Structural development of the Grampian Highlands

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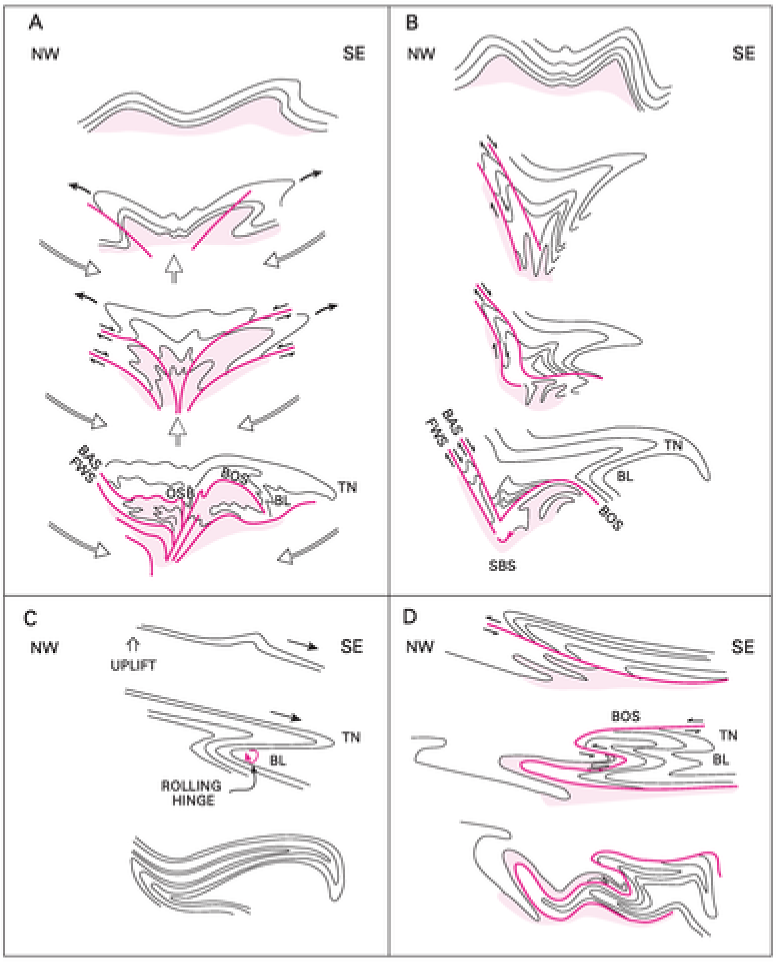
Early mapping in the Grampian Highlands concentrated on establishing the geometrical form of folds and other structures. Later, more-detailed work led to the interpretation of temporal structural sequences in individual areas. It was only when such studies became widespread, and attention was directed towards correlating groups of structures and phases of deformation between areas, that it became possible to speculate on the overall history and mechanism of regional deformation. Even today, such interpretations of structural development are based principally on the better known areas of the South-western, Central and Southern Highlands with much emphasis on the development of the Tay Nappe.



Alternative models for the structural development of the Grampian Highlands fold belt. P915431.

The early regional syntheses of Bailey and others made little comment on the mechanisms of nappe development apart from an 'eddy' theory in which NW-directed movements in the lower structural levels are compensated by movements in the opposite direction at higher levels (Bailey, 1938). South-eastward gravity sliding of the higher nappes was first proposed by Cummins and Shackleton (1955) and has subsequently been invoked by several authors in conjunction with various models. The concept of a root zone, from which nappes were expelled in opposing directions, was first introduced by Sturt (1961) and divergent 'mushrooms' or 'fountains' of nappes have dominated theories for many years. More recently emphasis has been placed on the importance of NW-directed primary structures, from which SE-facing folds such as the Tay Nappe developed by back-folding. Fundamental to all these theories have been discussions on the origin and geometry of the low-angled zones of high strain and dislocation which have been variously attributed to synsedimentary growth faults, early tectonic slides, later tectonic thrusts or polyphase combinations of these. The later, post-nappe phases of deformation and uplift are more clearly defined and their history has generated less debate than the early phases.

