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Kinematics of late Mesozoic thrusting, Pilot Mountains, west-central Nevada, U.S.A.

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Abstract—The northern Pilot Mountains of west-central Nevada, consist of a complexly deformed terrane of imbricate thrust nappes composed of rocks of Permian(?), Triassic through Jurassic, and possible Cretaceous ages. Three episodes of fold and thrust generation are recognized on the basis of folded thrusts and thrusted folds, and deformation and emplacement of the nappes is constrained as having occurred during the late Mesozoic. Folds are apparently coeval with thrust faults, and fold geometry is used in determining approximate directions of thrust displacement. The history of thrust displacement is complex and involves three directions of motion on a regionally extensive detachment surface, the Luning thrust. The first motion, from NW to SE, results in displacements of the order of several tens of kilometres and is the probable result of NW-SE regional compression. The final two episodes of motion are NE-SW followed by E-W; they result in small displacements and are possibly the product of gravity sliding of the thrust sheet into depressions in the autochthon. Sites of downwarp in the autochthon may have been formed either by load induced subsidence or regional compression.

INTRODUCTION

THE PILOT MOUNTAINS of the Mina-Hawthorne region of west-central Nevada (Fig. 1) expose a complexly deformed terrane of allochthonous and autochthonous rocks that represent an important key to understanding late Mesozoic tectonism in the western Great Basin of the U.S.A. Recent work (Wetterauer 1977, Oldow 1978a,

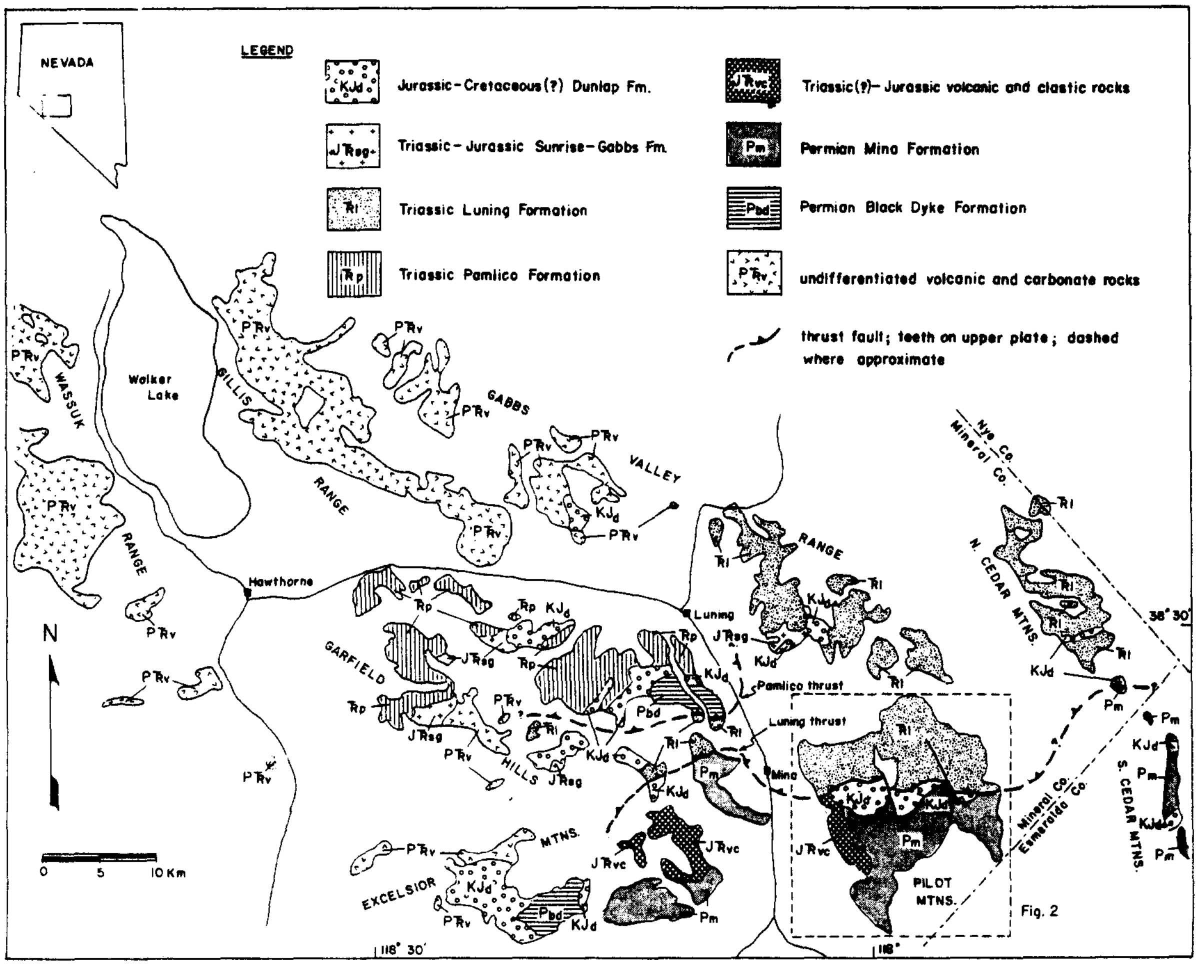

Fig. 1. Generalized distribution of pre-Tertiary layered rocks in the Mina-Hawthorne region, west-central Nevada.

