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DETACHMENT FOLDS ABOVE A PASSIVE-ROOF DUPLEX: AN EXAMPLE FROM THE NORTHEASTERN BROOKS RANGE, ALASKA

Wesley K. Wallace
Tectonics and Sedimentation Research Group
Department of Geology and Geophysics
and Geophysical Institute
University of Alaska
Fairbanks, Alaska 99775-0760

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794 University Avenue, Suite 200
Fairbanks, Alaska 99709

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K. Wallace)

ABSTRACT

In a "passive-roof duplex" (Banks and Warburton, 1986), shortening is accommodated above the roof thrust by a backthrust sense of displacement. Such a duplex formed during Cenozoic time in the northeastern Brooks Range of Alaska. The floor thrust of the duplex lies at depth in a heterogeneous assemblage of rocks deformed in pre-Mississippian time. The roof thrust lies near the base of the overlying Mississippian and younger cover sequence, in the Mississippian Kayak Shale. Horses were displaced to the north. Shortening above the roof thrust was accommodated mainly by detachment folds that range from open box folds to tight chevron folds, and display no consistent sense of asymmetry. The dominant unit in these folds, thick carbonates of the Mississippian-Pennsylvanian Lisburne Group, immediately overlies the Kayak Shale detachment horizon, which is thickened in the cores of anticlines. Few thrust faults cut the roof sequence, and these are mostly minor out-of-syncline faults where the detachment folds are tightest.

The passive-roof duplex and the detachment folds in its roof both disappear northward due to thinning and depositional discontinuity of the Kayak Shale. Sub-Mississippian and unconformably overlying Mississippian and younger rocks deformed together as a single structural unit where the detachment horizon is absent. Shortening in both the duplex and its roof must have been accommodated entirely south of this northward termination of the roof thrust, requiring a backthrust sense of displacement on the roof thrust.

South of the passive-roof duplex, the sequence above the Kayak Shale was shortened more and displays a different style of deformation. Folds are tight and asymmetrical, consistently displaying steep to overturned short limbs to the north. The limbs of the folds commonly are cut by south-dipping thrust faults. A thrust-emplaced roof is preserved locally above these folds, indicating that they constitute a duplex of fault-truncated folds.

Formation of the passive-roof duplex and the symmetrical detachment folds in its roof may have been facilitated by relatively low shortening and the effectiveness of the Kayak Shale as a detachment horizon. Strongly asymmetrical, thrust-faulted folds formed instead of symmetrical detachment folds where shortening was greater and significant forward slip occurred on the detachment horizon, where a structural roof was present and depositional overburden was greater, and where folds beneath the detachment horizon were smaller. The relative importance of these various factors in controlling the structural geometry remains uncertain.

INTRODUCTION

The objective of this paper is to present a well-exposed example from the northeastern Brooks Range of Alaska of a "passive-roof duplex" with a roof shortened by detachment folds. This interpretation is based on study of a transect across the northeastern Brooks Range, the "Canning River transect", and is illustrated using a balanced cross section first presented by J.S. Namson and W.K. Wallace (1986). The initial transect study was part of a joint project by ARCO Alaska and ARCO Research and Technical Services to characterize the regional structure of the northeastern Brooks Range. The cross section was based on a geologic map prepared by Wallace from published maps of the region (Reiser and others, 1971; Brosgé and Reiser, 1965) and mapping at a scale of 1:63,360 by Wallace, Namson, and others at ARCO. An initial cross section prepared by Namson and Wallace was balanced by Namson. Wallace and his graduate students at the University of Alaska have since conducted studies along the transect as part of a systematic study of the structural geology of the northeastern Brooks Range. This paper summarizes some of the more significant observations and interpretations about the structural geology of the transect. A future paper will describe the structural geology of the transect in considerably more detail, discuss alternative structural models, and outline the methods, constraints, and assumptions used in constructing the cross section.

The Brooks Range is a northern extension of the fold and thrust belt that forms the eastern margin of the North American Cordilleran orogen. The northeastern Brooks Range is a topographic and structural salient of the Brooks Range (Figure 1A) that formed during Cenozoic time by structural displacement in a generally northward direction. The aspects of the geology of the northeastern Brooks Range that are most relevant to this paper are summarized below. Wallace and Hanks (1990) provide a more complete overview of the structural geology of the northeastern Brooks Range.

STRUCTURAL STRATIGRAPHY

The stratigraphy of the northeastern Brooks Range is equivalent to that found in the subsurface of the Alaskan North Slope (Figure 1A), and has had a major influence on the structural geometry of the region. The stratigraphic section consists of several competent structural units that are separated by incompetent units that have acted as detachment horizons (Figure 2). The lowest structural-stratigraphic unit consists dominantly of a heterogeneous assemblage of stratified sedimentary and volcanic rocks that were deformed and weakly metamorphosed in pre-

Mississippian time. The sub-Mississippian rocks are inferred to have been shortened above a detachment at depth. In the north, the Mississippian Kekiktuk Conglomerate unconformably overlies the sub-Mississippian rocks and has deformed with them as part of a single structural-stratigraphic unit. At the south end of the transect, the Kekiktuk Conglomerate and similar rocks as old as Middle Devonian (Anderson, 1991; Anderson and Wallace, 1991) form a southward-thickening wedge of clastic rocks that acts as a separate structural-stratigraphic unit (not shown on Figure 2). The Kekiktuk Conglomerate is overlain by the Mississippian Kayak Shale, a thick, fissile shale that acts as an important detachment horizon throughout the region. The Mississippian to Pennsylvanian Lisburne Group is a thick carbonate unit that serves as the structurally dominant competent member of the overlying structural-stratigraphic unit. A sequence of dominantly terrigenous clastic Permian through Lower Cretaceous stratigraphic units overlies the Lisburne Group and has deformed with it. The Permian to Triassic Sadlerochit Group is the stratigraphically lowest part of this clastic sequence, and the part that has been most widely preserved from erosion in structural lows.

REGIONAL STRUCTURAL CHARACTER

The structure of the northeastern Brooks Range is dominated by a series of anticlinoria cored by sub-Mississippian rocks (Figure 1C). These anticlinoria are interpreted to have formed above fault-bend folded (Suppe, 1983) horses in a duplex with a floor thrust at depth in the sub-Mississippian rocks and a roof thrust in the Kayak Shale (Figure 3; Rattey, 1985; Namson and Wallace, 1986; Wallace and Hanks, 1990). Above the roof thrust of this duplex, shortening has been accommodated mainly by detachment folds, with only local thrust faults. Three structural provinces can be identified in the northeastern Brooks Range based on variations in the structural geometry above and below the detachment in the Kayak Shale (Figures 1B and 3; Wallace and Hanks, 1990).

This paper addresses the structure of a transect across the western structural province and extending a short distance south of the southern boundary of the province (Figures 4 and 5; Namson and Wallace, 1986). The western structural province can be divided into 2 structural domains, the Front Ranges and Franklin Mountains domains, based on variations in the structural geometry of Lower Cretaceous and older rocks (Figures 4 and 5). These two domains are distinguished mainly by differences in the dimensions of anticlinoria cored by sub-Mississippian rocks (Figures 1C and 4). The structural geometries found throughout the rest of the northeastern Brooks Range are essentially variations on the structural geometry seen in these two domains

(Figure 3; Wallace and Hanks, 1990). A third domain to the south, the Philip Smith Mountains domain, however, represents a significant departure from the structural geometry typical of the northeastern Brooks Range, and is more representative of structures exposed extensively in the main axis of the Brooks Range to the south and southwest (Figure 1A).

Each of these three domains will be discussed in more detail below. The middle or Franklin Mountains domain, will be discussed first because it is the domain in which the fault-bend fold geometry of the anticlinoria is best defined and the cover is everywhere detached along the Kayak Shale. The northern or Front Ranges domain will be discussed next because it displays smaller fault-bend folds and a northward termination of the Kayak Shale detachment. The southern or Philip Smith Mountains domain will be discussed last because anticlinoria cored by sub-Mississippian rocks are not a dominant element of its structure and the structures formed above the detachment horizon in the Kayak Shale are quite different from those in equivalent rocks to the north. One of the main objectives of this paper is to show the contrast in structural style between the northeastern Brooks Range, as exemplified by the Franklin Mountains and Front Ranges domains, and the north-central Brooks Range, as exemplified by the Philip Smith Mountains domain.

Franklin Mountains domain

The Franklin Mountains domain is dominated by two anticlinoria cored by sub-Mississippian rocks. A structural form surface marked by the Mississippian Kekiktuk Conglomerate and the underlying sub-Mississippian unconformity clearly defines the geometry of these anticlinoria. They are characterized by broadly curved but nearly planar dip panels defining a long, gently dipping backlimb, a flat crest, and a short, moderately dipping forelimb (Figure 5). It is this distinctive geometry that forms the basis for the interpretation that the anticlinoria mark fault-bend folds formed by the ramping of thrust faults from a detachment at depth in the sub-Mississippian rocks up to the Kayak Shale (Wallace and Hanks, 1990). The interpretation that the pre-Mississippian rocks have deformed as coherent horses, rather than by internal thickening, is supported by the fact that evidence of significant penetrative strain or small-scale folding or imbrication along the sub-Mississippian unconformity and within the overlying Kekiktuk Conglomerate is lacking in most places. The rocks above the Kayak Shale detachment are shortened primarily by detachment folds with a wavelength of 1-2 km, that display no consistent sense of asymmetry, and are only locally breached by thrust faults (Figure 5).

Front Ranges domain

The Front Ranges domain includes structures exposed in a series of ranges that lie to the north of the range front of the Brooks Range proper (Figures 4 and 5). This domain is characterized by a series of doubly plunging anticlinoria that are much smaller in strike length, wavelength, and amplitude than those in the Franklin Mountains domain to the south. In the southern part of the domain, these are interpreted to reflect horses typical of the duplex as a whole. However, some important structural changes from the rest of the transect are present in the northern part of the domain (northern Shublik Mountains and Sadlerochit Mountains). Here, the sub-Mississippian rocks are dominated by a thick sequence of structurally competent Proterozoic to Devonian carbonates, in contrast with the structurally less competent, lithologically heterogeneous sub-Mississippian rocks to the south. Detachment folds in the Lisburne and Sadlerochit Groups are not present in the Sadlerochit Mountains (Figure 5), corresponding with northward depositional thinning and disappearance of the Kayak Shale detachment horizon. Moderately south-dipping thrust faults mark the northern range fronts of both the Shublik and Sadlerochit Mountains (Figure 4). These apparent out-of-sequence faults are unusual in that they cut up-section from sub-Mississippian rocks to Cretaceous and younger rocks, thus cutting across the stratigraphic position of the Kayak Shale. These faults truncate older folds and faults and appear to be the last-formed structures in hindward-propagating thrust sequences localized at the leading edges of the Shublik and Sadlerochit Mountains anticlinoria (Meigs, 1989; McMullen, 1989; Rogers, 1989).

