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THE STRUCTURAL GEOMETRY OF DETACHMENT FOLDS ABOVE A DUPLEX IN THE FRANKLIN MOUNTAINS, NORTHEASTERN BROOKS RANGE, ALASKA

by

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ABSTRACT

Geometric and kinematic analyses conducted in the northeastern Brooks Range constrain the evolution of a detachment folded roof sequence above a regional duplex . At least some of the detachment folds formed by fixed arc-length kinematics above a detachment unit that changed thickness during deformation and served as the roof thrust of the duplex. The horses in the duplex are fault-bend folds with gently dipping limbs and sub-horizontal crestal panels and detachment fold-trains occur above bends in the fault-bend folds and are separated by straight panels in the roof sequence. Detachment folds above the gently dipping backlimbs of the horses are north-vergent, whereas those above the forelimbs are both north- and south-vergent. Folds above the crestal panels are largely symmetric and those above the synform that separates the fault-bend folds are highly north-vergent and truncated by thrust faults. This distribution of detachment fold asymmetries suggests a complex structural history involving both forward and hindward displacements and it suggests a kinematic relationship between the fault-bend folded horses and the detachment folded roof sequence.

INTRODUCTION

The purpose of this report is to present the results of field work conducted during the summer of 1993 at two localities near the Canning River in the northeastern Brooks Range of Alaska (Fig 1). The two study areas each expose part of a regional north-directed duplex, which extends from the continental divide of the northeastern Brooks Range northward to the Arctic coastal plain (Namson and Wallace 1986; Wallace and Hanks, 1990; Wallace, 1993). Overlying the duplex are kilometer-scale detachment folds which record deformation in the detached roof sequence. The field work was specifically directed toward documenting and interpreting the geometry and kinematic history of these detachment folds.

This study addresses two primary questions:

1) What is the geometry and kinematic history of individual detachment folds in the area? It is unclear whether detachment folds form by a process of hinge-migration (*i.e.* kinking) (Dahlstrom, 1990) above a detachment unit of constant thickness or by a process of fixed-hinge buckling above a detachment unit that changes thickness during folding. This study suggests that at least some of the major detachment folds formed as a result of fixed-hinge buckling above a detachment unit that changed thickness during deformation (Homza and Wallace, in press).

2) What constraints does the geometry of both the duplex and the roof sequence place on the kinematic history of the duplex? Wallace (1993) suggested that many of the detachment folds in the northeastern Brooks Range formed in response to a southward, or backthrust, sense of displacement due to the northward emplacement of horses in the underlying duplex. Results based on the geometric analyses and qualitative strain observations of this study agree with Wallace's (1993) conclusions but also show that a significant portion of the deformation in this area was north-directed. This suggests that the system formed by a process involving both forward and hindward displacements (e.g. Dunne and Ferrill, 1988).

This report is organized as follows: First, a general geologic description of the region is provided, then pertinent observations from the two study areas, the "northern area" and "southern area", are presented. Finally, conclusions are discussed about 1) the geometry and kinematics of the detachment folds in the area and 2) the relationship between the emplacement of the underlying duplex and the kinematics of the roof sequence.

LOCATION, METHODS, AND GENERAL STRUCTURAL SETTING

The northern area covers approximately 100 km^2 in the central part of the Mt. Michelson A-4 quadrangle along the drainage divide between Salisbury Creek and Plunge Creek (Fig. 1, Plate 1). The southern area includes about 80 km^2 of the south-central portion of the Mt. Michelson A-4 quadrangle and the north-central part of the Arctic D-4 quadrangle (Fig. 1, Plate 3). The areas are separated by about 10 km. Geologic maps (scale = 1:25,000, Plates 1 and 3) and cross sections (Plates 2a, 2b, and 4) were constructed using AutoCAD software.

Both study areas are part of the North Slope subterrane of the Arctic Alaska terrane (Moore and others, 1992) and include both pre-Middle Devonian rocks, here loosely referred to as "basement", and younger cover rocks consisting mainly of the lower part of the Mississippian to Neocomian Ellesmerian sequence (Plate 1). The dominant structures of the areas are part of a north-directed fold-and-thrust belt formed during the Cenozoic Romanzof uplift of Moore and others (1992). Two regional structural highs, the "northern Franklin

Mountains anticlinorium" and the "southern Franklin Mountains anticlinorium" occur in the northern and southern study areas, respectively. Structural contours in each area define a westward convex

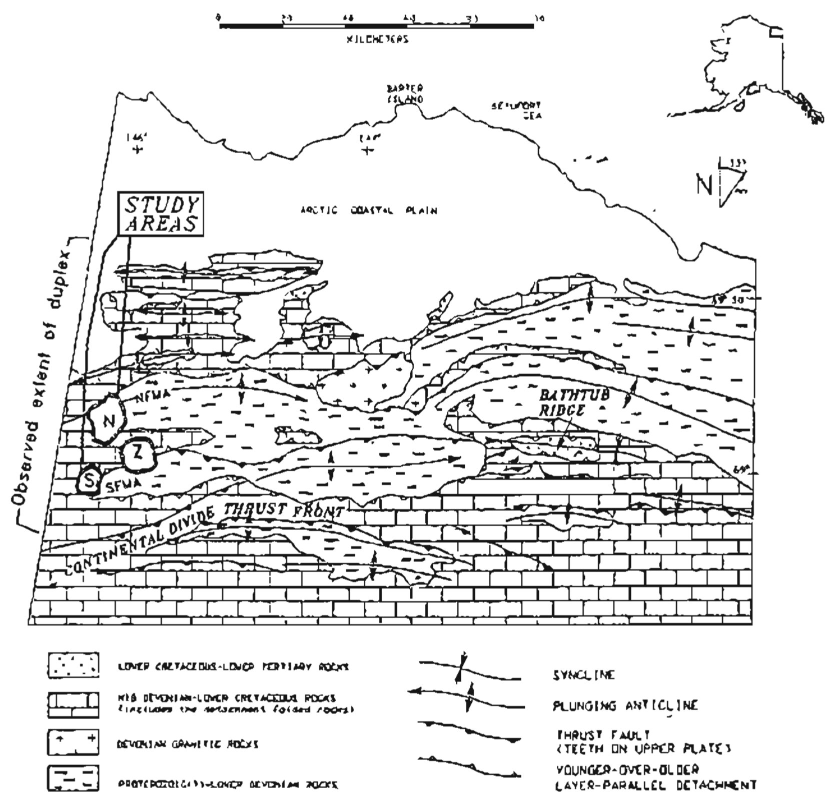

Figure 1. Generalized tectonic map of the northeastern Brooks Range showing the location of the northern study area (N), the southern study area (S), Ziegler's (1989) study area (Z), and the observed extent of the regional duplex.