Root-zone and 'mushroom' models

The divergence of NW- and SE-facing nappes on either side of the D_1 Loch Awe Syncline led to the suggestion that the nappes were generated by lateral compression of an underlying anticlinal root-zone. From here nappes were expressed sideways as primary recumbent folds separated by slides, giving the observed mushroom-like structure (P915431A). The root-zone was originally thought to be exposed in the Tummel Steep Belt, which was believed to lie beneath a north-eastern continuation of the Loch Awe Syncline (Sturt, 1961; Harris, 1963; Rast, 1963). However, this steep belt was subsequently shown to be a zone of tight D_3 folds which refold the primary recumbent structures. Furthermore the nappes on the north-west side of the steep belt, such as the Atholl Nappe, are now known to be south-east facing over much of the Central Highlands, so that the major divergence actually occurs much farther to the north-west, in the Ossian–Geal Charn Steep Belt (Thomas, 1979; 1980). Thomas therefore envisages a root-zone within the Ossian–Geal Charn Steep Belt, from which the large-scale Atholl and Tay nappes advance to the south-east, whilst comparable Mamore, Kinlochleven and Ballachulish nappes advance north-westwards. Major dislocations developed between the nappes as older rocks were brought up from below and hence slides commonly constitute the Grampian/Appin group boundary. Primary arching of the recumbent structures was particularly strong at deeper structural levels giving rise to the Drumochter and Glen Orchy domes, which had a marked influence on later phases of deformation.

In most areas the nappes were modified by a coaxial D_2 phase of folding. To the north-west of the Ossian–Geal Charn Steep Belt, this phase of folding strongly modified the attitude of the NW-facing nappes, producing upright folds such as the Stob Ban Synform as well as more asymmetrical folds such as the Kinlochleven Antiform and the Blackwater folds. However, to the south-east the Tay Nappe continued to develop. It became further separated from the Atholl Nappe by renewed movement on the Boundary Slide and was transported south-eastward under the influence of deep-seated D_2 simple shear on the lower limb (Harris et al., 1976). However, the upper limb and hinge-zone of the Tay Nappe, as seen in the Aberfoyle Anticline Complex, remained little affected by the D_2 movements. The Ben Lui Syncline, which probably separated the Tay and Atholl nappes following the D_1 movements, became marked by an antiformal complex of D_2 folds overlying the Boundary Slide.

Root-zone and ‘fountain’/nappe-fan models

The concept of a root-zone was adopted by J L Roberts and J E Treagus in a model, originally based upon work in the South-west Highlands (Roberts, 1974; Roberts and Treagus, 1977c), but subsequently expanded to encompass observations in the Central Highlands and Schiehallion area (Roberts and Treagus, 1979; Nell, 1986; Treagus, 1987). In this model, early nappes are considered to have originated due to lateral compression of a root-zone beneath the Loch Awe Syncline, which is deflected around the north-west of the Glen Orchy Dome into the area of the Ossian–Geal Charn Steep Belt (Roberts and Treagus, 1979). Whereas most earlier theories, and that of Thomas (1979; 1980), envisaged a primary lateral development of recumbent nappes, Roberts and Treagus consider that the first major folds were essentially upright structures which fanned outwards above the root-zone (the ‘nappe fountain’). The major slides were initiated during this D_1 phase. As the folds tightened, the fan collapsed under gravity to produce recumbent structures (P915431B). New fold hinges formed by this collapse became the D_2 folds, the most important of which, the Ben Lui Fold, has the overall effect of ‘righting’ the inverted limb of the Tay Nappe. According to Nell (1986) and Treagus (1987), the D_2 folds were overturned towards the north-west at deep structural levels where they were associated with NW-directed simple-shear along the Boundary Slide and related dislocations. At higher levels, SE-directed simple-shear, also of D_2 age, produced the intense deformation of the inverted limb of the Tay Nappe in the Flat Belt as described by Harris et al. (1976) and Mendum and Fettes (1985), echoes of the ‘eddy’ theory of Bailey (1938).

