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Description and origin of spatial periodicity in tectonic structures: report on a Tectonic Studies Group conference held at Nottingham University, 8 November 1978

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IF A DISCRETE and identifiable structure repeats at approximately equal intervals along a certain direction in space, the aggregate of structures or the system in which they occur has a spatial periodicity in that direction. Examples are arrays of fractures, en-echelon tension gashes, sinusoidal fold trains, patterns of diapirs and groups of boudins. Periodicity may occur along more than one direction at once, as in cross-folds or some arrays of veins.

To discuss the description and origin of such patterns, the Tectonic Studies Group (affiliated to the Geological Society of London) held a meeting on 8 November 1978 at the University of Nottingham, England. This report includes the abstracts of all contributions and summarizes some of the most important conclusions of the meeting, many of these having arisen in the general discussion following the contributions. In spite of the common occurrence of spatial periodicity on all geological scales, the authors of this report know of no other published report or general review of the subject. Hence a short review is attempted here. Without being comprehensive, it may nevertheless explain why the Nottingham meeting was held and what its objectives were.

Most geologists will have had the opportunity to observe that many natural structures due to deformation tend to repeat at more or less equal spatial intervals. This regularity is emphasized in many of the standard text books on structural geology. The wish to simplify and the desire for order may have led many authors to select and describe those examples with the most obvious periodicity, thus unconsciously giving the reader a biased impression of the prominence of such structures in nature. Indeed, we may all suffer from a perception bias (Chadwick 1975) towards those structures with the greatest regularity. Nevertheless, spatially periodic structures do exist. The question is, to what extent? It is almost impossible, unfortunately, to find amóng published reports any quantitative measurements of spatial intervals, far less any statistical treatment of these; important exceptions are studies of natural fold wavelengths by Sherwin & Chapple (1968) and Hudleston (1973a). Thus one of the objects of the Nottingham meeting was to draw attention to outstanding natural examples of periodic structures and to discuss quantitative methods for describing them.

In spite of the lack of data on natural examples, theoreticians have been quick to find physical and mathematical reasons for the appearance of spatial periodicity in some structures, notably buckle folds (e.g. Biot 1961, 1964, 1965, Ramberg 1963, 1964, 1970, De Caprariis 1974, Smith 1975, 1977, Johnson 1970, 1977, Fletcher 1974, 1977), diapirs (Daneš 1964, Ramberg 1967, 1972a, Biot & Odé 1965, Selig 1965, Biot 1966) and boudins (Smith 1975, 1977). Essentially these analyses assume that a periodicity will appear and proceed to examine which wavelength grows the fastest (see abstract by Ramberg, this report). Experimental corroborations of these theories (e.g. Biot *et al.* 1961, Ramberg & Strömgård 1971, Ramberg 1972b, Stephansson 1972, Hudleston 1973b) have been partially successful, but many experiments have produced structures with less regularity than anticipated by theory (and therefore more like natural examples). Physical theories that predict regular spacing of joints, faults, and crystal defects also exist (e.g. Cottrell 1953, Price 1966, Chinnery 1966) but work explicitly concerned with the spacing of these structures (e.g. Merzer & Freund 1976) is rare. One of the aims of the Nottingham meeting was to encourage the development of new theories, especially for structures such as veins and pressure-solution seams.

One of the major insights provided by experimental work has been into how individual structures appear and how they acquire an approximately equal spacing or periodicity. As early as 1894, Willis discovered that folds first developed (nucleated) at sites of initial disturbance (heterogeneities) such as small deflections in stratified layers. Paterson & Weiss (1966) verified this for kink-bands and observed that these structures spread (propagated) by increasing in length. Nucleation and propagation of wavelike disturbances has been observed in the buckling of single embedded layers (Cobbold 1975) and multi-layers (Cobbold 1976, Blay *et al.* 1977, Dubey & Cobbold 1977, Watkinson 1976, Watkinson & Cobbold 1978). Folding is characterised by the presence of flow-cells or circulation-cells, which may play an important part in fold propagation. Such cells have been observed in numerical models (Lewis & Williams 1977, Williams *et al.* 1978), but are difficult to model analytically (see however, Erzahnov & Egorov 1970). Evidence for propagation in natural examples (Cobbold 1975, 1976, Watkinson & Cobbold 1978) is fairly convincing but requires more detailed work. Nothing appears to have been published on propagation effects in diapirism or boudinage. Serial fracture development was observed experimentally by Cadell (in Peach *et al.* 1907). A major aim of the Nottingham meeting was to discuss recent experimental work and the light this may have thrown on periodicity development.