Philip Smith Mountains domain

The Philip Smith Mountains domain is characterized by a lower average structural relief than in the provinces to the north. This is manifested by exposures that consist mainly of Mississippian to Triassic rocks, with relatively few exposures of sub-Mississippian rocks (Figure 4). This decrease in structural relief and exposure of sub-Mississippian rocks reflects an abrupt southward decrease in the importance of the anticlinoria that dominate the northeastern Brooks Range. This change in structure corresponds with, and likely is genetically related to, the presence of a southward-thickening wedge of Middle Devonian to Lower Mississippian clastic sedimentary rocks, equivalent to those documented farther east by Anderson (1991).

The dominant exposed structures are strongly asymmetrical, north-overturned anticline-syncline pairs that are breached in their steep, short limbs by thrust faults (Figure 5). These folds and faults have formed above a detachment in the Kayak Shale and have a wavelength and fault spacing of 1-

2 km. The strong asymmetry and abundance of thrust faults represents a significant contrast with the domains to the north. The boundary between the Franklin Mountains and Philip Smith Mountains domains has been referred to as the "continental divide thrust front" (Wallace and others, 1988). The duplex and detachment folds north of this boundary are probably entirely Cenozoic in age, whereas the thrust-truncated folds in the Philip Smith Mountains domain could have begun forming in Late Cretaceous time (Wallace and Hanks, 1990). The domain boundary is marked by a regionally significant relative structural low (Figure 1C). Along the line of section, this low preserves a local remnant of Mississippian to Lower Cretaceous allochthonous rocks displaced a considerable distance (at least 46 km, and probably much more) from the south (Churkin and others, 1989). The rocks of this klippe were deposited in deeper-water environments than coeval rocks in their footwall, and are similar to allochthonous rocks that are very widespread in the central and western Brooks Range (Mull, 1982; Mayfield and others, 1983). The klippe itself is overprinted by folds and faults formed in the structurally underlying rocks. The presence of this klippe shows that a thrust-emplaced roof once existed over the faulted asymmetrical folds, indicating that they constitute a duplex of fault-truncated folds.

STRUCTURAL INTERPRETATION

The Kayak Shale serves as a fundamental detachment horizon that separates two distinct sets of structures exposed along the Canning River transect. Large anticlinoria have formed in sub-Mississippian rocks and the Kekiktuk Conglomerate below the detachment, whereas shorter wavelength folds and, to the south, thrust faults, have formed above the detachment. The geometry and kinematics of these two sets of structures are very different, although they quite likely simply represent different modes of accommodating the same shortening that have been controlled by structural stratigraphy. The first of the major interpretations discussed below is that the overall structure of the Front Ranges and Franklin Mountains domains is a passive-roof duplex with a roof thrust in the Kayak Shale. The second major interpretation regards the mode of shortening above the Kayak Shale: The primary mode of shortening in the roof of the duplex has been detachment folding, but to the south of the passive-roof duplex, in the Philip Smith Mountains domain, detachment folds have developed a strong asymmetry and have been truncated by thrust faults.

Passive roof duplex

The structural origin of the anticlinoria in the Front Ranges and Franklin Mountains domains must be explained in order to determine how shortening has been accommodated below the Kayak Shale. As explained in Wallace and Hanks (1990), two end-member models span a range of possible solutions to this problem: the anticlinoria may have formed by large-scale thrust duplication, resulting in formation of fault-bend folds, or by variation across strike in the amount of shortening and thickening resulting from some combination of penetrative strain, small-scale folding, and small-scale imbrication. As discussed above, the geometry of the anticlinoria suggests that each is a fault-bend fold formed by displacement of a horse over a ramp connecting a floor thrust in the sub-Mississippian rocks with a roof thrust in the Kayak Shale. If this interpretation is correct, then the backlimb of each anticlinorium reflects the dip of the footwall ramp and the geometry constrains the range of possible depths to the floor thrust, particularly since the depth to the roof thrust can be inferred directly from surface observations. A general lack of structural thickening, detachment, or penetrative strain in the Kekiktuk Conglomerate limits the extent to which internal thickening of the unconformably underlying pre-Mississippian rocks can have contributed to formation of the anticlinoria, and thereby places additional limits on the depth to the floor thrust.

Given the geometry of the anticlinoria, a variety of fault-bend fold interpretations are possible depending on the depth of detachment and the degree to which the horse is allowed to thicken by small-scale internal deformation. The interpretation chosen for the balanced cross section (figure 5) assumes no internal shortening and the minimum possible detachment depth because this geometry yields the shortening value which matches most closely that determined above the Kayak Shale. However, this interpretation alone does not account for the difference in elevation between the regional base level of the sub-Mississippian unconformity along the cross section (i.e. beneath the synclinoria) and in the subsurface of the coastal plain to the north (as determined, for example, from depth conversions of interpretations of seismic data by Bruns et al. (1987)). This discrepancy can most likely be accounted for by additional structural thickening below the basal detachment shown on the cross section.

Regardless of the exact horse geometry chosen, and consequent detachment depth and shortening value, the structure below the detachment in the Kayak Shale is by definition a duplex if it involves thrust duplication. Vann et al. (1986) recognized that this duplex is a passive-roof duplex. A "passive-roof duplex" (Banks and Warburton, 1986) or "low-taper triangle zone" (McMechan,

1985) is distinguished from other duplexes based on the way shortening is accommodated above the roof thrust. The shortening accommodated by forward displacement of each successive horse in a passive-roof duplex is accommodated above the duplex by hindward displacement on the roof thrust. This means that the displacement on each horse must be accommodated in the roof sequence by shortening either directly above or behind that horse. This contrasts with the more familiar "active-roof" duplex (e.g. Boyer and Elliot, 1982; Mitra, 1986), in which shortening above the roof thrust is accommodated ahead of each horse above thrusts with a forward sense of displacement.

Shortening in the roof in the examples of passive-roof duplexes described by Banks and Warburton (1986) and by McMechan (1985) is accommodated largely by thrust faults, with either forward or hindward displacement. The duplex in the northeastern Brooks Range differs from these examples in that shortening above the roof thrust is accommodated almost entirely by detachment folds (Figure 5). An idealized example of a single horse in such a duplex is illustrated in figure 6. Shortening below the roof thrust is taken up mainly by displacement on the thrust fault that defines the base of the horse (Figure 6C). An additional relatively small component of shortening is accommodated by the fault-bend fold formed by displacement of the horse over the footwall ramp. In contrast, the equivalent shortening in the roof is distributed over the entire horse in multiple detachment folds. In this case, backthrust displacement increases hindward from the leading edge of the horse to the point in the rocks above the roof thrust that originally overlay the leading edge in the undeformed state (Figure 6D). Backthrust displacement decreases progressively hindward of this point.

The strongest argument for backthrust displacement on the roof thrust of the duplex in the northeastern Brooks Range is found in the Sadlerochit Mountains, at the northern end of the cross section (Figure 5). Here, the stratigraphic horizon that elsewhere serves as the roof thrust, the Kayak Shale, depositionally thins and disappears to the north, thus pinning the roof thrust. Although thrust faults cut from sub-Mississippian rocks, across the roof thrust, and into rocks of the roof sequence along the northern range fronts of both the Shublik and Sadlerochit Mountains (Figure 4), the displacement on these faults is not sufficient to account for accommodation of shortening in the duplex by thrust duplication in its roof. Consequently, equivalent shortening in both the duplex and its roof must have been accommodated entirely south of the pin in the Sadlerochit Mountains (Figure 5). Thus backthrust displacement on the roof thrust must have occurred over at least the northernmost horse in the Shublik Mountains. Backthrust displacement over horses farther south is supported by the balanced cross section, in which the point in the rocks above the roof thrust that originally overlay the leading edge of each horse now lies to the south of that leading edge (note separation between numbered leading-edge cutoffs and corresponding points above the roof thrust in Figure 5).

Detachment folds

As its name implies, a detachment fold (Dahlstrom, 1990; Jamison, 1987) forms by displacement and shortening above a flat-lying detachment surface that generally lies within a structurally incompetent stratigraphic unit. Shortening of the incompetent layer is accommodated by thickening in antiforms formed in overlying more competent layers. The model for detachment fold geometry described by Jamison (1987) is for asymmetrical folds, but detachment folds commonly are characterized by the lack of a consistent sense of asymmetry, as in examples described from the Jura Mountains (Laubscher,1977) and the Appalachians (Wiltschko and Chapple,1977; Davis and Engelder,1985).

Detachment folds have formed above the roof thrust of the regional-scale duplex in the northeastern Brooks Range (Figure 5). In contrast with the most familiar examples of detachment folds, which have formed above evaporite layers, these detachment folds have formed above a shale unit. The Mississippian Kayak Shale is the incompetent stratigraphic horizon that serves both as the roof thrust of the underlying duplex and the incompetent layer above which detachment folds have formed. The Kayak Shale is a slick and highly fissile carbonaceous shale. It is about 200-400 m thick throughout most of the northeastern Brooks Range. It thins northward to 100 m or less in the Shublik Mountains, and is much thinner to absent in the Sadlerochit Mountains, where it has not served as a detachment horizon. The Kayak Shale is visibly thickened in anticlines, but a lack of appropriate exposures precludes determining whether it is thinned in synclines.

Carbonates of the Mississippian-Pennsylvanian Lisburne Group form the competent structural member that overlies the Kayak Shale. This unit is 450-850 m thick, and displays a broadly southward-thickening trend. Within the Lisburne Group, the upper Wahoo Formation is the more competent unit and defines the largest folds. The underlying Alapah Formation is thinner-bedded and more argillaceous and commonly is thickened in the cores of anticlines in the Wahoo Formation by smaller disharmonic folds. Terrigenous clastic rocks of the Permian-Triassic Sadlerochit Group overlie the Lisburne Group. Folds in the Sadlerochit Group are generally controlled by those in the underlying Lisburne Group, although parasitic folds and thrust faults also are present, particularly above a minor detachment horizon in the Kavik Shale (Figure 2).

The detachment folds in the Front Ranges and Franklin Mountains domains are generally open to tight chevron-shaped folds that are upright with respect to the underlying detachment surface. The detachment surface is tilted in the limbs of the regional anticlinoria, so the axial surfaces of the detachment folds may dip steeply north or south depending on their position with respect to the anticlinoria (Figure 5). The geometry of the folds varies depending on the local magnitude of shortening. The folds are tightest in the synclinoria, displaying high amplitude relative to wavelength. Although commonly eroded from the crests of the anticlinoria, the detachment folds are continuous over the anticlinoria downplunge. The folds are more open over the anticlinoria, particularly on the long backlimbs and in the Front Ranges domain. These folds display low amplitude relative to wavelength, and box-fold geometries are common. The fact that the detachment folds are continuous over the anticlinoria and are not restricted to the synclinoria suggests that they did not form entirely ahead of each successively emplaced horse, as would be the case in an active-roof duplex. Instead, it supports the interpretation that they formed directly above each horse as it was emplaced, requiring a backthrust displacement on the roof thrust. In the Front Ranges and Franklin Mountains domains, shortening of the Lisburne and Sadlerochit Groups is accommodated almost entirely by detachment folds, with rare small-displacement out-of-syncline and fold-breaching thrust faults being present only where the folds are tightest.

