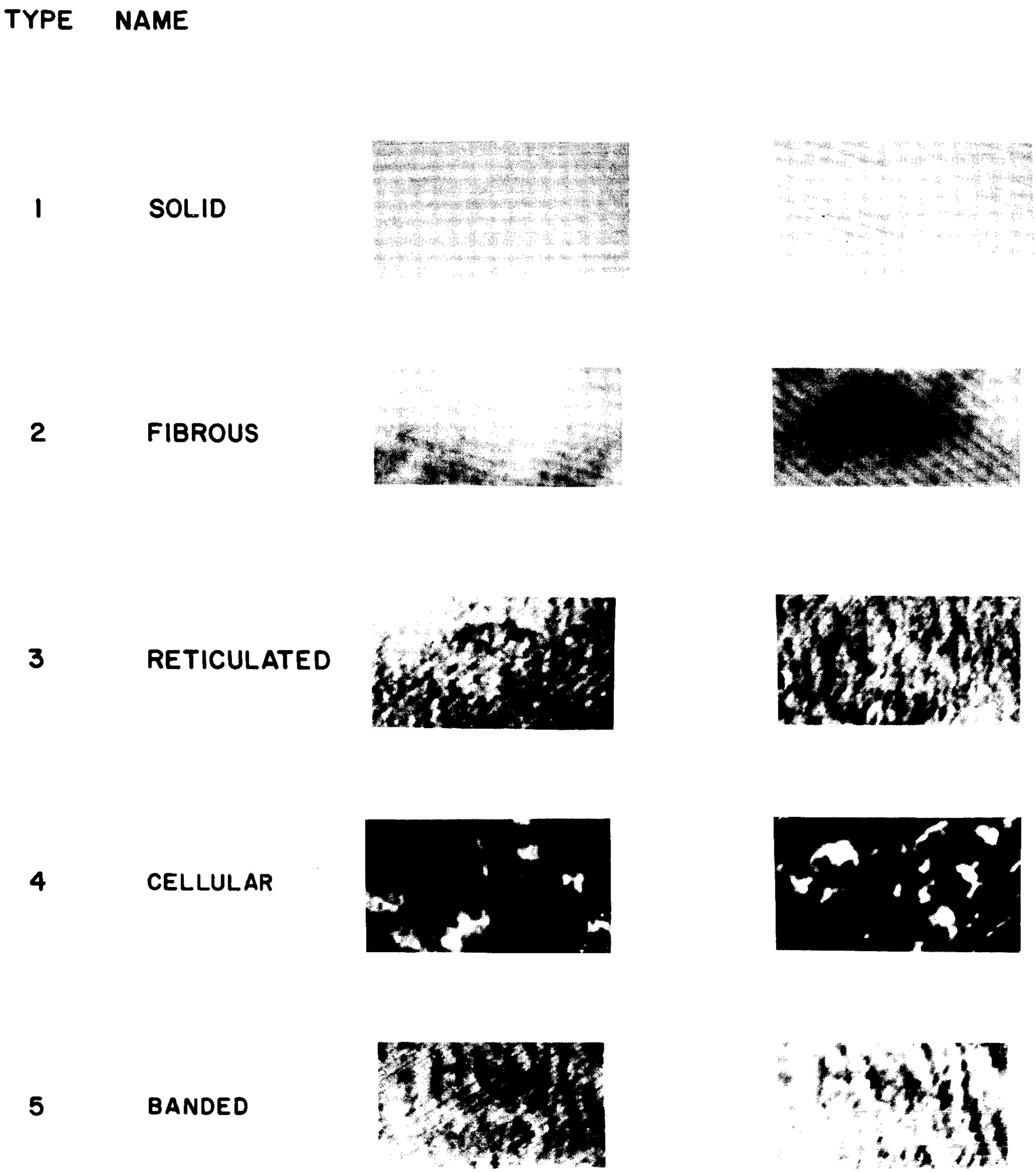


FIG. 7 CLOUD COVER SAMPLES USED IN PAIR COMPARISON EXPERIMENT

was paired with every other sample except itself, and the subjects were asked whether or not the samples in each pair were from the same cloud cover class. The instructions to the subjects, who were Budd Company draftsmen, were as follows:

> "I will present you with a number of pairs of pictures. Each picture is an example of a cloud type. The pairs of pictures are not identical but they may or not be examples of the same cloud type.
>
> Answer YES if you think the picture on the right is from a category similar to the one on the left. Answer NO if you think the pairs are dissimilar.
>
> Ignore any difference in density (gray scale) between the two pictures and any effects due to TV raster lines."

The results of this experiment are summarized in Figure 8. In spite of their having no prior knowledge about the number or natures of the cloud cover types used, a majority of the subjects always made a "same" judgment for the pair of samples which were actually of the same type. The "isolated cell" type was rarely judged "same" when paired with any other type. The area-covering types ("solid" and "fibrous", "bands" and "reticulated") were confused significantly often; this was true in particular for the two "unbroken" types ("solid", "fibrous") and the two "broken" types ("bands", "reticulated"). These results are consistent with the "decision tree" cloud pattern classification system outlined in Volume I.

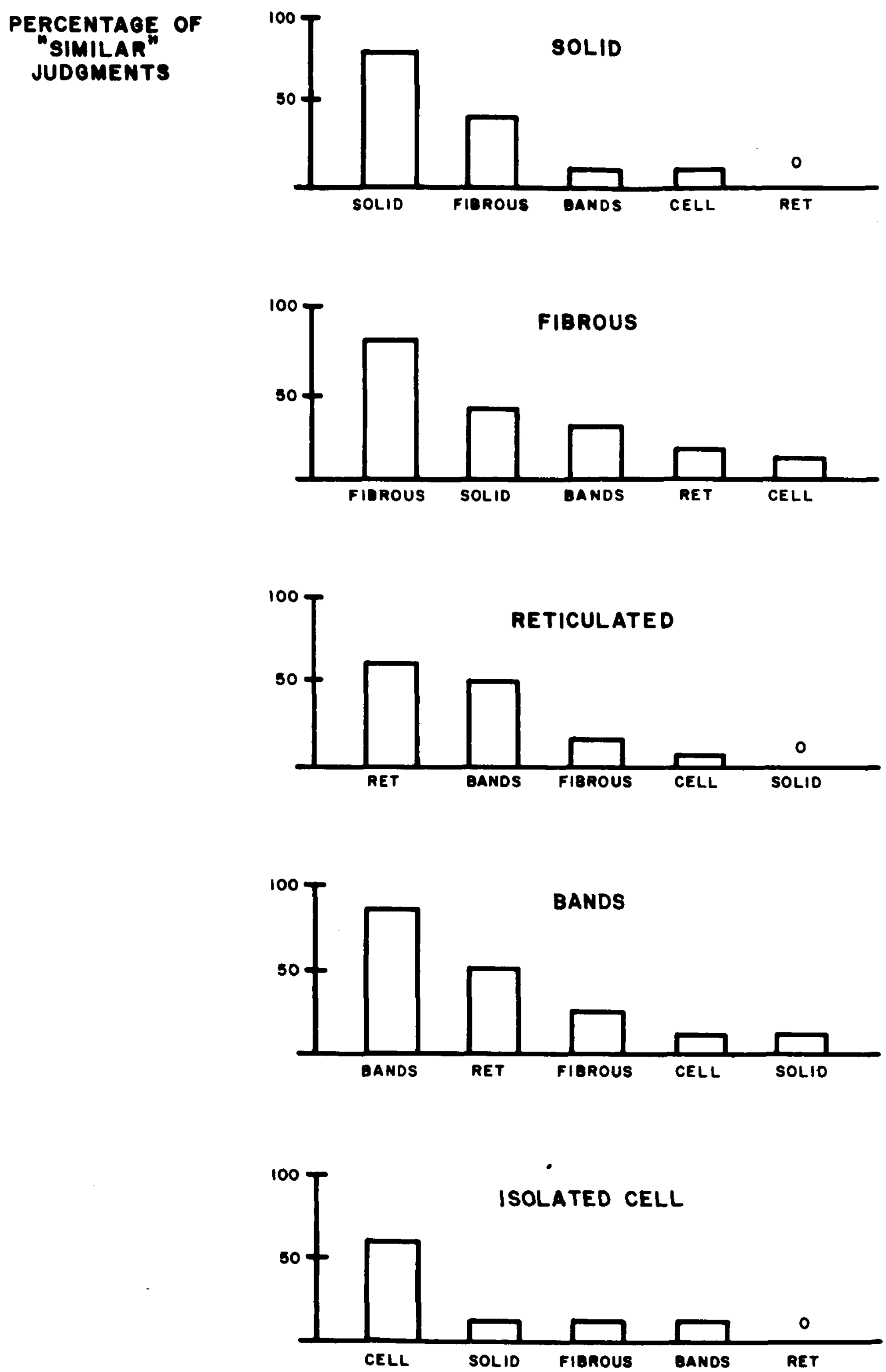


FIG. 8

PERCENTAGE OF SUBJECTS MAKING A JUDGMENT OF SIMILARITY BETWEEN EXAMPLES OF TWO CLOUD CATEGORIES

3. Cloud pattern classification

Six samples each of five basic area-covering cloud cover types ("solid," "fibrous," "reticulated," "cellular" and "banded") were selected after examination of several hundred TIROS IV frames. These samples are shown in Figure 9-13. (The frames on which they appear - sometimes more than one on the same frame - are listed in Volume III, Figure 13b.) They were used in the series of cloud cover classification experiments described below.

3.1 Preliminary Study

A preliminary experiment was performed to verify the feasibility of the general experimental procedure. In this experiment the cloud cover samples used were entire regions, cut out along their boundaries, as in Figures 9-13. Five reference or prototype samples, one of each cloud cover type, were selected. The subjects, who were Budd Company employees, were shown these samples and told that they defined five cloud cover classes; they then were shown the remaining samples one at a time and asked to identify them. The reference samples were identified by the letters A-E rather than by descriptive names. The instructions to the subjects were as follows:

> "Each of the photographs above is an illustration of a class of cloud formations. Study them for a minute. I am going to show you a series of photographs of representative samples of cloud formations. As I show you each sample, place it next to <u>one</u> of the five cloud formations. Each of the samples belongs to just <u>one</u> of the categories <u>and only ONE</u>, but there may be <u>only</u> a few samples of some of the classes and many samples