map pattern reflecting the westward plunge of the anticlinoria (Wallace and Hanks, 1990) (Fig. 1). Each anticlinorium is composed of two elements: 1) a basement core, interpreted to be an east-west trending fault-bend folded horse in a regional-scale northward-directed duplex with a roof thrust in the Mississippian Kayak Shale and a floor thrust at an unknown depth in the basement (Namson and Wallace, 1986; Wallace and Hanks, 1990; Wallace, 1993). These basement cores are referred to as the northern and southern Franklin Mountains horses; and 2) a roof sequence deformed into kilometer-scale detachment folds and defined by the competent Mississippian-Pennsylvanian Lisburne Limestone formed above the incompetent and internally deformed Kayak Shale (Wallace, 1993; Homza and Wallace, in press) (Plates 2a and 4). The Mississippian Kekiktuk Conglomerate is beneath the roof thrust in the Kayak Shale and thus is not directly involved in the detachment folding but instead deformed with the basement as part of the horses in the duplex (Wallace and Hanks, 1990) (Plates 2a and 4). A balanced (Plates 2a and 2b) and a schematic (Plate 4) cross section have been constructed across the northern and southern areas, respectively. The region between study areas includes the hangingwall cut-off of southern Franklin Mountains horse and the footwall cut-off of the northern Franklin Mountains horse (Ziegler, 1989). The balanced cross section of Ziegler (1989) is used in this study to characterize the structural geometry between the horses.

THE NORTHERN STUDY AREA - THE WESTERN END OF THE NORTHERN FRANKLIN MOUNTAINS ANTICLINORIUM

LOCAL STRATIGRAPHY

Sedimentary rocks of pre-Middle Devonian to Permian age are exposed in the northern study area (Plates 1 and 2) and are briefly described here in ascending stratigraphic order. The basement is composed of an unknown thickness of polydeformed chert and a chlorite-rich phyllitic argillite. It is unconformably (?) overlain by up to 100 m of resistant silt- to gravel-size, ripple cross-laminated, dark colored, quartz/lithic arenite that displays distinctive plumose fractures. Meter-thick beds of these rocks are interbedded with shale horizons and may represent a local deltaic or fluvial facies. This "sub-Kekiktuk (?) clastic unit" lacks the polydeformational history of the basement and is separated from the Kekiktuk Conglomerate by a low-angle erosional (?) unconformity that is best exposed in outcrops in Salisbury Creek. Since no fossils were found to constrain the age of this unconformity, the stratigraphic correlation of the sub-Kekiktuk (?) clastic unit is uncertain. The sub-Kekiktuk (?) clastic unit may be equivalent to the unconformity-bounded Middle to Upper (?) Devonian marine to non-marine succession found between the basement and the Kekiktuk to the south (Anderson and Wallace, 1993) or it may represent a thick basin-fill succession within the basal part of the Kekiktuk (LePain, 1993).

Overlying the sub-Kekiktuk (?) clastic unit, the Kekiktuk Conglomerate (LePain, 1993) varies from a nearly 40 m thick cobble conglomerate in the northern part of the area to a 3 to 4 m thick quartz arenite at Salisbury Creek to the south. Clasts of the sub-Kekiktuk (?) clastic unit and, more commonly, of the basement chert, are observed in the Kekiktuk and the unit is commonly channelized with well-developed channel-lag deposits. Where it is a sandstone, bedding is generally on the order of 10s of cm thick and contains poorly developed ripple cross laminae. Plant fossils and coal lenses are common in the coarser fraction of the Kekiktuk, which is composed of beds up to 1 m thick in this area. The Kekiktuk Conglomerate grades upward into the Kayak Shale.

Kayak Shale in this area is characterized by black fissile shale interbedded with carbonate beds up to 10 cm thick and meter-thick calcareous sandstone beds. The 10-20 m thick sandstone beds observed in the Kayak elsewhere in the northeastern Brooks Range (Homza, 1993; LePain, 1993) are lacking in this area. Here, the Kayak Shale varies in thickness from about 100 m to nearly 500 m and this variation represents primarily contractional strain and not stratigraphic thickness changes. Abruptly and conformably overlying the Kayak Shale are beds of the "lower" Lisburne Limestone.

The "lower" Lisburne Limestone is marked by 10 to 20 m of resistant crinoidal wackestone with abundant black chert nodules that grades upward into non-resistant limestone beds some 100 m thick and into another resistant unit of massive calcareous mudstone-to-crinoidal wackestone at the top. The entire unit thickens from 140 m at Plunge Creek in the north to nearly 300 m along Salisbury Creek in the south.

The "middle" Lisburne Limestone is generally recessive and composed of fossiliferous limestone and calcareous mudstone which reaches thicknesses of over 500 m. It passes up section into the massive beds of the "upper" Lisburne Limestone. Meter-thick beds of massive gray wackestone and grainstone characterize the "upper" Lisburne, which has a thickness exceeding 800 m. The entire Lisburne Group exceeds 1500 m in thickness in this area. This thickness is determined from the balanced cross section that is based on map data ~~from an~~ extensive dip panel that exposes easily discernible stratigraphic contacts immediately south of Salisbury Creek (Plate 2a), and thus is considered a reliable thickness estimate. However, it is considered a maximum estimate because it may include some covered folded intervals related to sub-surface structural thickening in the lower parts of the Lisburne in that area.

The Echooka Formation, which disconformably overlies the Lisburne Limestone, consists of brown-weathering lithic arenite and shale and is exposed only in isolated outcrops along the western and southern boundaries of the study area.

LOCAL STRUCTURAL STYLE

Two structural domains are defined in the northern area by distinct structural geometries (Plate 2a). The regional duplex defines the "duplex" structural domain. In this area it lies generally east of, and structurally beneath, the "roof" structural domain, which corresponds to the roof sequence (Wallace, 1993), or all rocks stratigraphically above the Kekiktuk Conglomerate.

The duplex structural domain

Rocks within the duplex structural domain include the polydeformed basement, the sub-Kekiktuk (?) clastic unit, and the Kekiktuk Conglomerate. The duplex domain is defined by the northern Franklin Mountains horse, which forms a regional antiform that trends approximately S85°W and has a wavelength of about 15 km. The northern Franklin Mountains antiform is defined by three well-defined dip panels. From south to north and from most-exposed to least-exposed these are: a gently dipping backlimb (Fig. 2a), a nearly horizontal crestal panel, and a moderately dipping forelimb. This geometry matches well with Suppe's (1983) mode 1 fault-bend fold model and led Namson and Wallace (1986) to interpret the northern Franklin Mountains antiform as a fault-bend fold with the change in dip between the two southernmost dip panels reflecting the underlying footwall ramp-flat transition. Although Namson and Wallace's (1986) study was more regional, the remarkable continuity and lateral extent of the dip panels (e.g. Fig. 2a) allowed them to make predictions about detachment depth beneath the northern Franklin Mountains horse that match very closely with those of this more detailed study (Plate 2a). Both studies interpret the detachment to lie at approximately 4 km subsea.

