Introduction

N. J. Price & K. R. McClay

An International Conference on Thrust and Nappe Tectonics was held, 9–11th April 1979, at Imperial College, London under the aegis of the Geological Society of London and the Geology Department of Imperial College. The conference, which was convened by the editors of this volume, was attended by over 320 participants, of whom less than half came from Britain. The remaining participants came from, or had worked in, every continent in the world (except, as far as we know, Antarctica) so the conference was truly international.

This book contains the proceedings of that conference, the 44 papers given here representing more than 80% of the material presented. The order of the papers in this volume is somewhat different from that in which they were presented at the conference because of the restrictions imposed by having Lecture and Poster Sessions during the meeting.

At the beginning of the conference, it was considered that an attempt should be made to define the structures which were to be the topic of discussion. Consequently, John Dennis took his courage in his hands and proposed, for the consideration of the participants, a definition of the words 'Thrust' and 'Nappe'. The ensuing discussion was lively and entertaining.

An edited version of this discussion and the written contributions which followed are collected by K. R. McClay and presented as the first paper in this volume and deals, in addition to the definition of thrusts and nappes, with other terminology used in this volume.

Then follows the first group of papers which review the environments and modes of emplacements of thrusts and nappes. Bally reviews the characteristics of gravity-glide structures as found in deltas and along continental margins. He concludes that, except in special cases, such as the Heart Mountain Thrust, Wyoming, and 'high-level' structures (see Graham, this volume), gravity-gliding is not the mechanism by which most thrusts and nappes are emplaced. Other authors in this group compare mechanisms or discuss a single mechanism from an analytical point of view. Most of these papers are mainly concerned with the mechanics of thrust emplacement. However, the study by Ramberg ensures that the emplacement of fold nappes is not completely neglected. We shall comment on this group of papers later in the introduction.

The movement of nappes over their footwall rocks produces 'fault rocks' and fabrics which are the subject of the second group of papers. It is shown that 'fault rock' studies may provide important information regarding the environmental conditions obtaining during thrust emplacement (see Aprahamian & Parais; Behr *et al.* and Sibson *et al.* this volume).

Of the remaining papers, the local evidence adduced often has an important bearing on one or the other of the theoretical aspects discussed in the first group of papers. It was, however, considered that, because a single paper could correlate with more than one theoretical hypothesis or theory, it would be impossible to group and juxtapose the field-orientated studies with the theoretical ones. Consequently, the field studies are, as far as possible, treated on a regional basis. In so doing, we start with the 'Old World' and then move to the Americas, the 'New World'. (Papers relating to areas in Africa and New Zealand are more conveniently placed in the section dealing with fault-rock products.)

In the studies situated in the 'Old World' we have, in general, migrated from NW to SE; from Scandinavia, Britain and the Alps to the East Indies. In the 'New World' the studies which have been carried out in the Canadian Rocky Mountains and the adjacent areas in the U.S.A. form a particularly significant group of papers. From Canada we move via the Appalachians to South America and the southernmost tip of Chile and Patagonia.

The reader will realize that this volume is not a textbook, nor is the coverage of the subject matter encyclopaedic. The contents are dictated by chance in that we had to rely on the topics which were presented. Hence, the regional studies are somewhat scattered; reflecting the increased attention which is paid to detailed studies of geometries and mechanisms.

Only the Canadian Rocky Mountains receive a reasonably widespread series of studies. The same problem obviously applies to the theoretical papers. The theoretical mode of emplacement of thrusts and fold nappes is dealt with in a number of papers in this volume. The statements and opinions expressed are sometimes contradictory and may lead to a confused state in the reader's mind. This situation, in part, reflects the state of the art. However, in an attempt to clarify the issue, the editors wish to make a few comments and offer a few opinions.

Mechanisms of thrust-nappe emplacement

The various concepts considered in this volume are that thrusts and nappes result from one another or, possibly, a combination of the following mechanisms:

1. The structures were 'pushed' from behind;
2. the structures were emplaced by gliding down an inclined plane under the action of gravity;
3. the structures are induced by gravitational spreading, possibly accompanied by an initial phase of diapirism.

(A fourth, contributory mechanism, which is not studied theoretically but is demonstrated to be viable (see Winslow), is that of shortening of the basement relative to the cover.)

In all the various theoretical studies, the 'rock masses' forming the nappes are considered to be homogeneous and isotropic and to conform to (1) elastico-brittle (2) Newtonian-viscous or (3) perfect plastic behaviour forms. In fact, the rock mass, particularly in the upper levels of the crust, will be anisotropic and therefore mechanically heterogeneous, so that its behaviour may approximate to none of the ideal types (elastic, viscous or plastic) noted above.

The reader must, therefore, exercise judgement should he wish to apply one of the theoretical models to a specific field example.

In some geological settings, e.g. deformation in deltas (see Mandl & Crans) or the emplacement of some high-level Alpine nappes (see Graham), the gravitational gliding mechanism is an appropriate one. One then needs to consider the mode of behaviour of the emplaced material. For soft sediment deformation of delta material, the viscous model (Wiltschko) or the weak plastic model (Mandl & Crans) may be appropriate; while for emplacements of high-level nappes the elastic-brittle model can be chosen.

