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# The structure of mountain fronts

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**Abstract**—Commonly the part of a mountain front which is visible at the surface consists of foreland-dipping thrust belt rocks elevated above their regional structural position and overlain more or less conformably by molasse. Several explanations for their geometry are possible. (1) Major detachments exist within or beneath the molasse resulting in transport of the foreland basin. Examples of this geometry come from the Swiss Molasse Plain, the Southern Pyrenees and the Mackenzie Mountains of Canada. (2) Displacement is lost on major backthrusts beneath the frontal monocline. Examples cited here are the Rockies of Alberta, the Sulaiman Ranges of Pakistan, the Mackenzies, and the Andes in Peru. (3) Thrust sheets travelled over an old land surface and syntectonic molasse contemporaneously offlaps the topographic high of the thrust front. This phenomenon occurs along the Alpine thrust front in Haute Provence. (4) The frontal fold represents deformation above a large-scale thrust tip. No unequivocal example of tip line strain at this scale has been recorded although this type of deformation may occur in the Brooks Range of Alaska. In many areas mountain fronts show a combination of these idealized geometries.

## INTRODUCTION

THE APPLICATION of thin-skinned structural models to the interpretation of mountain belts around the world has undergone a renaissance in recent years due in no small part to the work of Elliott and his co-workers. The increase in knowledge and understanding has been accompanied by the recognition of both complexities and variations that occur on the basic piggy-back, foreland-propagating, thin-skinned style of deformation, as outlined by Bally *et al.* (1966), Dahlstrom (1969) and Boyer & Elliott (1982). In recent years attention has focused particularly on the structure and internal geometry of the frontal structures of mountain belts (e.g. Jones 1982).

In many areas the mountain front consists of foreland-dipping thrust-belt rocks elevated above their regional structural position often by several kilometres, in a major monocline. This structure is overlain more or less conformably by molasse (Fig. 1). This type of structure causes a problem in attempting to balance sections since without outcropping thrusts it is often difficult to envisage how the major horizontal displacements, associated with the elevation of the mountains, are transferred to the surface. Four explanations of this phenomenon appear possible.

### *Sub-molasse detachments (Fig. 2a)*

Some monoclinal mountain fronts clearly do not represent deformation fronts. The detachment on which the mountain front culmination is built continues beneath undeformed molasse of the foreland basin to reach the surface some distance further into the foreland. The undeformed sediments of the basin must therefore be transported en masse by a distance equivalent to the shortening seen in the deformed rocks where this detachment crops out in the foreland. Examples of this come from the Jura and Swiss Plain, the Sierra Ranges and South Pyrenean basin and the Mackenzie Mountains area of Canada.

### *Backthrusts (Fig. 2b)*

In areas where there is significant deformation ahead of the mountain front monocline, bulk transport of the molasse basin above a simple thrust flat provide an elegant solution to the balance problem. However, in many areas it can be demonstrated by seismic reflection that there has been no significant deformation ahead of the frontal monocline whilst in other areas it appears that although some deformation has propagated into the foreland this shortening is not nearly great enough to account for the elevation of the mountains.

This situation is typified by the Triangle Zone (Gordy *et al.* 1977) which forms the western limb of the Alberta Syncline at the deformation front of the Rocky Mountain Foothills. Jones (1982) has discussed this structure at

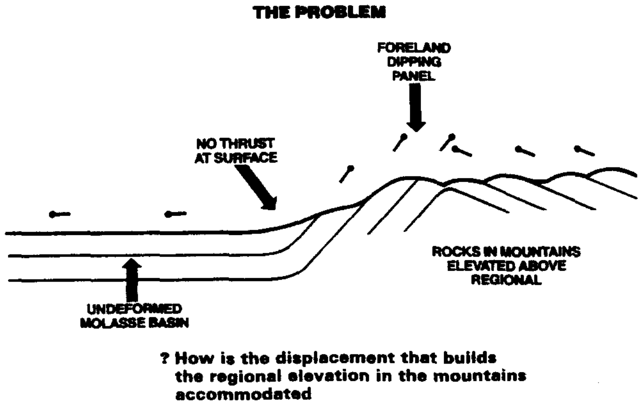


Fig. 1. The Problem. Foreland dipping rocks are elevated above their regional level and overlain conformably by molasse.

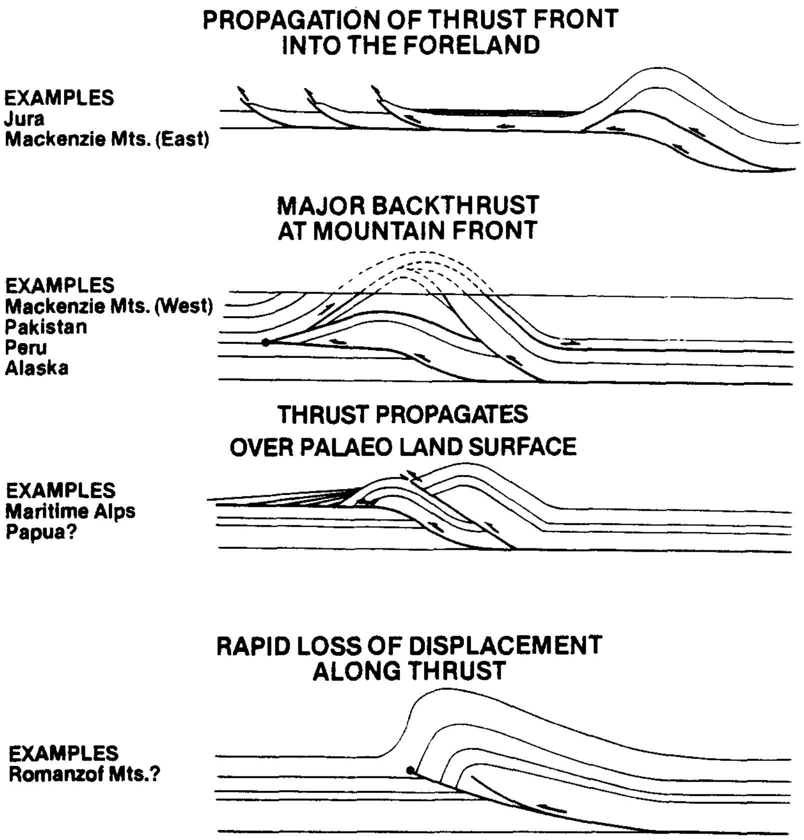


Fig. 2. Four possible solutions to the problem posed in Fig. 1. (a) Sub molasse detachment implying transported molasse basin. (b) Major backthrust at the mountain front. (c) Buried emergent thrust. (d) Tip line strain.

length and demonstrates with the aid of seismic reflection data that the Triangle Zone is formed by a wedge shaped duplex that underthrusts the Tertiary and Cretaceous sediments of the Albertan foreland basin. The emplacement of this duplex beneath a major east-dipping backthrust has lifted passively the overlying sediments without significant horizontal translation, thus creating the steep easterly limb of the Alberta Syncline. This type of structure has been termed a *passive-roof duplex* (Banks & Warburton this issue).

*Buried emergent thrusts (Fig. 2c)*

No displacement problem exists at a thrust front if thrusts are emergent and culminations travel across the old land surface. Such a land surface now appears as a molasse bedding plane and the thrust culmination becomes mantled by later onlapping molasse. In this instance, foreland dips in the molasse sequence adjacent to the mountain front are explained by original sedimentary dips associated with outwash fans and by accentuation of these dips due to differential compaction of the sediments, which necessarily are finer grained and hence more compactable towards the foreland. Examples of this type of structure are cited from the Provençal Alps and the Sierras Ranges of the Southern Pyrenees.

