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Diapirism and gravity tectonics: report of a Tectonic Studies Group conference held at Leeds University, 25–26 March 1980

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INTRODUCTION

IT IS now almost two decades since Hans Ramberg began his well known research of simulating diapiric structures in the laboratory and his application of this model work to the origin of major structures in orogenic belts (Ramberg 1963, 1967). Since then there has been a revolution of ideas in structural geology; ideas of horizontal tectonics based on the movements of the Earth's plates have largely taken preference to ideas based on vertical tectonics related to diapirism. It was therefore considered timely to review the relative role of diapirism in regional deformation, and hence the Tectonic Studies Group (affiliated to the Geological Society of London) held a meeting on this theme on 25–26 March 1980 at the University of Leeds. This report includes the abstracts of all the contributions and it also summarises some of the conclusions, most of which emerged during discussion following the contributions.

FACTORS CONTROLLING DIAPIRISM

The theory of gravitational instability of layered systems had previously been treated by a number of investigators, including Biot & Odé (1965), Odé (1966), Ramberg (1968, 1972), Berner *et al.* (1972) and Stephansson (1972, 1974). During diapirism, according to Ramberg's (1968) theory, the upper surface of low density, viscous strata rises spontaneously in a form of waves, whose wavelength is governed by the complex interaction of thickness, rheological properties and layer density. The effects of these parameters on the shapes of gneiss domes and granite bodies were demonstrated from field and model evidence by Soula.

The triggering effect of regional tectonics was also discussed. Perthuisot showed that salt diapirs in Tunisia were commonly elongated parallel to faults in the basement. Movement on these faults would presumably have triggered local diapiric growth and hence caused the preferred orientation of the diapirs. Presumably the diapiric waves propagated away from the triggering fault, similar to waves propagating in fold development (Dubey & Cobbold 1977). This could give rise to different sizes of diapirs especially where the waves interfered with another set triggered by a different fault (see also Brun 1980).

The role of fluids in diapirs was discussed by Nicolaysen. The rapid rise of a fluid-rich zone in the lower crust or mantle would be locally explosive, and would give rise to kimberlite pipes and also large krypto-explosive domal structures such as Vredefort, where lower crustal material was drawn to near the surface. Carol Pudsey described the mud breccias of the West Indies which have a chaotic clast arrangement, the whole breccia formation is soaked in oil and may represent the results of disturbance by rising mud diapirs which culminated in extrusion.

STRAINS AROUND DIAPIRS

The model work of Dixon (1975), Schwerdtner & Troeng (1978) and Dixon & Summers (this report) has shown the patterns of strain expected from variably shaped diapirs and also from the interference of different orders of diapirs. Dixon & Summers demonstrated not only variations in strain intensity due to interference but also variations in the k value of the strain ellipsoid (cf. Flinn 1962) where strains could range from oblate to prolate. Coward gave natural examples of these variations from Namibia where local extensional strains ($k > 1$) locally occur along the crest of a diapiric complex of migmatite veins.

Ramsay examined the deformation necessary to produce simple diapiric bubbles and showed that strain intensity is related to increase in the radius of bubbles, the cooling history of the magma and the number of influxes. Holder described an example from Ardara (Donegal, Eire) where most bubble expansion had taken place while the magma was still fluid and the xenoliths only recorded the strain after solidification of the particular phase of magma.

The problem of space for an expanding bubble was raised by Schwerdtner. He supported the idea of cylindrical diapirs, possibly open to the surface, as they expand they give fewer space problems than hemispherical bubbles. The example of the Criffel granite in SW Scotland (described by Coward for Heaton & Reader) gave a similar solution to the space problem. At Criffel the main intrusion was probably by stoping, there being no deformation of the country rocks due to granite intrusion. Measurements of xenoliths gave non-oblate strains, of approximately $k = 1$, with down-dip extensions on a steep foliation. In this body, post intrusive diapirism due to late magma influx, could be attained by vertical growth stretching and flattening the outer shell, and at the same time pushing up the cap rock.

The effect of diapirism on country rocks was discussed by Holder who demonstrated the deformation of contact metamorphic minerals around the Ardara pluton. In some areas it may be difficult to separate contact metamorphism from regional metamorphism. Brun described the regional strain pattern produced by diapirism superimposed on regional tectonics, in his particular example, simple shear in southern Spain. The foliation in the country rocks and granites was not everywhere parallel to the granite margins but crossed them, and there was also considerable variation in ellipsoid shape, from oblate to prolate.

FIELD IDENTIFICATION OF DIAPIRS

A recurring theme to the meeting was that of the problem of the recognition of structures whose origin was solely due to gravitational or buoyancy forces. There was a wide range of opinions, from contributors who were willing to admit that most fold nappes and thrust sheets originated by gravitational forces to those who were loath to admit the responsibility of gravity in any structures, except those related to intrusion.