Figure 7A illustrates a generalized and hypothetical model for the evolution of symmetrical detachment folds, like those in the Front Ranges and Franklin Mountains domains. It is beyond the scope of this paper to discuss the geometry and kinematics of detachment folds in detail, but the diagram illustrates some important points. As a detachment fold evolves, it must obey the laws of conservation of bed length and cross-sectional area (Dahlstrom, 1990). In other words, the length of the folded competent bed and the cross-sectional area of both the competent bed and the incompetent detachment unit must be the same in both the undeformed and deformed states (assuming plane strain). This constraint, which is followed in the model, places some severe limitations on the possible geometries and kinematic paths of folds; only a single geometric/kinematic path is possible for an ideal symmetrical chevron fold with a fixed detachment depth. The arc-length of the fold (i.e. the bed-length encompassed by the fold) must increase with increasing shortening if bed length and area are to be conserved. This requires that at least some hinges migrate as a fold evolves, rather than remaining fixed in their original positions with respect to bedding. As shortening increases, the interlimb angle decreases and the ratio of amplitude to wavelength increases. The natural fold geometries observed along the transect (Figure 5) display a similar range in geometric characteristics.

The geometry of folds in the Lisburne and Sadlerochit Groups is quite different in the Philip Smith Mountains domain to the south (Figure 5). Exposures of Lisburne Group limestones predominate for over 35 km to the south of a synclinal structural low in the vicinity of Porcupine Lake (Figure 4), reflecting relatively constant structural relief. Thus, anticlinoria involving sub-Mississippian rocks are not important in this domain, and a passive-roof duplex as seen in the Front Ranges and Franklin Mountains domain either is not present or has had little influence on the structures exposed at the surface. Folds in this domain are strongly asymmetrical, with a consistent northward vergence. These folds commonly are breached through their steep limbs by thrust faults with northward displacement. These folds are somewhat similar in geometry to fault-propagation folds (Suppe, 1985), and are represented as such on the present cross section (Figure 5). However, recent work shows that, in actuality, they differ from fault-propagation folds in that the fault cuts through the fold, rather than dying out in the fold, and cuts through the steep limb, rather than along its lower hinge. On average, the geometry of the folds in the Philip Smith Mountains domain is different from that of the detachment folds to the north, although they also formed above a detachment in the Kayak Shale. However, folds representing a complete transition between the end-member geometries are present, suggesting that the asymmetrical, fault-breached folds in the Philip Smith Mountains domain also are detachment folds.

Figure 7B illustrates a generalized and hypothetical model for the evolution and eventual thrust truncation of asymmetrical detachment folds, like those in the Philip Smith Mountains domain. The model obeys the laws of conservation of bed length and cross-sectional area. This places some constraints on the geometries that are possible, although they are not as restrictive as in the case of symmetrical detachment folds. A range of geometries is possible for a given shortening, and the model illustrates only one of the possible kinematic paths. Thrust breakthrough of the steep limbs of folds probably results from geometric and/or mechanical limits to continued fold growth with increasing shortening. It should be noted that in the natural folds, the fault flattens up-section in a detachment horizon in the Sadlerochit Group, resulting in superposition of a fault-bend fold geometry on the truncated asymmetrical detachment-fold geometry.

Possible controls on structural geometry

It is not clear what factors favored the formation of a passive-roof duplex in the Front Ranges and Franklin Mountains domains, and the accommodation of shortening above that duplex by upright detachment folds, as opposed to forward-vergent asymmetrical detachment folds and thrust faults as to the south, in the Philip Smith Mountains domain. However, comparison of the characteristics of the various domains offers some empirical clues to the factors that may have influenced the types of structures that formed in each.

Detachment occurred in the Kayak Shale in all three domains, resulting in formation of upright detachment folds in the two northern domains and forward-vergent asymmetrical detachment folds and thrust faults in the Philip Smith Mountains domain. A fundamental factor in formation of these structures must have been the structural stratigraphy, in particular the relative thicknesses of and competency contrast between the Kayak Shale and the overlying Lisburne Group. The thickness and mechanical weakness of the Kayak Shale was an essential element, as indicated by the lack of detachment folds in the Sadlerochit Mountains, where the Kayak Shale is thin to absent. The shale was sufficiently effective as a detachment horizon to allow formation of a low-taper, weak basal-layer wedge, as described by Davis and Engelder (1985) for a basal layer of salt. They argue that a particular sense of vergence will not predominate in such a wedge, as is the case over the passive-roof duplex in the northeastern Brooks Range.

There is little obvious change in the structural stratigraphy of the Kayak Shale and the Lisburne Group between the Franklin Mountains and the Philip Smith Mountains domains. This is consistent with the interpretation of detachment folding in both areas. However, it does not account for the differences in geometry and faulting, so other factors must be sought to explain them.

The structural stratigraphy and geometry beneath the Kayak Shale detachment differ dramatically between the Franklin Mountains and the Philip Smith Mountains domains. In the Franklin Mountains and Front Ranges domains, the Kayak Shale is underlain by a relatively thin Kekiktuk Conglomerate, which in turn unconformably overlies a polydeformed assemblage of lithologically heterogeneous stratified rocks. It is not intuitively obvious that these rocks should have behaved as a relatively rigid mass during Cenozoic deformation. However, the structures displayed by the Kekiktuk Conglomerate, which was structurally attached to and deformed with the underlying rocks, indicates that this is just what they have done. The general lack of penetrative strain, detachment, or imbrication in the Kekiktuk Conglomerate indicates that it and the underlying rocks behaved relatively rigidly during formation of the passive-roof duplex. The unit marks a form surface that defines the smoothly varying and long-wavelength geometry of the anticlinoria. and "Structural hardening" as a result of pre-Mississippian shortening and reactivation of favorably oriented pre-Mississippian structures, especially south-dipping faults or bedding, may help account for the apparently rigid behavior of the previously deformed rocks unconformably beneath the Kekiktuk Conglomerate.

A wedge of Middle Devonian to Lower Mississippian clastic sedimentary rocks, equivalent to those documented farther east by Anderson (1991), thickens southward from near the boundary between the Franklin and Philip Smith Mountains domains. The sub-Middle Devonian unconformity that defines the base of this wedge merges northward with the sub-Mississippian unconformity, which is ultimately succeeded to the south by a conformity in the Endicott Mountains allochthon (Anderson and Wallace, 1991; Brosgé and others, 1988). This wedge has been thickened by folds and thrust faults that are significantly smaller and more closely spaced than the anticlinoria to the north (Brosgé and Reiser, 1965; Brosgé and others, 1976; Anderson, 1991). If anticlinoria like those to the north exist beneath the wedge, they are much smaller, as indicated by the relatively constant level of structural relief across the Philip Smith Mountains domain.

The change in character of the rocks beneath the Kayak Shale detachment near the boundary between the Franklin Mountains and Philip Smith Mountains domains undoubtedly had a significant influence on the structures that formed in those domains, particularly beneath the detachment. The previously shortened and variably dipping sub-Mississippian rocks to the north behaved relatively rigidly, forming very large fault-bend folds, probably controlled in part by pre-Mississippian structures (Wallace and Hanks, 1990). Differences in the sizes of these anticlinoria are the main distinguishing characteristic between the Front Ranges and Philip Smith Mountains domains. The size of these structures likely was influenced by pre-Mississippian structures, as best indicated by the correspondence of Cenozoic anticlinoria with a pre-Mississippian structural repetition of stratigraphy in the Sadlerochit and Shublik Mountains. The northward decrease in the size of the anticlinoria may also be related to a decrease in the depth of the floor thrust.

In contrast with the anticlinoria to the north, smaller and closer-spaced folds and thrust faults formed in the previously undeformed clastic rocks beneath the Kayak Shale in the Philip Smith Mountains domain. Thus, duplexes formed beneath the Kayak Shale in both areas, but the horses were much larger to the north. It seems likely that both duplexes shared a floor thrust at about the same depth, but that the duplexes changed character northward as the Middle Devonian to Lower Mississippian clastic wedge pinched out over the previously deformed sub-Mississippian rocks to the north.

It is not obvious how the significant difference in the structural topography and the spacing and type of structures below the Kayak Shale detachment may have influenced the geometry of overlying structures. However, it is worth noting the relationships between structures above and below the detachment. The relatively smooth surface defined by the broad, low amplitude-to-wavelength anticlinoria to the north is overlain by upright detachment folds probably formed as a result of backthrust displacement. If displacement on adjacent horses in the passive-roof duplex occurred in part concurrently, as seems likely, then the structural relief of the more forward horse would serve as an impediment to forward displacement of the roof, and would favor the concentration of shortening in the anticlinoria and the formation of upright folds. In contrast with the anticlinoria to the north, the shorter-wavelength, lower-amplitude fold-and-thrust structures to the south are overlain by forward-vergent asymmetrical, thrust-truncated folds. These likely formed in a more typical fold-and-thrust wedge, characterized by a basal detachment stepping up-section in the forward direction and thrust faults with a forward displacement sense.

To the west-northwest of the northeastern Brooks Range, beneath the North Slope (Figure 1A), a southward thickening wedge of mid-Cretaceous and younger clastic deposits fills the Colville basin (Bird, 1986; Molenaar and others, 1987), and the sub-Mississippian unconformity dips southward beneath the basin from the Barrow arch (Bird, 1986). A similar pattern probably existed in the northeastern Brooks Range prior to Cenozoic shortening, uplift, and erosion (Wallace and Hanks, 1990), as suggested by projection of the Barrow arch and Colville basin into the northeastern Brooks Range (Bird and Bader, 1987; Molenaar and others, 1987). Thus, a greater depositional overburden of mid-Cretaceous and younger rocks probably existed southward prior to formation of the fold-and-thrust structures considered here. An additional structural overburden extended northward to the Franklin Mountains-Philip Smith Mountains domain boundary as indicated by the klippe near Porcupine Lake (Figures 4 and 5). The absolute timing of emplacement of this klippe is unknown, but it is analogous to Early Cretaceous allochthons farther west (Mull, 1982, 1985; Mayfield and others, 1983), and cross-cutting relationships indicate that it was emplaced before formation of the underlying asymmetrical folds and thrust faults that characterize the Philip Smith Mountains domain.

Thus, a greater combined tectonic and depositional overburden was present in the Philip Smith Mountains domain than to the north. The lesser overburden to the north could have facilitated the upright growth of detachment folds, whereas the greater overburden to the south may instead have favored the formation of asymmetrical folds and thrust faults. Similarly, the lesser overburden to the north may have favored backthrust displacement on the Kayak Shale detachment, as opposed to the forward displacement to the south. It is possible that the amount of overburden may also have had some influence on the mode of deformation beneath the Kayak Shale detachment, but it seems likely that the character of the rocks involved had greater influence.