*Tip line strains (Fig. 2d)*

Rapid loss of displacement of a sole detachment has been observed to produce small scale analogues of the crustal-scale monoclinal folds described here (Chapman & Williams 1984). While it is often not possible, in the absence of seismic data, to discount this as the mechanism of formation of mountain fronts, the application of the model presents a major problem. The rapid loss of displacement towards the thrust tip implies large-scale ductile shortening in the hangingwall rocks, in many cases in excess of 50%. Obviously shortening should produce recognizable effects such as stratal thickening and the production of a steep cleavage. Generally such effects have not been observed in examples we have examined. However, a possible example of this mechanism is described from the Brooks Range of Alaska.

The purpose of this paper is to illustrate these phenomena with examples from the Alpine–Himalayan chain, the North American Rockies and the Andes, with a view to identifying the diagnostic characteristics of each type of mountain front. In reviewing these geometries in many localities it has become clear that the style of any mountain front changes rapidly both along its strike and in the transport direction. In general the underlying controls of these changes can only be speculated upon but in a number of examples the stratigraphic pinch-out of evaporitic horizons closely coincides with dramatic changes in structural style.

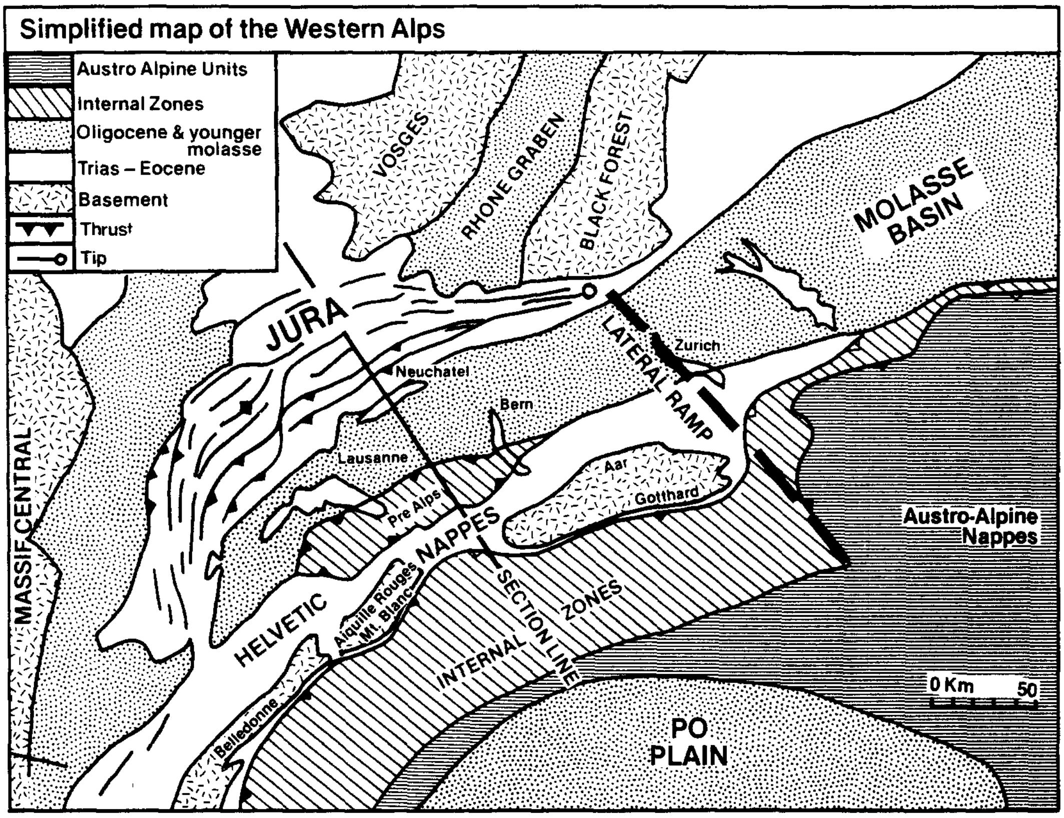


Fig. 3. Structural outline map showing the Jura in relation to the other units of the Western Alps.

## MOUNTAIN FRONTS

### *The Jura and the Northern Alpine molasse basin (Fig. 3)*

The interpretation of the Jura structure given by Boyer & Elliott (1982) is followed here. The Trias detachment from which the Jura thrusts splay, is assumed to continue beneath the molasse of the Swiss Plain and to form the basal detachment on which the external crystalline massifs of the Alps are built (Fig. 4). The molasse basin has thus been transported a distance equivalent to the shortening observed in the Jura, that is about 30 km (Fig. 5).

The Jura fold belt dies out both to the south and to the north-east, just south of the Black Forest (Fig. 3). No significant shortening exists on the north side of the molasse basin east of Zurich. This part of the basin cannot, therefore, have been transported and one might expect a different mountain front geometry on the southern side of the molasse basin in this eastern region. Certainly, the sections of Bachmann *et al.* (1982) across the eastern thrust front imply a structure akin to the Triangle Zone of Alberta beneath the molasse.

It appears likely that this change in structural style along strike from a transported basin to what may be a mountain front backthrust is due to the absence of salt

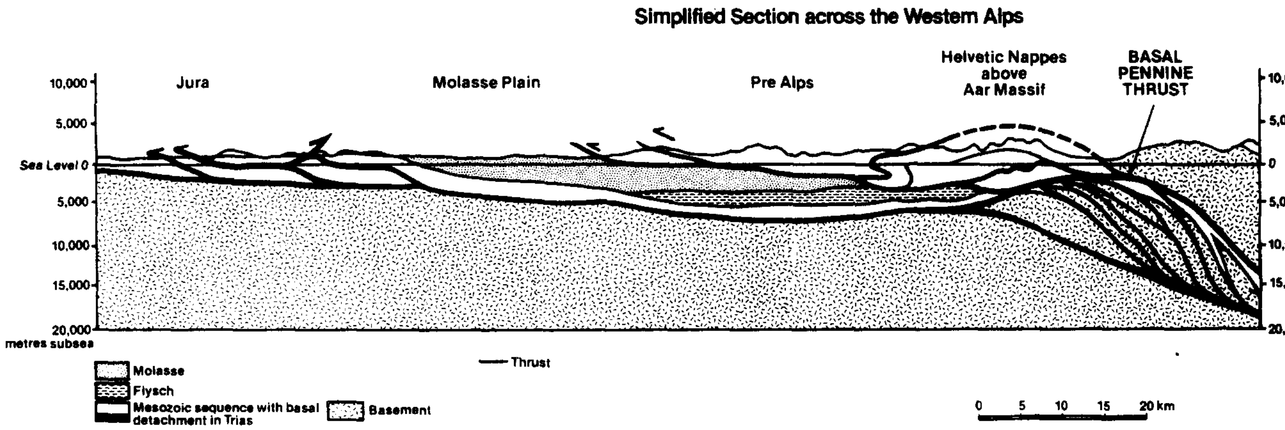


Fig. 4. Simplified structural cross-section from the external Alps to the Jura Mountains, illustrating the transported nature of the Northern Alpine Molasse Basin. (For location of cross-section see Fig. 3) modified from Boyer & Elliott 1982.

