

ESTIMATION OF PARAMETERS OF FORAMINIFERAL TEST GEOMETRY BY IMAGE ANALYSIS

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ABSTRACT. Outline analysis cannot be expected to yield good results when applied to foraminifera because of the uncertain relationship between outlines and three-dimensional morphology. Foram test morphology can often be described efficiently by means of a suite of geometrical parameters controlling chamber shape, size and accretion. These parameters can be obtained from images by an iterative optimization technique. The method has yielded good results when tested by application to simulated images.

PREVIOUS attempts at using image analysis to retrieve useful morphological information from foraminifera have focused on outline analysis. Outlines are easy to define by conventional image analysis (Hills 1988) and a range of techniques for processing outline information is available, including Fourier (Schwartz and Shane 1969) and eigenvector methods (Lohmann 1983; Lohmann and Schweitzer 1990). Although potentially useful for organisms such as ostracods (Kaesler and Waters 1972; Burke *et al.* 1987), this approach is unlikely to be successful in general application to foraminifera because their outlines are only an indirect consequence of the pattern of chamber accretion, the three-dimensional shape of the chambers, and the viewing direction. Consequently, it is difficult to argue that any derived numerical parameters have a meaningful relationship with biological information. Results based on outlines, such as those of Malmgren *et al.* (1984), do reflect genuine morphological information, but the relationship between the derived morphological characters and the true genotypic variation cannot be expected to be linear. The approach of Tabachnick and Bookstein (1990), using landmarks within and on foram outlines, involves similar problems.

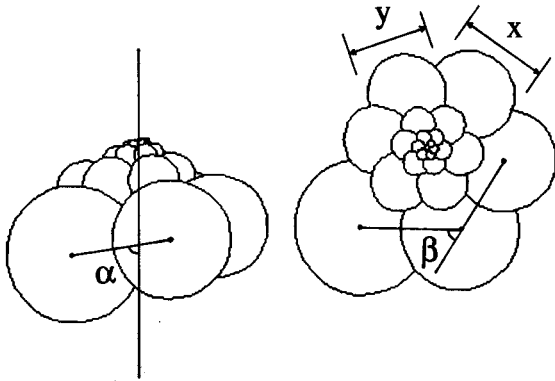
The new approach proposed here is to break the information content of the foram into two constructional components: (1) the shape and texture of each chamber; and (2) the rules governing the spatial disposition of successive chambers. Such an approach must yield parameters that are more directly related to the processes by which the foram test is constructed and the genetically coded information required to control these processes. This study focuses on the second of these constructional components. Once these components are resolved, the 'within-chamber' morphology can be distinguished and resolved using other techniques, such as textural analysis (Swan and Garratt 1995). The objective, then, is to retrieve from foram images values of the geometrical parameters which describe the test shape. These can then be used in studies of taxonomy, ecology and functional morphology. The method will only be useful in application to forams with geometrically regular test morphology: this includes many species from the Globigerinacea and other rotaliinid superfamilies.

The method described here is tested using idealized simulated foram geometries: application to real foram images awaits further work.

FORAM GEOMETRY

In most forams, chambers are added to the test in a highly systematic way. The relative position and size of successive chambers is commonly consistent, resulting in a helicoid, logarithmic spiral

arrangement. In this mode, shape is maintained with growth. Such geometries can be defined by a number of parameters, of which the three most important are defined here as α , β and W (Text-fig. 1).



TEXT-FIG. 1. Definitions of three parameters of foram geometry: α , angle between coiling axis and line connecting centres of consecutive chambers; β , angle between lines connecting centres of two consecutive pairs of consecutive chambers, when viewed parallel to coiling axis; W , chamber expansion rate x/y .

The hypothetical range of morphologies possible in this geometrical scheme can be illustrated by constructing representative arrays of morphologies on two-dimensional slices through the three-dimensional α , β , W morphospace. In this study, we considered the axial view of the structure, in which direction the effect of the α parameter is not marked; we were therefore only considering the β , W morphospace. The β , W morphospace diagram (Text-fig. 2) shows axial views of each simulation in an array with various permutations of the two parameters. To simulate image analysis, the graphical representation was designed to try to emulate the three-dimensional appearance of real forams, as represented on digitized images (Macleod 1990). This was achieved by constructing each chamber from many disks or varying colour density, and this shows the geometry of chamber intersections with reasonable realism.