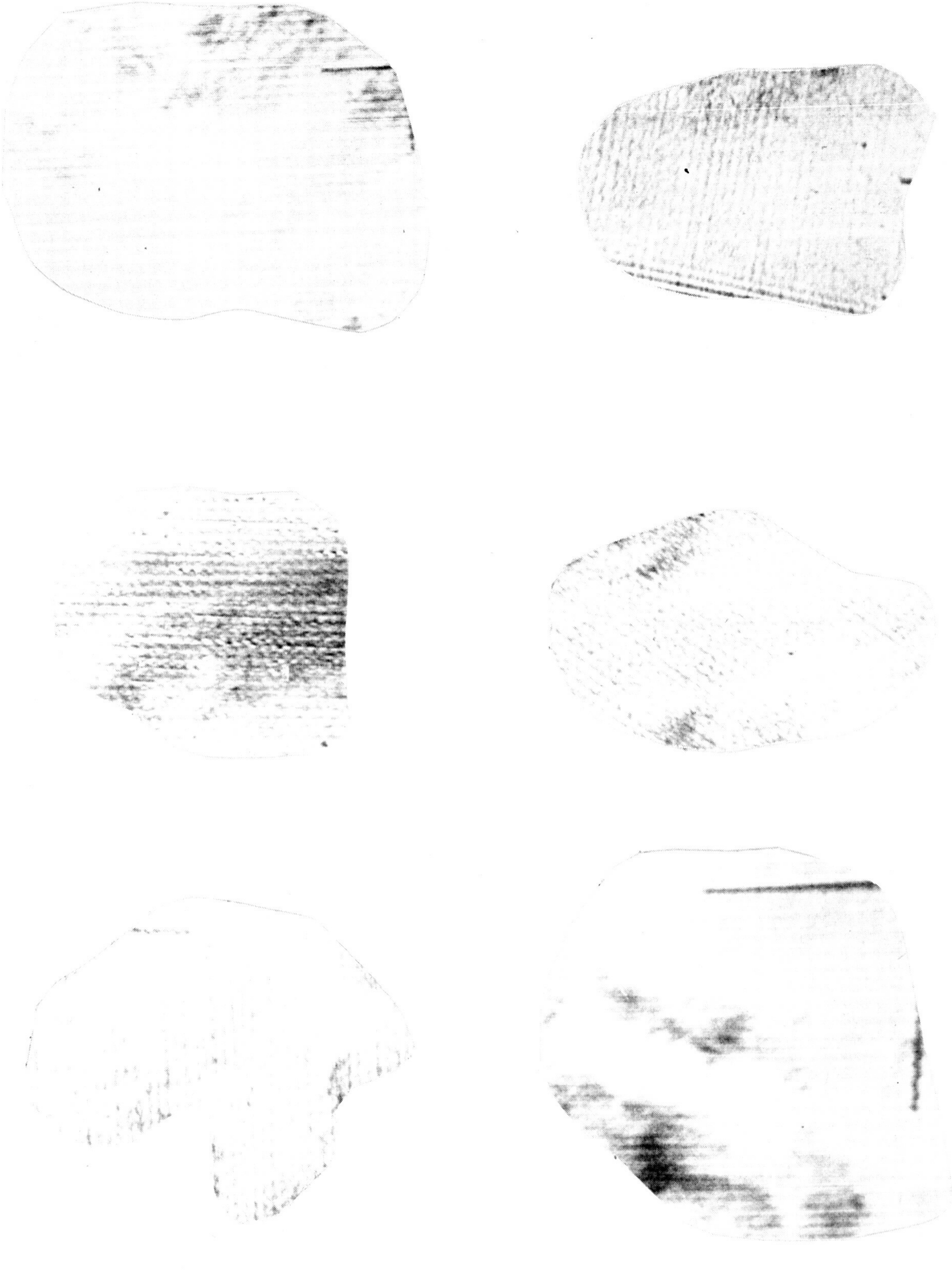


Figure 9

SAMPLES OF "SOLID" CLOUD COVER

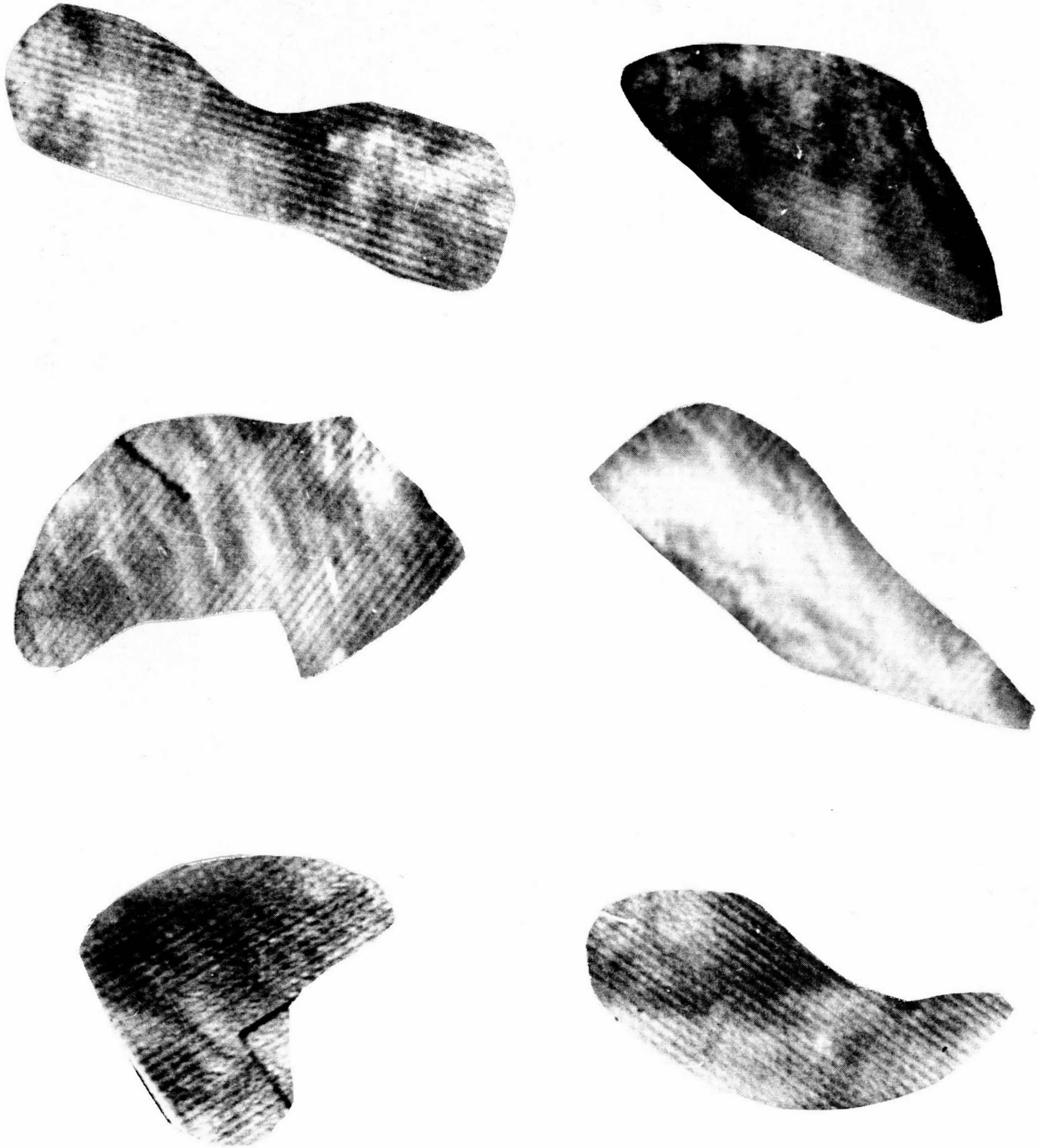


Figure 10

SAMPLES OF "FIBROUS" CLOUD COVER

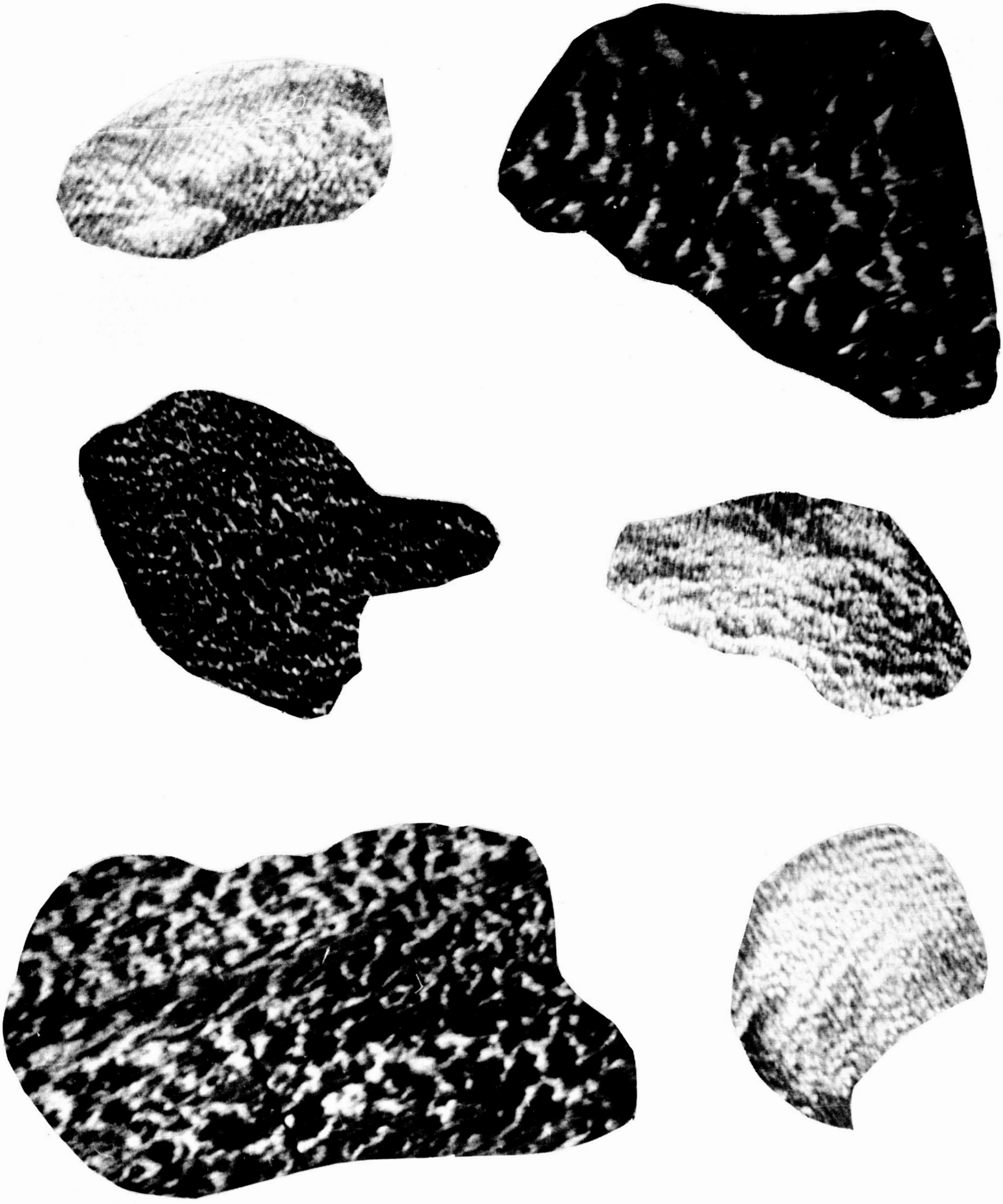


Figure 11

SAMPLES OF "RETICULATED" CLOUD COVER

Figure 12

SAMPLES OF "CELLULAR" CLOUD COVER

Figure 13

SAMPLES OF "BANDED" CLOUD COVER

of the other classes."[1]

The responses of the subjects are graphed in Figure 14. They indicate a high degree of discriminability among the five cloud cover types.

3.2 Study I: Effect of number of examples used to define the classes

In the first major study, which served as procedural model for all of the studies, the influence of amount of training on the accuracy of cloud cover classification was investigated. Training consisted of displaying one or more prototypes of each cloud cover class to the observer prior to his viewing of the test samples. The question arises whether use of more than one prototype of each cloud cover class in the training session will improve performance. Since the prototypes are not accompanied by any additional description, if only one per class is used the observer may incorrectly assume that some accidental feature of the particular example used is the property on which he is to base his classification.

Three of the six samples were randomly selected to be test figures. The remaining figures were used as "defining figures" in the training session. All samples were masked so that the observers

---

1. It is noted that no attempt is made to define verbally for the subjects the cloud cover types; they are shown examples of each type and make their judgments about the test data on the basis of these examples. A consistency of test results among subjects then assures that an understanding of the cloud type has been successfully conveyed to them without having to frame a formal definition.

This is also true of other experiments described below in which subjects are asked to make judgments based on a concept made known to them by example in lieu of a verbal definition.

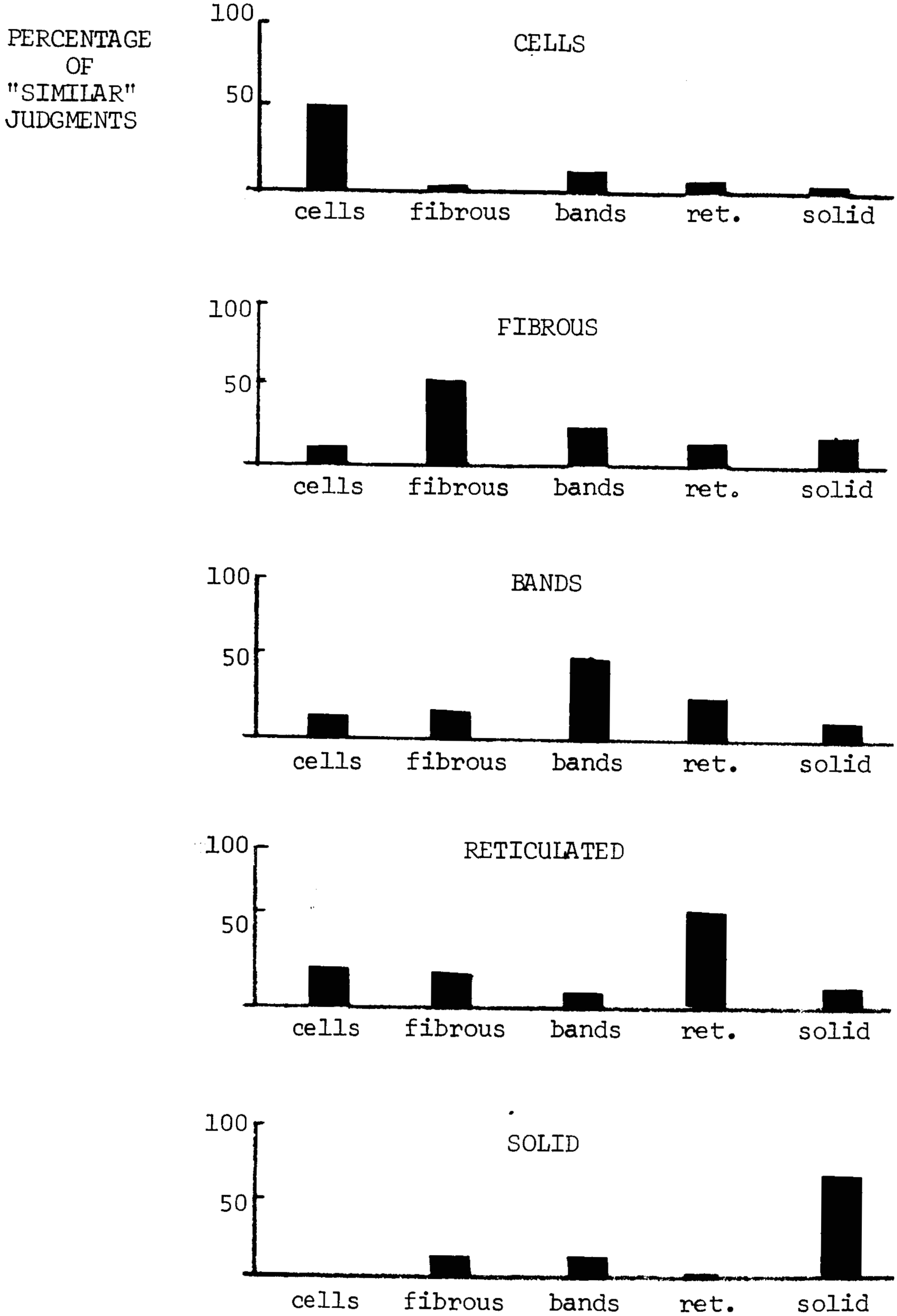


Figure 14

Subjects' Responses in Cloud Cover Classification Experiment saw only a square piece of each, approximately twenty resolution elements (= apparent raster lines) on a side, roughly 1" x 1" at the scale of the photographs used.

Fifteen employees of the Budd Information Sciences Center (BISC) were used as subjects for this first study. The subjects were primarily technicians and draftsmen who had no previous experience with cloud cover annotation. The test figures were displayed at room illumination for a time period of up to four seconds, which was sufficient time in all cases for an assignment to be made. The subjects were not told the names of the cloud cover types, since these names are descriptive of the relevant features of the cloud cover; instead, the defining figures were assigned letter designations, A, B, C, D, and E.