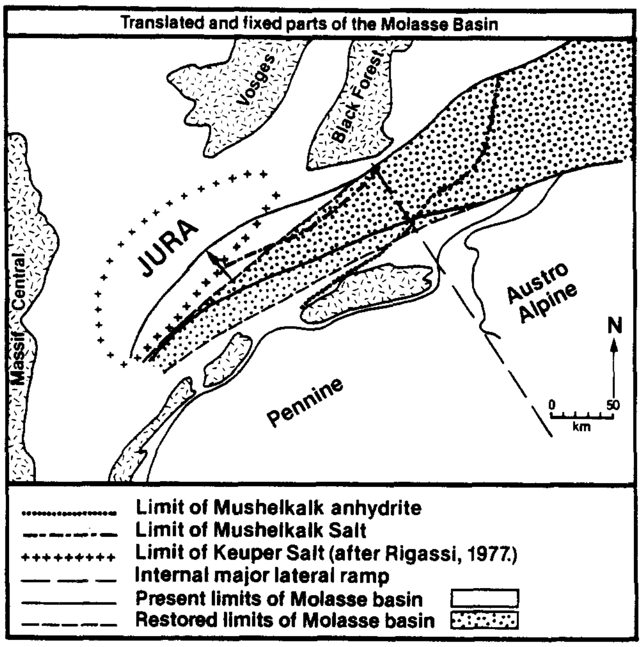


Fig. 5. Translated and fixed parts of the North Alpine Molasse basin.

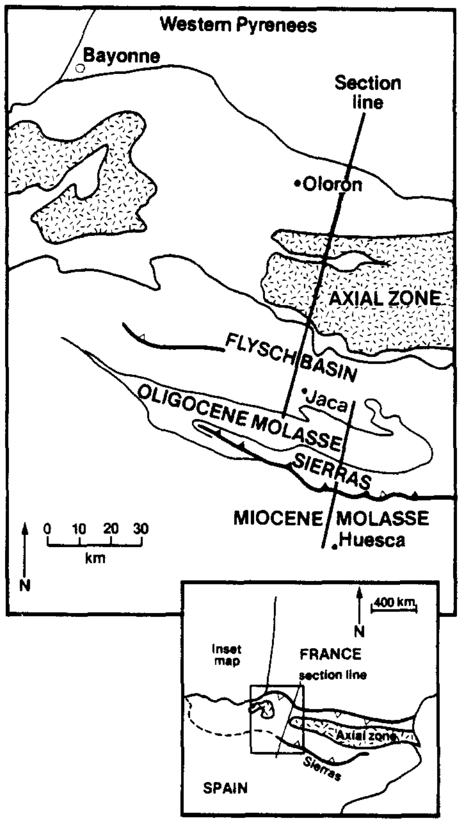


Fig. 6. Structural outline map of the Western Pyrenees showing the location of the Sierras and the southern Molasse basin.

beneath the eastern molasse basin. Major evaporite horizons are present beneath the Jura and the Swiss Plain both in the Keuper and the Mushelkalk (Fig. 5) but these horizons progressively onlap basement to the east and are entirely absent beneath the molasse basin in Germany where Jurassic rests unconformably on the basement. Even where the Trias is locally preserved in this eastern region it does not contain evaporites. It is possible to speculate that this stratigraphic change not only controls the structural style of the mountain front and the termination of the Jura but also coincides with the north-eastern limits of the external massifs.

*The southern Pyrenean thrust front (Fig. 6)*

The Pyrenees have a central 'axial zone' of Palaeozoic rocks flanked by folded and thrust Mesozoic rocks and Tertiary sedimentary basins. Detachments run within basement, in the Trias where it exists and 1 m above the basal unconformity in the Cretaceous. The thrusts on the south side of the mountain chain are emergent, climbing into the south Pyrenean flysch basin. As with the Swiss Plain a basal detachment passes beneath this sedimentary basin. It has been transported southwards by an amount equal to the shortening of the marginal Sierras ranges (*c.* 15 km).

The molasse basin continues south of the Sierras. Here the sediments are Miocene (locally pebbly at the thrust front). The geometry is complex and varies along the strike of the range. North of Huesca the structure is as shown in Fig. 7. Sediment thickness south of the Sierras is taken from Seguret (1972) and depth to detachment is extrapolated from surface geology. Although estimates of both of these parameters are probably in error some sort of culmination is required by the data below the Sierras. This might possibly involve elevated basement in a fore-bulge type structure or, more likely, it might be a stack of imbricated Mesozoic stratigraphy. The simplest possible version of the second interpretation is shown in Fig. 7. It obviously creates a geometry akin to the Triangle Zone of Alberta implying the presence of a significant backthrust.

*Mackenzie Mountains, North-West Territories, Canada (Fig. 8)*

The Mackenzie Mountains of the North-West Territories of Canada form a northward extension of the Rocky Mountain fold and thrust belt. The Mackenzie Mountains consist of large overlapping box anticlines separated by tight synclines. The anticlines are interpreted as large horses which together constitute a duplex that involves Proterozoic strata. Topographic relief in the mountains is directly attributable to the thickness of Proterozoic strata involved in the horses. It is likely that the lowest thrust flat corresponds with the top of the Archaean basement and that the complete overlying Proterozoic section is involved in the deformation. The upper thrust flat is probably near the top of the Proterozoic section. The mountain-front topographic feature corresponds to the edge of the leading horse in the duplex (Fig. 9).

Average shortening across the duplex is *c.* 80 km (45%) which must be accommodated in the Palaeozoic cover sequence. In the eastern Mackenzie Mountains (Fig. 9) shortening in the mountains is accommodated by the development of the Colville Hills and Franklin Mountains foreland fold-and-thrust belt ahead of the