Rather ambitiously, perhaps, it was hoped the meeting would help answer the following questions. Why do some structures become periodic, while others do not? What controls the spatial interval or wavelength? How does periodicity initiate and evolve? Are there any common processes responsible for the appearance of periodicity in all structures? Is the geologist in a good position to predict spatial intervals in certain situations? Can he obtain any useful information from a study of measured spatial intervals?

Not all these questions received even a partial answer, but the meeting did provide the following general conclusions, many of which emerged in the closing discussion. For convenience, they will be grouped under four separate headings.

MEASUREMENT TECHNIQUES

1. Appropriate statistical techniques are required to detect regularity of spacing in natural and experimental systems. Classical techniques for random variables are not as adequate as those of regionalized variables (Matheron 1965), which are more appropriate for picking out ordered structures. Autocorrelation and clustering are important parameters of object distributions. The technique of Leymarie (1968, see Fry in press) shows promising initial results. Methods are required to deal with small samples, because the total number of spatially repeated objects available for analysis may not be large.

2. Periodicity is most obvious when the repeat interval contains only a single structural element (fold pair, boudin etc.) but spatial periodicity may also be 'aggregative' (more than one structural element) or 'compound' (more than one period). It is important to distinguish between periodicity and other regular (i.e. non-random) patterns of spacing.

PERIODICITY IN NATURE

1. Some structures (folds, vein arrays, some crystal dislocation arrays) exhibit a more obvious periodicity than others (diapirs, boudins, some fracture sets and veins); others still (some fractures, shears, and pressure-solution seams) show little evidence of periodicity. But any classification along these lines is hardly possible with the present lack of careful and systematic measurements.

2. Obvious periodicity is often if not always confined to local sub-systems; in adjacent sub-systems the spacing of structures appears to be very much less regular. This is especially clear for folds and some arrays of veins. Information on diapirs and boudins is scarce.

3. Much work remains to be done on spatial variations in chemical and mineralogical composition.

EXPERIMENTS WITH PHYSICAL AND NUMERICAL MODELS

1. Periodicity in experimental models has so far been observed to arise in several ways, but that resulting from propagation of a wavelike disturbance is by far the most striking. In most examples, the propagation rate is finite and so therefore are the zones of periodicity.

2. Interference between propagating disturbances leads to a more complicated periodicity in certain zones.

3. Approximately equal wavelengths over large sub-systems are encouraged by rapid propagation rates and an absence of initial heterogeneities.

4. Experimental simulation is lacking for boudinage and for most structures (veins, pressure solution seams etc.) involving material transfer and volume changes (but see Means & Williams 1972, 1974).

5. Propagation and periodicity are aided by the simultaneous instability of positive and negative disturbances (e.g. anticlines with synclines, pinches with swells, domes with rim synclines and, less obviously, veins with solution seams).

6. In the absence of propagation, regular spatial patterns can result from the progressive nucleation and development of structures so as to 'fill all available space'. This appears to be the case for some folds and fractures. In other experiments fractures occur at approximately equal intervals even though they appear to nucleate simultaneously.

THEORETICAL WORK

1. Theories are relatively well advanced for regular wavelike disturbances in viscous or elastic materials, with little or no volume changes (e.g. buckling, boudinage, diapirism, thermal convection).

2. Thermal and mechanical anisotropy cause drastic changes in the behaviour of materials and often render them more liable to instability, thus favouring the development of ordered structures. But some instabilities predicted from isotropic theory are inhibited in anisotropic systems.

3. Theories are almost non-existent for predicting spatial intervals in rocks subject to volume changes and material transfer. There is a need for specific applications of a general thermodynamic approach.