The instructions to the subjects follow:

> "The Research Department has developed a series of classifications of cloud types for use in the analysis of TIROS photographs. Five such classes are shown on the desk labeled A, B, C, D, E, with (one, two, three) illustration (s) of each class.
>
> I will show you a number of cloud excerpts taken from typical cloud photographs. Compare each excerpt with the five cloud categories before you and tell me the category that you believe it resembles more closely.
>
> In order for the cloud excerpt to be assigned to a cloud category the excerpt must contain predominantly that cloud category. If the cloud shown in the excerpt does not resemble any of the five cloud categories it should be assigned to the remaining category, OTHER."

The subjects were divided into three groups of five each. Group 1 was shown only one defining figure for each cloud cover class;

Group 2 was shown two defining figures for each class; and Group 3 three defining figures for each class. The subjects examined the defining figures in the initial training session until they reported that they were ready for the test figures. The defining figures were not removed, so that the subjects were able to view them during the entire test session.

The subjects were then presented with twenty test figures in a random sequence. Three test figures were used for each of the classes A-E, and five test figures (shown in Figure 15) for the "other" class. This inequality helped to prevent the subjects from assuming that there were equal numbers of test figures for all classes, which would tend to restrict their choices for the last few test figures. They were asked to state to which class they believed each test figure belonged. Replies of "not known" or "undecided" were not permitted. The test figures were then re-randomized and two additional test trials were made. The procedure was identical for each group except that a different number of defining figures was used.

The score of the accuracy of assignment of a test figure to its proper class for each subject was his mean number of correct class assignments for the three test sequences. The analysis, summarized in Figure 16, consisted of a repeated measurements design for the analysis of variance. The effect of increasing the number of defining figures from one to three is clearly not significant.

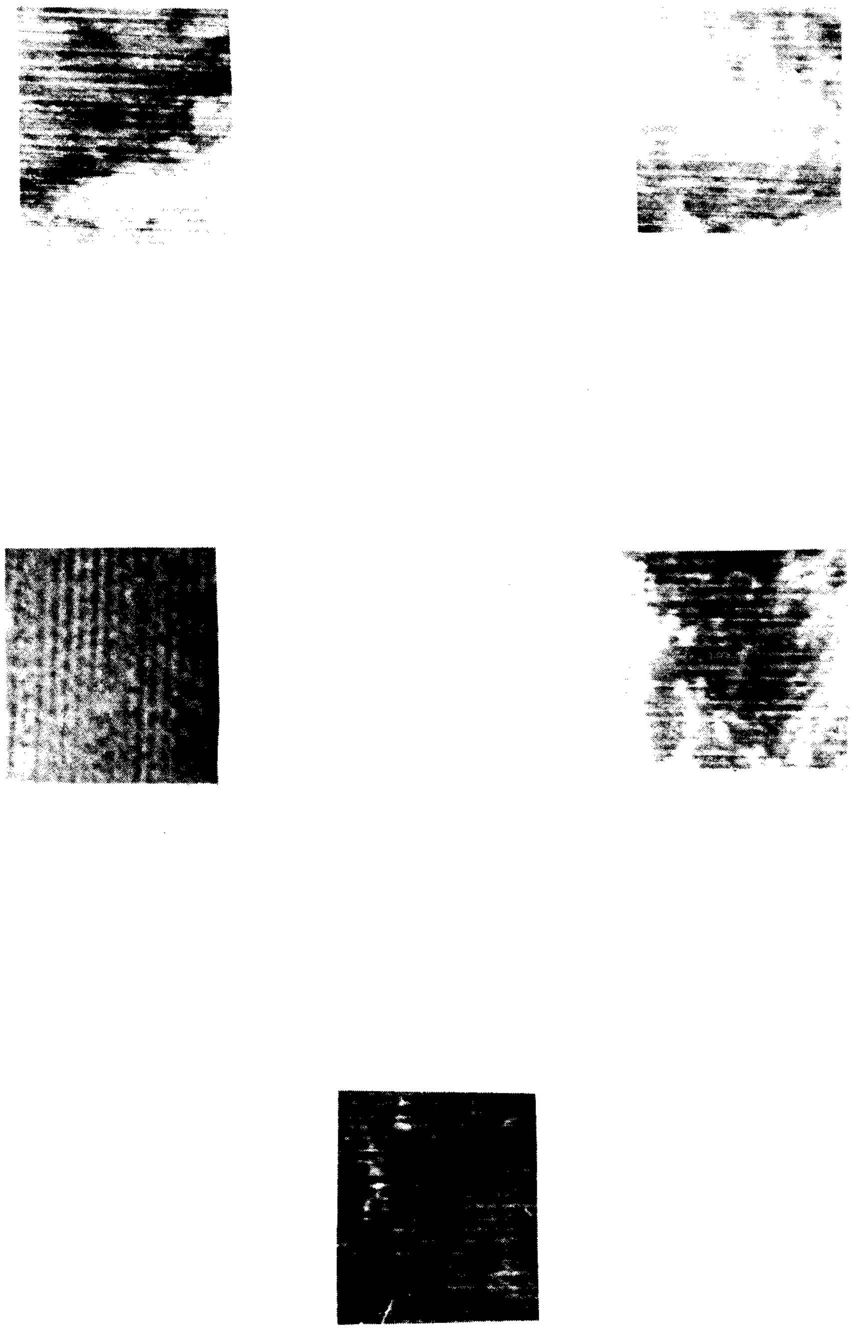


Figure 15

SAMPLES OF "OTHER" CLOUD COVER

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
Between No. of Def. Fig.	2.11	2	1.05	2.23	
Between Subj. in Same Def. Fig.	5.61	12	.47		
Between Cloud Classes	33.64	5	6.73	23.21	**
Classes x No. of Def. Fig.	6.53	10	.65	2.24	
Subj. x Classes[1]	17.63	60	.29		
TOTAL	65.52	89			

[1] Pooled from each group of defining figures
** Significant at .01 level

Figure 16

Analysis of Variance for Effect of Increasing Number of Defining Figures (Study I)

Since the numbers of defining figures used in the study were fixed, and only up to three defining figures were permitted, the generalization that increasing the number of defining figures will not improve performance is not warranted statistically (Edwards, 1960). However, in view of the fact that tripling the number of defining figures did not significantly alter performance, such a generalization is at least very plausible.

3.3 Study II: Effect of reduced sample size

One of the principal goals of this research program is the determination of the dimensions of the cloud cover samples which should be analyzed by an automatic cloud mapping system. If the sample is too large, the samples will tend to include more than one cloud cover type, making recognition difficult. On the other hand, if it is too small, not enough information for recognition may be present. The best sample size is probably that just above the threshold of minimum information needed for identification.

In the second study the analysis of variance was used to find a range of sample sizes containing the threshold, as characterized by the fact that a marked drop in performance occurs over the range, while further reduction in sample size does not significantly alter performance.

As suggested by the results of Study I, only one defining figure was used in this study. The procedure closely followed that of the first study, with the exception that the test figures were shown through one of three aperture sizes - the standard

1" x 1" size used in Study I; a quarter of this size (1/2" x 1/2") and a sixteenth of this size (1/4" x 1/4"). The defining figures continued to be displayed through the standard (1" x 1") aperture.[2]

Fifteen BISC employees were used as subjects. They were divided into three groups of five each, with each group viewing through only one of the three aperture sizes.

The repeated measurements design was again employed (Figure 17). The results clearly show a significant difference between the aperture sizes. A Duncan's Test (Duncan, 1955) was then computed for the three apertures (Figure 18), and significant differences were found at the .01 level between the 1" and 1/2" sizes and between the 1" and 1/4" sizes, but no significance was found between the 1/2" and 1/4" sizes. It is thus apparent that a threshold occurs somewhere betwen the 1" and 1/2" apertures. This conclusion is confirmed by the lack of significant change (actually a slight reversal) as the aperture is reduced from half to quarter size, a characteristic result when stimuli are changed below resolution levels.

To further define the threshold a method of limits study was employed, using an ascending sequence. Five examples of

---

2. The scale of these pictures, based on a TIROS IV average altitude of 420 miles and picture coverage of 700 square miles with optical axis normal to the earth's surface, is approximately 3.8 mi./in.

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
Between Aperture Sizes	12.15	2	6.07	15.97	**
Between Subj. in Same Size	4.59	12	.38		
Between Cloud Classes	22.23	5	4.45	9.89	**
Classes x Size	8.41	10	.84	1.87	
Subj. x Classes[1]	27.04	60	.45		
TOTAL	74.42	89			

[1]Pooled from each group of sizes
** Significant at .01 level

Figure 17

Analysis of Variance for Effect of Decreasing Aperture Size (Study II)

Means	1.36 (1/4 Size)	1.57 (1/16 Size)	2.27 (Full Size)		
1.36		.21	.91	R_2	.69
1.57			.70	R_3	.72
2.27					

** ______.

** Not significant at .01 level

Figure 18

Duncan's Test for Significance of Aperture Size Difference (Study II) each cloud type were selected at random, making a total of twenty-five test figures. The subjects (five BISC employees who had not been used previously in similar studies) were first shown one example of each cloud category. These were one square inch pictures of the cloud types that had been used in the earlier studies to define the cloud class ("defining figures"). They were permitted to study these figures until they reported that they were sufficiently familiar with them, after which the test series was begun. The defining figures were not removed and the subjects were permitted to view them during the course of the study. The test and defining figures were "pure" instances of a cloud type with a minimum of extraneous cloud features that might belong to other cloud formations.

The 25 test figures were randomized separately for each subject. The test series began with the smallest aperture for the first test figure. The subject was required to state to which one of the five classes he believed the test figure belonged. He was permitted to make statements of "not known", etc., but very few of these were actually made. The sequence for each test figure terminated when two correct assignments occurred in a row.

The minimum aperture size was 1/2 inch on the side or 1/4 square inch in area. Six apertures of side lengths 1/2", 5/8", 3/4", 7/8", 1", and 9/8" were used; the maximum aperture area was thus 81/64 square inches (Figure 19).

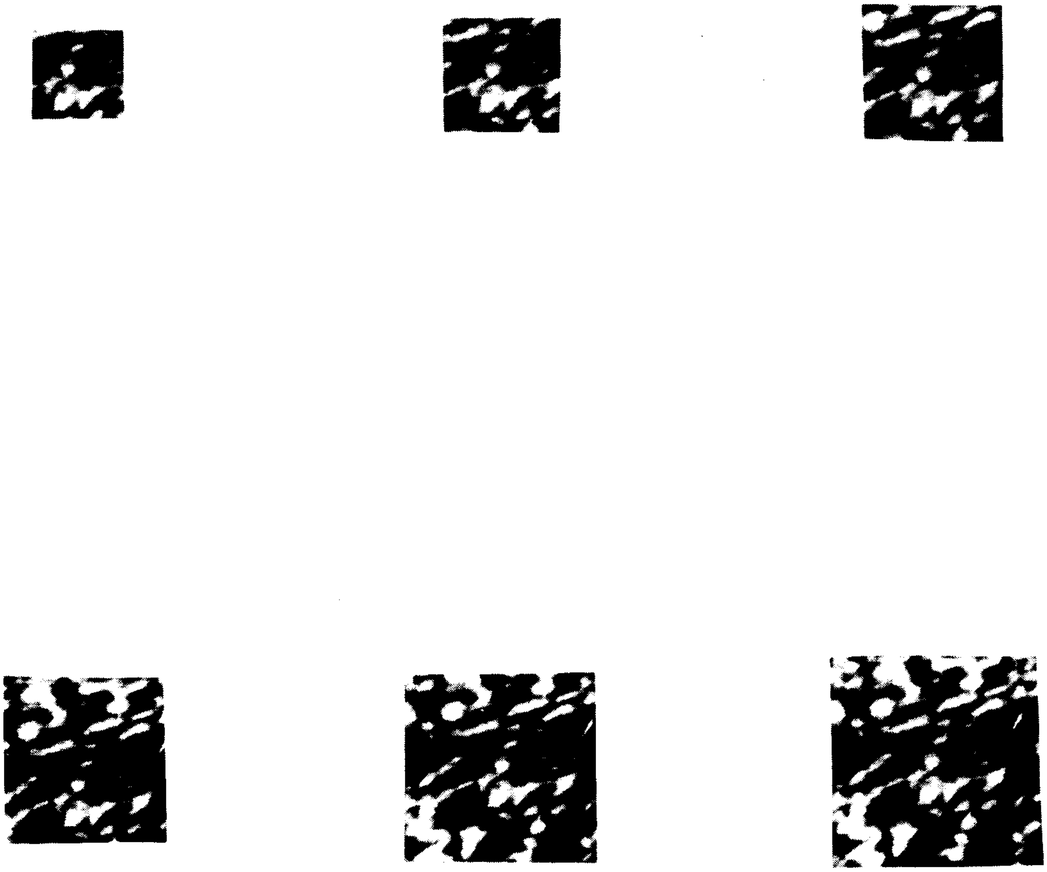


Figure 19

Aperture Sizes Used in Scaling Study

The proportion of the total number of accurate assignments made at each aperture size was then computed for all twenty-five cloud types. These were then converted to z scores, and the graphical method described by Woodworth (1954) was used to determine the threshold value and its standard deviation.

The threshold as determined by this procedure is .681 square inches, and its standard deviation is .106. The likelihood that the true or population threshold occurs between .889 and .473 square inches is ninety-five percent.

3.4 Study III: Effect of sample shape - regular vs. irregular

In the previous two studies the samples all had the same regular square shape. The question may be asked whether sample shape is a factor in performance. In this study two extreme aperture configurations were compared - the square used in the earlier studies and the irregular outline shown in Figure 20.