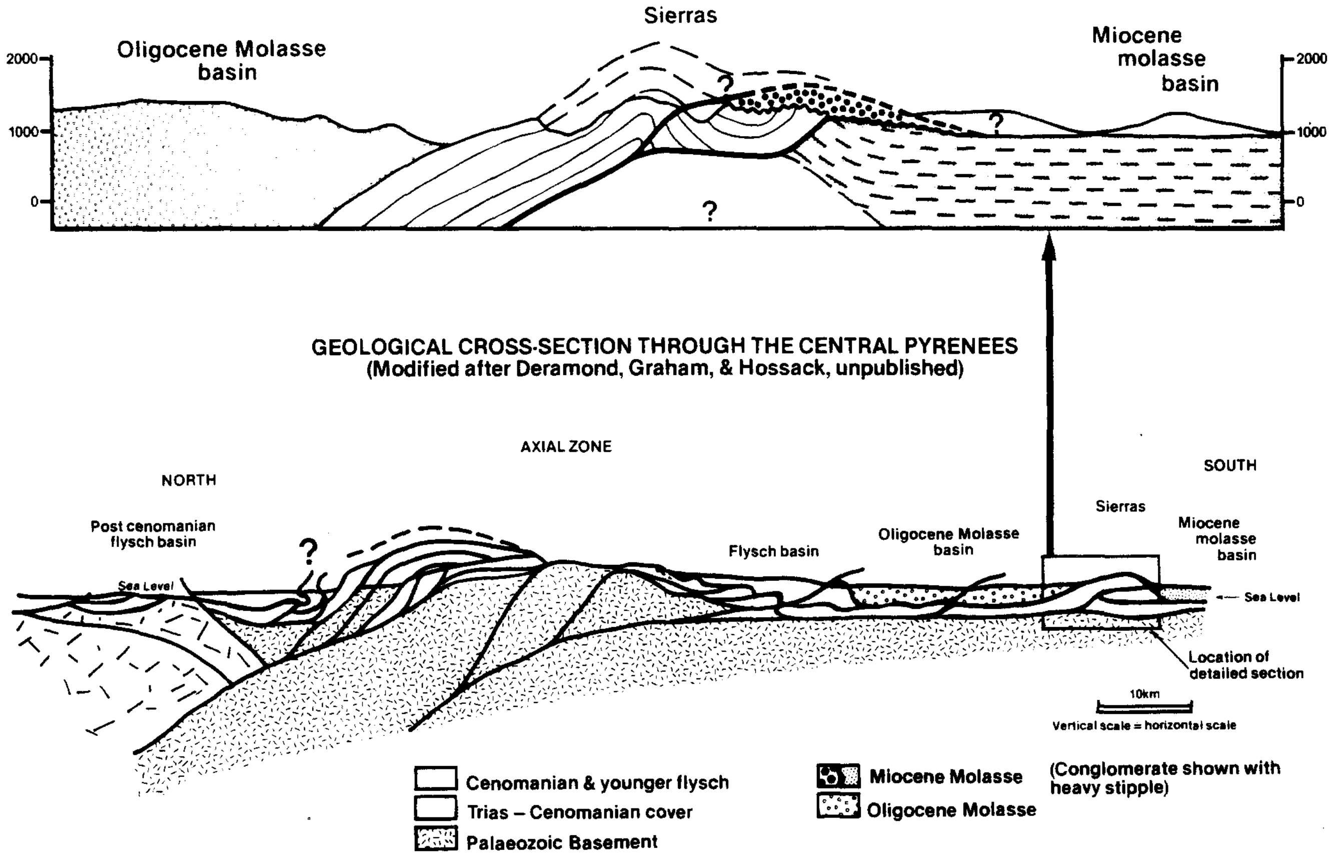


Fig. 7. Structural cross-section across the South Pyrenean fold and thrust belt, with more detailed section of the thrust front in the Sierras north of Huesca. Note the transported Eocene flysch basin. (For location of cross-section see Fig. 6.)

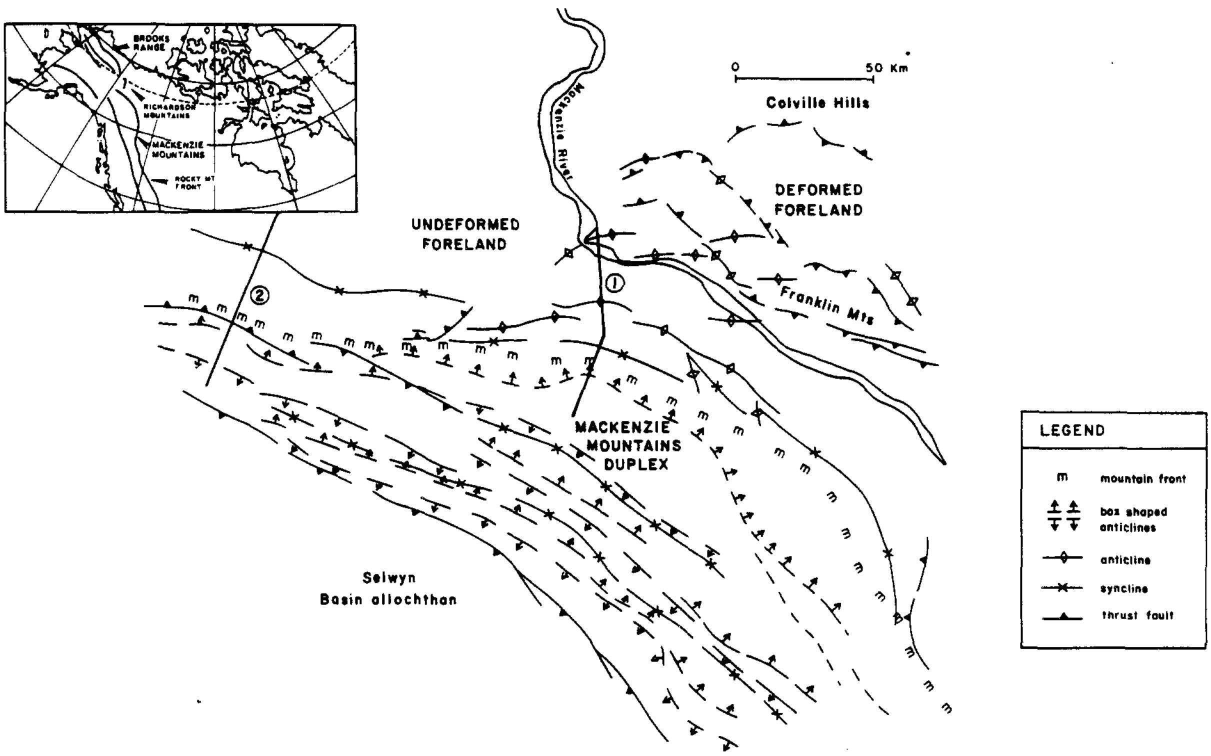


Fig. 8. Structural outline map of the Mackenzie Mountains. N.W.T. Canada. Note the contrast between the deformed foreland in the east and undeformed foreland in the west. Inset shows location in the North American Cordillera. Locations of section lines 1 (Fig. 9) and 2 (Fig. 10) are shown.

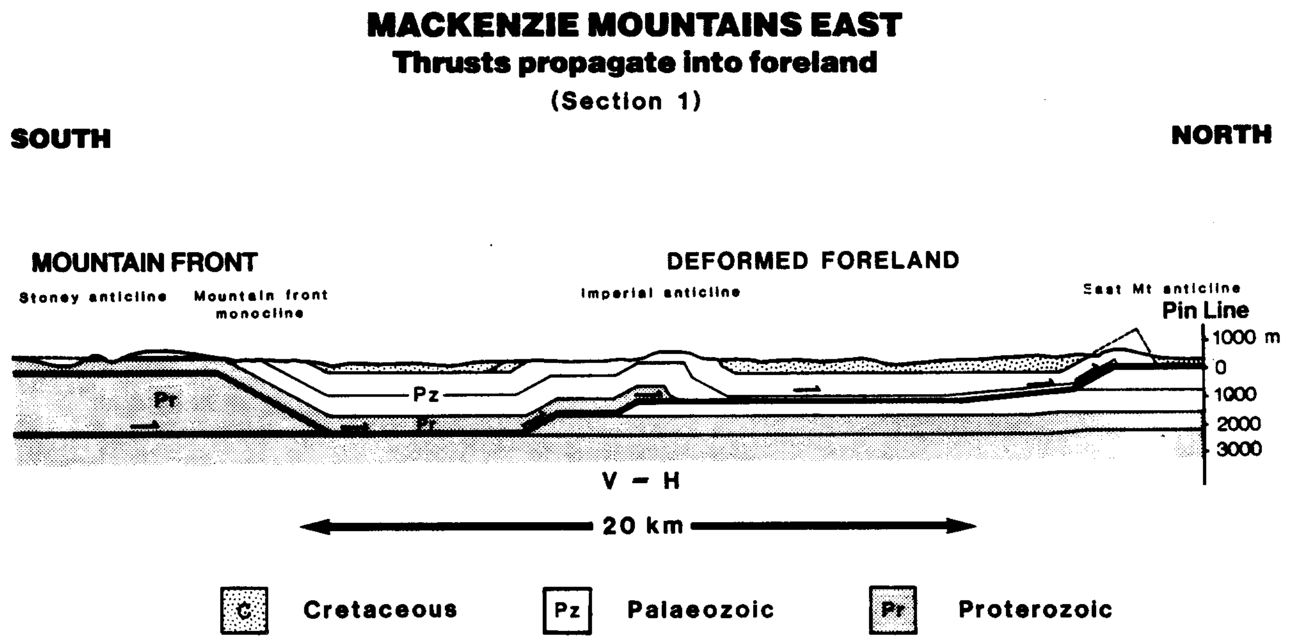


Fig. 9. Structural cross-section across the eastern Mackenzie Mountains and Franklin Mountains. (Section is line 1 on Fig. 8.)