Figure 2. a) Photograph of the backlimb of the northern Franklin Mountains horse taken from locality 2a on Plate 1. b) Photograph of the backlimb of the southern Franklin Mountains horse taken from locality 2b on plate 3. Both views are eastward and the base of each photo is about 1 km. pMD = basement, Mkt = Kekiktuk Conglomerate, Mk = Kayak Shale, PMll = "lower" Lisburne Limestone, PMl = Lisburne Limestone (undivided).

The roof structural domain

The structural style of the roof structural domain is controlled primarily by the local mechanical stratigraphy. Rocks overlying the competent northern Franklin Mountains horse define a gradient in mechanical competency from least competent in the Kayak Shale at the bottom to most competent in the "upper" Lisburne Limestone at the top. This mechanical stratigraphy lends itself to detachment folding (Jamison, 1987) and the roof structural domain is characterized by detachment folds (Plate 2a).

In the roof structural domain, four kilometer-scale symmetrical-to-north-vergent anticlinal detachment folds are defined by the Lisburne Limestone and cored by the Mississippian Kayak Shale (Plate 2a). The Kayak Shale is thickened in the cores of these anticlines by disharmonic folding, small-displacement thrust faulting, and penetrative strain (Fig. 3). Straight dip panels that parallel the backlimb of the underlying northern Franklin Mountains horse separate the detachment folds. In general, the folds have single, close, angular hinges in their structurally lower parts that give way up section to multi-hinged, open, angular folds (Plate 2a). The two major folds in the northern part of the study area are more upright and symmetrical than those to the south, which are more northward-inclined and asymmetrical. One of these north-vergent folds, the Salisbury Creek anticline, is discussed in more detail below.

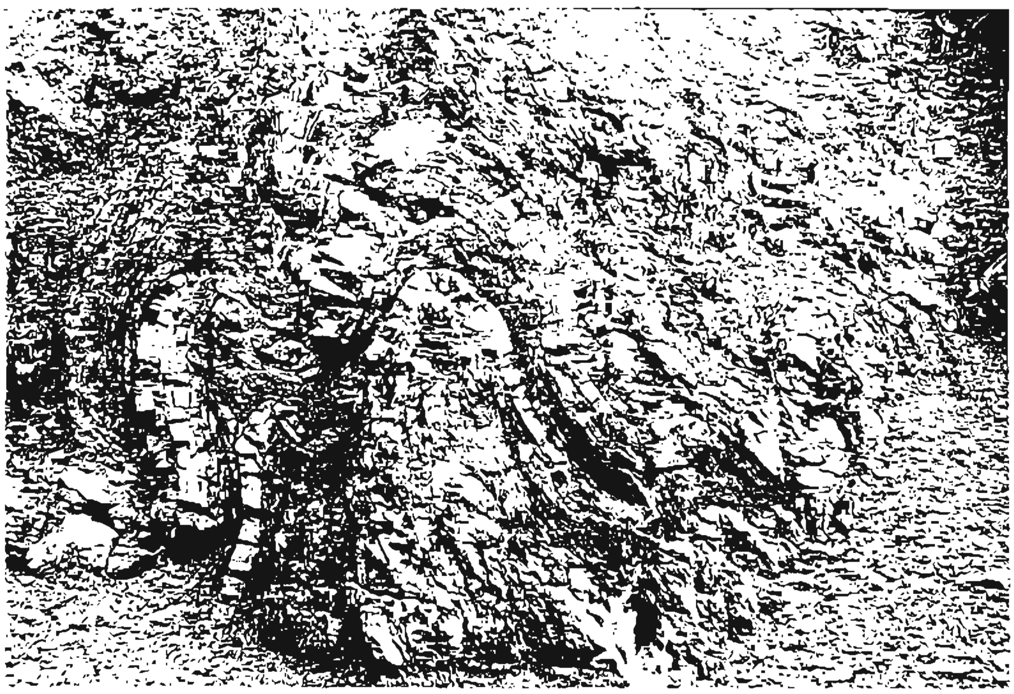

Figure 3 Photograph of structurally thickened Kayak Shale in the core of a kilometer-scale detachment fold in the roof domain of the northern study area. The base of the photograph is about 5 m.

The Salisbury Creek anticline. The Salisbury Creek anticline is well exposed for more than 10 km along strike (Plate 1) and its crest in the "upper" Lisburne Limestone defines Mt. Salisbury (7,060'). At the contact between the Kayak Shale and the Lisburne Limestone, the fold is asymmetrical and north-vergent, with a single, tight, angular hinge and planar limbs (Fig. 4a). The fold increases in wavelength from ≅160 m near the core to ≅1.5 km in the uppermost Lisburne at Mt. Salisbury, where it is a multi-panel, open anticline with a nearly horizontal crest (Fig. 5). The limbs, although complicated by parasitic folds, generally maintain a constant dip both down plunge and up structural section (Fig. 4b). The forelimb dips ≅ 85° N, the backlimb dips ≅ 25° S, and the interlimb angle is ≅ 69°. The Kayak Shale is thickened by about 50% in the fold core (Fig. 4) and the depth to the base of the Kayak (depth-to-detachment) is about 115 m (Homza and Wallace, in press).

Qualitative analysis of the distribution of strain in the Salisbury Creek anticline provides constraints on its kinematic evolution. Little solution cleavage and only very minor stylolitization are apparent in the backlimb. Centimeter-thick chert beds that make up the base of the Lisburne Limestone record only a few poorly developed veins and no tectonic brecciation in the backlimb. The only significant deformation in the backlimb is recorded by bed-parallel slickensides that indicate flexural slip and by a late-stage thrust fault with about 10 m of displacement (Fig. 4a). The anticlinal hinge is extremely strained and includes many minor contractional faults with a variety of orientations and offsets, abundant cm-scale folds, well-developed calcite-filled veins that parallel and cross-cut bedding, tectonic brecciation, solution cleavage, and stylolitization (Fig. 6).