Speed 1978) has involved reinterpretation of structural and stratigraphic relations established by earlier workers (Muller 1936, Muller & Ferguson 1936, 1939, Ferguson & Muller 1949, Nielsen 1963) and sought to explain observations in terms of current plate tectonic models. The stratigraphic relations, the geometry of deformation, and the kinematics involved during late Mesozoic tectonism of the region are still poorly understood; this paper is a report of an investigation to resolve these problems.

The allochthonous terrane, the Luning allochthon (Oldow 1975, 1978a, Speed 1977), forms an E–W belt across the northern Pilot Mountains and consists of thirteen thrust sheets some of which are bounded by subplanar or singly folded basal thrusts and others by multiply folded basal thrusts. Two thrust nappes outcrop continuously across the entire range whereas others are more restricted in exposure. The amount of displacement among thrust planes is varied, with displacement of one nappe estimated to be at least as great as 20 km. Displacements are deduced from lithofacies analysis of juxtaposed coeval rocks for nappes and from structural overlap for thrust imbricates. Detailed mapping and geometric analysis of folds of beds and thrust have established sequential and spatial relations for folding and thrusting which, in conjunction with displacement estimates, indicate imbrication of nappes at a distant locale or locales and displacement of the entire allochthon several tens of kilometres on a regional sole thrust. Development of the allochthon is thought to be similar to the nappe imbrication described in the eastern Rocky Mountains of Canada by Dahlstrom (1970) where progressive deformation resulted in younger thrusts cutting under older thrusts. Unlike the simple imbricate model for the Canadian Rockies, significant first phase folding predated imbrication of individual thrust sheets for the Luning allochthon. Throughout its deformational history, however, the Luning allochthon had a sole thrust which was essentially planar or ramp-like.

Current understanding of regional structural and stratigraphic relations (Oldow 1977, 1978b, Speed 1977, 1978) suggests that Mesozoic rocks involved in the late Mesozoic tectonism of this area are predominantly of shallow marine origin deposited in and around a successor basin bounded on the west by a volcanic arc terrane and on the east by continental uplands (palaeogeography in present day coordinates). The Mesozoic successor basin is the proposed product of thermal contraction of a Permian arc terrane after accretion of the arc on the western margin of North America in the late Palaeozoic or early Mesozoic (Speed 1978). Initiation of thermal contraction was effected after collision, when the convergent boundary jumped westward and the subduction related heat-source was eliminated (Speed 1978). Rocks juxtaposed in the Pilot Mountains are related to this regional scheme as follows: in the allochthon, shallow marine–deltaic carbonate and siliciclastic rocks (Luning and Sunrise–Gabbs Formations) were deposited in a shelf environment adjacent to a continental upland; in the autochthon, volcanic and siliciclastic rocks (Gold Range Formation) were accumulated in a subaerial segment of the Mesozoic volcanic arc terrane and are overlain by coarse clastic and shallow marine rocks (Dunlap Formation) deposited during an orogenic pulse prior to regional folding and thrusting. Additionally, thrust imbricates of volcanic-carbonate rocks in the allochthon are possible slices of the Permian arc terrane which acted as the preferred base to the detachment surface during late Mesozoic thin-skinned thrusting. The late Mesozoic tectonism is inferred to be related to collapse of the Mesozoic island arc and successor basin with attendant thrusting of arc, basinal, and basin-margin rocks towards the continent (Oldow 1977).

The focus of this paper is a brief discussion of the geometry of deformation, particularly within the allochthonous succession, and the development of a kinematic model for the emplacement of the allochthon in the Pilot Mountains. Several structural problems are addressed: (1) the origin of a pronounced E–W gradient in the style and degree of development of the second of three phases of folds in the allochthon, (2) the association of intense second phase fold development and exposure of numerous complexly deformed thrust imbricates in the western reaches of the Luning allochthon in the Pilot Mountains and (3) the apparent spatial correspondence in the degree of development of second phase structures in the autochthon with those in the overlying allochthon. For the sake of brevity, only data that are critical to the development of the model are presented here. The complete results of the investigation will be presented at length in a forthcoming paper.