Except for their irregular outline, the test figures in this study were constructed in the same way as those of Study I. The figures included only one cloud cover type each. The area of the irregular figure is nearly the same as that of the standard square. The experimental procedure was identical to that of the previous studies, with the exception that twenty subjects were used, ten for each of the two sample shapes.

The results of the analysis of variance are summarized in Figure 21. There is no significant difference between the two shapes, which strongly suggests that shape is not a factor

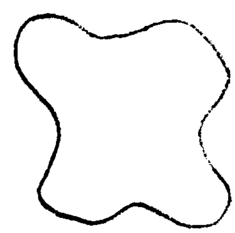


Figure 20

Irregular Aperture Used in Study III

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
Between Shapes	1.33	1	1.33	2.14	
Between Subj. in Same Shape	11.15	18	.62		
Between Cloud Classes	38.67	5	7.73	17.17	**
Classes x Shapes	5.81	5	1.16	2.57	
Subj. x Classes[1]	40.31	90	.45		
TOTAL	97.27	119			

[1] Pooled from each group of shapes

** Significant at .01 level

Figure 21

Analysis of Variance for Effect of

Irregular Aperture Shape (Study III)

in performance. This finding can be confirmed by performing additional studies using a variety of sample shapes.

3.5 Study IV: Effect of sample orientation

Some cloud cover types, such as the class "solid", are characterized by isotropy; others, notably the class "banded", have a marked "preference" for restricted directions. For such anisotropic classes, recognition may be sensitive to elongation of the sample relative to the preferred direction.

In this study the aperture was elongated to a rectangular shape of 2:1 proportions. It was used to select samples of the test figures with two orientations - one aligned with the "preferred direction" of the cloud cover and the other at right angles to this direction, when such a direction appeared to exist. Since changing the aperture orientation also changed the content of the sample, the same subjects were shown both aperture orientations in a 2 x 6 analysis of variance design. Fifteen subjects were used with one replication of each orientation in the test sequence. The scores consisted of the means of these two trials for each subject and class.

The results are summarized in Figure 22. They clearly demonstrate that for the dimensions of the rectangle employed, there is no effect of orientation as such, even for cloud cover types having preferred orientations. Strictly speaking, these results are specific to the rectangle size used. Certainly, significant differences may be expected when a rectangle becomes

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
Between Orientations	1.59	1	1.59	5.67	
Between Classes	74.00	5	14.80	52.86	**
Orientation x Classes	1.42	5	.28	1.00	
Within Treatments	47.73	168	.28		
TOTAL	124.74	179			

**Significant at .01 level

Figure 22

Analysis of Variance for Effect of

Aperture Orientation

so elongated that its width approaches the recognition threshold size.

3.6 Study V: Effect of context

In this final study the accuracy of performance was investigated under conditions of increasing "noise." The samples of cloud cover types were enlarged to include portions of neighboring types. Specifically, three levels of test figure were used in this study. Level 1 ("zero noise") used irregularly shaped test figures which included only single types of cloud cover. For Level 2, the irregular aperture was enlarged until some cloud cover that could be assigned to just one other class was included. At Level 3, the aperture was further enlarged until cloud cover was included that could be assigned to two or more other classes.

This study resembled Study I in that a repeated measurements design was employed with fifteen subjects, five being assigned to each level. The only major change consisted of altering the instructions to inform the subjects that they should report only the predominant cloud cover category if they perceived more than one cloud cover type. The "other" category was not included in this study, since enlargement of the aperture usually served to bring additional "other" clouds into view.

The results are summarized in Figure 23. They show that the inclusion of additional cloud classes in an aperture does not significantly affect the accuracy of class assignment performance as long as the principal class present clearly predominates.

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
Between Contexts	2.375	2	1.187	1.374	
Between Subj. in Same Context	10.369	12	.864		
Between Cloud Classes	24.358	4	6.089	14.532	**
Classes x Context	1.092	8	.137	--	
Subj. x Classes*	20.148	48	.419		
TOTAL	58.342	74			

* Pooled from each group of contexts
** Significant at .01 level

Figure 23

Analysis of Variance for Effect of

Increasing Context

3.7 Conclusions

A general result of this series of studies is the conclusion that recognition of the cloud cover classes used is highly immune to a variety of characteristics of the sample selection process. In the first study subjects were able to use a single defining figure to derive the properties required to identify the test figures. Since a defining figure includes accidental as well as essential properties, it can only be concluded that the essential properties are highly salient. The finding that the subjects are not influenced by reasonable degrees of contextual cloud cover is evidence that the results are not specific to ideal or "pure" instances of the cloud cover types.

These studies strongly suggest that recognition of these basic cloud cover types by an automatic interpretation system using the "window" approach should be feasible. They further provide a lower bound to the window size which should be used by such a system. The results of Volume II, Section 5, indicate that if a window of this size is used, it should be possible to identify close to half of the regions on a typical cloud cover picture correctly.

4. Cloud pattern parameters

Seven studies of parameters which appear to be important cloud cover descriptors, as described in Volume I, were performed. The parameters studied were fibrosity (for discrimination between the "solid" and "fibrous" cloud cover types); brokenness (for discrimination between these two "unbroken" types and such "broken" types as "reticulated," "banded" and cellular"); size (for discrimination between large cloud "masses" and smaller "pieces" such as cells and bands); elongation (for discrimination between cells and bands): and three basic shape parameters - regularity, straightness, and convexity - which provide a basis for discriminating cell and band subtypes (not distinguished in the studies described in Sections 2-3).

Psychometrics as propounded by Thurstone and as used in the studies described below uses as the original datum ordinal intervals along some subjective or psychological continuum. This technique is especially useful when the physical correlate of the phenomenal property being studied is not known. The studies reported in this section provide scaling values derived primarily from a rank order technique.

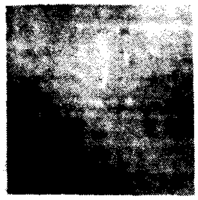
In the rank order technique subjects assign a cloud cover sample (or outline of a cloud mass) to one of a finite number of categories along a continuum of the property studied. Several assumptions are required in this technique which may qualify the results obtained. It is assumed that the subjects are in effect utilizing an underlying one-dimensional subjective continuum in their ordering. Although this is a seemingly serious objection to the rank order technique, it did not cause any difficulty in the present studies since the observed effects of a multi-dimensional continuum (frequent reversals in ranking, high variance in assignments, etc.) seldom occurred. In a direct test of this assumption, on the judged brokenness of cloud formations, the results of the rank order techniques were correlated with the findings of a pair comparison and a correlation of .84 was obtained. Since the pair comparison technique does not require the individual subjects to discern a one-dimensional continuum, a high correlation can be construed as evidence for their actual use of such a continuum.

Although the subjects' judgments are made on an ordinal metric, an important assumption is that the continuum contains class sizes and intervals which are equivalent (interval metric). If the intervals are of unequal width for the immediate categories, Edwards has proposed a statistical technique which permits scaling values to be derived by using differences in adjacent z values as the unit of the scale. A serious difficulty arises when the subject uses the extreme categories (1 and 5 in the present studies) exclusively. There seems to be no way to include these stimuli in the scaling studies as used here, short of expanding the continuum and increasing the number of stimuli. Since only a restricted number of stimuli were available the only recourse was to discard stimuli judged exclusively as 1 or 5 by the subjects. This explains why in the studies reported below fewer than the original number of stimuli are assigned scale values. (The original number was 10 in all studies except that of brokenness in which 15 stimuli were used.)

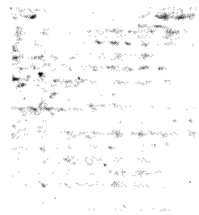
4.1 Fibrosity

The first scaling study investigated the property of cloud mass "fibrosity". Five examples of each of the cloud cover classes "solid" and "fibrous" were selected at random (Figure 24) with the restriction that in the experimenter's judgment they were distributed along the continuum from "extremely solid" to "extremely fibrous." The following instructions were read to the subjects (N=7):

> "I am going to show you a number of representative cloud photographs. Assign each of them to one of the five categories shown before you according to its degree of fibrosity.
>
> #1 - least fibrous
>
> #5 - most fibrous
>
> The numbers between 1 and 5 represent intermediate values of fibrosity.
>
> In making your judgment consider only the property of fibrosity. The clouds themselves will differ in many respects. However, it is only the property of fibrosity that we are interested in."



1



2

3

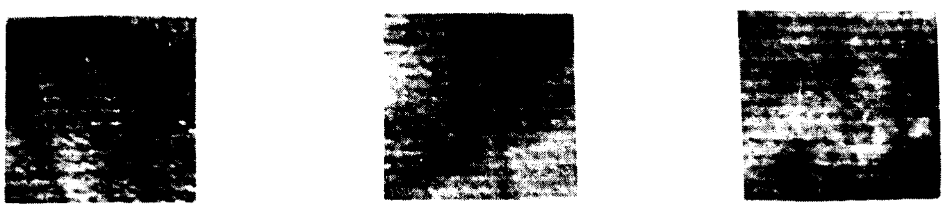
4

A: Samples given intermediate ratings by some observers.

Figure 24

Cloud Cover Samples Used in Fibrosity Study

B: Samples rated at solid end of scale by all subjects



C: Samples rated at fibrous end of scale by all subjects

Figure 24: (Continued)

They were permitted to study each picture for up to five seconds before they made an assignment of the picture to one of the five classes. "Fibrosity" was not defined. Instead, the subjects were presented with two random sequences of ten pictures intended to familiarize them with the stimulus material and which permitted them to formulate a psychological continuum of "fibrosity." They were then given three test sequences. The rank order assignments on these sequences were used to determine the final scale values. Separately randomized sequences were used for each trial and subject.

The method of successive intervals described by Edwards was used. A scale value is determined by converting p scores (proportion of times in which a cloud stimulus is assigned to a particular class) to corresponding z scores. A mean z score is determined for each class and differences between adjacent z scores for each class are then computed to determine the interval between classes. The scale value of a particular cloud stimulus is its median score on the continuum of fibrosity. Following Woodworth's suggestions, the scores are assigned to a new scale in which the lowest score is assigned an arbitrary value of zero and the highest score an arbitrary value of 100. This practice was followed for all of the studies of this type. Although it suggests incorrectly that the scale is a ratio scale and the maximum limits of fibrosity are realized, it is a convenient method of presenting the scale value (Figure 25).

	Transformed Scale Values	Original Scale Values	Scaled Ranking in Order of Fibrosity: Picture Number*
(Most fibrous)	100	2.79	1
	90	2.54	2
	80	2.29	3
	70	2.05	
	60	1.80	
	50	1.55	
	40	1.30	
	30	1.06	
	20	0.81	
	10	0.56	
(Least fibrous)	0	0.32	4

*Pictures shown in Fig. 24A

Figure 25

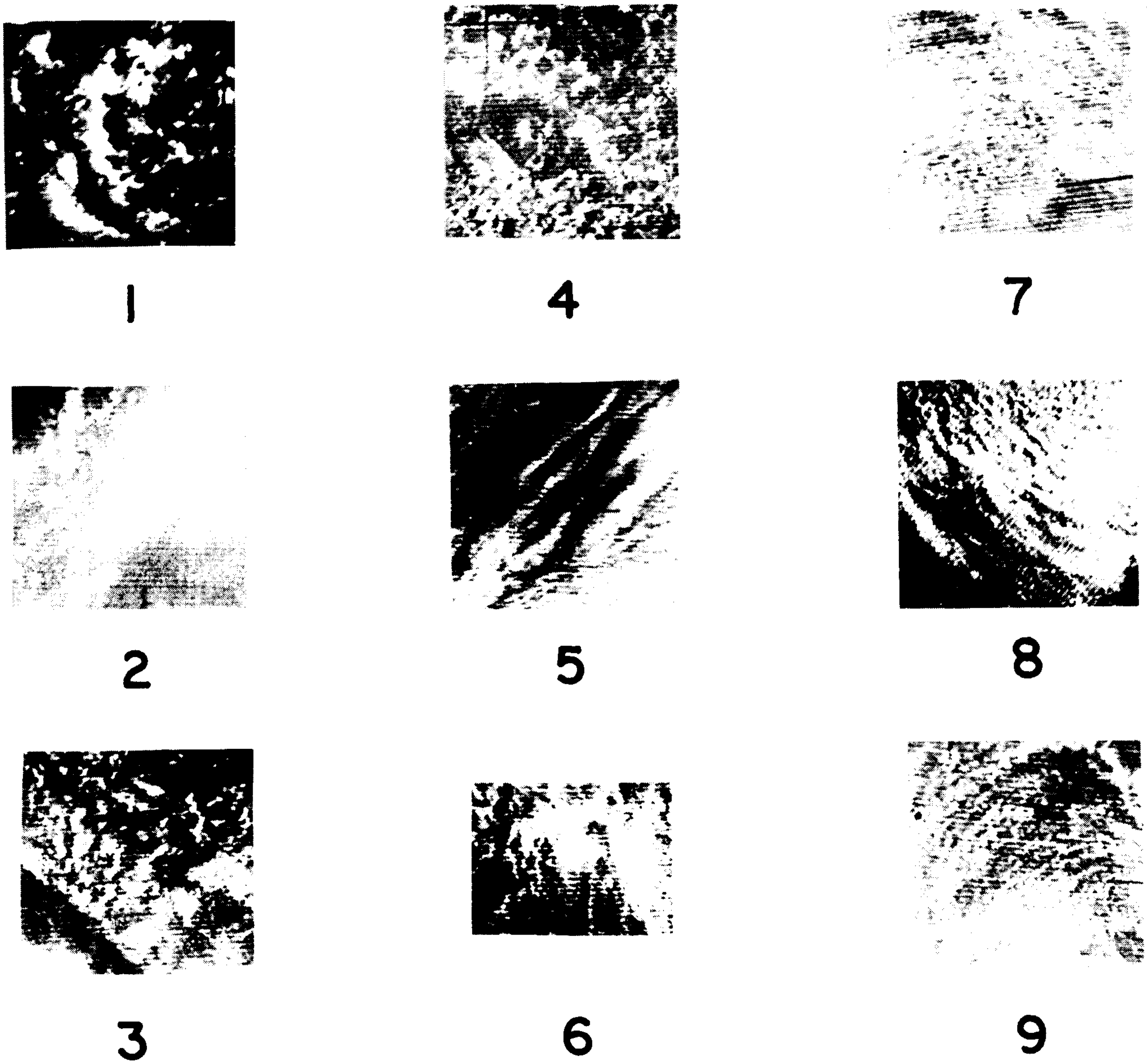
Results of Fibrosity Study

Since only four of the original ten cloud pictures could be scaled in this way, and for three of these the range is quite restricted, it appears that the subjects were not able to discriminate fibrosity very well for intermediate stages. Rather, they were proficient in determining whether a stimulus belonged to one of the extreme points of the continuum. This apparent dichotomization may reflect only the lack of experience of the subjects with the concept of "fibrosity." For the more familiar cloud properties described below smaller numbers of cloud stimuli were discarded.