The main criteria for the recognition of diapirs were the subject of intense discussion, (also see Stephansson (1977) and Schwerdtner, this report). The criteria may be summarised as set out below.

(a) Less dense material should occupy circular to oval shaped complexes surrounded by more dense material.

(b) There should be conformable structures such as foliation, cleavage and lineations in the complex and surrounding rocks.

(c) There should not be repetition of layers by folding of the overyling strata, unless earlier deformation phases are involved.

(d) The strain distributions should involve subhorizontal extension in the crestal regions of the less dense complex. The long axes of the strain ellipsoids should be tangential in the crestal region and there may be radial and/or tangential patterns of fractures and veins which have their origin in the complexes. However in the trunk region of diapiric complexes, the long axes of strain ellipsoids should be vertical, possibly associated with synchronous folds with radial axial planes.

(e) The oval shaped bodies should not form in any regular array such as would be produced by fold interference. Some early diapirs may be deformed by later bodies.

Sometimes these criteria are difficult to apply. Bronner discussed an example of gneiss domes which does fit the tectonic models of Dixon & Summers. However Dixon & Summers had applied their models to Archaean greenstone belt terrains, where dense basic volcanics sit in irregular, tight, commonly star-shaped, synclinal zones between granite masses. Such belts are obvious candidates for the application of diapiric theories, as has been shown by the large numbers of publications on the subject (e.g. Macgregor 1951, Anhaeusser *et al.* 1969, Windley & Bridgewater 1971, Drury 1977, Gorman *et al.* 1978). However at the meeting there was considerable discussion and disagreement on the applicability of diapiric theory to all greenstone belts. The following points are the main ones which arose during the discussion.

(a) Narrow umbilical necks have not been found to the granites of the greenstone areas, as would be expected from theory and models, and as have been described from gneiss terrains by Bronner.

(b) Several greenstones in southern Africa do not fit the simple Anhaeusser *et al.* (1969) diapiric model. The Tati and Matsitama belts of northern Botswana show evidence of recumbent folds and thrusts, with most of both belts having been inverted before granite intrusion (Coward & James 1974). Similarly, much of the deformation in the Rhodesian and South African greenstones (Coward 1976, Fripp *et al.* in press) is not due to local diapirism but to regional tectonics which thrust and uplift dense high-grade rocks.

(c) In some greenstone belts, such as Shabani (Bickle *et al.* 1975, Coward 1976), where the greenstone sediments sit on older basement gneiss, then deformation is associated with block uplift of the gneiss and downwarping with little internal strain of the sediments. This block uplift could, of course, represent the initial stages of diapirism in a viscous material (cf. Stephansson 1974).

(d) Much of the granitic rock which intrudes the greenstones is not locally derived. The granites and tonalites of the Rhodesian greenstone belts, dated at 2900–2600 Ma, have low initial $Sr^{87/86}$ ratios and could not have been generated from the gneissic basement dated at approximately 3500 Ma (Hawkesworth *et al.* 1975, Moorbath 1977). The granite rocks must have been intruded from a deeper source, either primitive mantle or young lower crust.

Within mobile belts there could also be difficulty in identifying deformation due to diapirism. Coward described large scale recumbent sheath folds (Quinquis *et al.* 1978) in Namibia and suggested that they were not due to diapirism but to intense deformation in a large scale low angle shear zone. However Tully showed that similar, though smaller scale structures occur within convection cells in evaporite deposits in NE England, and Talbot compared these structures with large scale recumbent structures in Greenland and East Africa.

ABSTRACTS OF PAPERS PRESENTED

Identification of gneiss diapirs. W. M. Schwerdtner, University of Toronto, Ontario, Canada.

Given an inverse density stratification as well as appropriate ratios of thickness and viscosity between ductile lithological units in the earth's crust, diapirism cannot be avoided regardless of whether a crustal segment is undergoing horizontal extension, shortening or no longitudinal strain. Although most diapirs are driven by the buoyancy of light strata, some are generated from major horizontal units of heavy ductile rock by virtue of high horizontal gradients of effective pressure in the overburden. Such horizontal gradients can be associated with normal faults and other structures due to crustal extension.

Following is a list of criteria whereby gneiss diapirs may be recognized in the field. Criteria 1 and 2 are applicable to buoyant diapirs only, the other criteria are valid regardless of the dynamic mode of ascent. Criterion 4 is restricted to mature diapirs. Unfortunately many gneiss diapirs occur in Precambrian shields in which they are exposed on a regional peneplain, that is, in two dimensions only.

Criterion 1. The cores of antiformal structures are composed of light granitoid rocks which are surrounded by denser, more mafic rocks. These granitoids and the more mafic rocks have undergone coeval ductile deformation in which their viscosity ratio was small.

Criterion 2. Where several orders of diapirs are developed, the first-order structures are the most elongate in plan and the lowest-order structures are nearly circular in plan.