The Front Ranges and Philip Smith Mountains domains are characterized by a relatively low average shortening (about 24%). The cross section shows only the northernmost part of the Philip Smith Mountains domain, and includes a major structural low characterized by less structural relief and, hence, less shortening than is typical for the domain. Thus, the shortening determined for the domain from the cross section (about 27%) probably is lower than the average shortening for the domain as a whole. The folds in the Lisburne Group in the Philip Smith Mountains domain are about the same arc-length as to the north, but generally are tighter, overturned, and truncated by thrust faults. Thus, a greater average shortening would be expected in this domain. This difference in shortening quite likely had an influence both on the sense of displacement on the Kayak Shale detachment and on the geometry of overlying structures. A low average shortening may have allowed backthrust displacement and formation of upright folds. However, as shortening and consequent structural thickening increased, it seems likely that structures would have developed a more consistent sense of forward vergence.

SUMMARY AND CONCLUSIONS

A transect across the northeastern Brooks Range in the vicinity of the Canning River displays well-exposed examples of a passive-roof duplex and shale-cored detachment folds. The structural stratigraphy of the region has played a fundamental role in the types of structures that formed. A thick shale unit, the Kayak Shale, has served as a major detachment horizon, separating structural-stratigraphic units that have deformed quite differently. Carbonates of the Lisburne Group form the dominant competent unit above the Kayak Shale, defining the characteristic fold and fault spacing above the detachment. Less competent clastic rocks of the overlying Sadlerochit Group have deformed with the Lisburne Group, but also display closer-spaced folds and thrust faults. Below the detachment, the structural stratigraphy varies from north to south. In the north, previously complexly deformed sub-Mississippian rocks plus a veneer of Mississippian Kekiktuk Conglomerate have deformed relatively rigidly, despite their lithologically heterogeneous, well-stratified character. To the south, a southward-thickening wedge of Middle Devonian to Lower Mississippian clastic rocks, including equivalents of the Kekiktuk Conglomerate, consititutes a structural-stratigraphic unit in its own right.

The transect can be divided into three structural domains based on variations in structure. Two domains constitute most of the transect and are characterized by anticlinoria cored by sub-Mississippian rocks with a cover shortened by upright folds formed above the Kayak Shale. The northern, or Front Ranges, domain is characterized by anticlinoria that are smaller in length, width, and amplitude than those in the central, or Franklin Mountains, domain. The southern, or Philip Smith Mountains, domain is characterized by north-vergent asymmetrical folds and thrust faults formed above the Kayak Shale and an absence of anticlinoria.

In the Front Ranges and Franklin Mountains domains, the structure below the Kayak Shale is interpreted to be a duplex with a floor thrust at depth in the sub-Mississippian rocks and a roof thrust in the Kayak Shale. Since the floor and linking thrusts of this duplex are not exposed, the depth to detachment, and hence the amount of shortening accommodated by the duplex, are conjectural. However, the geometry of the upper surface of the horses suggests a fault-bend fold model with a shortening approximately equal to that accommodated by the cover. Other models require a deeper floor thrust for the duplex, with a shortening less than that accommodated by the cover. The roof thrust is pinned to the north, requiring that shortening above the duplex must be accommodated by backthrust displacement on the roof thrust. Thus, the duplex is a passive-roof duplex, regardless of the actual geometry of the underlying horses. A balanced cross section illustrating the preferred fault-bend fold geometry for the duplex is consistent with the interpretation that the Front Ranges and Franklin Mountains domains are underlain by a passive-roof duplex in which shortening in the duplex and its cover are approximately equal.

The roof of this duplex is unusual in that it is well-preserved and has been shortened by folding, without significant thrust faulting. The folds in the roof are interpreted to be detachment folds that differ from the most familiar examples of detachment folds in that they are cored by shale, instead of evaporites. On average, the detachment folds in the Front Ranges and Franklin Mountains domains are upright (with respect to the underlying detachment horizon) and symmetrical. Hindward of the duplex, in the Philip Smith Mountains domain, forward-vergent asymmetrical, thrust-breached folds formed above the Kayak Shale display geometries found commonly in fold-and-thrust belts. These folds are also interpreted to be detachment folds because there is a complete transition in geometry from the definite detachment folds to the north. This suggests that a thrust-truncated-detachment fold model may be applicable to many fault-related folds, although fault-bend and fault-propagation fold models have most typically been applied in recent years.

The factors that resulted in formation of a passive-roof duplex and detachment folds, and in the variation between upright symmetrical and forward-vergent, asymmetrical, and thrust-breached detachment folds are unknown. However, some factors that may have influenced structural geometry are suggested by consideration of the structural stratigraphy and by a comparison between the characteristics of the domains and their distinctive structures. Shortening is accommodated differently above and below a thick shale unit that serves as a regional detachment horizon. Detachment folds have formed in a thick competent unit above this detachment horizon. A lateral change from upright, symmetrical detachment folds to the north to forward-vergent, thrust-truncated detachment folds to the south corresponds with 1) an increase in depositional and tectonic overburden, 2) an increase in shortening, and 3) a change from an underlying relatively high-relief but smooth structural topography defined by long-wavelength structures, to a lower-relief but "rougher" topography defined by smaller, closer-spaced structures. This change in structural topography beneath the regional detachment horizon reflects a southward decrease in the size of fold-and-thrust structures that corresponds with a southward change from previously highly deformed, lithologically heterogeneous rocks to a previously undeformed clastic wedge.

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FIGURE CAPTIONS

Figure 1. A. Map of northern Alaska, showing the major physiographic and tectonic provinces, including the northeastern Brooks Range. SR = Sagavanirktok River, CR = Canning River.

B. Generalized geologic map of the northeastern Brooks Range showing the major structural provinces. Brackets indicate approximate locations of schematic cross sections shown in figure 3. WSP = western structural province, OBSP = Okpilak batholith structural province, ESP = eastern structural province, CDTF = Continental Divide thrust front.

C. Generalized tectonic map of the northeastern Brooks Range showing the distribution of the major structural-stratigraphic units and structural features of the northeastern Brooks Range. Structural-stratigraphic units are as identified in figure 3. Solid teeth on thrust faults indicate older-over-younger thrust faults that duplicate stratigraphic section; open teeth indicate detachment surfaces along which there has been slip but no disruption of the normal stratigraphic succession.

Figure 2. Structural stratigraphy of the northeastern Brooks Range. A generalized stratigraphic column is shown to the left, and the structural-stratigraphic units and their dominant characteristics are shown to the right. Thicknesses are not to scale. Detachment horizons are shown with a wavy line pattern, which extends only partly across the column for minor detachment horizons. SU = structural unit (competent), DU = detachment unit (incompetent). The distribution of sub-units (A,B, and C) of structural unit 1 is shown in Figure 1C.

Figure 3. Cross sections illustrating schematically the structural geometry in each of the structural provinces of the northeastern Brooks Range. The approximate locations of the sections are shown in figure 1B. The sections are not to scale, and are intended to represent specific structures only schematically. Screws indicate places where little or no slip has occurred across horizons that elsewhere are major detachment horizons.

Figure 4. Generalized geologic map of most of the western structural province of the northeastern Brooks Range. Line of cross section in figure 5 is shown; segments are labelled with letters A to J from north to south.

Figure 5. Balanced cross section across the western structural province of the northeastern Brooks Range. Line of section shown on figure 4.

A. Deformed section. Section is separated into overlapping parts to illustrate relationships between structures.

B. Restored section. Note that restored section is shown at a different scale than the deformed section in order to save space.

Figure 6. Schematic cross section and displacement diagrams of idealized passive-roof duplex.

A. Accommodation of shortening by displacement of a single horse in a passive-roof duplex, and by detachment folding in its roof. A-J indicate positions of detachment fold hinges and the originally underlying points beneath the roof thrust. L-M are hinges in the fault-bend fold. X and X' mark the footwall and hangingwall cutoffs, respectively of the leading edge of the horse, and X" the originally overlying point above the roof thrust.

B. Restoration of A. Letter designations as in A.

C. Graph showing distribution of horizontal displacement as a function of original position in undeformed state. Letter designations as in A. Shortening beneath the roof thrust is accommodated mainly by displacement on a single fault, whereas above the roof thrust, the equivalent shortening is distributed over a series of detachment folds.

D. Graph showing amount of backthrust displacement across the roof thrust as a function of original position in undeformed state. Letter designations as in A. Backthrust displacement increases hindward from the leading edge of the horse to the point above the roof thrust that originally overlay that leading edge. Backthrust displacement decreases progressively hindward of this point.

Figure 7. Hypothetical sequence of evolution of detachment folds. Progressive evolution is shown with a series of arbitrarily spaced structures that accommodate increasing shortening to the left. Bed length and cross-sectional area are conserved in these models.

A. Series of symmetrical and upright detachment folds that increase in amplitude/wavelength with increasing shortening. Note that for a given thickness of detachment unit, the conservation laws uniquely determine the size and geometry of each fold as a function of the amount of shortening accommodated by that fold.

B. Series of detachment folds that increase in both asymmetry and amplitude/wavelength with increasing shortening. Additional shortening is ultimately accommodated by thrust breakthrough of the steep limb of a fold. Although the conservations laws restrict the possible geometries for a given thickness of detachment unit and shortening accommodated by a fold, a range of geometries are possible for a given value of shortening. Geometries shown here are arbitrarily chosen to approximate the apparent evolutionary path of observed folds.