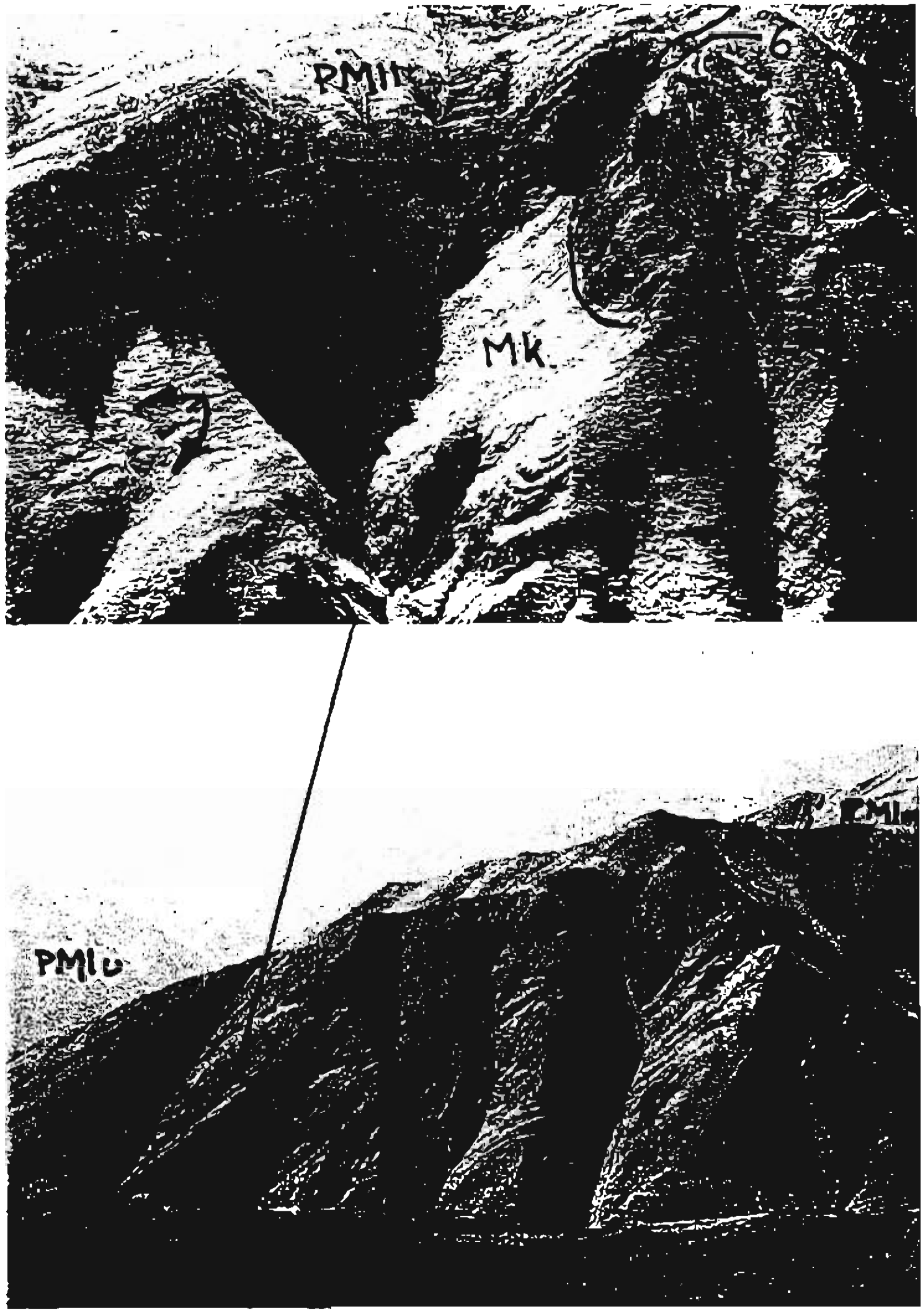

Figure 4. a) Photograph of the core of the Salisbury Creek anticline taken from locality 4a on plate 1. The base of the photograph is about 150 m and the view is westward. b) Photograph of the structurally lower parts of the Salisbury Creek anticline taken from locality 4b on plate 1. The base of the photograph is about 1 km and the view is southwestward. Mk = Kayak Shale, PMll = "lower" Lisburne Limestone, PMlm = "middle" Lisburne Limestone, PMlu = "upper" Lisburne Limestone, "PMl" = Lisburne limestone (undivided). (6) indicates the location of the photograph in figure 6.

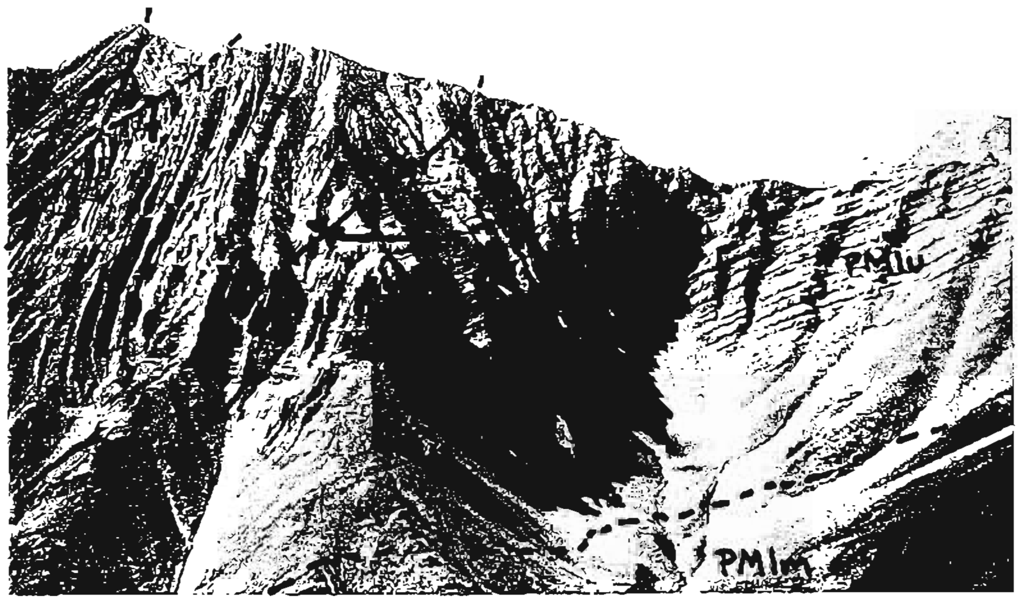

Figure 5. Photograph of structurally high parts of the Salisbury Creek anticline and the adjacent syncline and flat panel that lie to the north. Photograph taken from locality 5 on plate 1. the view is southwestward, and the base of the photograph is about 1 km.

Figure 6. Photograph of the intense small-scale folding and penetrative deformational features in the anticlinal core of the Salisbury Creek anticline in the "lower" Lisburne Limestone. See figure 4a for location, hammer head for scale.

The synclines bounding the forelimb and the backlimb are similarly very strained. The hinges of these synclines include each of the strain indicators listed for the anticlinal hinge, although here there are fewer indicators and they are not as well developed as in the anticlinal hinge. Forelimb deformation includes tectonically brecciated and boundinaged chert beds, minor cleavage, bed-parallel veins of stretched calcite fibers, and stretched bed-parallel slickenfibers indicating north-over-south flexural slip.