ABSTRACTS OF PAPERS PRESENTED

Periodicity in buckle folds, in boudinage and pinch-and-swell, and in diapirism. H. Ramberg, Geological Institute, University of Uppsala, Sweden.

Usually a system of viscoelastic bodies such as a complex of unlike rocks is theoretically able to respond to a given stress situation by a number of deformation mechanisms. For example, a layered complex may respond to a given layer-parallel compressive stress either by simple uniform compressive strain parallel to the layers — and corresponding thickening normal to the layering — or by buckling. Moreover, there is an infinite number of possible buckling mechanisms since one and the same shortening can theoretically be achieved by an infinite spectrum of wavelengths of the layered system. Similarly, a layered viscoelastic system can theoretically yield to a compressive stress acting normal to the layering by a number of different mechanisms, all involving shortening normal to the layers coupled with layer-parallel extension. Examples are a uniform strain in all layers, a periodic stretching in the form of pinch-and-swell structure, or the fragmentation of some layers to boudins. Again, a gravitationally unstable layered system, especially one in which there is a density inversion, may respond to the forces caused by the unstable density arrangement by a number of deformation mechanisms. In all cases mentioned above it is a general rule that the particular mechanism — or the particular way — which the system tends to follow is the one with which the greatest velocity releases the unstable stresses. We may say that the system selects the way of least resistance. This is a guiding principle for many dissipative mechanical processes. In buckling, for example, the wavelength whose amplitude grows with maximum rate will be the one which will form. Or we may also phrase it in terms of energy: the wavelength which requires minimum dissipation of energy will be the one which develops. Similar considerations can be applied to pinch-and-swell-, boudinage-, and diapir formation. In all these structures the periodicity is explained as the particular geometry which develops with maximum rate under the prevailing conditions.

The importance of geometric systems in multilayer folding. A. J. Watkinson and J. I. D. Alexander, Department of Geology, Washington State University, Pullman, WA 99164, U.S.A.

Detailed examination of fold profiles and surfaces in natural multilayer media, in rocks from different areas and metamorphic grades, suggests the existence of recognisable geometric systems. Where geometric systems have been recognised they consist of folds having either a set of characteristic wavelengths, fold sizes, or a dominant wavelength common to all of the layers. These properties are not continuous outside the system.

Physical models of the deformation of multilayer sequences appear to show that interactions between developing geometric systems are an important control on the finite fold geometry.

Observations of folds in natural multilayer sequences suggest the existence of localised spatially periodic folds. In some cases, system–system interactions may have contributed to the overall geometries of the layers in such a way that any periodic components of folded layers may be masked.

Periodicity of en-echelon tension gash veins. M. Casey, Department of Earth Sciences, University of Leeds, England.

En-echelon arrays of tension gashes are commonly observed in arkoses and greywackes deformed at low metamorphic grade. A single array of veins forms a shear zone and the amount of shear is observed to vary over a wide range. Frequently, pressure solution seams are observed perpendicular to the veins and crossing them near their midpoints.

Two hypotheses for the formation of these arrays are presented. In one hypothesis the veins and associated pressure solution seams are given an important role in the development of the structure and a strong periodicity of tension gash spacing is predicted. In the other hypothesis the veins are regarded as secondary to the development of a shear instability involving cataclastic flow, and periodicity of the veins is not predicted.

Results of observations on the spacing of tension gashes in arrays are presented and the two hypotheses are discussed in the light of these results.

The nature and periodicity of pressure solution stripes in the Old Red Sandstone of South-West Ireland. M. H. King, Department of Geology, University of Liverpool, England.

Spaced pressure solution stripes or cleavages are well developed in deformed sedimentary rocks. In the Old Red Sandstone of the Beara and Iveragh peninsulas of south-west Ireland cleavages have a constant strike throughout a structurally simple region. Cleavage formation is considered to be intimately associated with metamorphic reactions e.g. the breakdown of some detrital minerals such as feldspars, and the upgrading of clay matrix minerals to form mica and chlorite.