4.2 Brokenness

The phenomenal quality of increasing brokenness in a cloud formation was determined by two scaling methods, the method of pair comparison and the method of equal appearing intervals (rank order). Either of these scaling techniques produces examples of increased cloud cover brokenness on a psychological interval scale. These in turn can then be associated with an increasing physical or mathematical property of the cloud cover. While the present scaling study assumes a unidimensional functional relation between the physical change and the phenomenal report, this is not a necessary restriction.

Fifteen of the cloud cover samples used in the studies of Section 3 were chosen to reflect increasing degrees of cloud cover brokenness (Figure 26). The figures were randomly selected from among the five cloud cover types and shown through an



A: Samples given intermediate ratings by some observers.

Figure 26

<u>Cloud Cover Samples Used in Brokenness Study</u>

B: Samples rated at broken end of scale by all subjects

C: Samples rated at unbroken end of scale by all subjects

Figure 26: (Continued)

aperture used previously for the test figures which allowed only cloud cover from a single class to be seen.

Two groups of subjects, drawn from among BISC employees, were used. Five subjects were used in each scaling study. In the first study, each of the fifteen figures was shown twice with every other figure in a pair comparison format. (The positions of the figures were reversed to minimize any left-right bias). Each subject was asked to state which of the two figures appeared to him as more broken. Judgments of equality or "undecided" were not permitted. The relevant portions of the instructions follow:

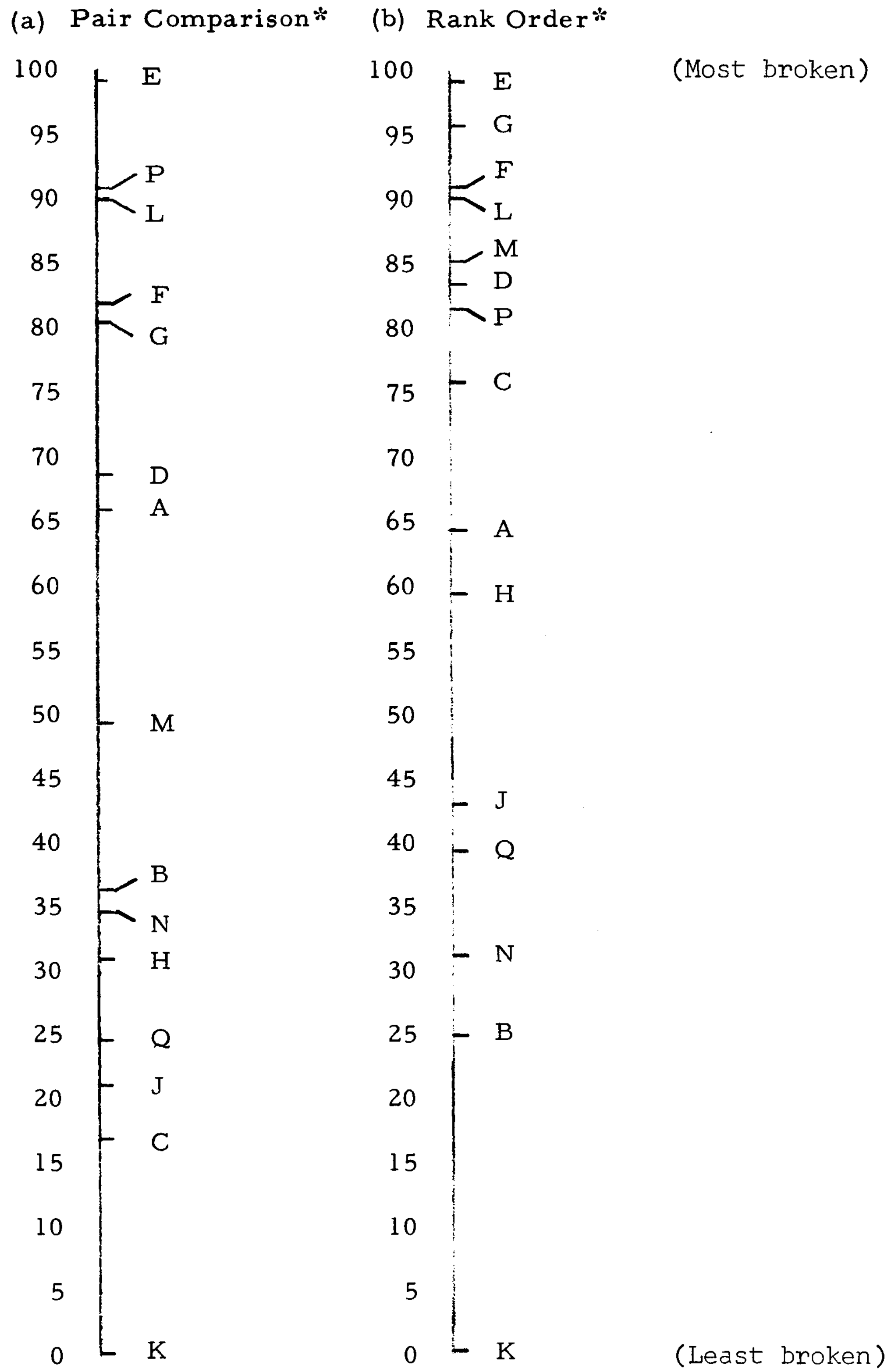
> "I am going to show you a number of pairs of representative cloud photographs. I want you to tell me which one of the pair you feel is the more broken of the two.
>
> In making your judgment consider only the property of brokenness. The clouds themselves will differ in many other respects. However, it is only the property of brokenness that we are interested in."

The scores (numbers of times a figure was judged as more broken than another figure) were converted into a z matrix and a mean z value computed for each figure. Following Edwards (1957) and Woodworth (1954), the smallest mean z value was assigned a value of 0 and the highest a value of 100. The intervals between adjacent figures were then calculated by multiplying each score by 100/(mean z value of the highest figure). The results are shown in Figure 27a. The values 0 and 100 do not mean that the two extreme samples are absolute extremes of brokenness of which cloud cover is capable, but only that within the restricted sample of fifteen figures employed in these studies they proved to have the most extreme amounts of brokenness.

The second group of subjects was shown each of the fifteen test figures in three randomized sequences and told to assign each figure to one of the ranks (1, 2, 3, 4, or 5) for degree of brokenness. The relevant portion of the instructions follows:

> "I am going to show you a number of representative cloud photographs. I want you to assign each of them to one of the five (5) categories shown before you according to its degree of brokenness:
>
> #1 - least broken
>
> #5 - most extremely broken
>
> The categories between #1 and #5 represent intermediate values of brokenness.
>
> In making your judgment consider only the property of brokenness. The clouds themselves will differ in many other respects. However, it is only the property of brokenness that we are interested in."

Following Woodworth (1954), the first trial was treated as a learning session intended to familiarize the subjects



*Pictures shown in Figure 26

Figure 27

<u>Results of Brokenness Scaling Study</u>

with the population of test figures and permitted them to derive a mean level of brokenness. After the first trial the subjects did not experience any difficulty in assigning the cloud cover samples to the classes of increasing brokenness. Edwards' method of equal appearing intervals (Edwards, 1952) was used, due to the number of test figures whose p value for judged brokenness relative to the other figures was greater than +.98 or less than +.02. The test figure with the minimum mean z value was assigned a score of 0, while that with the highest mean z value was assigned a value of 100. These scores were obtained in a manner similar to that used in the pair comparison technique. The results are shown in Figure 27b.

A rank order correlation of .78, significant at the .01 level, was found between the two scaling techniques. Although this is slightly less than that usually obtained between the two methods, it is encouraging in light of the complex nature of the cloud cover figures.

In the rank order technique subjects may not utilize all of the possible categories. They will frequently "bunch up" around one of the classes as shown in Figure 27b. In the pair comparison format, on the other hand, the scores are dispersed through the scale (Figure 27a). The pair comparison technique permits the observer to make his evaluation on a multidimensional scale or on a shifting one-dimensional scale. The rank order technique compels the observer to use a single one-dimensional scale. The relatively high correlation between the two techniques obtained in the study indicates that the subjects were employing some unidimensional property as a basis for the judged brokenness even in the pair comparison study.

The complexity of the stimuli is demonstrated by the extreme shifting in four of the test figures between the two scales of Figure 27. When these figures are excluded, the rank order correlation between the two scales rises to .84. The unstructured nature of these four test figures probably made judgments unusually difficult or compelled the subjects to make the judgments on a multidimensional basis.

4.3 Size

In deciding which portions of the cloud cover are "masses", to be mapped as individual entities, and which are "pieces," to be mapped as parts of groupings which they form with other pieces, context (and in particular, isolation) undoubtedly should play a major role. It may, however, be possible to formulate at least an approximate criterion for such a decision on "absolute" (context-free) grounds. Two factors which can reasonably contribute to an absolute criterion of this type suggest themselves : Area and diameter (largest distance between any pair of points in the given cloud mass). Intuitively, it seems plausible that area is a stronger factor in size judgments than diameter, the latter becoming important perhaps only for extremely elongated (but low-area) masses. It is of interest to determine whether both of these factors do indeed contribute to observers' judgments of size.

A simple experiment has been performed in connection with this question. This experiment was exploratory; the experimental materials used were rectangles rather than tracings of actual cloud masses and pieces. (For rectangles, "diameter" is just the length of the diagonal.) Typical rectangles used are shown at actual size in Figure 28. The subjects were Budd Company employees. They were shown pairs of the stimulus rectangles and asked which of each pair was the larger. Their responses are plotted as Figure 29, which shows the percent of instances in which a rectangle of a given area was called larger than other rectangles. The near-linearity of this graph indicates that even for relatively extreme cases, but ignoring contextual factors, the piece/mass decision will normally be made on the basis of area alone. (Since area is much easier to measure on a digitized cloud picture than diameter, this is certainly a welcome conclusion).

4.4 Elongation

An approach to a mathematical definition of elongation which can be applied even to complex, tortuous shapes was outlined in Volume I, Section 2.4. For most natural cloud masses, however (exception: highly elongated and highly curved cloud bands), elongation can probably be defined usefully in terms of some type of maximum to minimum diameter ratio. A simple experiment has been performed in connection with this