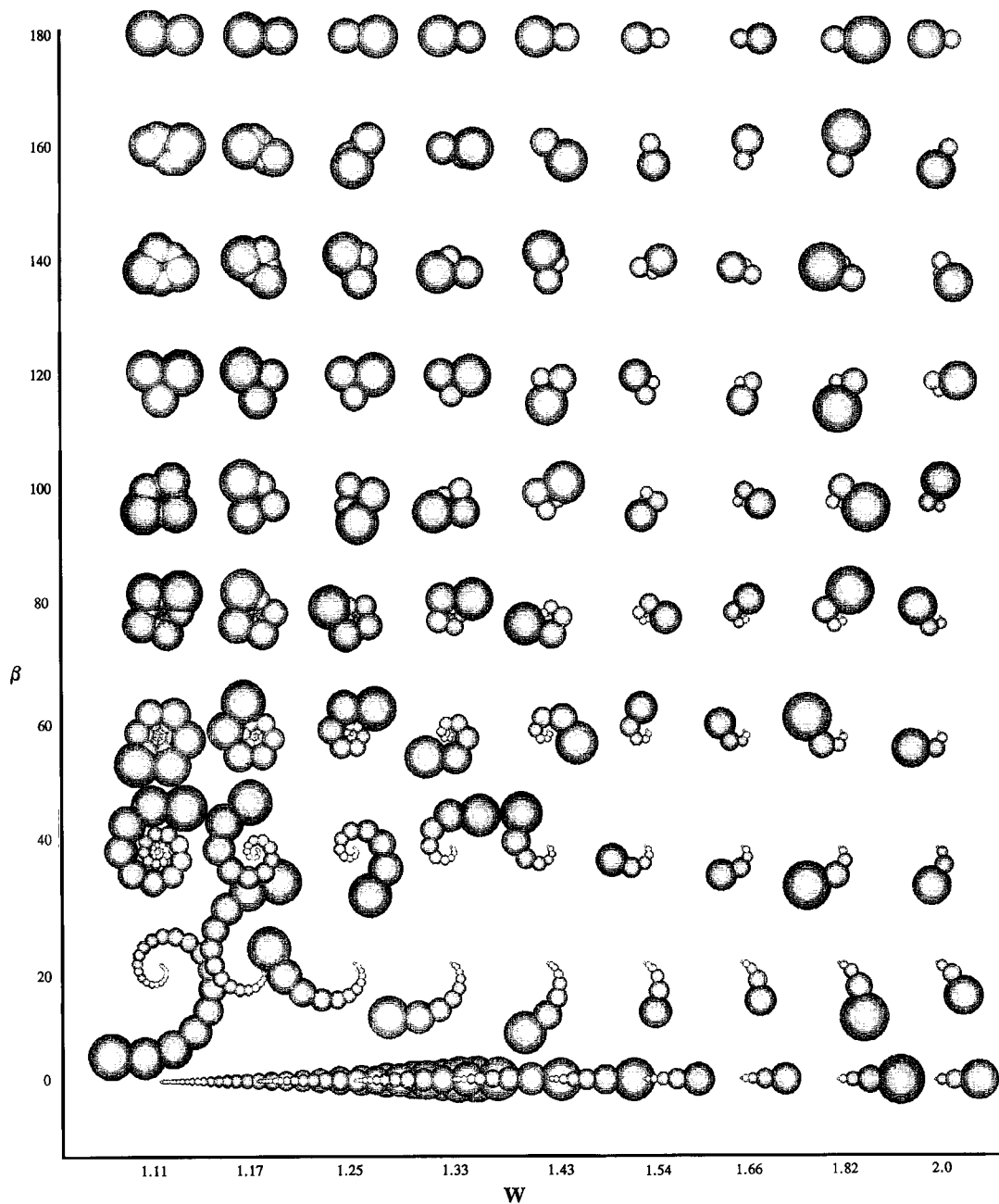
The β , W morphospace diagram demonstrates the morphological effects of changes in the geometrical parameters. It is clear that such morphological variations are of taxonomic importance (e.g. globigerinids tend to have high β) and functional significance (e.g. planktonic forms tend to have higher W). It is also apparent that this information is only indirectly reflected in the outlines.

The initial objective of the new method was to be able to find β and W from the pixel values on 'pseudo-images' such as those of Text-figure 2.

IMAGE ANALYSIS

A property of the present geometrical model, and of log spirals in general, is that the structures are self-similar on enlargement and rotation. In this case, the structures are self-similar on rotation by β and enlargement by W . Consequently, pairs of pixels related by that β , W transformation should have similar greylevel values. If, then, values of β and W could be found such that pairs of pixels on an image related by that transformation tend to have similar greylevel values, it could be inferred that those are the appropriate parameter values to describe the object under consideration. For a robust result, the correlation coefficient between greylevels of multiple pairs of pixels can be assessed (Text-fig. 3). In practice, 100 pixels within the object were selected at random and each paired with another found by the β , W transformation. This was then repeated for a range of combinations of β and W , the combination yielding the highest correlation giving the best estimate of these parameters.