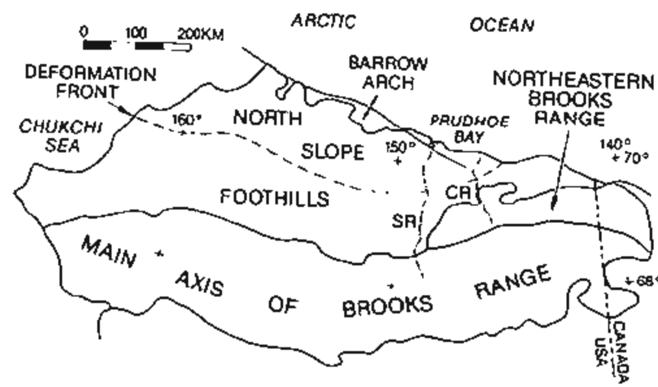


Figure 1.A. Tectonic provinces of northern Alaska

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K. Wallace)

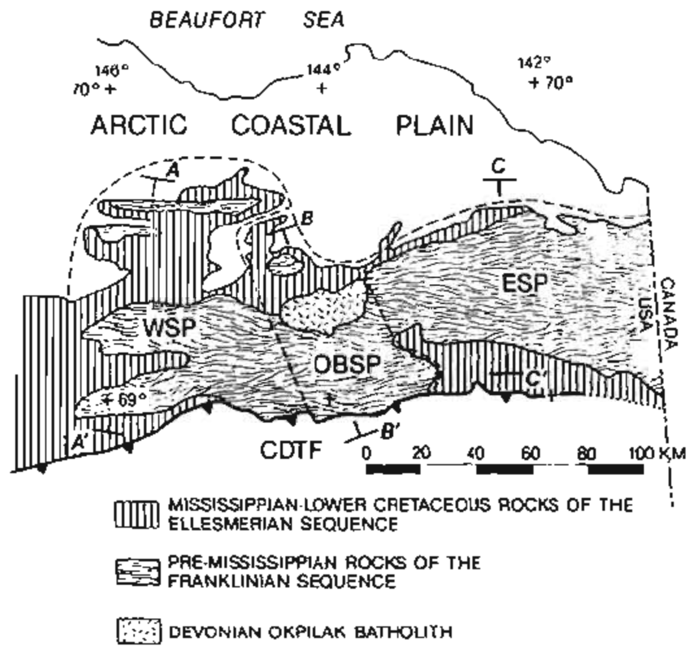


Figure 1.B. Structural provinces of the northeastern Brooks Range

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K.Wallace)

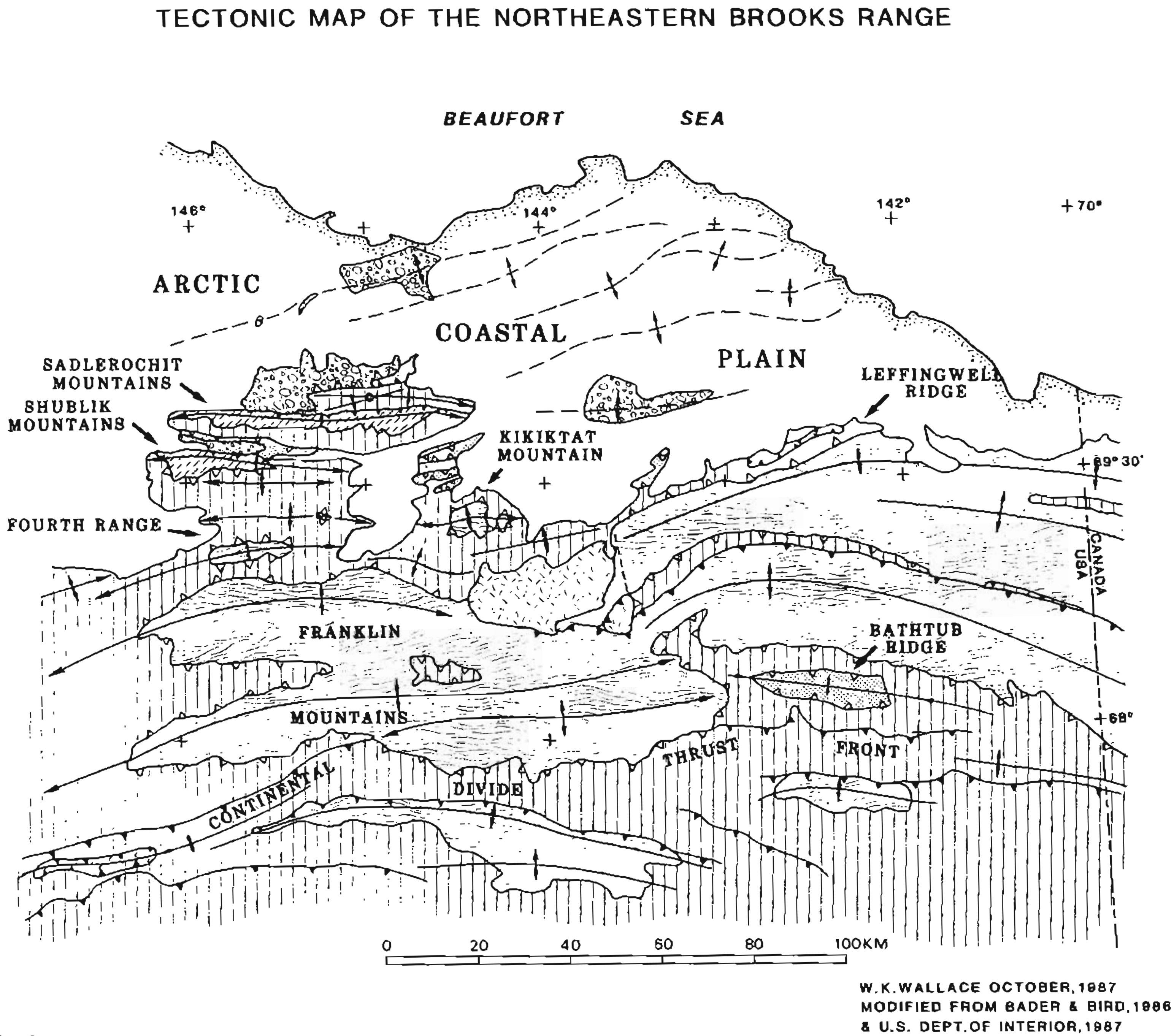


Figure 1.C. Generalized tectonic map of the northeastern Brooks Range

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K. Wallace)

EXPLANATION

Quaternary deposits

Structural unit 4:
Hue Shale, Canning Formation, Jago River Formation, and Sagavanirktok Formation (Upper Cretaceous to Tertiary)

Detachment unit 4:
Pebble shale unit (Lower Cretaceous)
Structural unit 3:
Ignek unit of Kemik Sandstone (Lower Cretaceous)
Also includes Arctic Creek facies north of Okpilak Batholith and Kongakut Formation at Bathtub Ridge (both Lower Cretaceous)

Detachment unit 3:
Kingak Shale (Jurassic to Lower Cretaceous)
Structural unit 2:
Lisburne Group, Sadlerochit Group, Shublik Formation, Karen Creek Sandstone, and Marsh Creek unit of Kemik Sandstone (Mississippian to Lower Cretaceous)

Detachment unit 2:
Kayak Shale (Mississippian)
Structural unit 1A:
Undifferentiated pre-Mississippian rocks (Proterozoic to Devonian) (Exclusive of Katakturuk Dolomite, Nanook Limestone, and Okpilak batholith), and Kekiktuk Conglomerate (Mississippian)

Detachment unit 2:
Kayak Shale (Mississippian)
Structural unit 1B:
Katakturuk Dolomite and Nanook Limestone (Proterozoic to Devonian), and Kekiktuk Conglomerate (Mississippian)

Detachment unit 2:
Kayak Shale (Mississippian)
Structural unit 1C:
Okpilak batholith (Devonian), and Kekiktuk Conglomerate (Mississippian)

Klippe near Porcupine Lake:
Allochthonous Mississippian to Lower Cretaceous rocks

Figure 1.C. Generalized tectonic map of the northeastern Brooks Range (Explanation)