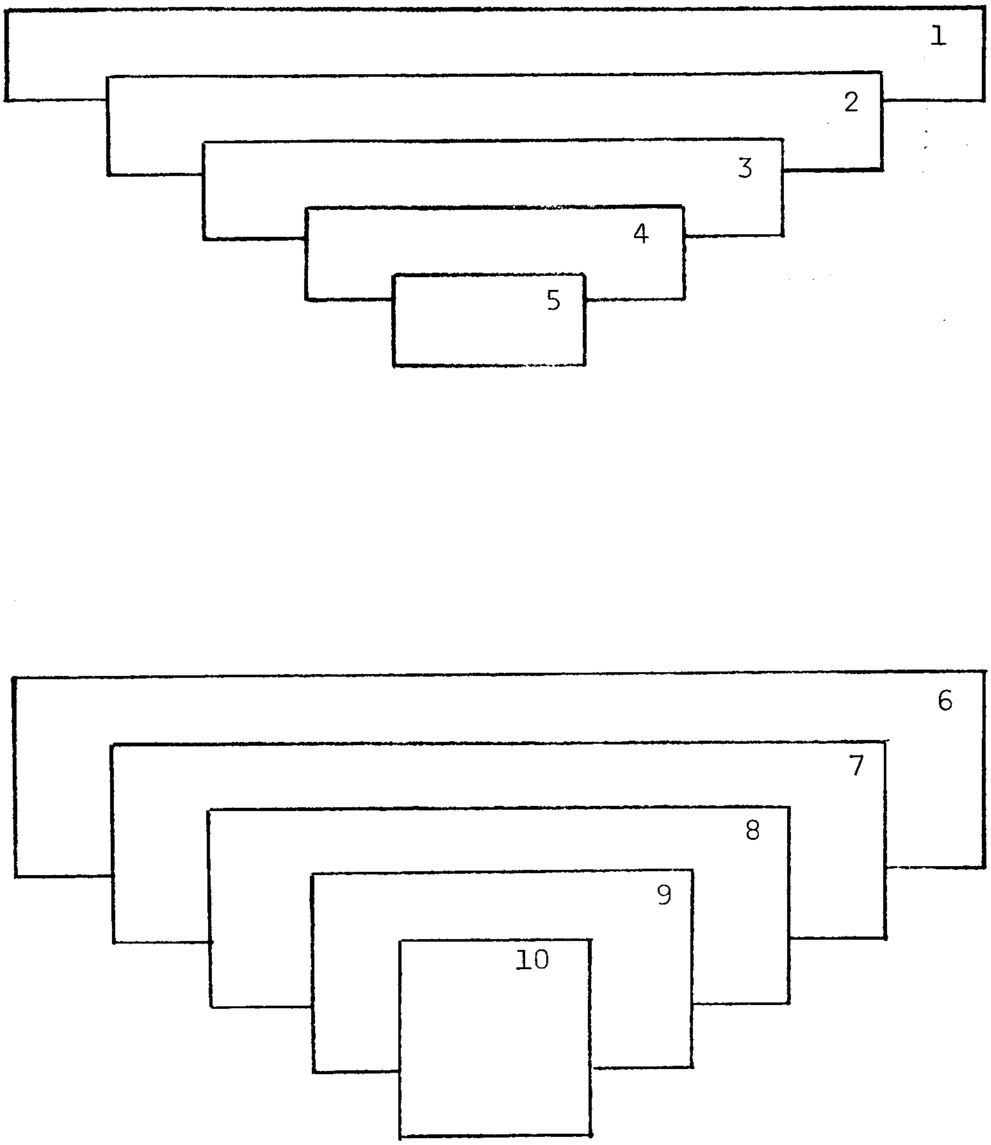
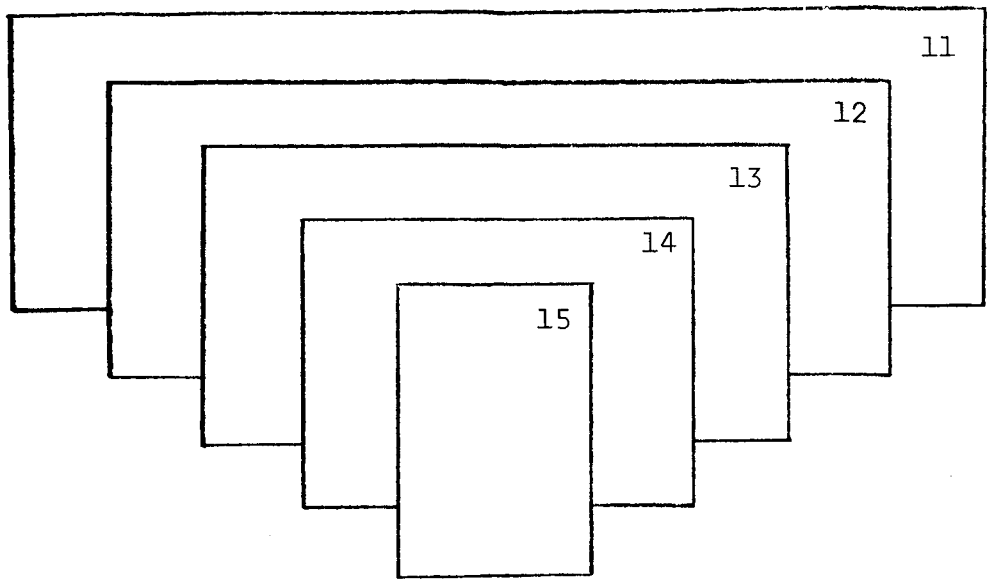


Figure 28

Typical Stimuli for "Largeness" Scaling Experiment



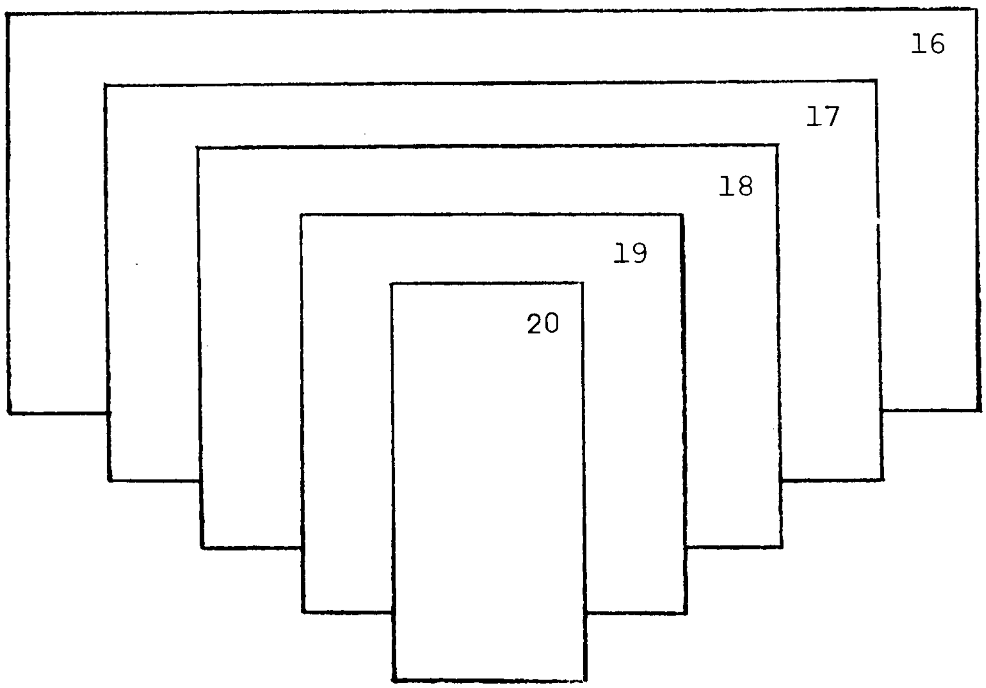


Figure 28: (continued)

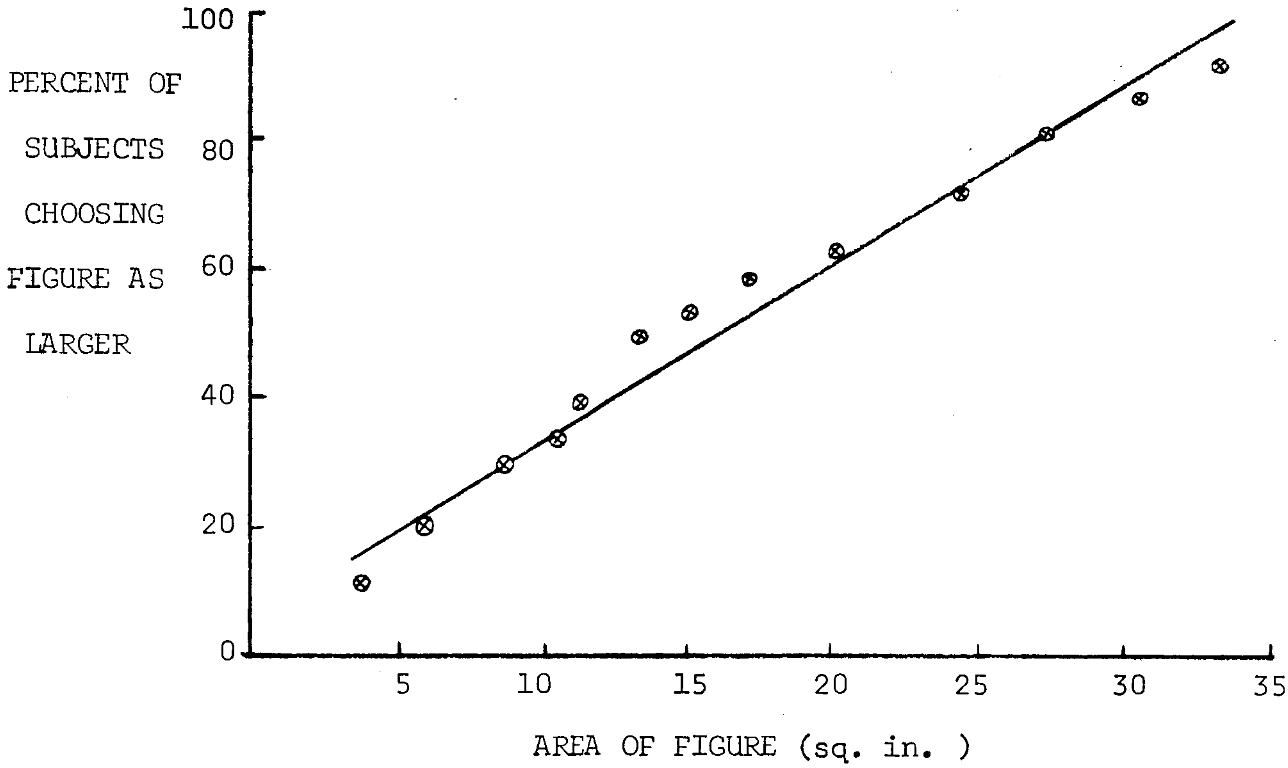


Figure 29

Judged "Largeness" as a Function of

Increasing Area

suggestion, using drawings of two representative cloud pieces which were compressed and elongated to varying degrees in each of two principal directions (Figures 30-31).

The subjects in this experiment were Budd Company employees. They were shown single cloud piece drawings and asked whether the piece shown was or was not "elongated". Their responses are plotted in the figures. They indicate that a length to width ratio of 3 or more will result in "band" judgments by observers, while a ratio of 2 or less will similarly result in "cell" judgments.

4.5 Shape - regularity, straightness, convexity

The remaining three scaling studies dealt with shape properties of cloud contours. The three properties studied were regularity vs. irregularity, straightness vs. curvature, and convexity vs. concavity. The original stimulus materials were randomly selected cloud cover samples; a separate group of stimuli was used for each of the three studies. The experimenter restricted the samples only in limiting them to reflect in his judgment different portions of the continuum. The cloud cover samples were then placed over a light box and the outline cloud contour drawings of Figures 32, 34 and 36 were made with india ink.

The procedure and statistical analysis for the scaling studies for these three properties were identical with those used for the fibrosity study. The only changes in the