STRUCTURE OF THE PILOT MOUNTAINS

Luning allochthon

In the northern Pilot Mountains, the Luning allochthon consists of a stack of four thrust nappes of which the lower two are composed locally of several thrust imbricates. The thrust nappes are composed dominantly of carbonate and siliciclastic rocks of the Upper Triassic Luning Formation and to a lesser extent the Triassic–Jurassic Sunrise–Gabbs Formation and an unnamed volcanic-volcanogenic sedimentary succession of probable Permo-Triassic age (Oldow 1978a). The allochthon is bounded on the south by an E–W trending thrust fault that dips gently northwards in the central Pilot Mountains (Fig. 2) but varies from low angle to near vertical in the western and eastern Pilot Mountains. The western, northern, and eastern boundaries are high-angle faults where they are not covered by Cenozoic volcanic and sedimentary rocks.

Rocks within the Luning allochthon are complexly folded and faulted with beds and some thrusts deformed in two and locally three superimposed fold sets. Analysis of folded faults and faulted folds within the allochthon indicates at least three episodes of thrust fault motion each of which is associated with a particular fold set.

The allochthon is subdivided into western and eastern domains (Fig. 3) on the basis of: (1) the number of fold sets, (2) the tightness of folds and (3) the apparent

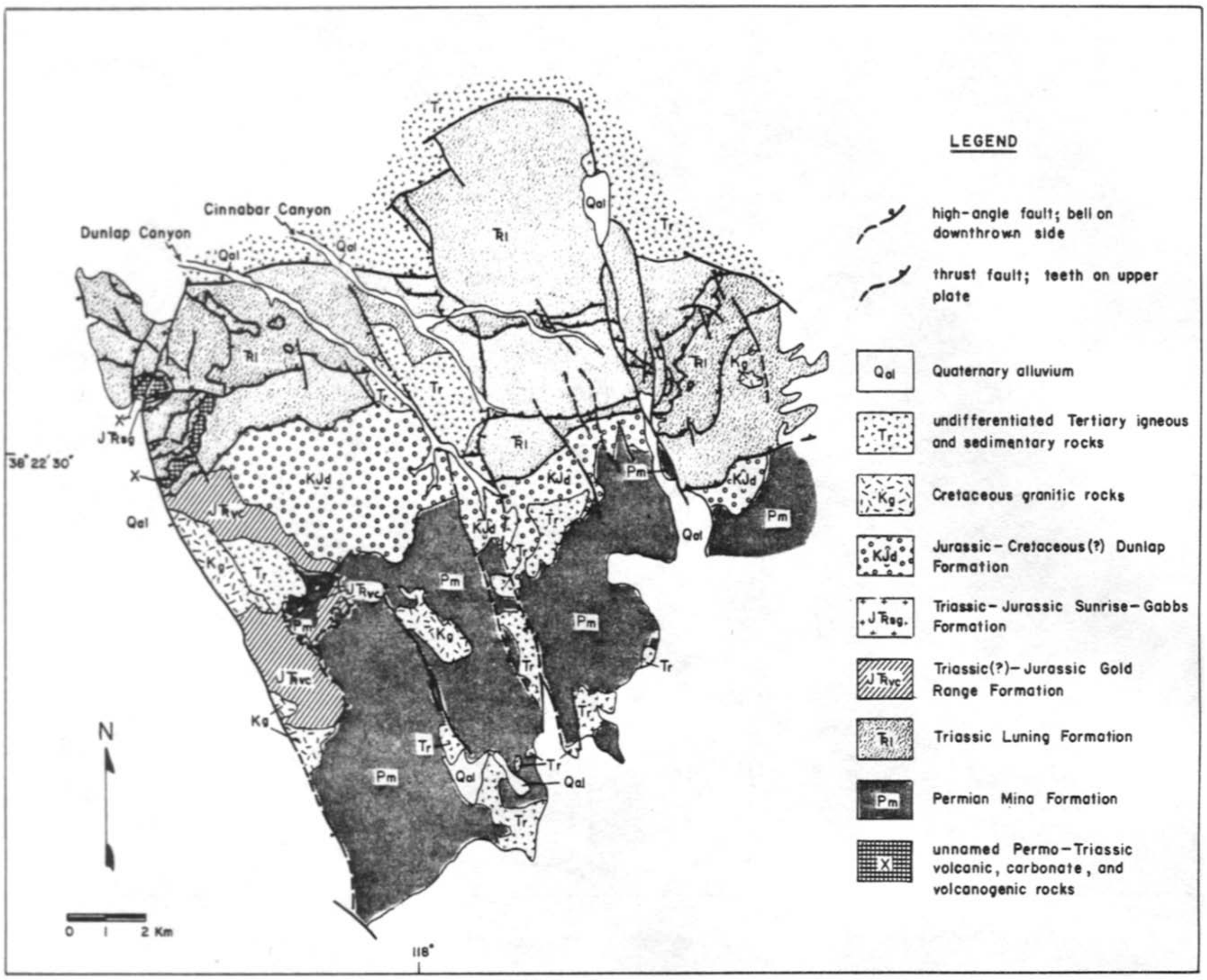

Fig. 2. Generalized geologic map of the Pilot Mountains.