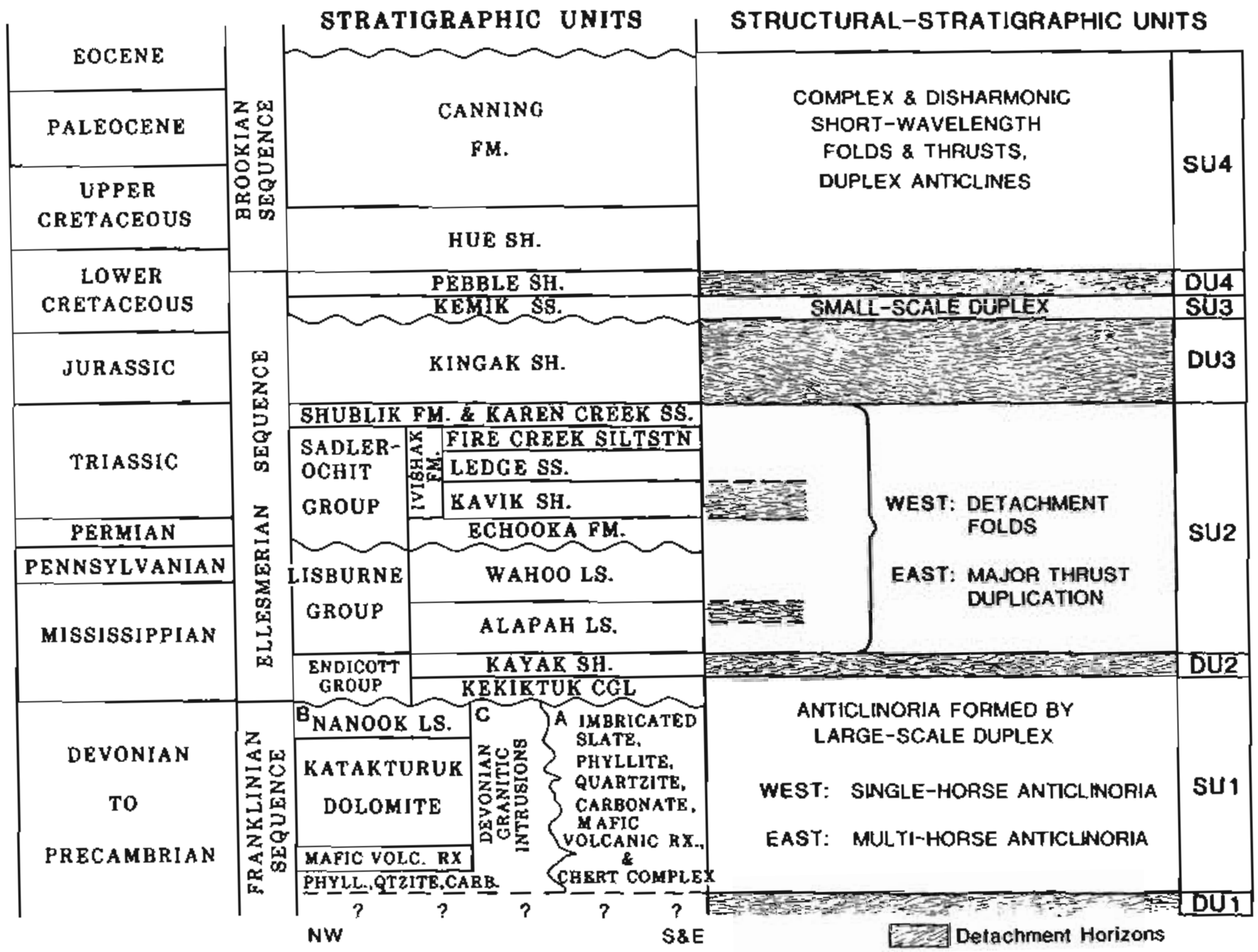


Figure 2. Structural stratigraphy of the northeastern Brooks Range

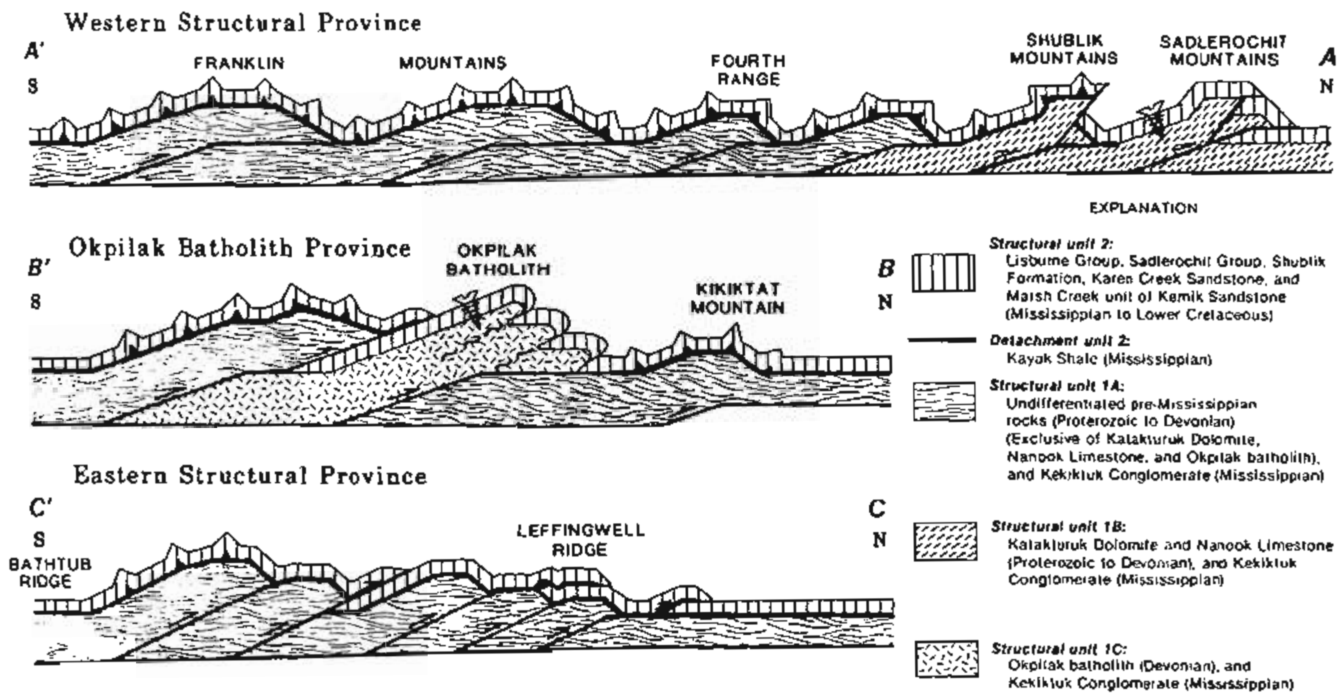


Figure 3. Schematic cross sections of the structural provinces of the northeastern Brooks Range

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K. Wallace)

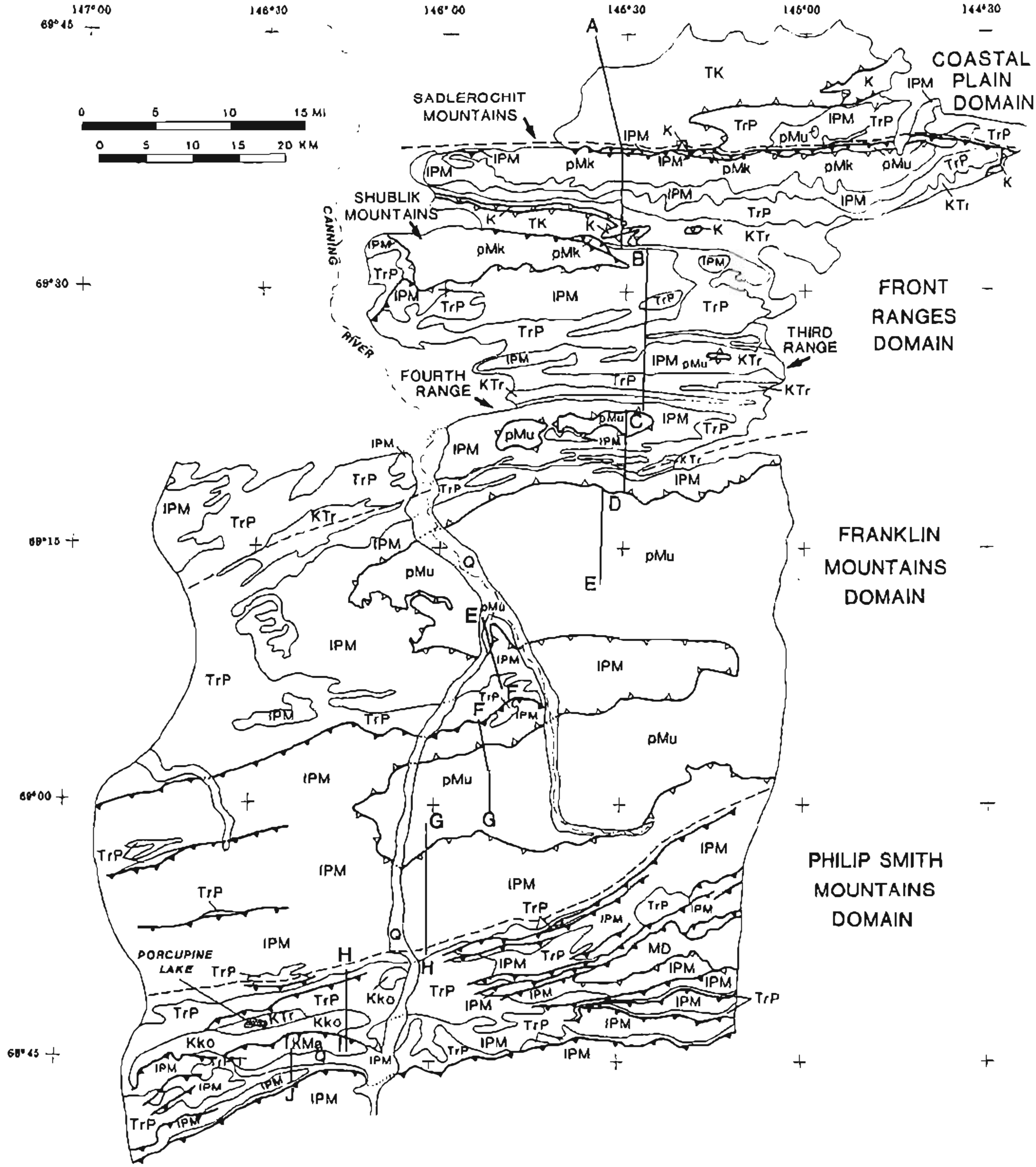


Figure 4. Generalized geologic map of the Canning River transect

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K. Wallace)

EXPLANATION

TK Hue Shale and Canning Formation
(Cretaceous to Lower Tertiary)

K Kemik Sandstone and pebble shale unit
(Lower Cretaceous)

KTr Shublik Formation and Kingak Shale
(Triassic to Lower Cretaceous)

TrP Sadlerochit Group
(Permian to Triassic)

IPM Kayak Shale and Lisburne Group
(Mississippian to Pennsylvanian)

pMu Undifferentiated pre-Mississippian rocks and
unconformably overlying Mississippian Kekiktuk Conglomerate

Units restricted to the north (Sadlerochit & Shublik Mountains)

pMk Mafic volcanic rocks, Katakturuk Dolomite, and Nanook Limestone
(Proterozoic to Devonian)

Units restricted to the south (Porcupine Lake vicinity)

KMa Mt. Annette allochthon
(Mississippian to Lower Cretaceous)

Kko Kongakut Formation
(Lower Cretaceous)

MD Kekiktuk Conglomerate, possibly transitional to Kanayut
Conglomerate (Upper Devonian? to Mississippian)

Symbols

 Older-over-younger thrust faults

 Detachment surfaces (thrust faults across which normal stratigraphic order is maintained)

— — — Domain boundaries

Figure 4. Generalized geologic map of the Canning River transect (Explanation)

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K. Wallace)