Although Roberts and Treagus describe the nappe development as a two-stage process, recorded as separate events in the rocks of any one area, it is difficult to imagine nappes actually forming in this manner. It therefore seems more likely that the upward expulsion of upright primary folds, the tightening and the subsequent lateral gravity collapse were all part of a continuous process as described by Anderton (1988).

The most recent versions of this model, described by Nell (1986) and Treagus (1987), are based upon accurately constructed cross-sections through the Central and Southern Highlands. They include a reappraisal of all the earlier work by Roberts, Treagus, Thomas, Harris and others and are the best available syntheses at the time of writing.

Gravity sliding and ‘rootless’ nappe models

Although models involving root-zones have dominated the literature for many years, the tightly folded nature of the steep belts makes it very difficult to prove that they involve primary D_1 folds which can be confidently identified as roots to the flanking recumbent nappes. Furthermore, several authors are opposed to the overall concept, finding it difficult to see how such an enormous volume of nappes can be ejected from such a narrow root zone (Shackleton, 1979; Coward, 1983).

The formation and lateral movement of recumbent nappes by deep-reaching gravitational flow were first suggested by Cummins and Shackleton (1955), based upon the attitude and character of the Ben Lui and Ben Udliadh folds. Studies of the Tay Nappe revealed evidence of extensive D_2 simple shear of the lower limb (Harris, Bradbury and McGonigal, 1976). This in turn led to a model in which the nappe nucleated at a high level (with no root) and moved south-eastwards on a shear zone above a ‘rotation zone’ located in the Tummel Steep Belt (Bradbury, Harris and Smith, 1979). The ‘rotation zone’ acted as a rolling hinge which connected the inverted limb of the Tay Nappe, through the Ben Lui Fold, with the underlying right way-up succession (P915431C). Movement of the nappe was seen as being due to gravitational instability, possibly accentuated by a density inversion of the Dalradian succession, whereby dense metagreywackes and basic igneous rocks of the Argyll and Southern Highland groups overlie less dense carbonates, pelites and siliceous rocks of the Grampian and Appin groups. This model was extended by Shackleton (1979) who envisaged a general gravity-operated, down-plunge flow of both D_1 and D_2 folds away from a Central Highlands plunge culmination, south-westwards towards a plunge depression in the Loch Awe area. There is, however, no evidence to support this down-plunge flow and much contradictory evidence exists.

Other authors, whilst not attributing the whole structural development of the region to gravity gliding, do accept the possibility that gently dipping gravity structures may have contributed to lateral flow at high structural levels (Anderton, 1988). Indeed, the continued south-eastward translation of the Tay Nappe during D_2 deformation in the model of Thomas (1980), which accepts the deep-seated simple shear described by Harris et al. (1976), is suggestive of a gravity structure.

North-westward movement and backfolding models

Wider considerations of the tectonic evolution of the whole of the Scottish Caledonides emphasise the north-westerly overturning and movement of most major structures (Coward, 1983; Dewey and Shackleton, 1984; Watson, 1984). Some detailed structural models of the Grampian Highlands also include a strong element of NW-directed thrust movement on such structures as the Fort William, Ballachulish and Boundary slides, possibly rising from a fundamental basal or ‘floor thrust’ (Bradbury, 1985; Nell, 1986). North-westerly movement has been demonstrated in the Eilrig Shear Zone (Phillips et al., 1993) but in many areas, particularly in the Western Grampians Complex, major dislocations have the geometry of extensional faults with younger rocks emplaced on older, and it has been argued that they may have originated as growth faults during basin formation (Soper and Anderton, 1984; Anderton, 1988). It is therefore necessary to postulate reactivation and reversal during the subsequent compressional phase. Anderton (1988) argues that this need not necessarily involve significant north-westerly tectonic transport.