Mackenzie Mountains duplex. These two areas are formed of both anticlinal horses and listric thrust splays detached in the upper part of the Proterozoic section. The Mackenzie Plain that lies between the Mackenzie Mountains and Colville Hills/Franklin Mountains comprises a molasse basin that has been transported an equivalent amount to the shortening, estimated at *c*. 35 km, in the Colville Hills/Franklin Mountains.

To the west, the foreland is undeformed and shortening in the Mackenzie Mountains duplex is accommodated by a major backthrust at the mountain front (Figs. 8 and 10). The two foreland structural provinces are separated by a major lateral ramp that is coincident with a significant facies change within the Upper Proterozoic sequence.

*The Sulaiman Range, Pakistan*

In this volume, Banks & Warburton describe the structure of the mountain front of the Kirthar and Sulaiman Ranges of Pakistan. Their descriptions present type-examples of the *passive roof duplex*.

Balanced sections across this mountain front (Banks & Warburton this issue) imply that the roof thrust of the duplex between its tip below the Sibi Trough and its present erosional outcrop has a displacement of the order of 20 km in a backthrust sense. This interpretation appears to imply rather serious mechanical difficulties apparently demanding continued movement on a complexly folded roof thrust. This objection is of course invalid if the roof thrust is eroded as elevation is built by

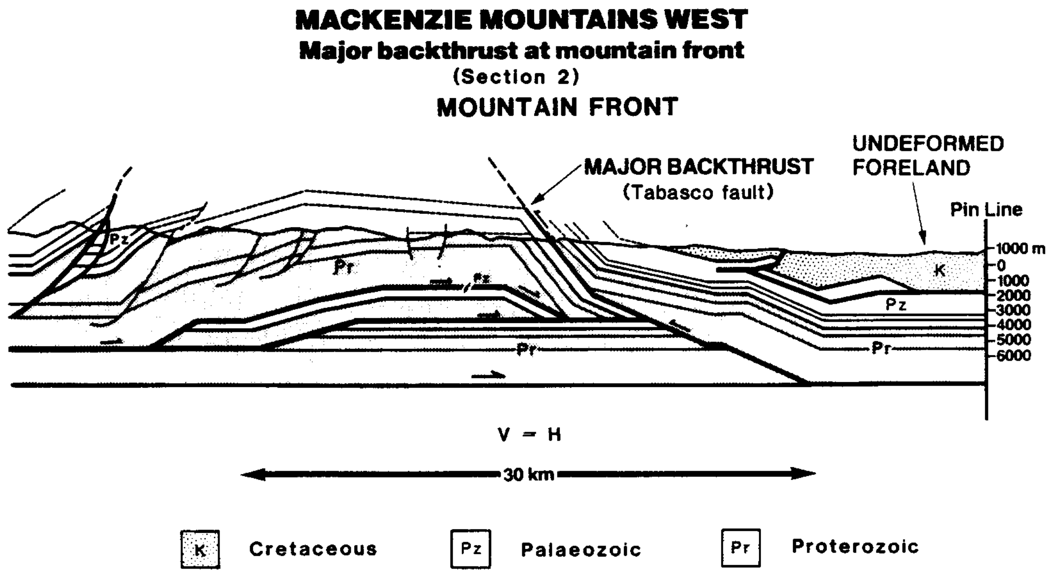


Fig. 10. Structural cross-section across the western Mackenzie Mountains and Franklin Mountains. Note the presence of a major backthrust at the mountain front and the undeformed foreland ahead of the mountain front. (Section is line 2 on Fig. 8.)

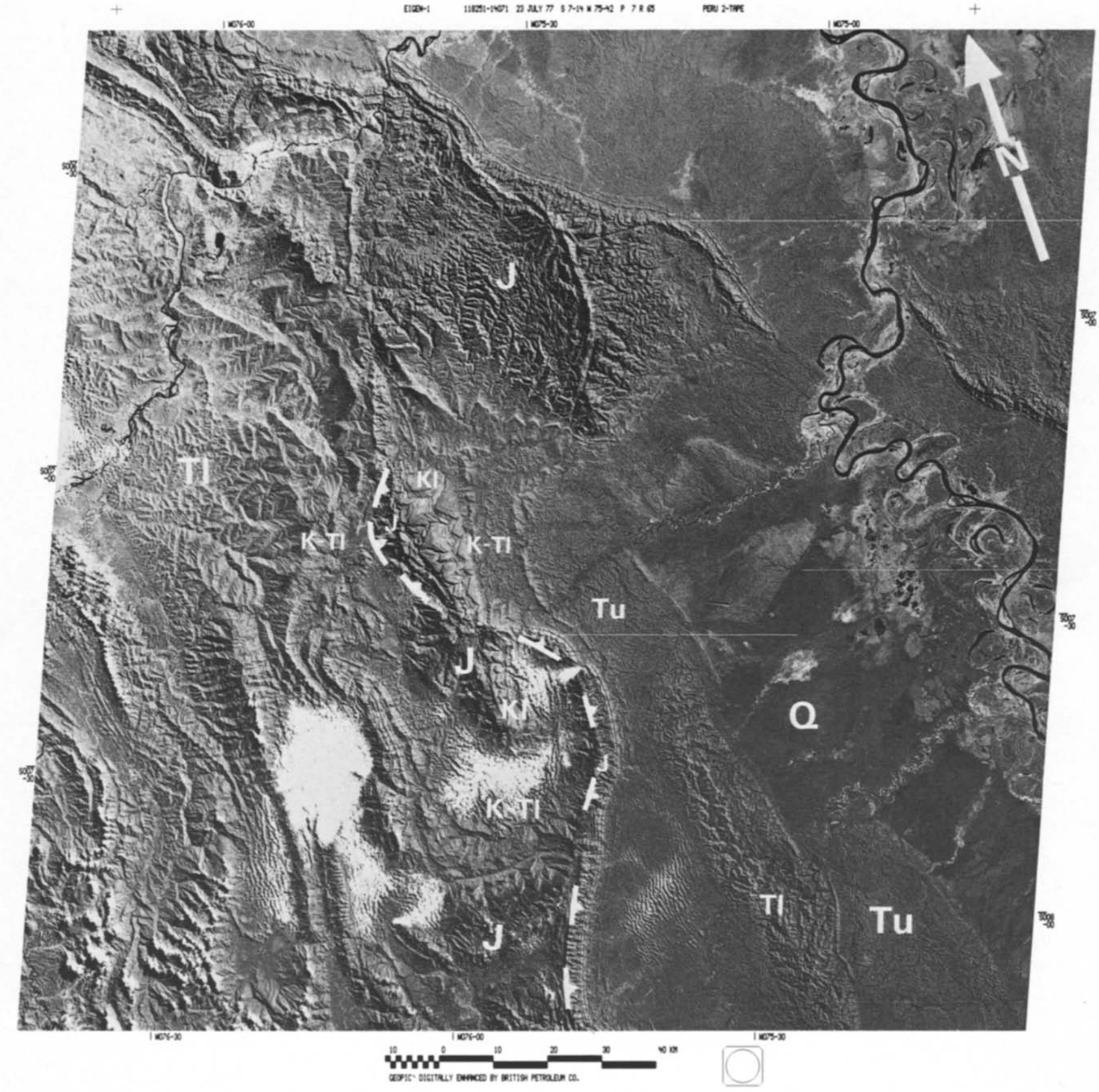


Fig. 11. Landsat image of the eastern margin of the Andes Mountains, Peru. The major backthrust is indicated by the barbed line. Note the presence of a major lateral ramp that offsets the mountain front and the essentially undeformed nature of the foreland. Key: J, Jurassic; K–Tl, Cretaceous–Lower Tertiary; Tu, Upper Tertiary; Q, Quaternary.