Criterion 3. Within the crestal region of typical gneiss diapirs, ellipsoids of total diapiric strain are subhorizontal. Because the total-strain ellipsoids are subvertical in the trunks of all diapirs, there is a surface of zero total strain between the crestal region and the trunk region. Such neutral surfaces of total strain are not expected to occur within upright major folds in typical gneiss complexes.

Criterion 4. Large, upright mushroom-shaped structures of granitoid gneiss mantled by supracrustal rocks are apt to be diapirs. Mushroom-style major structures in the interface between thick lithological units do not develop by simultaneous or successive cross folding. Buckling of thin, widely-spaced ultracompetent members does lead to elasticas-type folds resembling mushroom-like surfaces. But such structures are not akin to mantled gneiss domes, and should not develop on a large scale in typical metamorphic assemblages with low competency contrasts.

Characteristics and mode of emplacement of diapiric gneiss domes and plutonic domes in Central-Eastern Pyrenees. Jean-Claude Soula, Laboratoire de Tectonophysique, Université Paul Sabatier, Toulouse, France.

Gneiss domes and plutonic granitoid domes make up almost 50% of the ante-Hercynian terrains in the Central and Eastern Pyrenees.

From a structural study of the shape and internal structure of the domes and of their relationships with the enclosing rocks (briefly reported) it can be shown that both types of domes were diapirically emplaced during the major regional deformation phase and accompanying paroxymal regional metamorphism.

The structural study also shows that the internal structure, the overall shape, and the general behaviour relative to the host rocks are wholly similar for plutonic domes and for gneissic domes. This appears to be in agreement with Ramberg's model studies (Ramberg 1967, 1972) which showed that dome-like structures or mushroom-like structures similar to those observed, require a small viscosity ratio between the rising bodies and enclosing media in order to develop. This implies a high crystal content for the granitoid magma. This crystal content has been estimated: (i) by calculating the viscosity and density in natural conditions, from the petrological data for magmas considered as a suspension; (ii) by using the recent results of the experimental deformation of partially melted granites, and (iii) by comparing the preceding results with the data obtained by deformation experiments on rocks similar to those enclosing the domes.

The minimum crystal content for the development of dome-like structures is thus estimated to be about 70%, that is very close to the critical value separating granular framework flow from suspension-like behaviour.

The effect of small variations of viscosity in the rising body were studied by centrifuge experiments. These small variations appear to control strongly the shape and rate of rise of the domes. They are thought sufficient to explain the variations in shape and structure, and the level of emplacement of the different types of gneissic domes and of plutonic domes.

Based on these results, more complex experiments were carried out with models built to fit, as close as possible, the natural initial state of the region as deduced from petrological and structural data. Their implication for the regional interpretation of the relationships of gneissic and plutonic domes will be discussed.

Diapiric structures in the Archaean basement of the south west Reguibat Shield (Mauritania). Georges Bronner, C.N.R. Laboratory, Faculty of Science of St. Jerôme, Marseille, France.

The southwest part of the Reguibat Shield is essentially composed of Archaean middle to high grade metamorphic rocks and migmatites. Two regions show interesting megascopic tectonic features: the Tiris district, characterized by an abundance of iron-formations and the Tasiast district where an ophiolitic series overlies a thick and highly migmatised acidic complex.

The first region, studied in detail, shows catazonal facies and low migmatisation. After several isoclinal fold phases, the main tectonic phase produced folds of ejective style and about 1 km wavelength. The folds developed locally into antiformal swellings to become spherical or ellipsoidal 'bulbs' outlining a 'joint' system of large polygonal cells with vertical walls. The most common dimensions measured in the horizontal plane are between 8 × 8 and 12 × 30 km. The domes have few folds of lower wavelength suggesting extension whereas synforms developed into very narrow gutters with many folds. Where three domes are neighbours, the triangle they bound, centred by a navel structure, shows folds with radial axial planes and constriction features, suggesting sinking. During doming and sinking, buckling was predominant with very important thinning and thickening, stretching and deflection, suggesting a very low viscosity of the material involved during this deformation.

The density map established from sample measurements and mining data shows that bulbs are made of rocks with granite density ($2.63\ gm/cm^3$), whereas the sinking bodies have a higher density (3.1–$3.3\ gm/cm^3$). These facts and the very high density contrast (0.4–$0.6\ gm/cm^3$) induce me to consider gravity as an active element in the genesis of such deformation.

The second region has had no detailed analysis except for photogeological and field compilation. Nevertheless the study had revealed typical mantled gneiss dome structures. The dome shapes are between 16 × 16 and 18 × 36 km in size; one dome measures 20 × 40 km with an apex at more than 10 km above the topographic plane and another, composed of four smaller domes, is about 40 × 45 km.