existence or lack of thrust imbricates within thrust nappes. Because strata and some thrust nappes are continuous from one domain to the other, except for displacements along high-angle faults of Cenozoic age, these differences are indicative of a lateral change in structural style between domains.

Of the four major nappes constituting the Luning allochthon, the lower two, N1 and N2, consist of six and five thrust imbricates, respectively in the western domain (Fig. 3). The uppermost nappes, N3 and N4, are exposed only in the eastern domain and apparently contain no thrust imbricates.

Age of deformation

The age of emplacement and related internal deformation of the Luning allochthon in the Pilot Mountains is post-Early Jurassic and pre-67 Ma. These age constraints are based on the age of the youngest rocks deformed during emplacement of the allochthon, the Dunlap Formation exposed in the subjacent autochthon, and a granitic intrusion in autochthonous rocks of the western range-front of the Pilot Mountains. The granite pluton, whose emplacement thermally metamorphosed rocks of the autochthon and the basal part of the western Luning allochthon, has yielded biotite dated by K–Ar at 67 Ma (Schilling 1965). Some doubt currently exists concerning the minimum age of the Dunlap Formation (J. S. Oldow and R. C. Speed unpublished data) but a maximum age for the formation within the Pilot Mountains is established on the occurrence of flap clams *Weyla* of probable Early Jurassic age (Speed 1977) in rocks of the uppermost Gold Range Formation which is disconformably overlain by the Dunlap Formation (Fig. 2).

Folds

First generation folds. First phase folds offer little variability in abundance or style throughout their exposure in the Luning allochthon. First folds are isoclinal to close major and minor folds* with well developed axial-plane cleavage and have half wavelengths ranging from a

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* Major fold: single fold with half wavelength of over 30 m. Minor fold: single fold with half wavelength of 30 m or less.