Cleavage stripes are thickest, most sinuous and widely spaced (2 cm) in fine grained, small-scale cross or planar laminated immature sandstones. Spacing and thickness decrease towards both finer siltstones and coarser sandstones. Development of such cleavages depends on several factors including grain size, mineralogy of the original rock, sedimentary structure, pressure, temperature, and the pH of the pore fluid.

Frequency plots of the spacing of the stripes are good approximations to log normal distributions. With such a wide spread of data it is almost impossible to find a simple periodic function to describe the distributions. Successive sampling of simple beds shows that at least 50 measurements are required for each frequency graph. Some data show autocorrelative characteristics i.e. although the spacing has a random element, previous spacings influence, but do not rigidly control, subsequent spacings. The preliminary results provide the first data on the distribution of such cleavage stripes.

Some examples of large scale periodicity in the Grampian Caledonides. M. A. J. Piasecki, Department of Geology, University of Hull, England.

In the Grampian mountains, the Dalradian Super Group is underlain by the Central Highland Granulite Moines, which have recently been the subject of a differentiation into basement and cover assemblages, called the Central Highland Division and the Grampian Group respectively. The Central Highland Division forms a high-grade, gneissose assemblage, believed to be Grenvillian in age. The Grampian Group is a cover assemblage of lower grade, affected by a Morarian tectonometamorphic event and by Morarian pegmatisation. It is thought to be post-Grenvillian but pre-Morarian in age, at least in its lower part.

The recognition of Grenvillian and Morarian assemblages in the Grampian Caledonides in addition to the Dalradian assemblage suggests the existence of large-scale periodicity of sedimentary associations and leads to the recognition of large-scale periodicity of tectonic sliding phenomena. Thus, apparently very similar shallow water to inter-tidal pelite–carbonate–quartzite associations are present at the bases of both the Grampian Group and the Dalradian. Sliding between the Grampian Group cover and the Central Highland Division basement can be demonstrated to have been initiated during the Morarian event and to have resumed in the early phases of the Caledonian orogeny.

Extensional crenulation cleavage. J. P. Platt, Geological Institute, University of Amsterdam, Netherlands.

Extensional crenulation cleavage is a distinctive variety of crenulation cleavage with the following definitive characteristics. (1) The crenulations are very open (interlimb angle » 90°) : small scale transposition of the older foliation does not take place. (2) The cleavage lies at a low angle (« 45°) to the enveloping surface of the older foliation, and is oblique to the axial planes of the crenulations. (3) The cleavage is defined by narrow zones of intense deformation approximately parallel to one set of limbs of the microfolds. (4) The sense of displacement along the cleavage zones is such as to cause a component of extension parallel to the older foliation.

Crenulation cleavage with this *geometry* can form by extensive solution transfer along one limb-set of open microfolds (*P*-zones). This structure does not need to be distinguished as a distinct type of cleavage. Extensional crenulation cleavage has the same geometry, but forms by shear along discrete zones at a low angle to the older foliation (*S*-zones). It appears to be responsible for much of the fish-scale, button-schist, and augen-schist textures described from major shear zones. It has the following non-definitive characteristics.

(1) It occurs in rocks with a very strong pre-existing foliation.

(2) It is commonly associated with crystal-plastic and cataclastic deformation, mylonitic textures, and retrograde metamorphism.

(3) The microshear zones defining the cleavage have a distinctive microstructure indicating intense crystal-plastic or cataclastic deformation.

(4) The shear-zones anastomose, and tend to weave between the older foliation and the limbs of the open crenulations.

(5) The new cleavage, which may have a spacing ranging from 1 mm to 1 m, is generally a poorly defined surface. It is difficult to measure directly, and has a very poorly defined intersection on the older foliation. For these reasons it is readily overlooked.

(6) The associated deformation may produce substantial finite strains, important modification of the microstructure, and possibly entirely

new preferred orientations of quartz lattices, without obvious mesoscopic effects. Many 'mylonitic' foliations may in fact be older foliations that have been strongly modified by deformation of this type.