The density contrast is about 0.4 to $0.6\ gm/cm^3$ between the granitic rocks and the basic and ultrabasic rocks which overlie them and form narrow rim synforms surrounding the domes. From the boundaries to the centres, some domes show evident petrographic differentiation, from simple gneisses and migmatites to granitic rocks rich in pegmatites. This suggests mobilization during doming.

In these two examples, the shapes and dimensions of the domes are different and so are the rocks involved although the density contrast is the same. In both examples the main direction of predomal large folds may still be observed but possible antiformal fold intersections which may produce doming are not obvious. In the first example, high density material, concentrated after early fold superposition, should have produced the gravity instability which generated the sinking and doming.

Pan African gneiss domes, diapirs and sheath folds. M. P. Coward, Department of Earth Sciences, Leeds University, Leeds LS2 9JT, England.

The northern part of the Damaran belt in Namibia is a zone of high temperature metamorphism and granite intrusion, dated at about 550–500 Ma (Kroner 1980). The structures are dominated by large circular to ellipsoidal outcrop patterns of metasediments with gneissic cores, previously considered as mantled gneiss domes. The majority of these are re-interpreted as large flattened recumbent tubes, with hinges co-axial and parallel to the well developed mineral lineations and maximum extension direction in the rocks. They are considered as large examples of sheath folds, several kilometres in wavelength, formed within a major, gently dipping shear zone. This shear zone formed in an area of high heat flow and granite intrusion, the significance of which will be discussed. However, diapirism is an active deformation mechanism in the late stages of this shear zone as the sheath folds are re-orientated and deformed by late granites and by the rise of large domal masses of granites and pegmatites.

Diapirs driven by high pore fluid pressure. L. Nicolaysen, B.P.I., Witwatersrand University, Johannesburg, South Africa and J. Ferguson, B.M.R., Canberra, Australia.

In Nicolaysen (1973) most of the North American crypto-explosion structures were interpreted as diapirs driven by fluid pressure. The driving force is now better understood. Consider a source of highly compressed fluids in a source below a basin of stratified rocks. The fluids are carbonated and capable of permeating the wall rock and forming potassic fenites as they ascend. The difference between their internal pressure and the ambient lithostatic pressure increases sharply as they moved up. At a critical level, the compressed fluid expands violently.

Where first there was explosive permeation of supracrustal and crustal rocks by these fluids, and then cratering, this led to a mechanical instability in which rapid centripetal inflow of the pressurised stratigraphic section occurred, leading to a polygonal 'diapiric' uplift of the Crooked Creek type. However, where cratering alone absorbed most of the violent expansion, a structure like Brent Crater developed; explosive penetration by the fenitising fluids had a major role in the disruption.

Detonation of the carbonated fluid (during the violent expansion) was responsible for shock metamorphism. If the compressed fluid was in a superheated metastable condition, this was polymorphic deterioration.

An investigation of deformation patterns in Archaean greenstone belts using centrifuged models. J. M. Dixon and J. M. Summers, Department of Geological Sciences, Queen's University, Kingston, Ontario, Canada.

A number of competing conceptual models have been proposed in the literature for the tectonic framework in which Archaean greenstone belts initially accumulate and subsequently deform. In one class of models it is proposed that deformation is produced by vertical gravity tectonics involving the subsidence of the relatively dense volcanic–sedimentary sequence of a greenstone belt and the associated diapiric rise of a buoyant substrate of sialic composition. It has been suggested that this substrate may have either been a pre-existing sialic basement, remobilised during diapirism, or an extensive sheet of granitoid batholiths intruded at depth below a greenstone cover and subsequently remobilised into diapiric domes.

A series of model experiments has been carried out to simulate the type of deformation proposed in these conceptual models. The experiments involve models with a simple, two-layer inverse density stratification—a thin, relatively dense surface layer representing a cover of volcanic–sedimentary rocks and a thicker, relatively light substrate layer representing the source layer for basement domes. The models are constructed from silicone putties. In the majority of experiments there is no difference in rheological properties between surface layer and substrate and the density contrast is approximately 1.07–1.

Two types of experiments have been carried out: (a) the surface layer is locally thickened to form parallel, linear troughs which act as controlled initiators for the subsidence of this layer and (b) no attempt is made to localise doming or subsidence, and hence diapiric structures evolve naturally from a planar interface. Progressive strain development on the upper free surface of models is monitored by the use of a millimetre grid printed on this surface. Horizontal and vertical colour banding is incorporated into the body of the models to permit strain analysis of vertical, profile sections.

In those experiments in which linear trough initiators were used the simulated greenstone belts evolve into inverted diapirs separated by broader basement domes. The early stages of subsidence are characterised by vertical extension within the inverse diapir that is maximum at the surface, decreases in magnitude with depth and gives way to horizontal extension at or just below the base of the subsiding trough. Subsequently, the trough tends to 'mushroom' and the lower levels of the trough undergo horizontal extension.