There are no structural relationships suggesting hinge-migration through the backlimb nor is there any definitive indication of hinge-migration in the forelimb (e.g. Thompson, 1989; Fischer and others, 1992). The intensity of tectonic brecciation and interbed shear in the forelimb permits the possibility that either adjacent hinge migrated through the forelimb during the early stages of fold growth. However, a fixed-hinge interpretation is preferred because the contractional faults, cross-cutting veins, minor folds, and intense solution cleavage that characterize the adjacent fold hinges are lacking in the forelimb.

The Salisbury Creek anticline is interpreted to have formed by fixed-hinge buckling, with late-stage strain related to clockwise (north-over-south) flexural-slip rotation of the forelimb, late-stage north-directed thrust faulting in the backlimb and an increase in the thickness of the detachment unit (Homza and Wallace, in press). The north-vergent asymmetry of the fold, together with the north-directed thrust fault along the backlimb suggest that this deformation involved a significant component of north-directed motion.

THE SOUTHERN STUDY AREA - THE WESTERN END OF THE SOUTHERN FRANKLIN MOUNTAINS ANTICLINORIUM

LOCAL STRATIGRAPHY

Rocks as old as the pre-Middle Devonian basement and as young as the Mississippian-Pennsylvanian Lisburne Limestone are exposed in the southern area (Plates 3 and 4) and are briefly described here in ascending stratigraphic order. An undetermined thickness of pre-Middle Devonian basement is composed primarily of massive beds of light-colored chert in this area and is unconformably overlain by the Kekiktuk Conglomerate. No sub-Kekiktuk (?) clastic unit was observed in the southern study area. The Kekiktuk Conglomerate consists of about 20 m of cobble and lesser pebble conglomerate and quartz sandstone. Well-developed channels and, in the sand-rich beds, ripple cross-laminations are apparent. Up to 100 m of tan-weathering highly crenulated siltstone overlies the Kekiktuk, is informally referred to as the "lower" Kayak, and may represent the "Ms" unit of Bader and Bird (1986). The "upper" Kayak is a black fissile shale that includes minor orange-weathering carbonate beds but lacks the significant thicknesses of sandstone observed near the range front (Homza, 1993; LePain, 1993). The entire Kayak Shale is about 500 m thick but, as in the northern area, is significantly thickened in the cores of anticlines.

The thickness of the Lisburne Limestone in the southern area is only estimated on the schematic cross section (Plate 4) because its upper contact is not exposed in the area and up-plunge projections from the nearest upper-contact exposures yield unreasonable and inconsistent thickness values. Also, individual structural units in the Lisburne are poorly defined in the south.

LOCAL STRUCTURAL STYLE

As in the northern study area, two structural domains are identified in the southern area: the "duplex" and "roof" structural domains (Plate 4). Here, the duplex domain is defined by the southern Franklin Mountains horse and the roof domain is defined by the roof sequence, including all rocks stratigraphically above the Kekiktuk Conglomerate.

The duplex structural domain -

The southern Franklin Mountains horse includes the polydeformed basement and the Kekiktuk Conglomerate and, like the northern Franklin Mountains horse, it approximates the geometry of a fault-bend fold (Wallace and Hanks, 1990; Wallace, 1993) (Plate 4). The flat crestal panel that characterizes the southern horse east of this area narrows westward toward this area where the horse has only a very narrow crestal panel, a gently dipping backlimb that extends eastward and southward from the study area (Fig. 2b), and a gently dipping forelimb. Rocks in the duplex domain of this area are nearly entirely in the forelimb position of the fault-bend fold.

No detachment is observed between the basement and the Kekiktuk in this domain. Although a meter-displacement thrust fault occurs in the Kekiktuk (Plate 3), there are no other indications of significant shortening in the well-exposed straight dip panels of Kekiktuk save for that due to its overall fault-bend fold geometry.

The roof structural domain -

The roof domain is characterized by detachment folds defined by Lisburne carbonates deformed above the internally deformed and thickened Kayak Shale (Plate 4). Roof sequence rocks in the map area lie mostly above the forelimb of the southern Franklin Mountains horse enabling characterization of detachment folds in that structural position. The lower parts of the Lisburne and the Kayak-

Lisburne contact are well exposed in the area and, together with the well-defined geometry of the lower parts of the detachment folds, yield information about the development of the folds.

The kilometer-scale detachment folds in the southern area occur in three sub-domains defined by fold trains with distinctive geometries that are separated by straight panels which roughly parallel panels in the underlying duplex domain. These three sub-domains are, in decreasing structural elevation and from south to north: the crestal, forelimb, and cut-off sub-domains. The sub-domains are named for their position above the southern Franklin Mountains horse.

The crestal sub-domain. The crestal sub-domain is directly above and immediately forward of the narrow crest of the underlying horse and is characterized by several generally close, north-vergent to symmetrical, northward-overturned to upright folds. Each fold has a complex angular to curved geometry with numerous parasitic folds on the limbs (Fig. 7). As in the northern study area, penetrative strain in the form of solution cleavage and stylolitization and distributed strain in the form of meter-scale faults and folds are very common in the hinge areas and there is less strain on the limbs. Although the difference in the intensity of strain between hinge and limb areas is less in this sub-domain than in others due to the multitude of parasitic folds and their associated structures here, many of the largest anticlinal closures along the Lisburne-Kayak contact have eroded away (e.g. Fig. 7), leaving local topographic lows and suggesting decreased resistance to erosion due to strain. Several north-vergent out-of-syncline thrust faults with displacements measured in meters occur in this sub-domain.