The distinctive geometrical characteristics of this type of cleavage suggest that the orientation of both finite and incremental extension axes stood at angles of less than 45° to the older foliation throughout the development of the new cleavage. The crenulations are a periodic response to flow of an anisotropic solid where the extension axis lies close to the plane of anisotropy. The shear zones produce a component of bulk extension lying in the acute angle between the older foliation and the new cleavage. This deformation history distinguishes this type of cleavage from other types of crenulation cleavage, in which the older foliation lies initially in the shortening field of the incremental strain ellipsoid. For this reason, I propose the name extensional crenulation cleavage for this type of structure.

Conjugate sets of extensional crenulation cleavage may form where the extension direction is parallel to the older foliation. This results in phacoid or augen structure.

Spacing of mantled gneiss domes in Eastern Finland. J. P. Brun, C.A.E.S.S., Université de Rennes, France.

The Carelian mantled gneiss domes of Finland occur in a band about 50 km wide and at least 200 km long, bordering the Archean basement. In the Kuopio area, structural features strongly suggest a diapiric origin for the domes.

The domes are aligned into seven ridges, trending N–S to NW–SE, with an average spacing of 23.3 km. Along each ridge, the shape and spacing of domes are variable and apparently controlled by regional deformation.

Once the effects of regional deformation are set aside, the pattern of domes is comparable with that of salt domes in the Zechstein basin of Germany (Trusheim 1960) and with patterns obtained in experimental non-centrifuged models (Ramberg 1967). The ridge spacing (23.3 km) observed in Finland is very close to the value (22.5 km) calculated by Ramberg (1972a) for his model of "upheavals of gneiss granite basement in orogens".

Anticlines without synclines. R. E. Chapman, Department of Geology & Mineralogy, University of Queensland, Australia.

Tertiary basins in South East Asia and Australasia tend to be deformed into narrow steep anticlines separated by broad gentle synclines (a feature referred to informally in New Guinea 25 years ago as 'anticlines without synclines'). This structural style, with a dominant wavelength typically 10–20 km, is associated with regressive sequences, shales with abnormally high pore-fluid pressures, and mud volcanoes. The structures themselves are growth structures.

There is unambiguous evidence that some of these anticlines formed during subsidence in a stress field with the greatest principal stress vertical. The cause of the deformation is mechanical instability in the regressive sequence, not horizontal compression. The role of orogeny is the supply of sediment.

Variants of interest are sliding and overthrusting at anticlines, as in Papua New Guinea, leading to 'synclines without anticlines'. The dominant wavelength is then represented by overthrusts or thrusts.

An approach to the development of regular instabilities. A. Beach, Department of Geology, University of Liverpool, England.

We are accustomed to looking at metamorphic assemblages in rocks and interpreting them in terms of equilibrium phase diagrams. In the same rocks we may measure the finite strain as the end point of ductile deformation. More detailed studies may lead to an evaluation of the mechanism and rate of deformation whilst the petrologist copes with the problems of reaction processes. The fact that deformation and metamorphic processes are essentially the same is usually over-looked and their physical relations left unexplored. The very fact that we now interpret the observed end points of deformation and metamorphism in terms of mechanisms and processes means that we are dealing with systems continuously evolving — and hence not at equilibrium — towards a state which may or may not be an equilibrium state. In order to do away with the arbitrary division between the metamorphic and structural geologist we merely have to consider all processes in an evolving rock system under one heading in terms of their rates. It does not matter whether we are interested in temperature gradient and heat flow, stress gradient and mass flow, chemical potential gradient and diffusion etc.

The method of treatment stems naturally from the simple concepts of classical thermodynamics — an attempt to find a quantitative expression defining the direction in which natural or spontaneous processes proceed — by concentrating on non-equilibrium systems. A spontaneous process is always accompanied by an increase in entropy, and the system evolves to an equilibrium state of maximum entropy.

The total entropy production is given by the sum of the products of the flux and the generalised force for each process in a defined system. Close to equilibrium, linear phenomenological relations exist between flows and forces. Immediately, we see a possibility of coupling two or more processes which may all proceed spontaneously together where individually some may not proceed at all. The only requirement is that the total entropy is positive for the sum of the processes. In general only forces of the same tensorial order, i.e. scalars, vectors, or tensors can be coupled in this manner, though there are some important exceptions to this.