Analysis of deformation of the upper surface of models reveals locally complex progressive deformation in material elements which migrate from areas affected by vertical contraction, above rising basement domes, to regions of strong vertical extension in the core of subsiding troughs. Such complex deformation histories would be characterised by fabric overprinting in a natural prototype system. During the later stages of surface deformation, horizontal shortening in excess of 95% and vertical extension greater than 1000% accumulates within the simulated greenstone belts.

Analysis of surface deformation also reveals patterns of strain variation along the axis of a single trough that reflect the shape of the trough base at depth. Surface strain within a non-cylindrical trough, for example, can be shown to vary from prolate (vertical extension) above zones of maximum trough subsidence to oblate (vertical extension) above intervening regions of shallower subsidence. Such variations result from movement of surface material along the trough axis towards the sites of greatest subsidence.

The Mid Palaeozoic orogen of Svalbard: an example of gravity inversion Tectonics? G. M. Manby, Department of Geology, Goldsmith's College, London SE14, England and A. P. Morris, Geology Department, Wayne State University, Detroit, Michigan, U.S.A.

Previous attempts at fitting the Mid-Palaeozoic orogen of Svalbard into a broader geotectonic framework have relied largely on stratigraphic evidence. The models that have been proposed require extremes of either lateral or vertical plate motion. However, an examination of the pattern and nature of the metamorphic deformation events allows an alternative model, which it is believed reconciles to some extent the extremes. It is suggested that the Svalbard orogen originated within the late Precambrian to early Palaeozoic intracratonic trough which developed in the early stages of the opening of the Iapetus Ocean. This trough perhaps a principal branching trough or aulocogen of Iapetus was subjected to extensive crustal thinning and faulting allowing the accumulation of vast thicknesses of sediment. Gradual geothermal heating mobilized the less dense basement giving rise to gravitational overturn, thus driving the main Mid-Palaeozoic deformation and modifying the earlier metamorphic event where basement diapirism and migmatization occurred.

Rounded magnetic anomalies in the Baltic Shield of Sweden interpreted as diapiric structures. H. Henkel, Geological Survey of Sweden, Uppsala, Sweden.

From extensive low-altitude aeromagnetic measurements a large number of rounded negative anomalies can be detected in the Baltic Shield of Sweden. Their average diameter varies between 4 and 20 km. Contact patterns and surrounding magnetic structures indicate three different types of rounded magnetic minima, that is discordant, conformable and irregular type anomalies. The magnetic information is rather sensitive to the dip of contacts of these structures. The rounded magnetic minima are caused by low density granitoid rocks. Using measured densities and existing gravity measurements, the depth of a large number of these structures has been estimated. Computed depths are always considerably smaller than the corresponding widths.

The Lizard Complex—a mantle diapir? J. R. Vearncombe, Department of Earth Sciences, Open University, Milton Keynes, England.

The Lizard Complex, southwest England has variously been described as a mantle diapir (Green 1964a, b) or an ophiolite (Bromley 1976, Styles & Kirby 1980). It is the purpose of this contribution to review the evidence for the diapiric hypothesis and present a brief interpretation compatible with available evidence.

Green (1964b) reported the presence of a spinel lherzolite within the ultrabasic rocks of the Lizard Complex. This rock type forms less than 10% of the ultrabasic rock, but presumably formed in equilibrium at pressures greater than 8 kb (approximately 25 km depth). The remainder of the ultrabasic complex is plagioclase lherzolite with recrystallised hydrous assemblages indicative of formation at higher levels. In the diapiric model the ultrabasic is intruded from depth, as a vertical plug. Emplacement of the diapir resulted in the metamorphism of pre-existing rock types, the Landewednack hornblende schists and the Old Lizard Head metasediments. The hornblende schists were converted to brown hornblende, pyroxene–hornblende and two pyroxene grade rocks (the Traboe schists). The metasediments preserve cordierite, garnet, staurolite, andalusite and sillimanite. The Crousa gabbro, basaltic dykes and Kennack gneiss (a migmatite) are regarded as late and unrelated to the diapir.

There are five objections to the mantle diapir hypothesis. (1) Sanders (1955) has demonstrated that the southeastern portion of the ultrabasic is underlain by hornblende schists with a flat contact. A borehole (Institute of Geological Sciences, Report 78/21) at Predannack Airfield, the supposed centre of the diapiric plug, reached the base of the ultrabasic and penetrated into hornblende schists at 298 m. Recent seismic evidence (M. Brooks personal communication) also suggests that the Lizard Complex is a thin sheet-like body. (2) The Landewednack hornblende schists are metamorphosed and deformed lavas, dykes and gabbros. The Trabroe rocks are heterogeneously deformed and metamorphosed layered gabbros commonly with ultrabasic horizons, and are not derived from the Landewednack hornblende schists. Metamorphism does not always increase in the direction of the ultrabasic. (3) The Crousa gabbro is without a chilled margin and is only exposed where it intrudes the ultrabasic. The gabbro appears to have been intruded while the ultrabasic was still warm and thus the two cannot be regarded as unrelated. (4) The Kennack gneiss is spatially restricted to outcrops immediately beneath the peridotite sheet. Its absence in any other locality implies a genetic connection that cannot be regarded as unrelated or coincidental. (5) The geology of the Porthkerris region (northeast Lizard) described by Green (1964a) as a small-scale example of a diapiric intrusion comprises no structural features compatible with diapiric intrusion. The ultrabasic at Porthkerris forms part of a heterogeneously deformed layered complex.