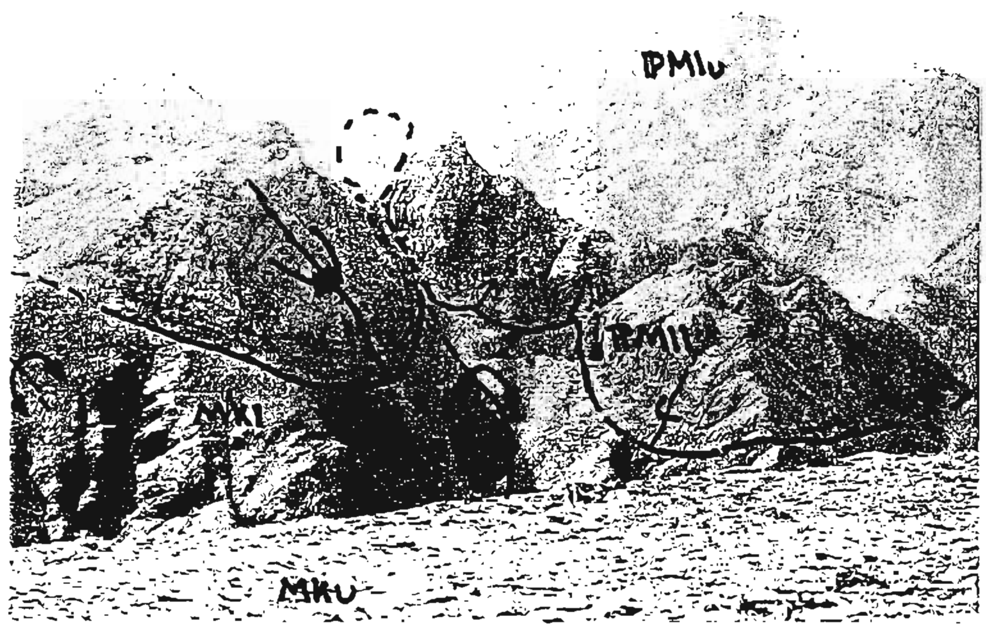

Figure 7. Photograph of a large upright, symmetrical detachment anticline in the crestal sub-domain of the roof domain in the southern area taken from locality 7 on plate 3. The view is west-northwestward and the horizontal distance across the photograph at the level of the mountain in the foreground is about 1.5 km. The fold lies above the narrow crestal panel of the southern Franklin Mountains horse. Mkl = "lower" Kayak Shale, Mku = "upper" Kayak Shale, PMll = "lower" Lisburne Limestone, PMl = Lisburne Limestone (undivided).

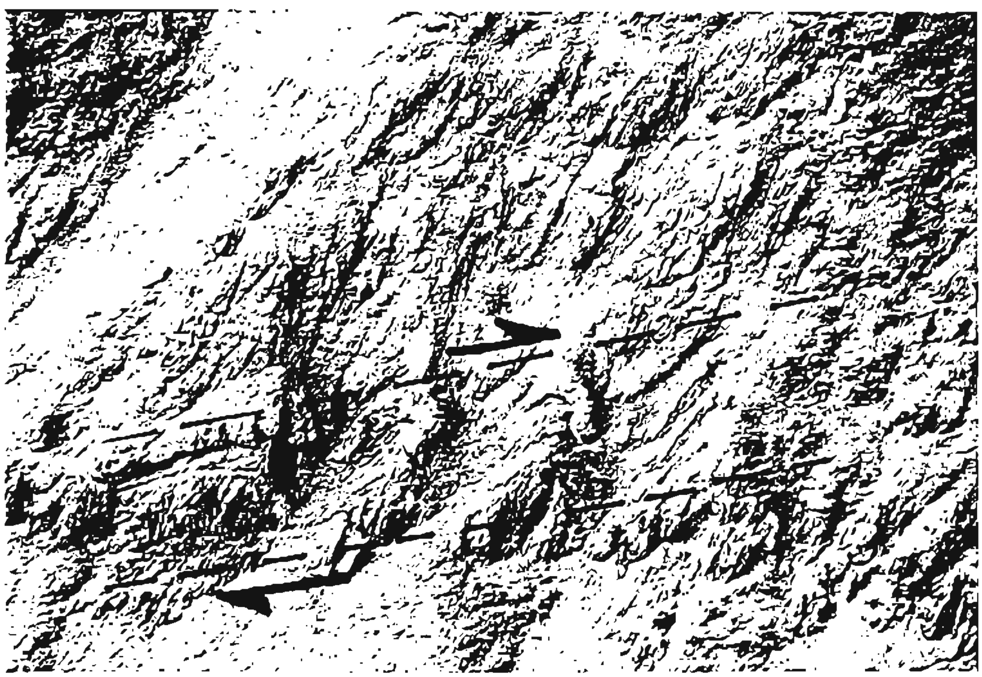

Figure 8. Photograph of a small-scale fold train in the Kayak Shale with vergence toward the core of a larger-scale detachment fold that lies to the right and structurally upsection. The base of the photograph is about 10 m

The vergence of meter-scale fold-trains in the carbonate beds in the Kayak Shale in the crestal sub-domain indicates top-toward-the-anticline simple shear (Fig. 8). This suggests that the detachment unit was tectonically transported into anticlines from beneath synclines. The Kayak Shale in anticlinal cores is thickened and extremely strained by minor faulting and folding and by intense solution cleavage with carbonate precipitated as an orange rind surrounding centimeter-scale gray siliceous lenticular bodies resembling fault gouge.

The forelimb sub-domain. Detachment folds in the forelimb sub-domain are clustered above a change in dip in the forelimb of the underlying horse and they grade in geometry from a close, north-vergent fold in the hindward position to an upright isoclinal fold in the forward position (Fig. 9, Plate 4). Although the amount of thickening in the Kayak Shale beneath these folds is uncertain, top-toward-the-anticline simple shear is indicated by small scale fold trains in the Kayak (as in Fig. 8). As in the crestal sub-domain, the Kayak in anticlinal folds is contractionaly strained by solution cleavage and minor faults and folds.

Outcrop-scale observations of the distribution of strain in these folds show a drastic decrease in strain from hinges to limbs and there are few parasitic folds. This difference in strain is most obvious in the tighter anticlines where intense solution cleavage, stylolites, and small-scale folds and faults in the hinges give way to coherent, planar beds on the limbs.

The cut-off sub-domain. The cut-off sub-domain was accessed only at a few locations within the Lisburne Limestone. The domain is dominated by a single, large anticline-syncline pair which can be traced at least 6 km down plunge to the west where spectacular exposure was observed from a distance. The anticline is slightly asymmetrical and, unlike other folds in this study area, is slightly south-vergent.

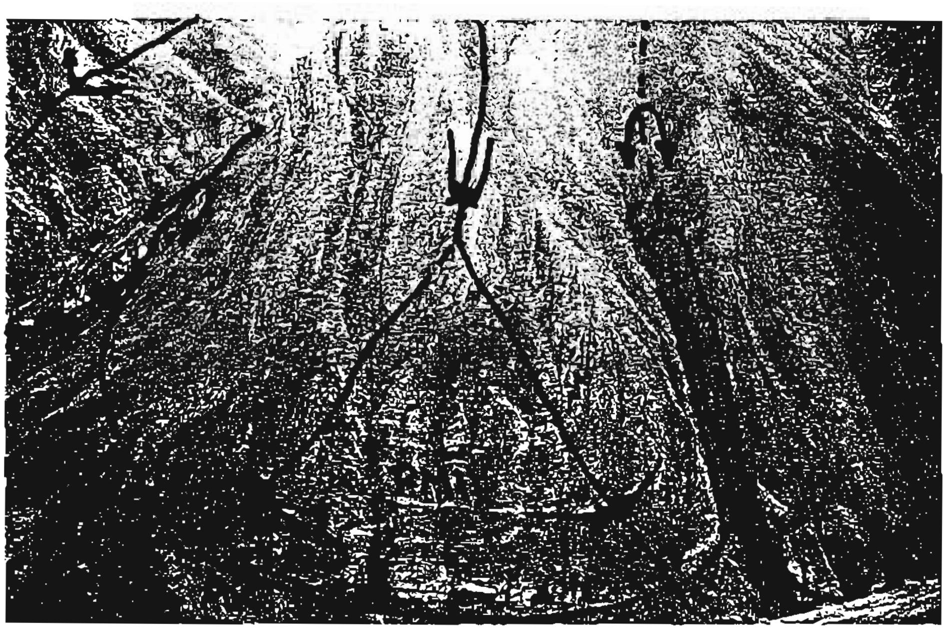

Figure 9. Photograph of an isoclinal detachment syncline above a bend in the forelimb of the southern Franklin Mountains horse taken from locality 9 on plate 3. The base of the photograph is about 0.4 km and the view is westward.