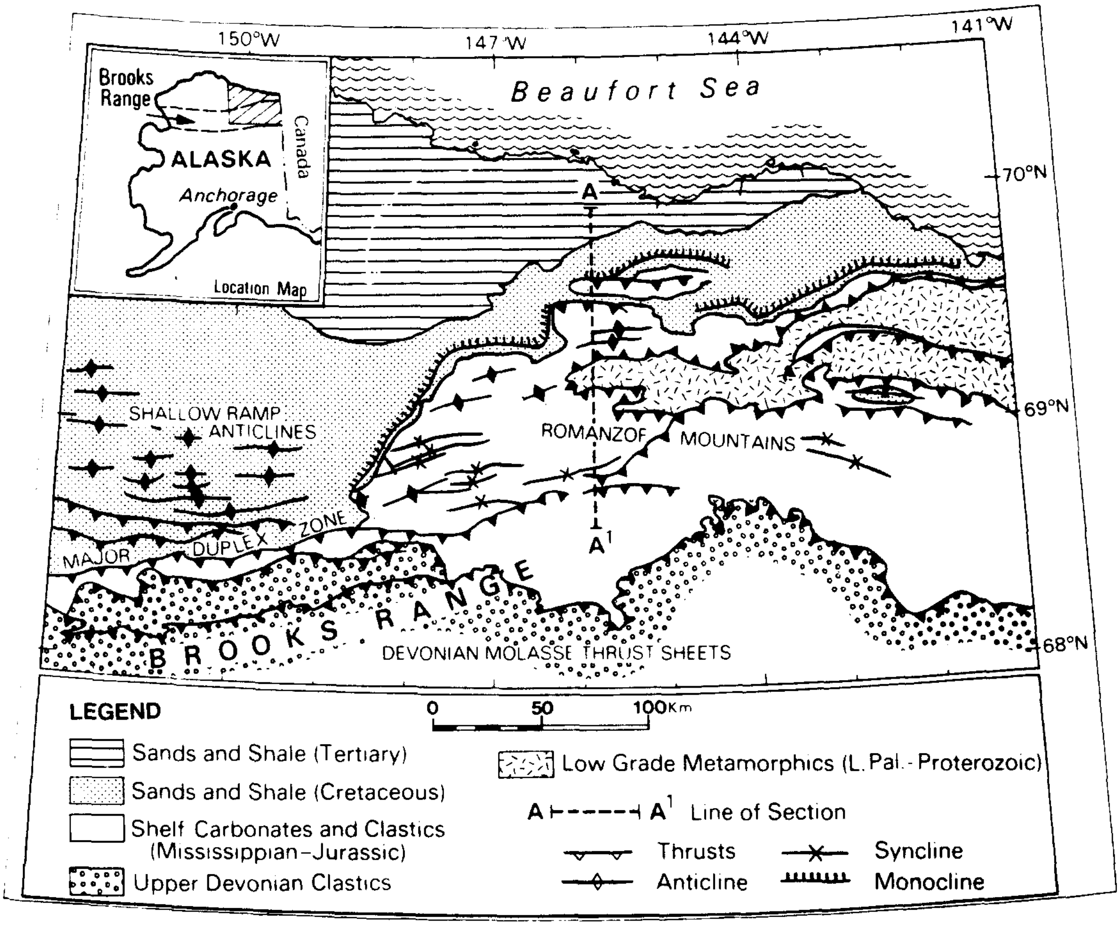


Fig. 12. Simplified structural outline map of the Romanzof Mountains, eastern Brooks Range, Alaska.

the underlying duplex. In this case movement on the roof thrust would occur only on that segment between its tip and the frontal monocline.

*The Peruvian Andes (Fig. 11)*

A spectacular frontal monocline forms the eastern margin of the Andean foothills in northern Peru. The sedimentary column exposed in the frontal monocline is 6 km thick ranging from middle Jurassic shelf sequences to Miocene molasse. This sediment pile dips eastwards at up to 30° for a distance of 15 km. The foreland basin ahead of the monocline is almost structureless, the low amplitude anticlines that do occur being due to drape over reactivated basement horsts.

The western limit of the monocline is formed by a major east-dipping thrust which is a hangingwall flat in the middle Jurassic above an upper Cretaceous to lower Tertiary footwall ramp. Below this thrust are a complex series of large-scale thrust-related anticlines terminated by major lateral ramps and tear faults, all of which are truncated by the east-dipping thrust plane.

The movement on the backthrust is at least 20 km and its geometry in seismic reflection profiles is precisely analogous to that seen in Alberta (Jones 1982, fig. 11). It is interesting to note that many of the foothills anticlines of Peru are intruded by lower Jurassic salt diapirs. This salt seems to form the basal detachment horizon throughout the foothills but east of the mountain front it is absent. It is possible that this stratigraphic pinchout controls the position of the backthrust.

*The Brooks Range, Alaska (Fig. 12)*

The Romanzof Mountains of north eastern Alaska form a major northward salient on the general E–W trend of the Brooks Range mountain front (Fig. 12). In this area Mississippian platform carbonates up to 1500 m thick are deformed into large-scale flat topped box folds, typically with a wavelength of 2 km, for a cross-strike distance in excess of 100 km. The fold envelope of this package is essentially horizontal over the entire area of the Romanzof Mountains with the basement culmination of the central part of the plateau coring a broad low amplitude anticline with limb dips of less than 5°. Upward and downward continuations of the exposed boxfolds indicate the presence of major detachment surfaces within the overlying Jurassic shales and in the Mississippian shales which form the base of the sedimentary sequence in this area. Both these detachment surfaces mark profound changes in deformational style. Structure within basement is dominated by major thrusts many of which belong to a much earlier Ellesmerian (mid-Devonian) deformation. Mapping to date does not allow separation of Ellesmerian and Laramide events within these basement rocks (Reiser *et al.* 1980, Reed