All the above evidence suggests that the Lizard complex cannot be regarded as a diapir. The complex possesses a lherzolitic base, overlain by gabbro and cut by dykes which locally comprise 80% of the rock and probably represent the base of a sheeted dyke complex (Bromley 1973).

Pillow lavas and cherts occur in the sedimentary Meneage mélange to the north. These rock types are best interpreted as a dismembered ophiolitic sequence. The Traboe and Landewednack hornblende schists are interpreted as ophiolitic rocks, part of a thrust slice beneath the main ophiolitic nappe which was subjected to a subophiolitic dynamothermal metamorphism. The Kennack gneiss may be an extreme product of this metamorphism.

This ophiolitic interpretation leaves one major problem, the existence of spinel lherzolite at a moderately high level in an ophiolitic pile. The ultrabasic possess an upright N–S trending foliation predating intrusion of the Crousa gabbro. This fabric is interpreted as resulting from an early sub-oceanic deformation, related to a (?transform) fault, up which the spinel lherzolite may have been emplaced tectonically.

Emplacement mechanics of the Chindamora Batholith, Zimbabwe. John G. Ramsay, ETH, Zurich, Switzerland.

The geometric features of a large (50 × 40 km) granitic batholith and its surrounding greenstone belt envelope are described. The batholith is made up of several intrusive components, and an intrusion sequence based on contact relations and xenoliths has been established. The igneous rocks show a local foliation (*S*-fabric) and preferred orientation of minerals. The intensity of this fabric accords with the finite strain determined from xenolith shape analysis. When the strain variations are analysed in detail it appears that the batholith was built up by a succession of magmatic pulses each of which led to a stretching of the previously consolidated igneous material—so called 'balloon' tectonics. Evidence is presented that xenolith deformation commences only when the surrounding igneous material has crystallised, and a method is suggested whereby the position of the surface separating crystallised material from melt at different stages in the plutonic history can be determined. Ductile shear zones are present and their geometry accords well with the shape changes necessary to allow the outer parts of the pluton to stretch.

Some aspects of intrusion by ballooning: the Ardara Pluton. Martin T. Holder, Institute of Geological Sciences, Exeter, England.

The Ardara pluton possesses three phase concentric zoning and a concentric schistosity which contains the long axes of ellipsoidal wall-rock xenoliths. That these xenoliths have been deformed within the schistosity cannot be in doubt as their axial ratios vary with the intensity of the schistosity. Using these xenoliths as strain markers an irregular pattern of flattening strain increasing towards the pluton margin is displayed. The geometrical relationship between the strain at any point within the pluton and its distance from the centre of the pluton implies an inflation of the pluton during intrusion, and this view is supported by the intense deformation of the country rocks bordering the granite mass.

Using Ramsay's (1975) model of spheroidal distortion, not only can the original size of the pluton be determined but so can the entire growth history, since progressively later stages of growth have been 'frozen in' as the granite cooled from the outside.

The results of such an analysis for the Ardara pluton show that not only was the rate of growth of the pluton non-uniform, but that increases in the rate of growth correlate with the appearance of new granite compositions. The granite must, therefore, have been intruded as a series of three separate magma pulses, broadly defined by the three compositional zones in the pluton. Moreover, comparisons between results obtained for three separate traverses in the pluton show that part of the inflation of two of the pulses has not been recorded by internal deformation. This situation is caused by the liquid nature of each intruding pulse creating considerable delay before consolidation of the magma took place. Inflation of the pluton during this interval is not capable of deforming xenoliths and so remains unrecorded. Therefore a greater volume of the pluton was created by inflation than has been recorded by the xenoliths.

Brittle processes acting simultaneously to the ductile inflation increased the volume of the pluton still further, formed apophyses and created large numbers of xenoliths. The relationship of brittle to ductile deformation has been entirely controlled by the relative ductilities of the granite wall rock.

Patterns of interference between granite diapirism and regional deformation. Jean-Pierre Brun, C.A.E.S.S., Université de Rennes, France and Jose Pons, Université de Toulouse, France.

Using maps of cleavage fronts and trajectories, we have demonstrated that some classical Hercynian post-tectonic granites are truly syntectonic. The cleavage trajectory maps may be interpreted as resulting from interference between regional and local strain fields. The latter corresponds to a pluton ballooning (Ramsay 1975, Holder 1979). Typical features of these maps are triple points and geometric continuity between pluton internal fabric and country rock cleavage, even where these are oblique to the contact. Natural examples are presented for coaxial deformation (Flamanville granite, west France) and non-coaxial deformation (Sierra Morena granites, south Spain).