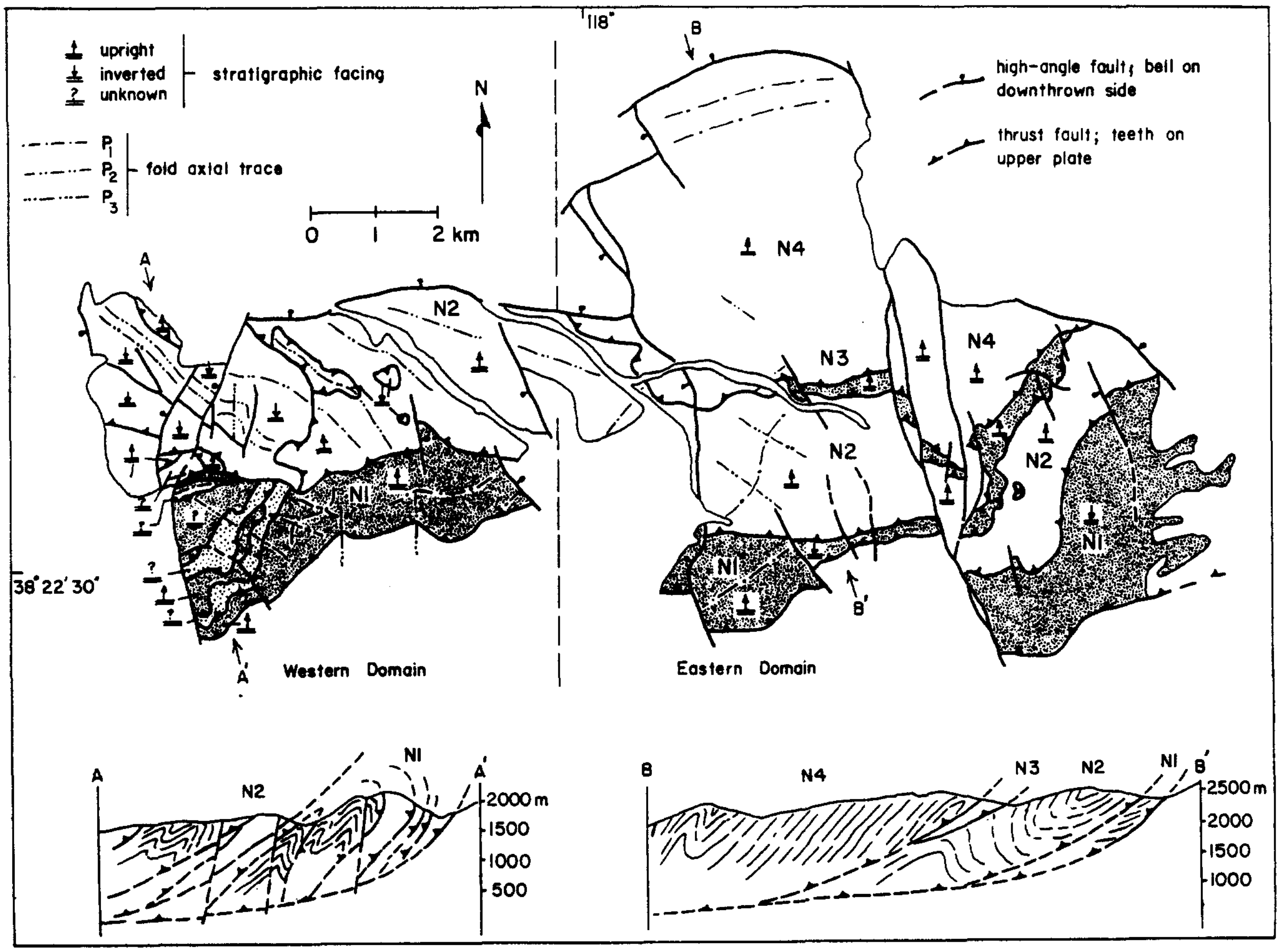

Fig. 3. Generalized structure map and cross sections of the Luning allochthon, northern Pilot Mountains.

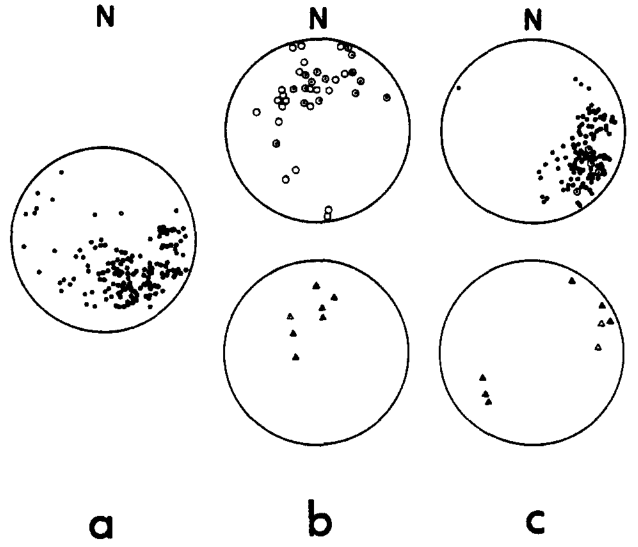

Fig. 4. Lower hemisphere equal-area projections of the structural fabric for nappes in the eastern domain of the Luning allochthon. Columns are: (a), poles to bedding; (b), fold axes, circles represent first phase axes (open circle, bedding-cleavage (first phase) intersections; circle-dot, direct measurement or construction from folds of bedding), triangles represent second phase axes (triangle-dot, direct measurement or construction from folds of bedding; solid triangle, construction from folds of first phase cleavage); (c) poles to axial planes and axial-plane cleavage (dot, poles to first phase, cleavage; circle-dot, poles to first phase axial planes; open triangle, poles to second phase cleavage; triangle-dot, poles to second phase axial planes).

few millimetres to probably greater than 2 km. They are generally upright to overturned to the south in the eastern domain, where reorientation by later second phase folds is slight, and they are southerly vergent to recumbent in the western domain, where second phase folding is severe.

The original orientation of axial planes of first folds is approximated in the eastern domain (Fig. 3) as N35E 60NW, which is the mean attitude of measured first phase axial planes and axial-plane cleavage (Fig. 4). Though generally unreliable the mean is, in this case, a reasonable estimate of the initial orientation because second phase deformation in the eastern domain is not very intense and thus, results in only minor reorientation of the earlier structures. Within the western domain where second folds result in intense deformation, exposures of first structures also yield a mean attitude of axial surfaces and axial-plane cleavage of about N35E/60NW (Fig. 5). Hence, the mean attitude of corresponding structures are the same in both the eastern and western domains.