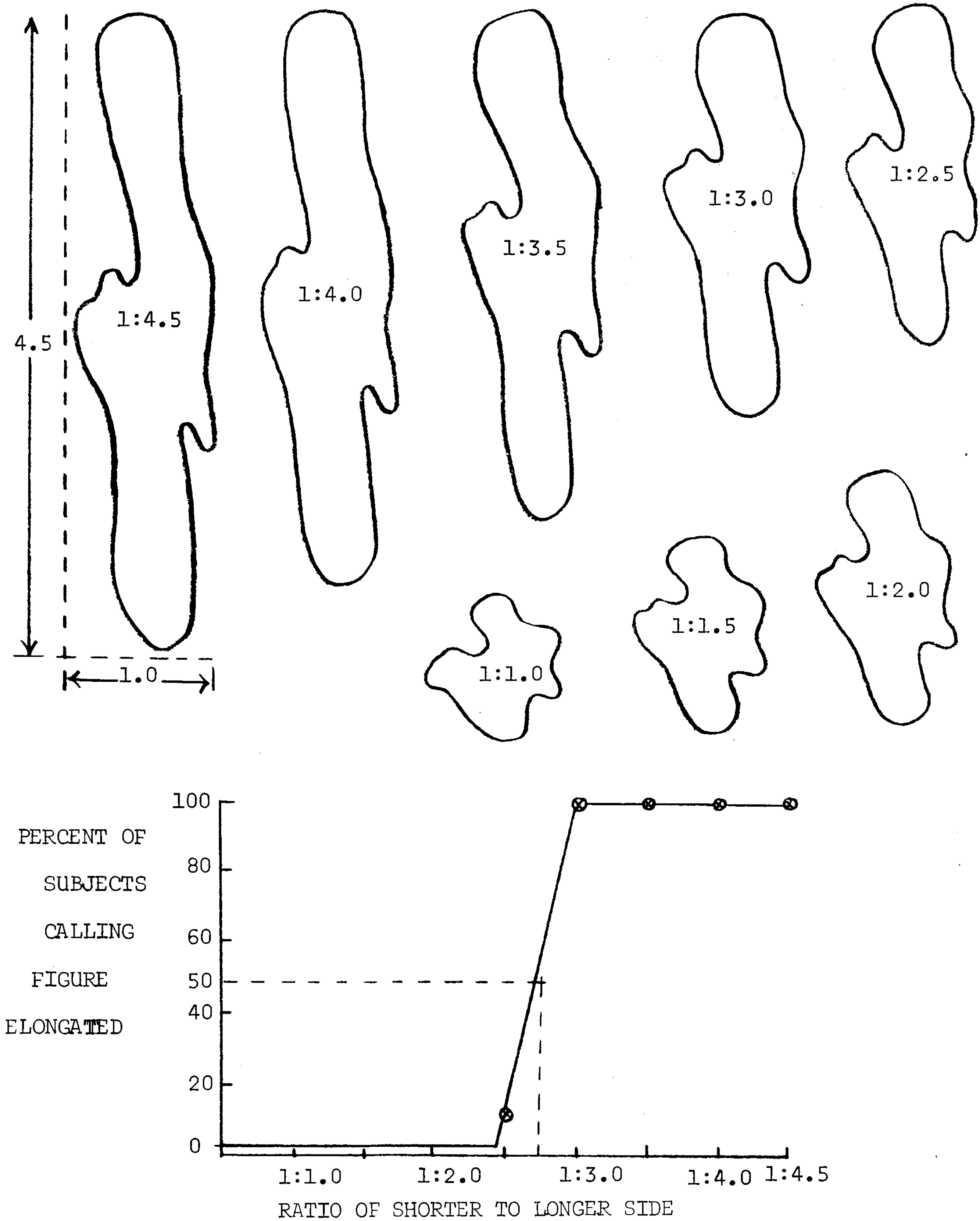


Figure 30

Report of a Figure as Elongated as a Function of

Increasing Length of One of its Sides

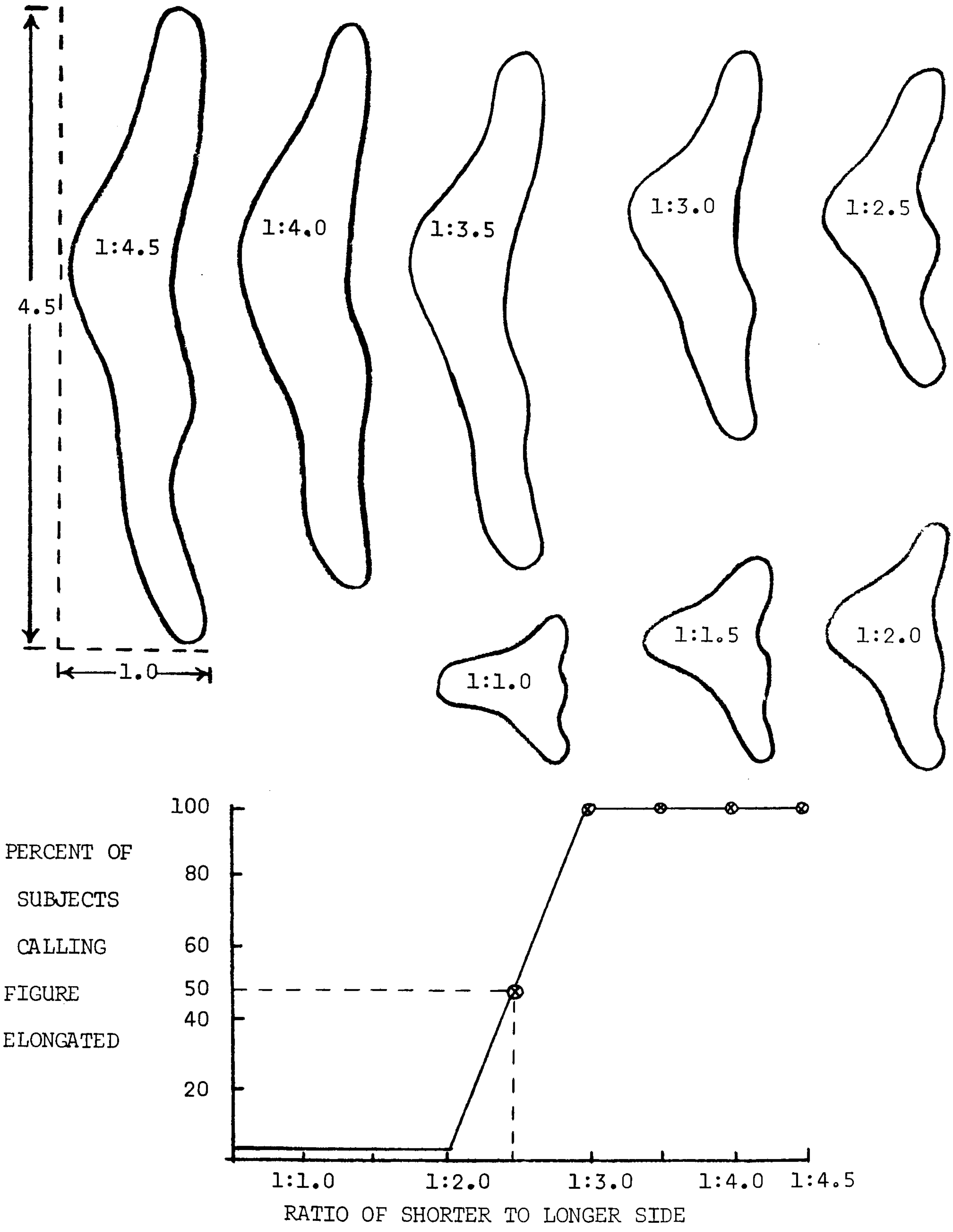
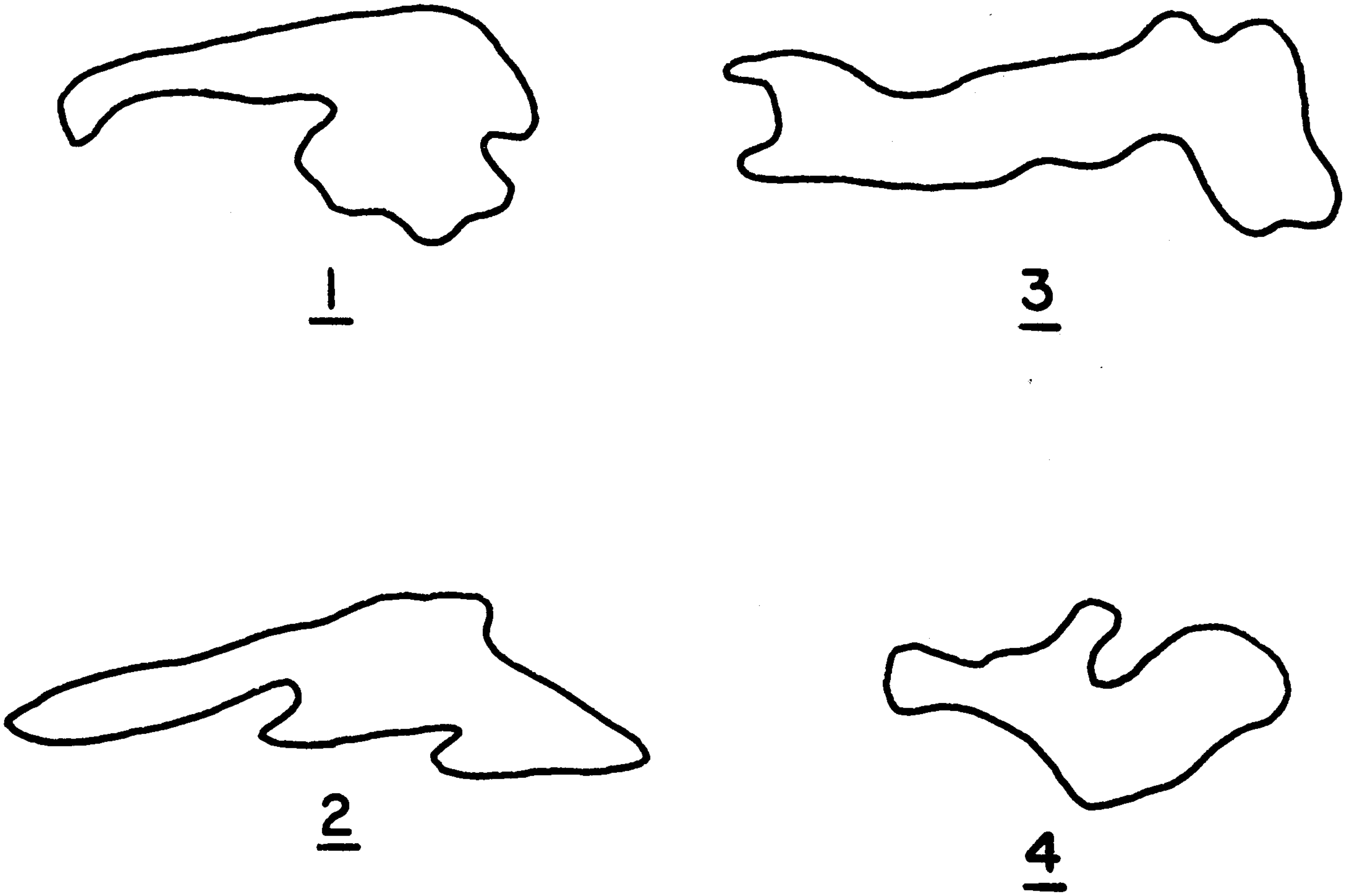


Figure 31

Report of a Figure as Elongated as a Function of Increasing Length of One of its Sides



A: Samples given intermediate ratings by some observers.

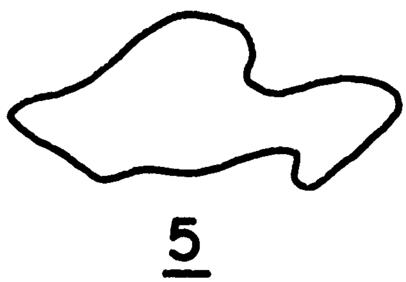
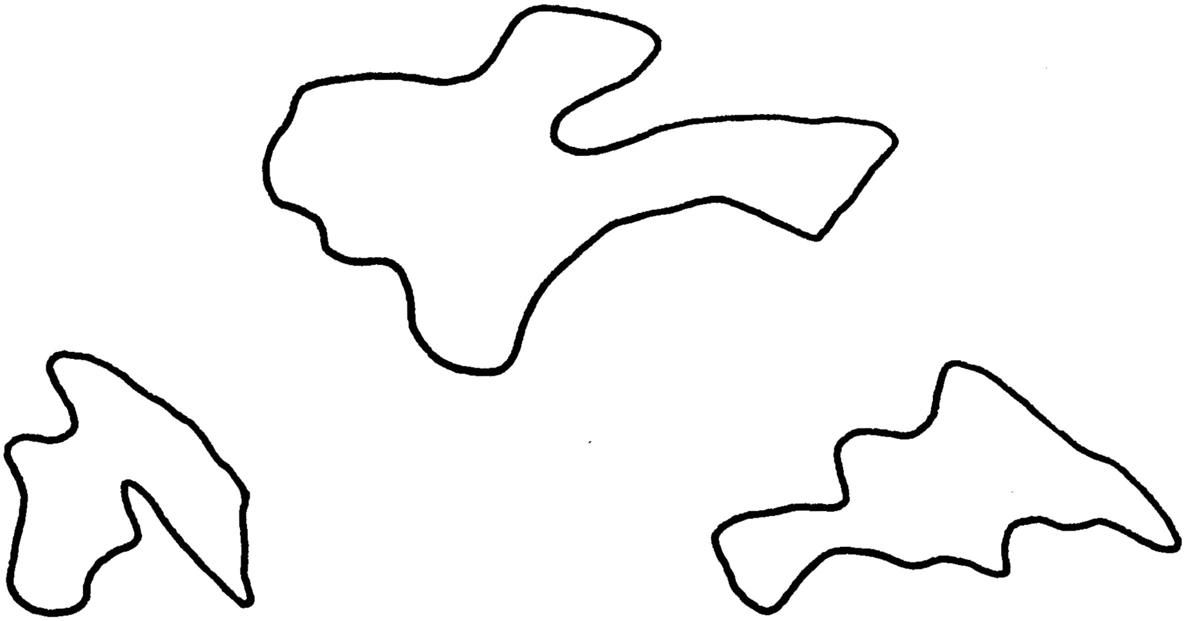
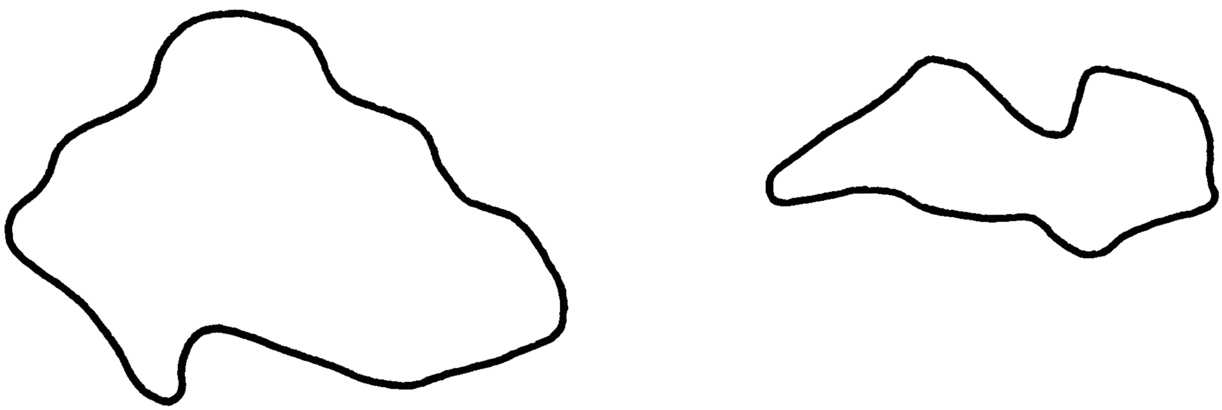


Figure 32

Cloud Outlines Used in Regularity Study



B: Samples rated at irregular end of scale by all subjects



C: Samples rated at regular end of scale by all subjects

Figure 32 : (Continued)

	Transformed Scale Values	Original Scale Values	Scaled Ranking in Order of Irregularity: Picture Number*
(Most irregular)	100	3.24	1
	90	3.12	
	80	3.00	2
	70	2.88	3
	60	2.76	
	50	2.64	4
	40	2.52	
	30	2.40	
	20	2.28	
	10	2.17	
(Least irregular)	0	2.05	5