A simple mathematical model of interference between ballooning and simple shear is presented. In this model, the ballooning may be spheroidal (Ramsay 1975, and this report) or ellipsoidal. The model is used to predict: (a) the position of triple points; (b) patterns of principal trajectories and (c) variations of finite strain. A comparison is made with plutons from the Sierra Morena.

The main Donegal Granite: lateral wedging in a syn-magmatic shear zone. D. Hutton, Geology Department, Trinity College, Dublin, Eire.

The Main Donegal granite is a variable granodioritic to granitic body elongated parallel to the NE–SW strike of the Dalradian country rocks in Co. Donegal, Ireland. This granite is radiometrically synchronous (400 Ma, Halliday *et al.* 1980) with other members of the Donegal granite complex which variously exhibit diapirism, cauldron subsidence and stoping as emplacement mechanisms, and yet it is uniquely characterized by a highly deformed envelope, a penetrative strike-parallel internal foliation and a strike-parallel petrographic banding. Previous emplacement models have explained these features by: (a) strike parallel magmatic flow and lateral wedging (Pitcher & Read 1959); (b) *in situ* pure shear deformation with NW–SE horizontal shortening and vertical wedging (Pitcher & Berger 1972) and (c) emplacement in a shear zone (Chenevix-Trench 1975). This paper attempts to confirm and develop the latter hypothesis.

The main granite aureole contains a steeply inclined post regional cleavage (locally D_4) which is synchronous with granite emplacement and metamorphism and occurs in the pluton as the strike parallel foliation (Hutton 1977). Strain analyses of pebbly quartzites in the aureole indicate increasing deformation towards the granite along a $K = 1$ deformation path in which X is sub-horizontal NE–SW, Y vertical and Z sub-horizontal NW–SE. Combined with the clockwise rotation of cleavage strike and the reorientation of stratigraphic markers within the deformed zone. This suggests sinistral simple shear. Northeast of the granite the shear zone narrows and can be traced as far as central Fanad where it appears to be fault bounded. In the southeast the zone swings to NNE–SSW, narrows and runs into south Donegal, where it is overlain by undeformed Carboniferous rocks.

The orientation distribution of extended and shortened magmatic veins within the main granite confirms sinistral rotational strain but suggests a flattening deformation ($K \simeq 0$). This indicates that $K = 1$ simple shear in the shear zone was superimposed on a pure shear granite ellipsoid of $0 < K \leqslant 1$ type in which X was probably vertical, Z horizontal NW–SE and Y horizontal NE–SW. This implies that the granite was constrained to move upwards between the confining walls of the synchronous shear zone. Late stage conjugate crenulation cleavages in the shear zone indicate that the stress orientations for sinistral shear continued to operate after most of the pluton had cooled.

Estimates of the shear zone displacement indicate relatively high values at the northeast end ($>9<20$ km) but much lower values (~ 2 km) in south Donegal. This variation in displacement probably caused the observed bend in the shear zone. Local stress variations around this bent and tapering shear zone can account for the variability in emplacement mechanisms of the other Donegal granites. Space for the main granite itself may have been created by a large shear fracture on which displacement was arrested and which opened during the shear zone distortion.

Diapirism in Northern Tunisia. V. Perthuisot, Paris, France.

Triassic outcrops are numerous in Northern Tunisia. They are especially concentrated northward from a Tunis–Tebessa line. In the southeastern part of this region, the Triassic series forms intrusive bodies cutting through Cretaceous and Tertiary strata. This is the so-called 'zone des diapirs', 40 km wide. In the northwestern part, however, the Triassic forms laminated masses in the lower parts of allochthonous formations.

Both autochthonous and allochthonous formations have been folded together by the last orogenic movements. The main structures in Northern Tunisia date from the Neogene and Early Quaternary, and the formation of nappes from the Middle Miocene.

The Tunisian diapirs generally appear as strongly folded, chaotic masses of gypsum, anhydrite and carbonates. The lack of halite in outcrops is probably due to superficial dissolution (collapse features are common). The contact surfaces between the Triassic and surrounding formations dip gently toward the interior of the diapirs; post-Triassic beds are locally overturned and strongly laminated. Near the diapirs, the thickness of Cretaceous and Early Eocene strata is reduced, indicating permanence of positive structures at the site of the present diapirs.

Important lithological variations occur around the diapirs. For example, Aptian coral reefs appear at the top of diapirs. Emergence of Triassic diapirs is proved by detrital material (pebbles, quartz crystals etc.) in the surrounding sediments. Similar processes occurred during the Cenomanian, Maestrichtian and Lower Eocene in some diapirs but the first diapiric manifestation seems to be of Aptian age.