Second generation folds. One of the most striking features of the Luning allochthon is the great variability in style and abundance of second folds between the eastern and western domains. The change in second phase folds is gradational and independent of stratigraphic control and is established in a single stratigraphic unit of the Luning Formation which is continuously exposed from eastern to

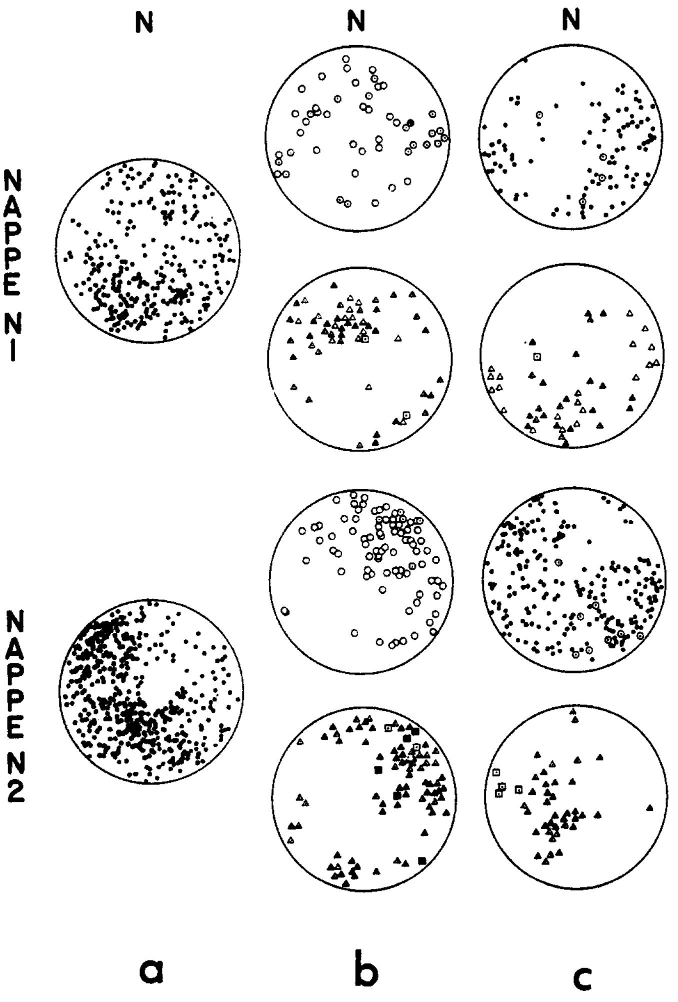

Fig. 5. Lower hemisphere equal-area projections of structural fabric for nappes N1 and N2 in the western domain of the Luning allochthon. Rows represent data for nappes N1 and N2, and columns are; (a), poles to bedding; (b), fold axes, circles represent first phase axes (open circle, bedding cleavage (first phase) intersections; circle-dot, direct measurement or construction from folds of bedding; circle cross, construction from folded thrust surface); triangles represent second phase axes (open triangle, bedding-cleavage (second phase) intersection; triangle-dot, direct measurement or construction from folds of bedding; solid triangle, construction from folds of first phase cleavage), squares represent third phase axes (square-dot, construction from folds of bedding; solid square, construction from folds of first phase cleavage; (c), poles to axial planes, axial-plane cleavage, and foliations (dot, poles to first phase cleavage; circle-dot, poles to first phase axial planes; open triangle, poles to second phase cleavage; triangle-dot, poles to second phase axial planes; square-dot, pole to third phase axial planes).

western domain in one nappe (Fig. 3).

In the eastern domain, second folds are gentle major folds with axial-plane cleavage only locally developed in hinge regions; no minor folds were observed. The folds are symmetrical, trend NW and have steep axial surfaces. In the western domain, on the other hand, second generation structures consist of close to tight major and minor folds; mapped axial traces of second phase major folds trend between N20W and N85W. Locally in hinge regions of major folds, an axial-plane cleavage is developed that clearly cuts first phase cleavage. Occasionally, where second phase cleavage has not formed, crenulations of first generation cleavage define the orientation of second phase axial surfaces.

Many second folds in the western domain are the product of a complex deformational history involving coaxial folding of early second generation folds by later second folds. The measured axial planes of early second phase folds, defined by bedding and first generation axial-plane cleavage, yield a fold axis colinear with that of all second folds (Fig. 5). Second cleavage, where present, is transection cleavage (Borradaile 1978), and crosscuts the early second phase folds but is axial-plane to later second folds. The second generation fold-set is characterized by NW trending folds generally overturned to the SW. The characterization is reasonable even in light of complex fold relationships within the fold set. Even though initial dips of early axial planes cannot be determined, the initial strikes can be estimated and are consistently NW, the same as later second folds with axial surfaces that generally dip NE. Third phase folds are sporadically developed and only locally fold second generation structures. Therefore, the mean orientation of second phase folds (late stage) is a good approximation to their initial orientation, assuming that later regional rotation has not occurred.