Where the basement and glide surfaces slope, for long distances, against the direction of nappe or thrust emplacement, the gravitational gliding mechanism seems inappropriate (Bally, this volume) and one must turn to the gravitational spreading or the push from the rear mechanisms (Smith, Murrell etc., this volume).

However, even in these situations, one must bear in mind that the increase in vertical loading which takes place as the thrust develops will result in isostatic adjustment and depression of the thrust plane. In these circumstances, because the movement of the thrust block 'up' the basement slope can be largely, or even totally, off-set by the depression of the basement, the centre of mass of an individual thrust wedge, or unit, may remain at the same level, or even be depressed. Hence, an element of gravity-gliding may be maintained in the mode of emplacement even if the dominant mechanism is gravitational spreading, or push from the rear.

The evidence of rock mechanics experiments permits one to infer that most competent rocks at high crustal levels are too strong to flow at the differential stress that is required for the gravitational spreading mode of emplacement. Such a mode of emplacement can only become important where such rocks are hot and therefore ductile.

It can be argued that even in high level environments the rock mass may achieve 'macroscopic' ductility through the existence of a multiplicity of fractures. Such a conceptual model would liken the behaviour to that of dry sand. Each grain exhibits great strength relative to the pile of sand, which possesses 'macroscopic' ductility. However, the analogy is not a good one. The ductility of sand is related to the void spaces, the geometry of the grain contacts and the ability of a large proportion of these contacts to move at any one instant. None of these features is representative of conditions in a thrust belt. Consequently, for the upper level structures, such as those exposed in the Canadian Rockies, one is left with the 'push' mechanism. Immediately one becomes involved in the old debate regarding the permissible length of thrust blocks. The most outstanding papers on the topic of overthrust mechanics were, without doubt, those written by Hubbert & Rubey in 1959. In these companion papers, they draw to the attention of geologists the important role of fluid pressure in reducing the effective stress normal to the thrust plane, so that frictional resistance to shear along the plane was reduced. In the following two decades, the concepts proposed by Hubbert & Rubey were debated and modified. It may come as a surprise to the reader, therefore, that the concept of high fluid pressure receives relatively little emphasis in the papers in this volume. High fluid pressures are not neglected, of course; they are considered by Gretener and by Murrell and are an important element of the arguments presented by Mandl and his co-authors. More often one will note in this volume that the authors require that 'the resistance to shear movement along the thrust plane be small', often of the order of about 10–20 bars.

Nature of the thrust or décollement surface

A low shear resistance at the base, or sole, of a thrust nappe of 10–20 bars can only exist if (a) a high fluid pressure exists below the 'thrust block' or (b) the thrust moves over a very weak material with a shear strength of only 10–20 bars. Such weak materials could include clays or evaporites. Drained clays under high confining pressures are capable of sustaining relatively high shear stresses. Hence, a clay layer will meet the requirement of low shear strength only when it approximates to the undrained state and the interstitial pressure is so high that the effective confining pressure is reduced to a few tens of bars (i.e. $\lambda = p/\sigma_v \approx 0.9$). If slip takes place on evaporites, the gypsum/anhydrite dehydration reaction would also generate a comparable situation with a high interstitial fluid pressure.

The evidence of metamorphism by frictional heating during thrust movement (Apprahamian & Parais) is compatible with moderate, average fluid pressure ($\lambda = 0.7 \rightarrow 0.8$) on the sole thrust. There may, however, be problems if clay minerals are used as indicators of this type of metamorphism, particularly when textural changes are involved.

For the more deep-seated structures, the nappes may glide over a thin layer of fine-grained material, such as 'lochseitenkalk', which exists below the Glarus Nappe (c.f. Schmid *et al.*, this volume). Theoretical (Rutter 1976) and experimental studies (Schmid 1976) have demonstrated that such fine-grained material (in this case calcite) may deform by diffusion/grain boundary sliding processes at low differential stresses and at temperatures greater than 200°C. Hence, there is no inherent reason for invoking high fluid pressures in the deformation of such materials, but it must be noted that the presence of pore fluids tends to accelerate diffusion deformation processes.

The problem of the generation of such weak layers is indicated by Murrell (this volume), who suggests that an early phase of cataclasis may sometimes be involved. Unfortunately, evidence of such cataclasis would be destroyed by subsequent diffusion processes.

Alternatively, initial dislocation creep deformation may give rise to a reduction in grain size by dynamic recrystallization. The new small grains can then deform at low differential stress by diffusion/grain boundary sliding. Such a process, which has been invoked for the formation of mylonites (White 1976), may thus produce a weak plastic layer at the sole of the thrust/nappe.

However, the processes related to high fluid pressure and to crystal plasticity are not mutually exclusive. Indeed, they are probably often complementary. Evidence of such combined effects may be inferred from Ramsay's paper on the Helvetic Nappes (this volume). These Helvetic Nappes deformed in a ductile manner. However, the 'crack' of the 'crack-seal' mechanism can be attributed to hydraulic fracture, and this attests to, at least, moderately high fluid pressures existing during nappe deformation.