During this period there was no important folding in Northern Tunisia. The only known deformation seems to be in connection with movements of large basement blocks ('N–S axis' structures in the western part of the Sahel coastal plain). It is very likely that these deep movements were the triggering factors of the first halokinetic uplifts in areas where post-Triassic series were sufficiently thick. This would explain the synchronism of the first uplift during the Aptian and the alignment of diapirs above deep NNE–SSW faults which are common in the African basement.

After the Eocene, the diapiric structures were deformed by the Atlas orogeny and the diapirs were locally amplified. In areas where tectonic movements were more intense, Triassic masses were bent toward the southeast, laminated and dragged under the nappes. Piercement of allochthonous overthrust material occurred locally where great amounts of plastic material were available for a last halokinetic uplift of the original diapirs.

High-level deformation related to mud diapirism: Tertiary of Barbados, West Indies. Carol J. Pudsey, Department of Geology and Mineralogy, Parks Road, Oxford OX1 3PR, England.

The exposed Tertiary succession of Barbados is:

(3) Oceanic Group	U. Eocene to Miocene
(2) Joes River Formation	M. Eocene?
(1) Scotland Group	L. to M. Eocene

The Scotland Group is a 1.5 km thick clastic sequence interpreted as a submarine fan deposit. It was strongly deformed, both during and shortly after sedimentation. An ENE structural trend is present throughout the island and is anomalous in the tectonic setting adjacent to a N–S trending island arc. Deformation increases in complexity from simple, tight gently E-plunging folds at the base, to variably oriented, commonly steeply plunging folds at the top. The Joes River Formation is a mudflow breccia containing small to large blocks of sand in a structureless gritty mud matrix: the whole formation is soaked with oil. It is thought that the minor Scotland Group structures resulted from slumping on slopes partly generated by rising mud diapirs, locally culminating in actual extrusion of hydrocarbon-rich mud. The oblique ENE trend may be related to cross-faulting in the downgoing Atlantic plate, or possibly to subduction of an E–W plate boundary beneath the arc. Terrigenous sedimentation ceased at the end of the Middle Eocene and the pelagic Oceanic Group sediments were deposited. They are undeformed except for ENE faulting and gentle tilting.

Multi-directional lobate folding and movement cells in evaporite gneisses of NE England. C. P. Tully, University of Dundee and Cleveland Potash Limited, U.K.

Sylvinite and halite gneisses of Zechstein 3 (EZ3) exposed in the Boulby Mine (Cleveland Potash Ltd.) in NE England display substantial chemical and physical mobilization. Asymmetric, nappe-like rooted folds, exhibit a systematic variation in geometry parallel and transverse to the local flow direction and result in sub-horizontal sylvinite lobes. The general pattern of variations and reversals in movement directions, as indicated by the asymmetry and one-sidedness of strain shadows or 'comets', and by lobe asymmetry, suggests circulation of the sylvinite and its immediate cover into small-scale multi-wavelength movement cells.

Large scale movement controls are exerted by fault-backed lobes of halite gneiss which locally core the sylvinite structures.

Subsidiary folds are formed most commonly by differential flow in the direction of lobe movement, but can also be nucleated on anomalies in the local structural relief which act as mechanical obstructions.

Some major reverse faults extend at a low angle through the chloride layers of the evaporite group causing locally severe deformation as high as the overlying Triassic.

Pseudo-diapiric deformation of this character extends over large areas of the NE England evaporite basin outside the normally accepted limits of North Sea halokinesis.

Structure at Boulby Mine: genetic model and implications. C. J. Talbot, University of Dundee, Scotland.

In the preceding abstract Tully has outlined the structural pattern visible in Boulby Mine. The Boulby Potash is deformed into a series of rooted sub-horizontal lobes which define a pattern of movement cells which are locally subservient to larger sub-horizontal lobes in the underlying halite.

Various genetic models have been considered for the deformation and it is argued that surface or near surface slumping and lateral shortening are unlikely causes. Gravitational stabilisation of lithological density inversions are not the complete answer, for although inversions are present, the most spectacular deformation affects neutral or stable interfaces (e.g. halite rose and spread in less dense sylvinite). The preferred model will invoke the gravitational stabilisation of density inversions due to thermal gradients in chlorides softened by water liberated by the dehydration of underlying gypsum. In other words, a layer of potash and shale may have thermally convected, and mine sections may be interpreted as indicating that this layer overturned several times in some parts of the mine.

The implications of such a model are explored for both salt and silicate gneisses. After a brief theoretical discussion of the likelihood of thermal convection developing in 'bedded' salt deposits two possible examples of such deformations will be illustrated (Talbot 1978). Comparisons are then drawn between the structures of the gneissic sylvanite at Boulby and some silicate gneisses in East Greenland (Talbot 1979). It is argued that sub-solidus thermal convection is an aspect of crustal gravity tectonics which deserves more attention.

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