Further away from equilibrium, fluctuations in the flows become important, and the excess entropy production equation is derived in a similar way to the entropy production equation to describe these fluctuations. More complex coupling between processes may occur and points are often reached where coupling produces an instability, where a fluctuation grows into a finite structure requiring greater organisation of material in the system than previously existed.

Some of the most obvious examples involve the formation of a regular structure through viscous convective effects, but more emphasis here is made on the important class of largely dissipative structures formed in chemical systems where convective effects are absent or minimal. For example, in the steady state near to equilibrium, diffusion controlled reactions give rise to spatially organised structure such as segregations (not necessarily periodic). Further away from equilibrium, a reaction scheme proceeding in one direction only, involving diffusion and an autocatalytic subsidiary reaction, may result in the formation of a periodic chemical (mineralogical) structure.

Reference is made to pressure solution cleavages as spatially organised structures controlled by a reaction–diffusion–stress interaction.

Origin of periodicity : saturation or propagation? P. R. Cobbold, C.A.E.S.S., Université de Rennes, France.

Experiments with model materials and observation of natural examples both suggest that structures can become regularly spaced in many different ways, but that it is useful to distinguish between two ideal models, the saturation model and the propagation model.

In the *saturation* model, individual structures (e.g. folds, fractures) nucleate at various points throughout a deforming material and at various times. No structure can nucleate at less than a certain limiting distance from any other structure already established. The process continues until all available space is occupied. Thus the spatial interval between neighbouring structures has a limited range of values.

In the *propagation* model, early structures nucleate at sites of heterogeneity. Each early structure triggers the appearance of new neighbours at fixed spatial intervals. The process continues, producing spreading zones of wavelike disturbance. Within these zones, periodicity is very regular. Elsewhere, it is nonexistent or it is irregular due to interference between propagating disturbances.

The theory of regionalized variables (Matheron 1965), applied to spatial intervals (Leymarie 1968, Barbier & Leymarie 1972, Fry in press) is useful for distinguishing between the two models, although in general these may operate simultaneously to form geological patterns.

Some periodic instabilities in anisotropic fluids. C. C. Ferguson, Department of Geology, University of Nottingham, England.

Most theoretical and experimental work on periodic instabilities in model geological systems has been concerned with mechanically isotropic materials. Some of the instabilities predicted from isotropic theory do not develop in 'equivalent' anisotropic systems (i.e. systems having the same average properties but in which some or all of the layers are anisotropic); conversely, forms of instability may arise that have no counterpart in isotropic systems. These points are illustrated by reference to the literature on deformations of liquid crystal systems.

Liquid crystals are anisotropic fluids that occur as mesomorphs (i.e. phases with molecular order intermediate between crystalline solids and isotropic liquids) termed nematic, cholesteric and smectic according as their molecular anisotropy is (in tectonite terminology) of L, LS and S type respectively. In a smectic liquid crystal layer (planar anisotropy parallel to layer boundaries) overlain by a denser isotropic fluid, the development of *gravitational instability* is inhibited relative to that in an 'equivalent' isotropic system : diapirism requires much greater layer thickness and/or density difference. Smectics also exhibit *dilational instability*, a buckling-type deformation of the molecular layers induced by extension across the layers without concomitant shortening parallel to the layers : such behaviour is unknown in isotropic systems. In 'planar' nematic layers (anisotropy vector *n* parallel to layer boundaries) *thermoconvection* occurs at Rayleigh numbers much smaller than in the isotropic case. If anisotropic rocks behave similarly, thermoconvection would be expected in rock systems with linear dimensions and temperature differences appropriate to the continental crust. But in homeotropic nematics (*n* normal to layer boundaries) the anisotropy stabilizes the system unless the thermal gradient is inverted!

It would be imprudent to suggest that these 'unusual' instabilities necessarily have geological analogues. Nevertheless, they reinforce the view that isotropic theories may not provide even rough approximations to some of the mechanical and thermomechanical behaviour of anisotropic rocks.

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