Shape and size of thrust units

There is a tendency, followed in various papers in this volume, to consider the displacement of wedge-shaped blocks rather than the rectangular, 'boot-box' type unit originally invoked by Hubbert & Rubey (1959). For a given set of parameters, strength, stress conditions etc., this automatically doubles the size of thrust block (of comparable thickness/average thickness) that can be moved. Moreover, rock mechanics data (see Fyfe *et al.* 1978) permit one to infer that, at high levels in the crust, some massive limestone and arenaceous units are capable of sustaining differential stresses up to, or even somewhat beyond, 1 kbar (the comparable figure for rock strength taken by Hubbert & Rubey was ≃700 bars). If we combine these factors of shape of thrust block and possible differences in rock strength, we may infer that a wedge-shaped thrust block may be between three and four times longer than that of the rectangular blocks postulated by Hubbert & Rubey. Indeed, 'cold, dry crystalline rocks' can support a differential stress of several kilobars so that a wedge of such material could be thrust eight to ten times further than that indicated in Hubbert & Rubey's analysis. Hence, the emplacement of thrust wedges with an extent of 50–100 km is not a great problem, even when the fluid pressure at the base is only moderately high.

Fold nappes

Theoretical models dealing with the emplacement of fold nappes have received relatively little attention in this volume. This reflects both the difficulty of the analytical and model problem and the paucity in the general literature of such studies. Most of the model studies dealing with this problem have been produced by Ramberg and his school. The similarity of geometry between their model structures and natural fold nappes is persuasive. His main thesis is, of course, that fold nappes result from density inversion, instability and diapirism. In this volume he also indicates the possible importance of gravitational spreading as a mechanism of emplacement.

Because he is dealing with the development of relatively deep-seated structures, the physical properties of rocks are likely to be such that they will flow under low differential stresses: which is one of the requirements of the gravitational spreading mechanism.

However, high ductility and low strength will only be maintained in the so-called competent rocks while they are at high temperatures and confining pressures. That is, we are not dealing with surface extrusion but possibly a form of intrusion. Are fold nappes analogues of laccoliths? Certainly the fold nappe flows over the 'floor'. Of course, it may also displace the floor, so that a succession of nappes are formed 'piggy back' fashion (see Ramsay, this volume). What happens at the roof of the nappe? Does differential movement between fold nappe and roof take place, or does the fold nappe carry the roof with it, so giving rise to considerable extension of the cover rocks?

There is certainly abundant evidence of normal fault development in and above fold nappes (see for example the Glarus Nappe). These normal faults are often of very small displacement and are, therefore, more likely to have developed during subsequent uplift rather than during the emplacement of the fold nappe. In addition, it is often difficult to relate these extensional events directly to the thrusting.

It is probable, therefore, that differential movement of the nappe relative to its roof has occurred. Cleavage in the upper region of the nappe is sometimes inclined away from the 'root' (Hossack, pers. comm.) and this can be explained in terms of differential movement of the nappe relative to the roof. Even a lack of evidence for such differential movement does not necessarily negate the concept. High level thrust nappes can be emplaced without granulation etc., provided that the fluid pressure below the nappe is high. Fold nappes may similarly be emplaced without granulation etc., if the fluid pressure at the upper interface of the nappe is high. Such conditions are not incompatible with the evidence adduced by Ramsay in this volume.

Hence, it would appear from these arguments and those presented in this volume by Smith, that both fold and thrust nappes may be driven by the forces associated with diapirism and intrusion.

Basement relationships

One of the key questions in thrust/nappe regimes has often been that regarding the degree of basement involvement and what happens to the structures at depth. Basement involvement is well illustrated in classic Alpine fold nappes. Decoupling within the basement is found in the Moine Thrust Zone (Coward & Kim, this volume). Decollement above an unaffected basement is well defined in the Canadian Rocky Mountains (Price, this volume). In many situations, however, the relationships regarding the nature of the faults at depth are uncertain.

Deep seismic reflection profiling, cf. the COCORP project, (see Brewer *et al.*, this volume) may provide some exciting answers to these questions. The Wind River Thrust (Wyoming) has been shown to be a relatively steeply dipping structure extending to 30–35 km depth. In contrast, results of seismic work across the Appalachians (Brewer *et al.*, this volume and Cook *et al.* 1979) indicate that the Piedmont is allocthonous with thrust displacements of at least 250 km. Clearly, more exciting discoveries are at hand and the application of geophysical techniques to the study of thrust belt geometries promises new information which may, in certain areas, (cf. the Moine Thrust Zone) resolve the thick versus the thin-skinned debate.

The reader will most likely conclude from the collection of papers presented in this volume, that our knowledge of the geometry and the mechanics of thrusts and nappes still needs to be improved. Nevertheless, it is apparent that the problem is now tractable and we have the elements necessary for its solution within our grasp.

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N. J. PRICE, Department of Geology, Imperial College, London SW7 2BP.
K. R. MCCLAY, Department of Geology, University of London Goldsmiths College, New Cross, London SE14 6NW.