KINEMATICS OF THE DETACHMENT FOLDS

Outcrop-scale geometric and strain observations in both the northern and southern areas show that fold hinge zones have been intensely and irreversibly strained during deformation. If the folds grew by migration of the hinges through the rock, remnants of such hinge strain should be recognizable in fold limbs (Thompson, 1989; Fischer and others, 1992; Homza and Wallace, in press). No such overprinting relationships were observed in fold limbs. In order for the folds in the area to have formed by fixed-hinge kinematics and obey the assumption of constant cross-sectional area, then the Kayak Shale is required to have changed thickness during deformation (Homza and Wallace, in press). The wide variety of thicknesses determined for the Kayak Shale on the cross sections and the observed internal deformational features (e.g. top toward the anticline shear, solution cleavage, core stylolites and precipitation rinds) support the interpretation that the Kayak changed thickness, and perhaps cross-sectional area, during deformation. Thus, the observations reported here suggest that the kinematic evolution of detachment folds in the Franklin Mountains anticlinoria involved changes in the thickness of the detachment unit and a significant component of fixed-hinge buckling (see Homza, 1993 and Homza and Wallace, in press). This conclusion is incompatible with most geometric models for detachment folds (*e.g.* Jamison, 1987; Mitra and Namson, 1989), which are based on assumptions of fixed detachment depth and hinge-migration kinematics, but is compatible with Homza and Wallace's (in press) more general model for detachment anticlines above a detachment unit that changes thickness during deformation.

GEOMETRY AND KINEMATICS OF THE ROOF SEQUENCE

The roof sequence in the northern study area lies structurally above the backlimb and crest of the northern Franklin Mountains horse whereas the roof sequence in the southern study area lies above the crest and forelimb of the southern Franklin Mountains horse. Ziegler (1989) constructed a north-striking balanced cross section across the hangingwall cutoff of the southern Franklin Mountains horse in the area between the Canning River and the Marsh Fork (northeast of the southern area, Fig. 1). Thus, taken together, observations from these areas are well suited to analyze the nature of roof sequence deformation in terms of its position above horses in the regional duplex (Fig. 10).

Detachment folds above the backlimb of the northern Franklin Mountains horse are north-vergent and are generally separated by straight panels that parallel the backlimb of the horse. Folds above the forelimb of the southern Franklin Mountains horse are north-vergent to south-vergent in the southern area but are strongly north-vergent east of the Marsh Fork (Ziegler, 1989), where the forelimb of the horse is steeper and is defined by a smaller-scale duplex within the basement (Fig. 10). More symmetrical and upright geometries characterize the detachment folds that lie above the sub-horizontal crestal panels of both horses. Folds are more abundant and complex where there is a change in dip between panels of the underlying horse than they are above straight panels. These geometric observations suggest a complex deformation history for the roof sequence that is related to the geometry and kinematics of the underlying horses, the details of which are beyond the scope of this report. However, a general interpretation of the overall geometric and kinematic evolution of the Franklin mountains anticlinoria is presented below.

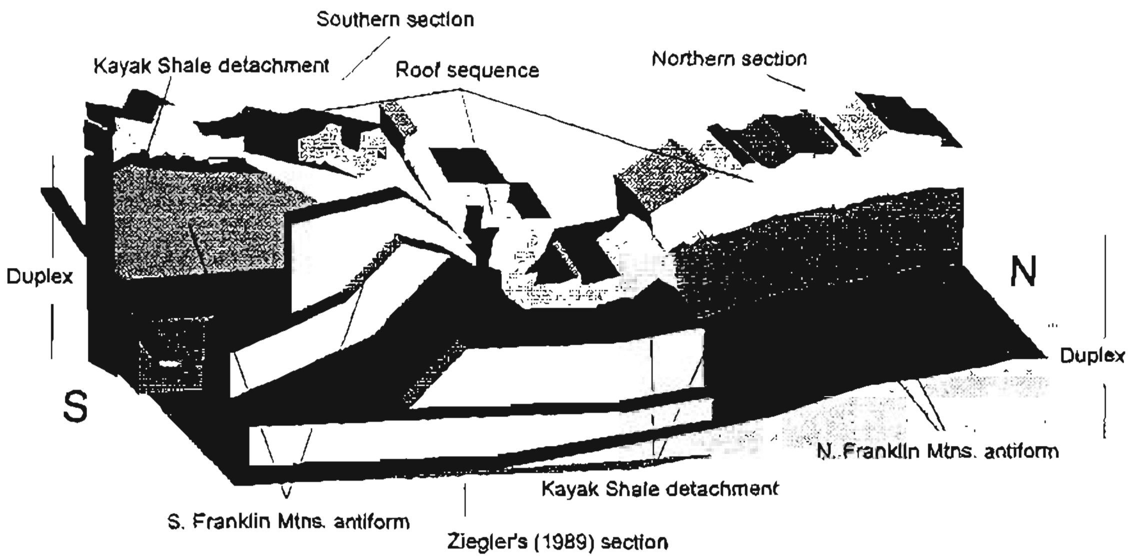

Figure 10. 3-dimensional view of the Franklin Mountains anticlinoria, looking northwestward. The bar at the southern end of the diagram runs east-west at sea level and the N-S extent of the figure is about 40 km..

STRUCTURAL EVOLUTION OF THE FRANKLIN MOUNTAINS ANTICLINORIA

In interpreting the structural evolution of the Franklin Mountains anticlinoria, two general observations must be explained. First, the drastic difference in both structural geometry and apparent shortening between the duplex and roof domains must be accounted for. This is best accomplished by calling on the fault-bend fold duplex model (Wallace and Hanks, 1990; Wallace, 1993), as described above. Second, the form, distribution, and apparent kinematic path (i.e. fixed-hinge buckling) of detachment folds in the roof sequence must be explained, preferably in the context of the fault-bend fold model.