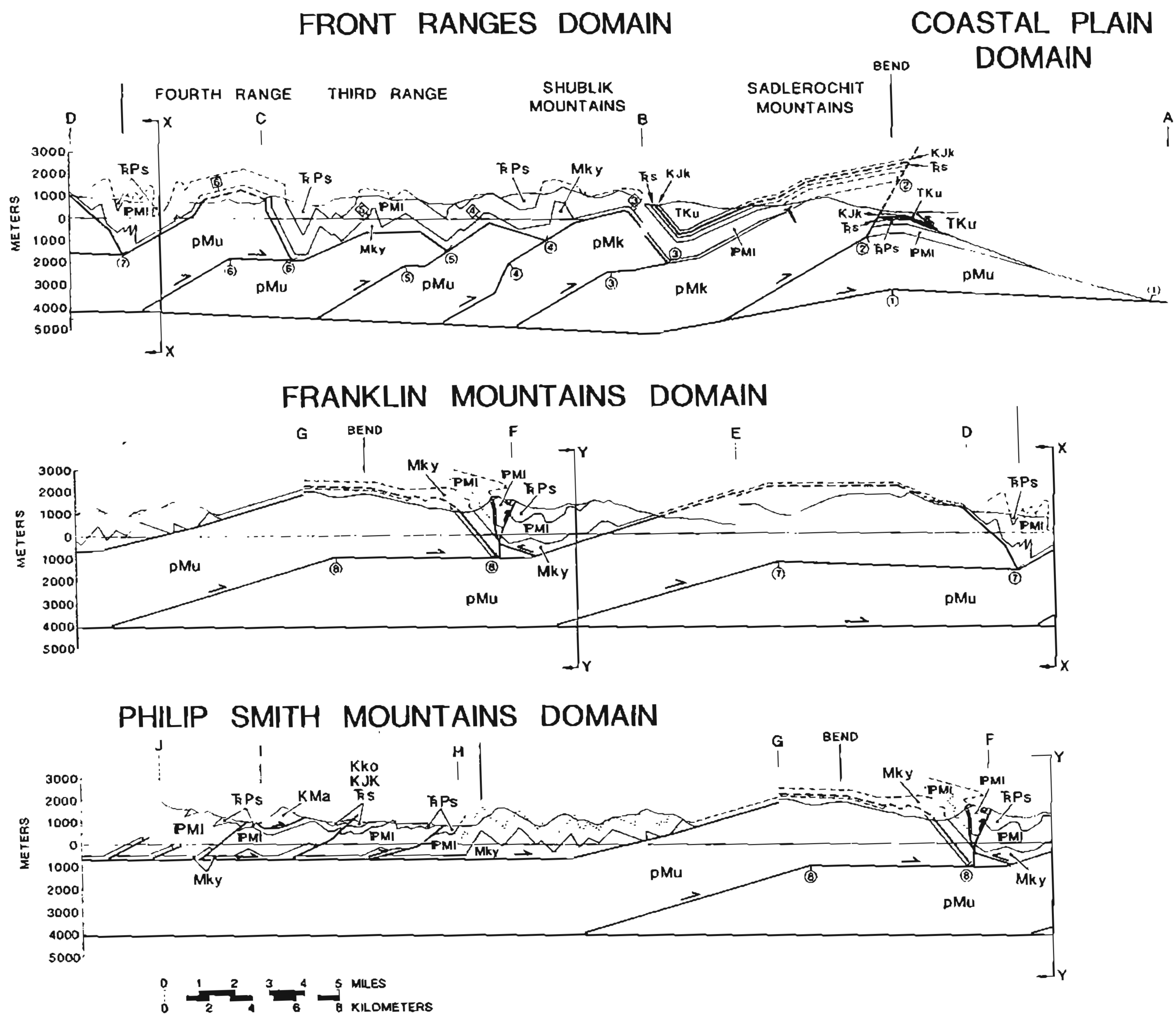
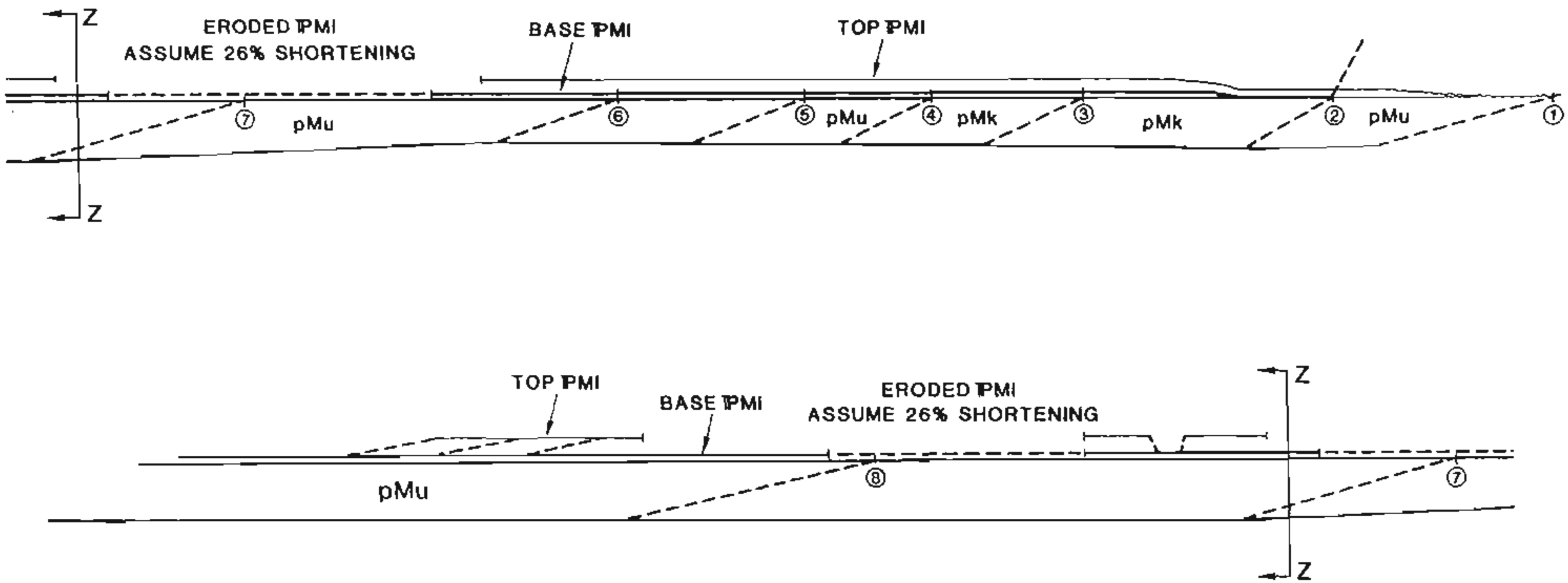
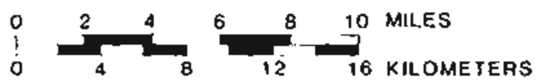


Figure 5.A. Balanced cross section of the Canning River transect, deformed section

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K. Wallace)

RESTORED CROSS SECTION





BASE IPMI $\frac{\text{106 KM DEFORMED LENGTH}}{\text{144 KM RESTORED LENGTH}}$ = 26% OR 38 KM SHORTENING

TOP pMu BASEMENT $\frac{\text{111 KM DEFORMED LENGTH}}{\text{151 KM RESTORED LENGTH}}$ = 27% OR 40 KM SHORTENING

BASE pMu BASEMENT $\frac{\text{111 KM DEFORMED LENGTH}}{\text{156 KM RESTORED LENGTH}}$ = 29% OR 45 KM SHORTENING

Figure 5.B. Balanced cross section of the Canning River transect, restored section

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K. Wallace)

EXPLANATION

TKu Kemik Sandstone, pebble shale unit, Hue Shale, & Canning Formation
(Lower Cretaceous to Lower Tertiary)

KJk Kingak Shale
(Jurassic to Lower Cretaceous)

TRs Shublik Formation
(Triassic)

TRPs Sadlerochit Group
(Permian to Triassic)

IPMl Lisburne Group
(Mississippian to Pennsylvanian)

Mky Kayak Shale
(Mississippian)

pMu Undifferentiated pre-Mississippian rocks and
unconformably overlying Mississippian Kekiktuk Conglomerate

Units restricted to the north (Sadlerochit & Shublik Mountains)

pMk Mafic volcanic rocks, Katakturuk Dolomite, and Nanook Limestone
(Proterozoic to Devonian)

Units restricted to the south (Porcupine Lake vicinity)

KMa Mt. Annette allochthon
(Mississippian to Lower Cretaceous)

Kko Kongakut Formation
(Lower Cretaceous)

Symbols

A – J Offsets in line of section

(3) Leading-edge cutoffs (Footwall & Hangingwall) for each horse
(numbered from North to South)

◇3 Point at base of IPMl originally overlying leading-edge cutoffs
for each horse

Figure 5. Balanced cross section of the Canning River transect (Explanation)

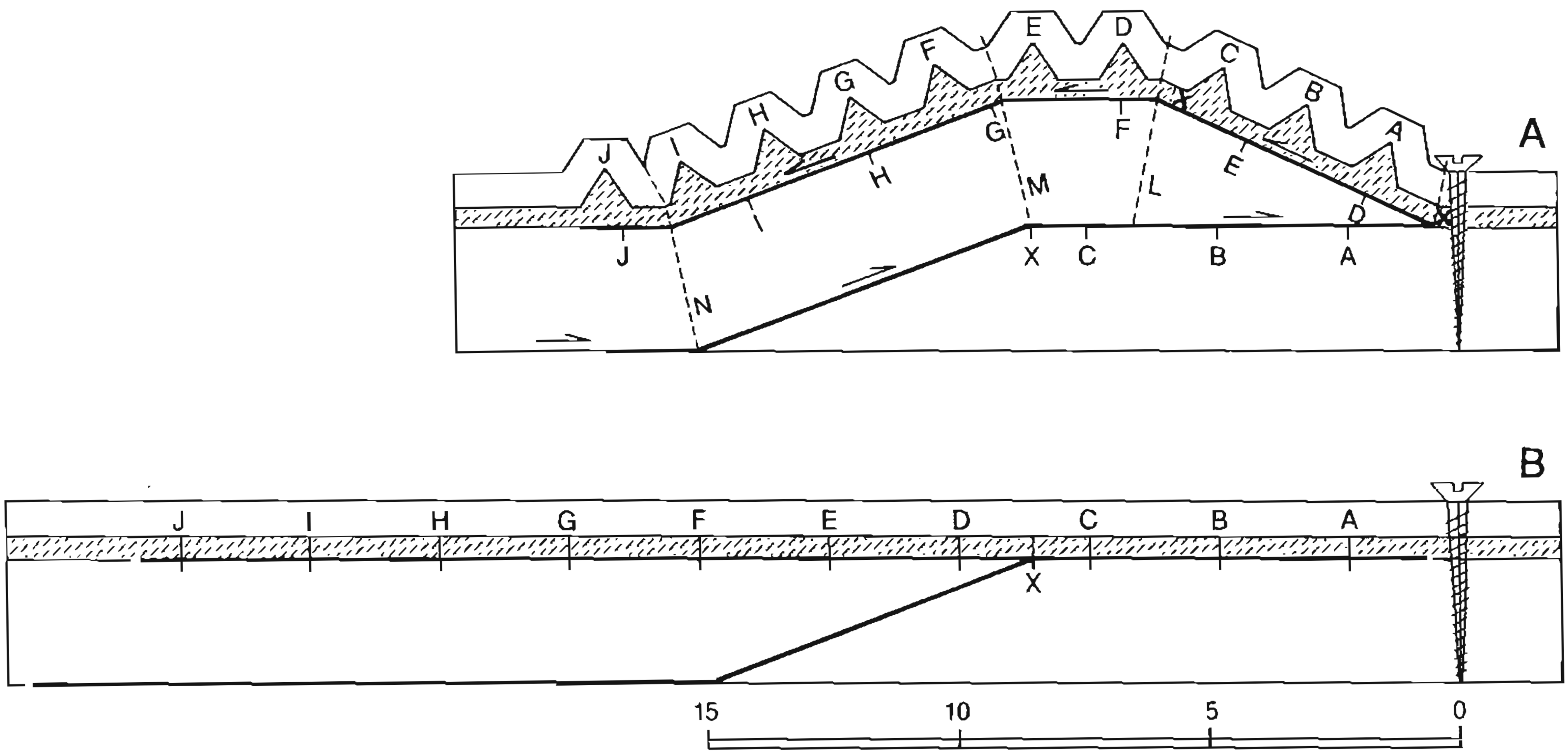


Figure 6. Schematic cross section of an idealized passive roof duplex, A. deformed & B. restored

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K. Wallace)