*Pictures shown in Figure 32A

Figure 33

Results of Regularity Study

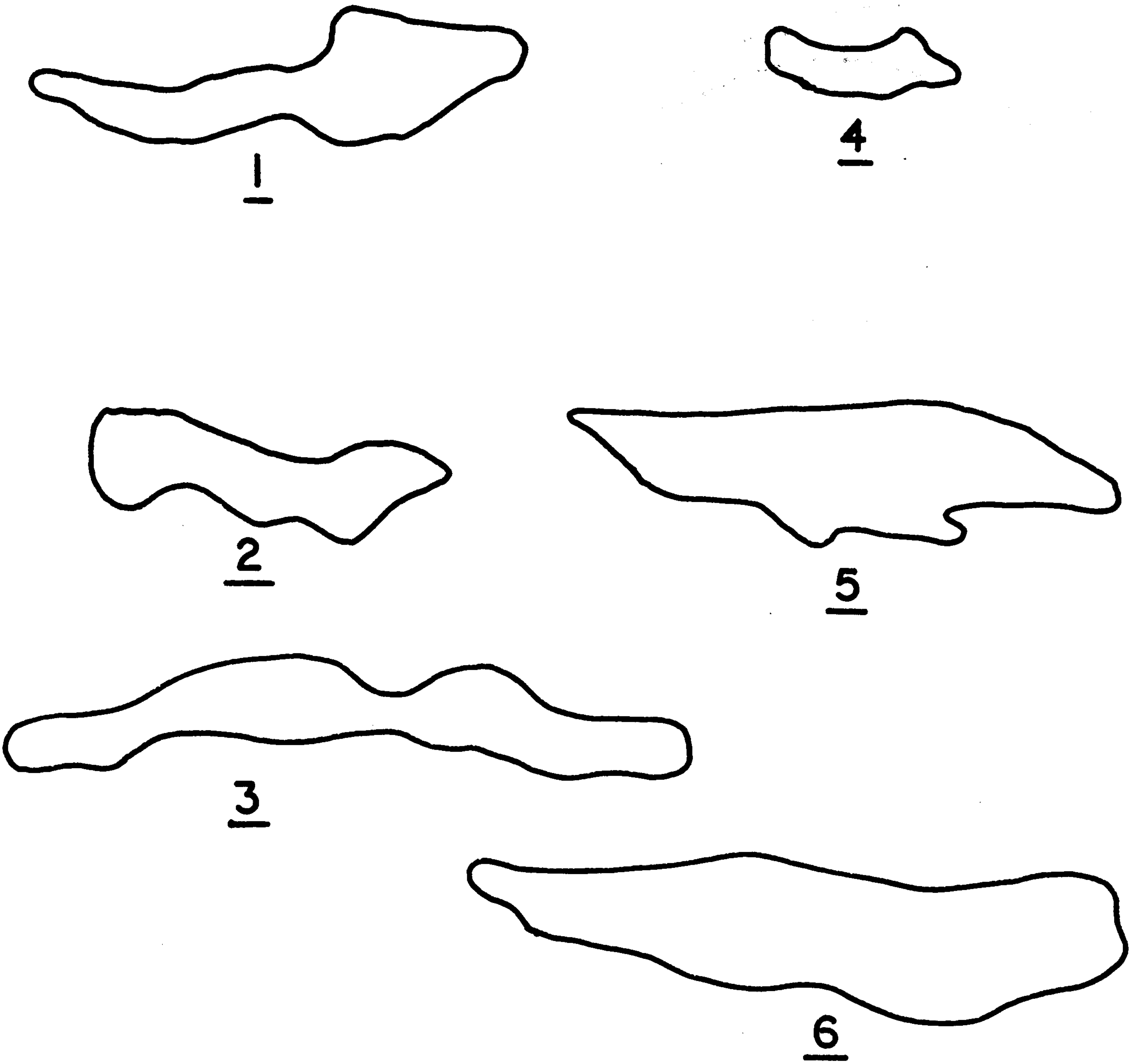
instructions quoted in Section 4.1 were the substitutions of the words "irregularity", "curvature" and "concavity" ("irregular", "curved" and "concave") for "fibrosity" ("fibrous").

The subjects showed somewhat greater comprehension of these continua as evidenced by the smaller numbers of stimuli that had to be discarded due to assignment to the extreme categories 1 and 5.

The scale values obtained are shown in Figures 33, 35 and 37.

All of the stimulus material in these studies is quite complex, in that the figures differ in many respects (area, perimeter, "familiarity", etc.). In spite of this, the subjects indicated no special difficulty, and the evidence suggested that they were successfully evaluating the material on a unidimensional continuum.

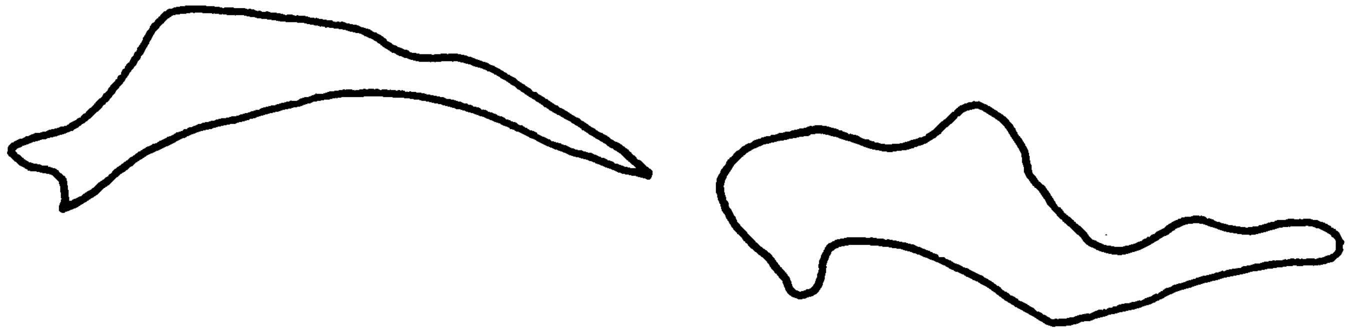
The scaling results were in accordance with conventional use of the terms employed, at least for "extreme" forms. For example, a highly concave form is given a scale value corresponding to its appearance; a jagged rough outline is assigned a scale value showing a high degree of irregularity, etc. For intermediate shapes it is not as easy to discern the form property used in assigning a scale value. An interpretation in keeping with this finding is that the central scale values of 2, 3 or 4 are in actuality "neutral" relative to the extreme points which are used to define the property. If this is actually the case, definitions of these form properties can be made in terms of bipolar statements of extremes in the property continuum. This technique has been successfully used by Osgood (1952) in devising a statistically defined "space" which can be used in evaluating the meaning of verbal and pictorial stimuli.



A: Samples given intermediate ratings by some observers.

Figure 34

Cloud Outlines Used in Straightness Study



B: Samples rated at curved end of scale by all subjects

C: Samples rated at straight end of scale by all subjects

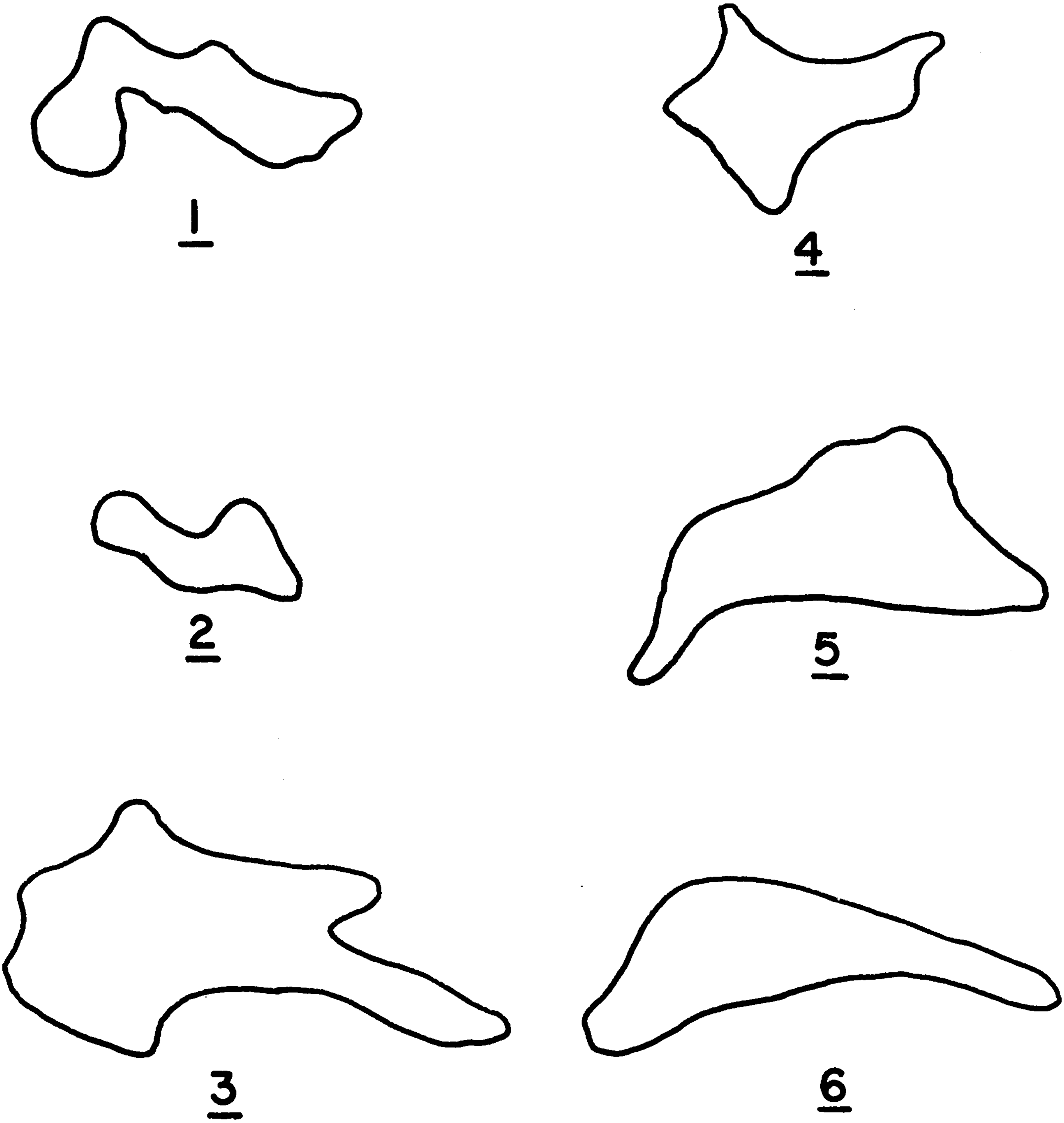
Figure 34: (Continued)

	Transformed Scale Values	Original Scale Values	Scaled Ranking in Order of Straightness: Picture Number*
(Most straight)	100	2.30	1
	90	2.18	2
	80	2.06	
	70	1.94	
	60	1.82	3
	50	1.70	
	40	1.58	
	30	1.46	4 5
	20	1.35	
	10	1.23	
(Least straight)	0	1.11	6

*Pictures shown in Figure 34A

Figure 35

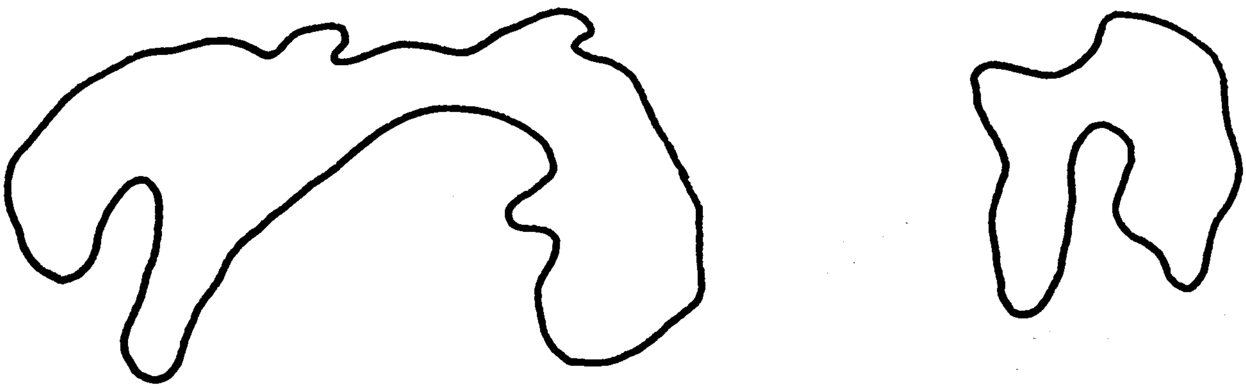
Results of Straightness Study



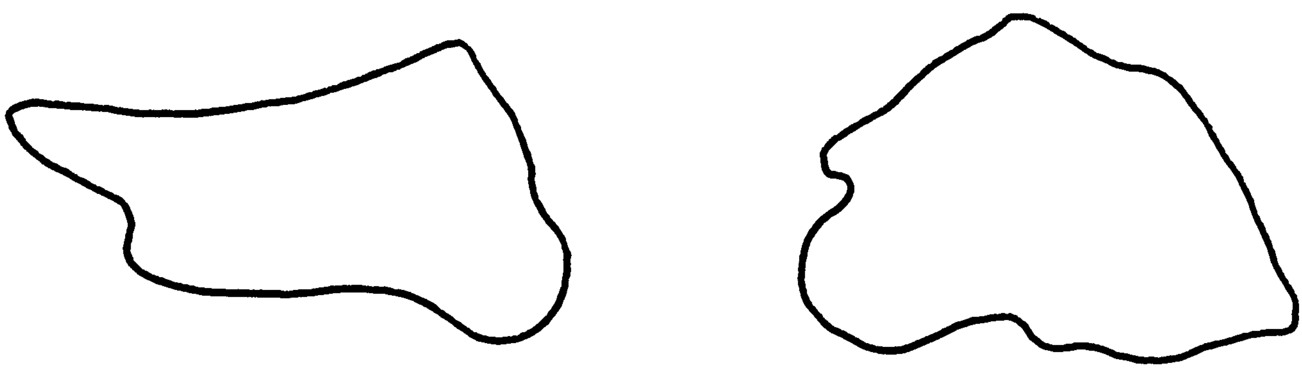
A: Samples given intermediate ratings by some observers.

Figure 36

Cloud Outlines Used in Convexity Study



B: Samples rated at concave end of scale by all subjects



C: Samples rated at convex end of scale by all subjects

Figure 36 : (Continued)

	Transformed Scale Values	Original Scale Values	Scaled Ranking in Order of Convexity: Picture Number*
(Least convex)	100	4.60	1
	90	4.30	
	80	4.01	
	70	3.71	
	60	3.41	
	50	3.11	2
	40	2.82	3
	30	2.52	
	20	2.22	4
	10	1.93	
(Most convex)	0	1.63	5 6

*Pictures shown in Figure 36A

Figure 37

<u>Results of Convexity Study</u>

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