Figure 11 shows a simplistic model for the structural evolution of the area. Since the complex kinematics, together with a general paucity of relative timing data, preclude construction of accurate sequential, balanced models, figure 11 is very schematic. Stage 1 shows an undeformed sequence with incipient faults in the basement shown. Emplacement and uplift of the southern Franklin Mountains

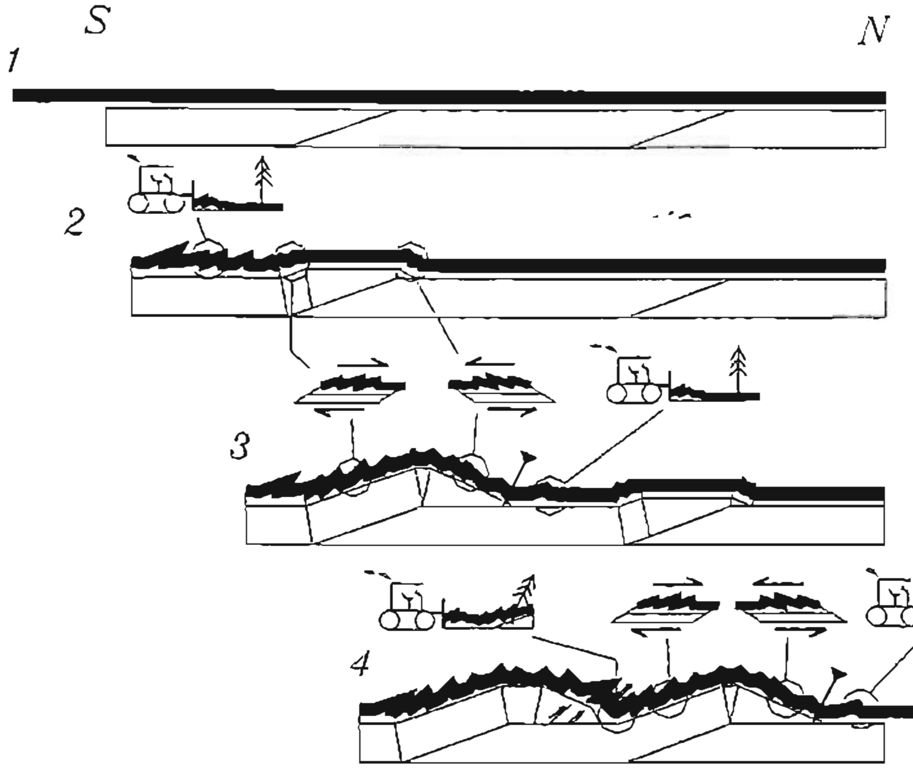

Figure 11. Schematic diagram representing the kinematic evolution of the Franklin Mountains anticlinoria. Detachment folds form by fixed-hinge buckling above a detachment unit that changes thickness (see text for explanation).

horse begins in stage 2 with the single horse bounded by a roof thrust in the Kayak Shale and a floor thrust at depth in the basement. Fault-bend fold kinematics (Suppe, 1983) occurs in the horse itself and the associated shortening is accommodated in the roof by fixed-hinge detachment folding concentrated above the bends and growing dip panels of the underlying horse. The original position of these folds with respect to the migrating hinges of the fault-bend fold is uncertain. North-vergent folding in the roof over the backlimb could have been related to north-directed thrusting that occurred south of the southern Franklin Mountains horse (Wallace, 1993), which may have resulted in northward displacement of the roof as far north as the barrier created by the backlimb of the southern Franklin Mountains anticlinorium.

As deformation progressed (Fig. 11 - stage 3) the detachment folds above the backlimb of the horse developed a north-vergent asymmetry, the folds on the forelimb developed a slight south-vergent asymmetry, and those above the crestal panel were generally upright and symmetrical. This geometry may be explained by "passive roof" (Banks and Warburton, 1986) deformation in the forelimb and "active roof" deformation in the backlimb. The north-vergent folding on the backlimb may be the result of either "bulldozing" from the south (as above) and/or it may be an upsection continuation of the north-over-south flexural slip folding involved in the emplacement of the horse. Fold geometry in the crestal panel may represent a continuation of either the active or passive roof deformation, or it may describe the spatial intersection of the two.

Apatite-fission track data suggest that the southern Franklin Mountains anticlinorium began to form before the northern anticlinorium (Wallace and others, in prep.). It is likely, however, that displacement of the southern horse continued after displacement of the northern horse began (Wallace, pers. comm. 1993) (Fig. 11, stage 3). At this stage, the southern Franklin Mountains horse had reached its full amplitude but forward displacement continued, allowing the roof sequence to be bulldozed northward ahead of the forelimb as south-directed "passive" displacement continued above the forelimb.

In stage 4, deformation associated with the emplacement of both horses overlapped in the intervening syncline. Further northward translation of the southern horse caused extreme thickening and northward asymmetry in the roof above its leading edge and contributed to north-directed shear along the backlimb of the northern horse. Northward asymmetry above the hangingwall cut-off of the southern horse may be related to the north directed duplexing in the forelimb of the southern horse that Ziegler (1989) described. The northern Franklin Mountains horse developed like the southern horse, with fold geometry reflecting passive roof deformation in the forelimb and north-directed shear related to bulldozing and/or fault-bend-folding in the backlimb.

LOCALIZATION OF DETACHMENT FOLDS ABOVE BENDS IN THE HORSES

The detachment folds in the roof sequence are concentrated above bends in the underlying horses and commonly the sense of shear indicated by the asymmetry of these folds changes across the underlying bend. This geometry is clear in the southern study area where straight non-folded panels in the roof sequence lie above panels in the horse and trains of folds in the roof sequence lie above bends in the horse (Plate 4).

This geometry suggests a general kinematic relationship between the fold trains and the bends in underlying structures. However, this relationship is problematic because the fold trains in the roof sequence must move relative to the bends in the horse whether or not the horses formed by ideal fault-bend-folding. If ideal fault-bend-folding is assumed for the horse, then the fact that the fault-bend-fold hinges (bends) migrate through the basement during folding introduces a further complexity. One speculative kinematic scenario is that the bends in the fault-bend-fold horses served as nucleation points for the detachment folds and the fold trains moved with the migrating hinges of the fault-bend-fold and accumulated shortening as the total shortening increased.

CONCLUSIONS

Structural relationships in a regional duplex along the Canning River in the northeastern Brooks Range suggest that detachment folds in the roof sequence formed in response to both forward- and hindward-directed contraction. Qualitative strain analysis indicates that at least some of the detachment folds formed by fixed arc-length kinematics above a detachment unit that changed thickness during deformation. The horses in the duplex are fault-bend folds and the distribution of detachment fold asymmetries relative to the horses constrains the kinematic relationship between the horses and the roof sequence. Detachment fold trains may have nucleated above, and migrated with, hinges in the fault-bend-folds.

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