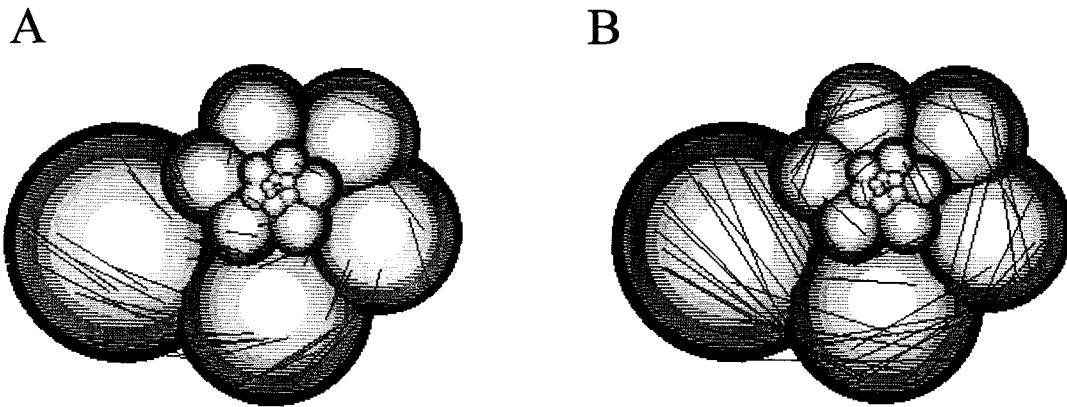
It is possible to plot the correlation coefficient for many combinations of β and W (e.g. Text-fig. 4). The palest parts of the graph show the highest correlation and indicate the β and W values for



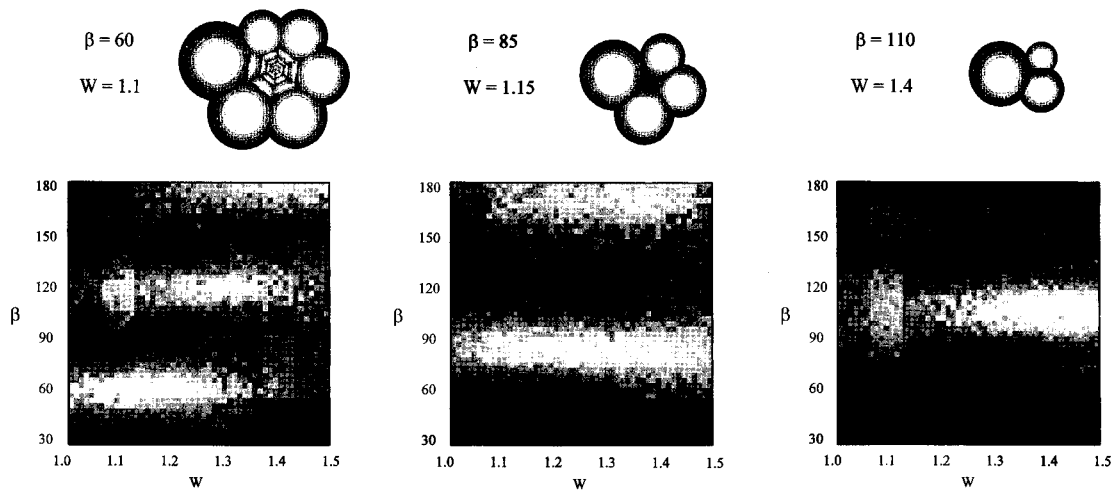
TEXT-FIG. 2. An array of simulated morphologies in β , W morphospace.

the structure. This procedure, using 100 pairs of pixels and 2601 combinations of β and W , requires excessive computer time and is not suitable for routine data retrieval.

The time taken to find the highest correlation coefficient amongst all possible β , W permutations can be reduced by an iterative search procedure. In this method, values of β and W are randomly 'mutated' to generate a set of 'descendant' combinations and the best of these becomes the



TEXT-FIG. 3. Lines connect pairs of pixels related by transformation by rotation β and enlargement W . A, little or no correlation between pixel greylevels. B, high correlation between pixel greylevels, the β and W values used matching the geometrical parameters of the foram structure.



TEXT-FIG. 4. Three simulated morphologies with specified β and W and the results of systematic searches of parameter space. The graphs show the correlation coefficient (paler = higher correlation) between pairs of pixels related by various combinations of β and W values. In all cases, the highest correlation occurs at the β , W values that correspond to the true values for the structure.

'ancestor' for the next iteration. This procedure finds an accurate estimate of the geometrical parameters in under 10 seconds on a PC 486 computer.

FUTURE DEVELOPMENTS

The 'pseudo-image' analysis procedure has achieved the objectives of a pilot study. However, the 'pseudo-images' are more geometrical and more ideally oriented and 'illuminated' than a real foram. The constraints under which the procedure will succeed on real forams need to be investigated. Modifications to allow for imperfections of orientation will be necessary but these should not present major difficulties. Developments in image analysis technology are such that it

should be possible to resolve automatically any pattern of test morphology that can be perceived by the human observer.

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