Third generation folds. Third phase folds occur only in the western domain, west of Dunlap Canyon (Fig. 2), and, with the exception of one easterly vergent fold, consist of upright to westerly vergent major and minor folds of gentle to close limb appression. Major third folds have axial traces that trend N–S and no axial-plane cleavage exists. The folds occur sporadically, and are commonly absent over areas of up to 16 km^2. The spatial distribution of third folds appears to be random in the western domain.

Thrust nappes

The eastern domain, composed solely of rocks of the Luning Formation, consists of four nappes, designated N1 to N4 in ascending structural position (Fig. 3), all of which are bounded by subplanar basal thrusts that truncate axial traces of first and second generation folds of beds. Only the lowermost two nappes are exposed in the western domain and are there found to be composed of several thrust imbricates. The upper two nappes are not present in the western domain as expected, and apparently have been removed by erosion. This stems from the fact that the western domain is 200–300 m topographically lower than the eastern domain, and the western projection of the subplanar basal thrusts of the uppermost two nappes in the eastern domain from their westernmost exposure in Cinnabar Canyon (Fig. 2) attain a structural height above the elevation of the western domain.

Though dissected by a Tertiary intrusive body (Fig. 2), the structurally lowest nappe (N1) is inferred to be continuous between the western and eastern domains on the basis of correlation of a stratigraphic unit of the Luning Formation exposed on both sides of the Tertiary intrusion. The basal thrust of the nappe cuts both first and second folds, but in the western domain is folded in major third phase folds in at least three locations. The basal thrust is readily identified along its trace because of marked differences in lithologies juxtaposed at the contact: Luning Formation in the upper plate and Dunlap and Gold Range and Mina Formations in the lower plate (autochthon). Locally, the thrust surface is well exposed and generally consists of a foliated gouge zone up to 1 m thick. Lineations measured on the fault plane indicate the last motion was nearly parallel to the pre-third phase folding strike of the fault which implies E–W or W–E displacement of the Luning allochthon. The possible slip directions are discussed later in relation to the emplacement of the allochthon.

Within the western domain, the lowest nappe consists of six thrust imbricates. Thrusts bounding the imbricates are, with few exceptions, easily traced and locally exhibit thin gouge zones. Beds within the imbricates (Fig. 3) are deformed in folds of all three fold sets, and the thrust imbricates themselves are deformed in second and third generation folds. One imbricate is additionally folded in a major first fold, interpreted as a late stage structure of first phase deformation. Timing of emplacement of this imbricate during first folding is indicated by: (1) truncation of first fold axial traces by the imbricate thrust and (2) deformation of the trace of the thrust by a major first fold (late stage). This relationship is of particular importance because it demonstrates the formation of folds prior to and during first phase thrusting. All other thrusts truncate first generation axial traces. Deformation of thrust imbricates in major second folds indicates stacking of the imbricates prior to second phase folding.

The overlying nappe (N2) is laterally continuous between eastern and western domains as established by continuous exposure of intra-nappe strata around the northern margin of Tertiary intrusive rocks that cut the base of the nappe (Fig. 2). The basal thrust of the nappe cuts folds of the first two generations and locally both cuts and is folded by folds of the third fold set. The thrust is locally well exposed and consists of a foliated gouge zone up to 0.5 m thick. The thrust is easily traced where different stratigraphic units of rocks of the allochthon are juxtaposed but is located with some difficulty where the same members of the Luning Formation compose both thrust plates.

Five imbricates (Fig. 3), constitute the nappe (N2) in the western domain and contain beds folded in all three generations of folds. Imbricate thrusts are easily recognized by their juxtaposition of different stratigraphic units and locally they exhibit thin gouge zones. All of the imbricate thrusts cut first fold axial traces and are deformed in second and third folds, indicating imbrication after first phase folding and before second phase folding. The facing of the imbricates (Fig. 3) alternates from upright to inverted, suggesting that the imbricates represent thrusted limbs of major first folds.

The apparent absence of imbricates in the eastern domain has two possible explanations: (1) that they were not formed in the east, or (2) that their absence is only apparent and a function of different levels of exposure and relative structural position of the two domains within the allochthon. The second alternative is supported by the following reasoning. The western domain is much more deeply eroded than the eastern domain; thus allowing greater access to the interiors of the thrust nappes. Also, in the eastern domain, nappes, with the exception of the uppermost, are exposed as narrow E–W trending belts, and exposures are much more two-dimensional than those in the western domain.

Autochthon

Structures within the autochthon are briefly discussed only in regard to their significance in the development of the overlying allochthon. The autochthonous succession underlying the Luning allochthon is largely undeformed by folds of the same age as those in the allochthon, with the exception of a zone (medial zone) in the vicinity of the basal thrust of the Luning allochthon. The medial zone is characterized by late Mesozoic folds and a few thrust faults confined to an E–W trending belt that attains a width ranging from about 10 km in the western Pilot Mountains to about 7 km in the eastern Pilot Mountains (Fig. 2).