It is possible that the SE-facing folds, such as the Tay Nappe, originated as high level ’rootless‘

gravity nappes triggered by the thrusting and consequent crustal thickening. However, in many current models the distinction between these and the NW-facing folds is of lesser significance. Although they may well have originated as primary structures, their current facing direction is probably a result of backward gravitational collapse or of subsequent deformational events.

Both Treagus (1987) and Anderton (1988) suggest that the south-eastward translation of compressional upright folds took place at high level, above NW-directed thrusts. Other authors envisage large-scale isoclinal backfolding of an original NW-facing Tay Nappe by the D_2 Ben Lui Folds, during continued NW-thrusting (Bradbury, 1985; Nell, 1986; L M Hall, in Fettes et al., 1986) (P915431D).

Accepting an overall north-westerly movement enables the construction of more realistic continuous structural cross-sections from the Highland Border north-westwards across the Great Glen to the Moine Thrust Zone (P915432), where Caledonian structures override the foreland (Coward, 1983; Fettes et al., 1986). The structural development of the whole of the Scottish Caledonides can be modelled as a complete entity and thereby be more easily related to even wider plate tectonic reconstructions (Garson and Plant, 1972; Lambert and McKerrow, 1976; Phillips et al., 1976; Watson, 1984; Dewey and Shackleton, 1984; Soper, 1988).

Post-nappe deformation and uplift

Following the development of the primary nappes, the later phases of defor-mation were, with notable local exceptions, generally less intense and produced more-open, near-upright structures trending between ENE and north-east. Refolding and overprinting by still later fabrics are generally only of local extent. Although the numbering of later phases is frequently inconsistent and complicated by local variations, most authors are agreed on the overall sequence of events.

In most areas the peak of metamorphism is coeval with or immediately predates the D_3 deformation (the Grampian Event of some authors; P915452) and later deformations are associated with retrograde effects. Most authors therefore attribute the initial D_4 deformation to the commencement of late-orogenic isostatic uplift (Watson 1984; Harte et al., 1984; Dempster, 1985). The scale, monoformal nature and lateral continuity of many of these early D_4 folds, especially the Highland Border Downbend, suggest that they are controlled by a parallel series of major basement lineaments. Between these lineaments episodic uplift of crustal blocks at different rates in both space and time generated the pattern of contrasting flat and steep belts which now dominates the Southern Highlands. Minor folds and crenulation cleavages, which locally overprint the early D_4 major flexures, can be traced north-westwards across the flat belt, where they are seen to be related to broad, upright folds such as the Ben Lawers Synform. These are taken to indicate a late D_4 compressional phase which postdates the early D_4 uplift event. Roberts and Treagus (1977c; 1979) and Treagus (1987) also consider that the Drummochter and Glen Orchy domes are late D_4 structures (their D_3). The D_4 deformation is also probably responsible for the steepening of major D_2 (and/or D_3) fold limbs in the Knapdale and Tummel steep belts.

Other late major folds, such as the Bohespic Antiform and Errochty Synform, which have a more north–south trend, are attributed to D_4 (his D_3) by Thomas (1979; 1980), but are considered to belong to a later phase by Treagus (1987). The Turriff Syncline, Buchan Anticline and other late NE- to NNE-trending open folds in the North-east Highlands, together with renewed movements on major shear-zones such as those of the Portsoy Lineament, may also belong to this phase. Still later structures tend to be small-scale, brittle open box folds and conjugate kink-zones, although NW-trending flexures and monoforms affect the limbs of the Errochty Synform (Thomas, 1980) and Roberts (1974) describes a complex sequence of late structures from the South-west Highlands.

Full list of references