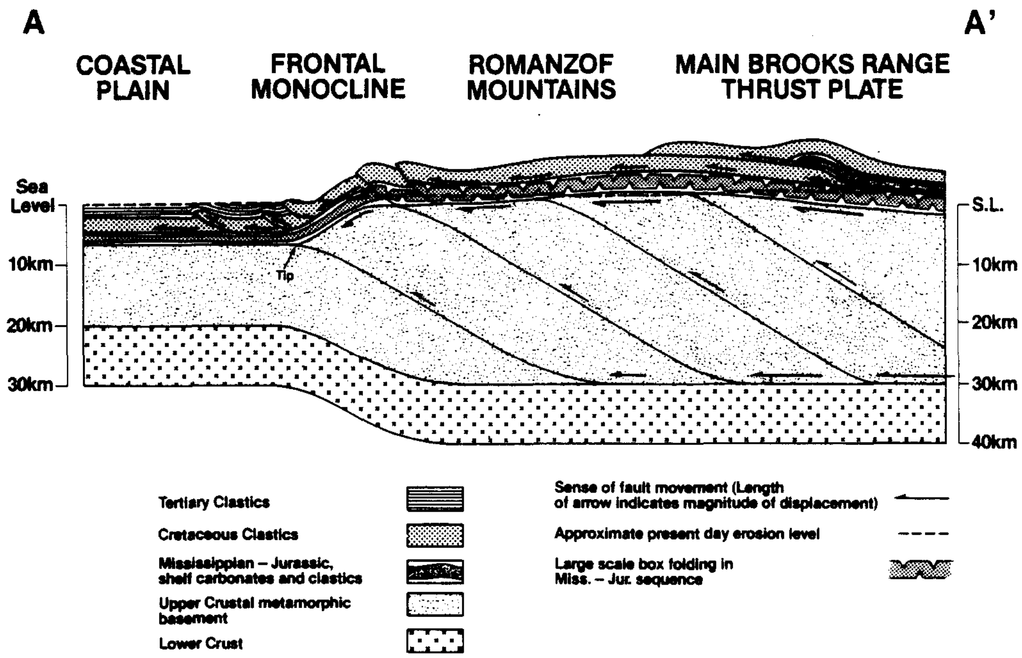


Fig. 13. Schematic cross-section across the Romanzof Mountains and Brooks Range along line A Fig. 12. See text for discussion.

1968). Thrusts are also common in the Cretaceous and Tertiary clastics which overlie the upper detachment of the folded rock panel. This gross geometry is the same as that proposed by Dahlstrom (1969) for parts of the Albertan Rockies with a folded rock panel allowing upward propagation of displacement from a floor thrust to a roof thrust.

The northern and western flanks of the Romanzof Mountains are formed by a major monocline with an amplitude in excess of 5 km. Locally this simple fold is modified by minor thrusting with displacements rarely exceeding a few hundred metres.

A major problem arises in attempting to balance sections in this area. The shortening within the folded Mississippian is approximately 50 km (30%). Along strike, however, within the duplex zone which forms the Brooks Range front to the west of the Romanzof Mountains (Fig. 12) shortening is at least 100 km and may be significantly more. Considerations of isostatic equilibrium between the Arctic Coastal Plain and the Romanzof Mountains with a plateau elevation of 1500 m indicate a thickening of the crust of approximately 15 km (Fig. 13). This thickening could be achieved either by horizontal shortening of the entire crustal section by 50 km (compatible with shortening observed in the overlying Mississippian sediments) or by 100 km of shortening in the upper crust, originally 15 km thick. Two lines of evidence favour this second hypothesis. Firstly, this shortening is compatible with that observed along strike and secondly, deep seismic reflection profiles from other mountain belts (e.g. Appalachians; Cook *et al.* 1979, 1981 and Caledonides; Brewer & Smythe 1984) and areas of extension (e.g. Bay of Biscay; Montadert *et al.* 1979) indicate that a mid-crustal detachment is more common than deformation involving the entire crust.

There appear then to be two possible models for the uplift of the Romanzof Mountains. Either (a) deformation occurs above a floor detachment surface close to the Moho and the entire overlying section shortens by approximately 50 km, in which case the top basement/base Mississippian detachment surface has no significant displacement or (b) shortening of approximately 100 km occurs above a mid-crustal detachment (as shown in Fig. 13). In this case the top basement detachment is a significant backthrust on which the displacement increases from zero at the northern tip to around 50 km at the southern end of the section, i.e. the structure is a passive roof duplex. The additional 50 km of displacement within the Mississippian to Jurassic sedimentary package required to make this section balance is taken up on the higher thrust sheets of the main Brooks Range thrust plate.

This uncertainty could be resolved by section balancing across the entire Brooks Range but the absence by erosion of the hangingwall cut-offs within the upper thrust plates makes such a solution impractical. For the reasons outlined above, we tend to favour the backthrust model but for the time being at least, the origin of the frontal monocline in this region remains enigmatic.

*Haute Provence (Fig. 14)*

The external part of the Alps in Haute Provence is a thin-skinned thrust belt in Mesozoic rocks with the basal detachment lying within Triassic evaporites (Fig. 15). Late Eocene to Plio-Pleistocene molassic sediments are found throughout the belt, the older more internal sedimentary basins having been transported large distances (43 km for the Clumanc syncline, more for the more internal Gres d'Annot basins).