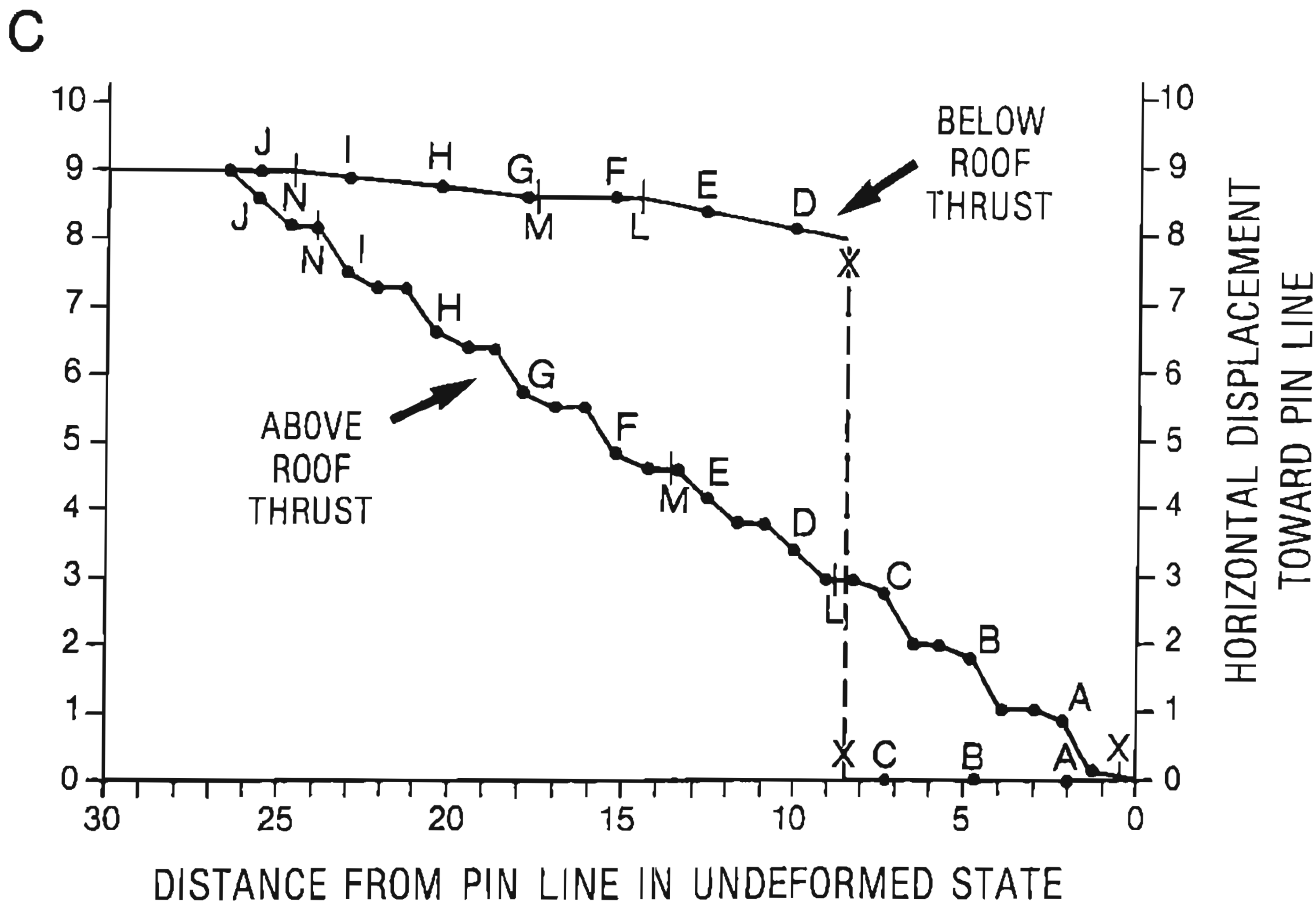


Figure 6.C. Distribution of displacement in an idealized passive roof duplex

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K.Wallace)

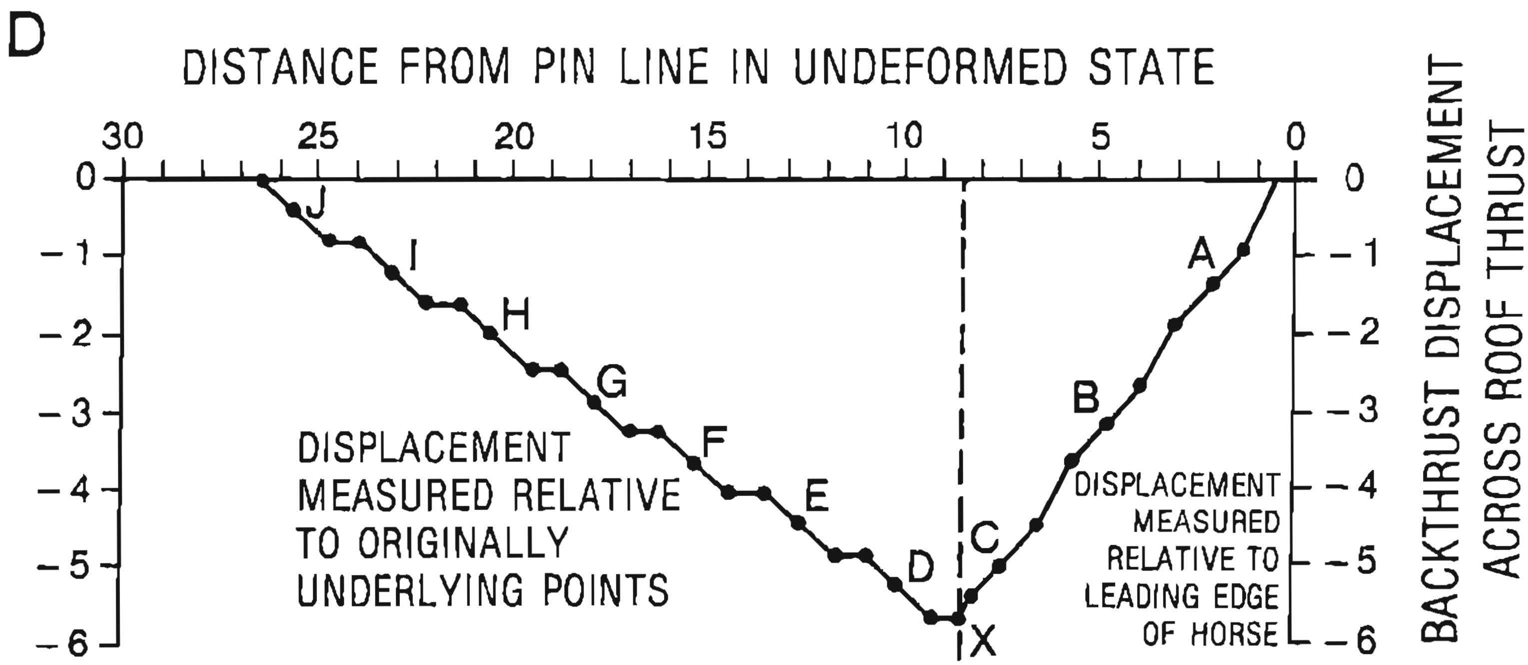


Figure 6.D. Distribution of displacement in an idealized passive roof duplex

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K.Wallace)

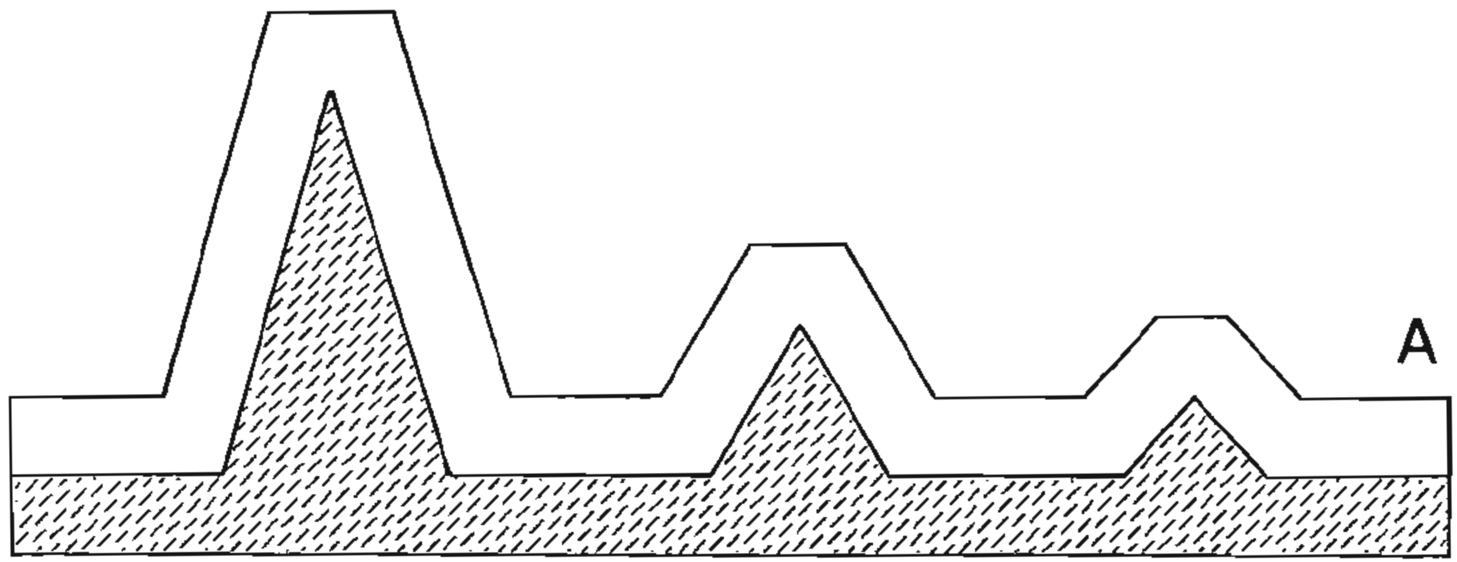


Figure 7.A. Progressive evolution of idealized symmetrical detachment folds

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K.Wallace)

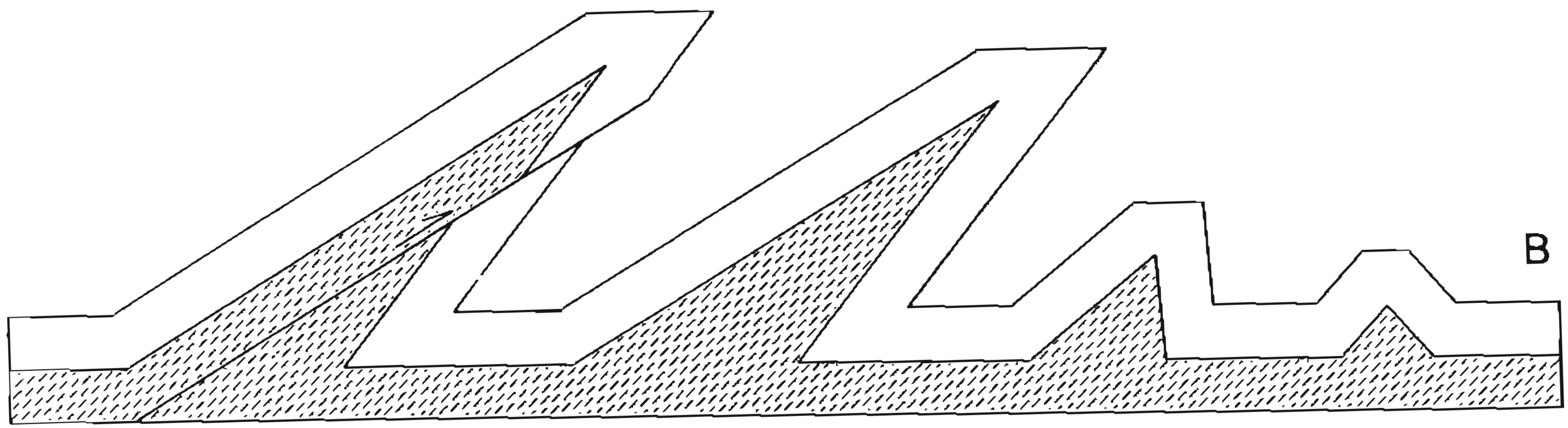


Figure 7.B. Progressive evolution of idealized asymmetrical detachment folds

Detachment folds above a passive-roof duplex, northeastern Brooks Range, Alaska (W.K. Wallace)