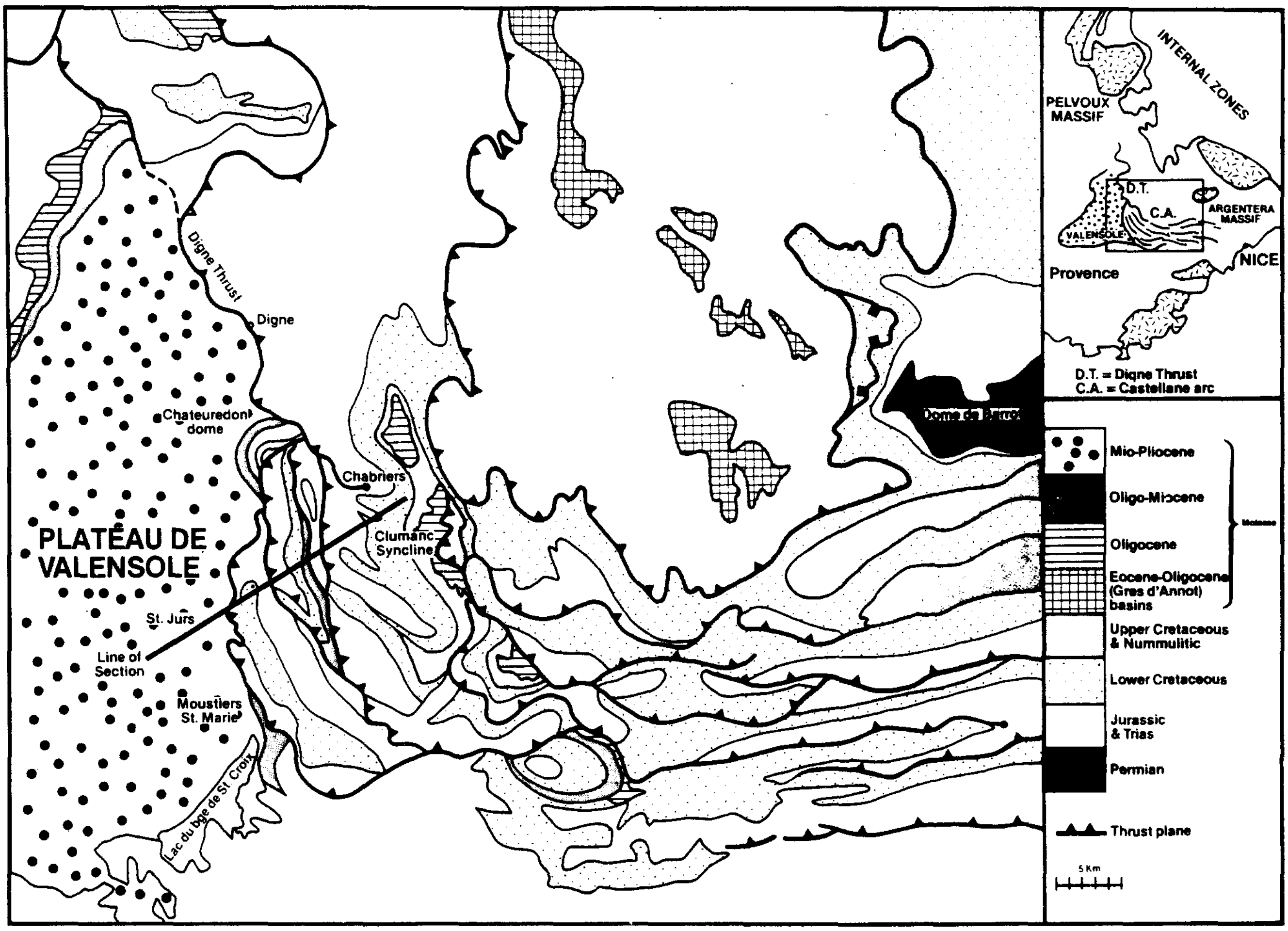


Fig. 14. Structural outline map of Haute Provence, western external French Alps.

The mountain front in Provence between Digne and Moustier St. Maire is an abrupt 300 m topographic step of Mesozoic carbonates above the Miocene–Pleistocene sediments which form the Plateau de Valensole. The plateau surface rises gently towards the mountain front (a slope of 5° or so) and it cuts the bedding of the molasse so that the slope cannot be depositional dip on an outwash fan but must presumably be due to isostatic uplift of the mountains (Fig. 15).

The thrust front coincides with the mountain front north of Digne where 7 km of post-Messinian movement across a land surface has been recorded by Siddans (1979). South of here, at Chabriers, Mesozoic rocks below the Digne thrust in the western limb of the Chateauredon Dome are overlain with slight angular unconformity by Upper Oligocene or Lower Miocene sands. The unconformity is folded over the dome and the Miocene rocks pass up conformably into the younger molasse of the Plateau de Valensole.

The Chateauredon Dome is a culmination whose height above the regional level suggests that it must belong in an imbricate stack with the consequent implication that it has suffered 12–14 km displacement. It therefore presents a 'foreland dip' problem like those of

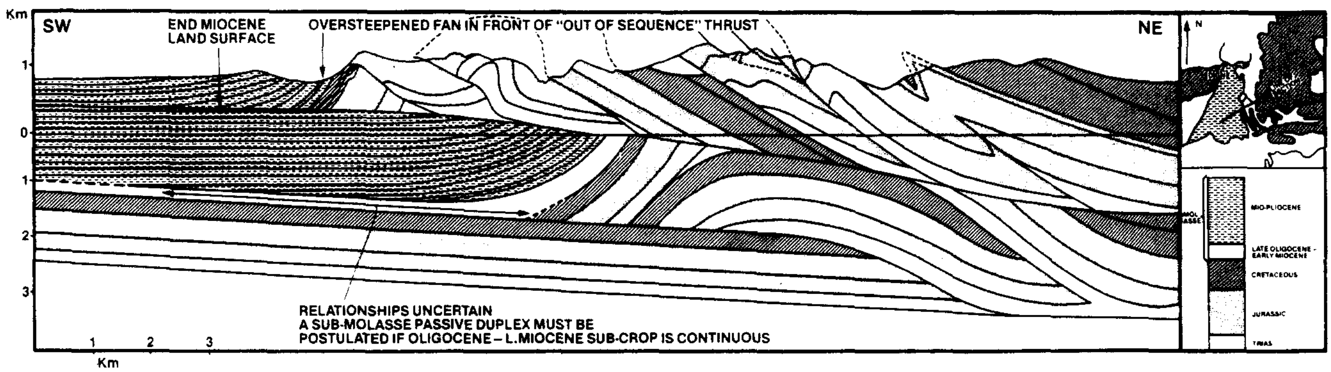


Fig. 15. Structural cross-section along the line shown on Fig. 14. Note the decapitated culmination and the major out of sequence thrust at the mountain front. See text for discussion.

other thrust fronts described in this paper (Fig. 15). The Chateauredon Dome is not the absolute limit of deformation since thrusts exist to the west, but their displacement is small. However, the Dome is the site of the most important change in displacement and there must either be a backthrust, on an unrecognized detachment within the molasse, or the Chateauredon culmination travelled over an old land surface.

The Chateauredon Dome is decapitated by the Digne thrust (Fig. 15). The geometry of this cut-off dictates that movement occurred on the higher structure after the displacement on the lower thrust (i.e. 'out-of-sequence' movement). The displaced head of the culmination forms the thrust front south of Beynes and once again the Mesozoic rocks of the culmination dip towards the foreland beneath an unconformable molasse blanket, though here the molasse is Mio-Pliocene in age, the older blanket having been eroded away.

The out of sequence movement is almost certainly the same as the post-Messinian displacement on the Digne thrust further north and it seems certain that the decapitated Chateauredon Dome travelled across a land surface for some 7 km. The foreland dip in the molasse is interpreted as offlapping outwash fans somewhat deformed and oversteepened by later minor displacements.

## CONCLUSIONS

We have attempted to illustrate with examples from a variety of geological provinces four different origins for the occurrence of mountain front monoclines. Whilst we cannot rule out the possibility of other origins for this phenomenon we are convinced that none of the alternatives presented to date are generally applicable (e.g. dissipation of movement by ductile strain within molasse basins or uplift above high-angle reverse faults cutting through the entire crust).

Each of the possibilities we have presented has a distinct set of geological consequences which can be used to distinguish between the pure end members. These criteria are as follows. (i) The presence of a foreland fold belt ahead of an undeformed molasse basin. This implies that the basin has been transported. (ii) Molasse sediments onlapping the frontal monocline and dipping significantly less steeply towards the foreland. This geometry implies movement of a hangingwall culmination across an old land surface prior to deposition of the near surface molasse. (iii) Pronounced horizontal shortening strains in the rocks of the monocline possibly with the formation of steeply dipping cleavage. These features imply large-scale deformation above the tip of the basal detachment. (iv) The absence of any of the above features implies that a major backthrust is present. Generally, the backthrust is extremely difficult to recognize in the field since it is often a hangingwall flat on a footwall flat with no stratigraphic separation (as are most duplex roof thrusts).

We support the contention of Jones (1982) that backthrusts are very much more common than is generally realized and that examples of this type of structure can be found at the deformation front in many mountain belts. The marked absence of similar structures in the more internal parts of thrust belts may be due either to erosion of the backthrust (implying that these only occur in the very highest parts of the deforming stratigraphic column) or that backthrusts represent deformation in the dying phase of thrust belt formation and hence are only ever created at the deformation front at one very particular time in the history of the thrust belt. This latter hypothesis is lent some support by the observation in the Swiss/German Molasse Plain, the Mackenzie Mountains and the Andes that backthrusting occurs where a very efficient detachment horizon (e.g. salt) pinches out and, presumably, the thrust deformation has a tendency to lock-up.

In many of the examples we have quoted there are rapid changes of styles both along the strike of the mountain front and through time. We believe such variations are the norm and in addition to transitions between the styles described here, transitions to the normal emergent erosional thrust front are common.

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