Three formations, the Permian Mina, Triassic(?)–Jurassic Gold Range, and Jurassic–Cretaceous(?) Dunlap compose the medial zone, and exposures of each are truncated by the basal thrust of the Luning allochthon. The part of the medial zone lying between the eastern margin of exposures of the Gold Range Formation and Dunlap Canyon (Fig. 2) is thought to represent the northerly trending hinge region of the eastern flank of a Mesozoic basin (Oldow 1978a) which apparently contributed significantly to the deformation of the Luning allochthon. Local deposition and/or differential preservation of the Gold Range Formation and marked lateral variation in thickness and composition of Dunlap Formation across the inferred hinge suggests either continued basin activity from Triassic(?) through at least Early Jurassic or the sudden onset of basin subsidence in pre-Dunlap Formation, Early Jurassic.

Structures in the Dunlap Formation of the medial zone (Wetterauer 1977) comprise two major sets of folds which correspond to the first and second fold sets in the overlying Luning allochthon.

First generation structures consist of a southerly vergent tight to isoclinal fold set with axial traces trending from E–W to N–S, due to reorientation during second phase folding. First phase traces have a mean trend of NE. First generation folds are sparse, and axial-plane cleavage exists only in the hinge regions of minor folds.

Second structures consist of major open upright folds with axial-plane cleavage; minor folds are absent. Axial traces of second folds trend NW. Second phase cleavage exhibits a lateral gradient in development, being well developed west of Dunlap Canyon (Fig. 2) but nonexistent east of there. The area of the medial zone in which the cleavage is absent is subjacent to the eastern domain of the Luning allochthon.

Folding in the medial zone was related to Luning allochthon encroachment and emplacement. First structures in both terranes are tight to isoclinal major and minor folds, and in both cases the initial orientation of axial traces is NE. Following first deformation, NW trending second folds developed in both terranes. An E–W structural gradient in second fold development is evident in the allochthon, and a similar gradient exists in the medial zone and is manifest in the degree of second phase cleavage formation. Correspondence of orientation, sequential development, and lateral variability of structures indicates a related origin for allochthonous and autochthonous fold sets. Within the medial zone, pronounced attenuation of first folds away from the basal thrust of the overlying allochthon supports formation of first folds in the autochthon during allochthon emplacement. Investigation of Gold Range Formation structure in the western Pilot Mountains by R. C. Speed (1976, personal communication) indicates that first generation folds decrease in tightness from north to south. Near the basal thrust of the Luning allochthon, first folds in the Gold Range Formation are tight to isoclinal and progressively decrease in tightness to the south over a 10 km distance to where they are nonexistent. A N–S deformational gradient in second folds of the medial zone has not been established.

The autochthonous rocks south of the medial zone in the Pilot Mountains have not been extensively studied, but on the basis of reconnaissance mapping by R. C. Speed (1976, personal communication) they apparently have not undergone any appreciable late Mesozoic deformation. The southern part of the autochthon is composed entirely of the Permian Mina Formation (Speed 1977) which is folded in easterly trending major isoclinal folds developed prior to Gold Range Formation deposition.

KINEMATICS OF DEFORMATION

Intra-allochthon contraction

The contraction within the Luning allochthon is estimated by comparison of facies in juxtaposed nappes and by length of overlap between imbricates. Stratal shortening by folding and cleavage formation have not been calculated but probably do not exceed 50 per cent, thus about half of the calculated shortening is attributable to displacement on thrust faults. Balanced cross sections were not constructed for the Luning allochthon in the Pilot Mountains because of the existence of pervasive penetrative cleavage and lack of control on the geometry of the basal detachment surface. Though specific details of the geometry of the sole thrust are largely unknown it is important to stress that its existence is demanded by lithologic homogeneity among thin thrust sheets that have undergone large displacements. Regionally, the sole thrust has been fragmented by Cenozoic Basin and Range faults and is preserved locally only in isolated mountain ranges in the western Great Basin of North America.

Nappe displacements. Displacement estimates for nappes within the allochthon are made by comparison of facies in nappes N1, N2, and N4 of the eastern domain (Fig. 3); the third nappe (N3) was not used in the estimation due to inadequate exposure. The sole constituent of nappes in the eastern domain is the Luning Formation of which only the clastic member is useful in contraction estimates. Abrupt depositional differentials in thickness or composition of the clastic member have not been found within individual nappes. Regionally, exposures indicate widespread terrigenous clastic deposition (Muller & Ferguson 1939, Ferguson & Muller 1949) during part of the Late Triassic, and although facies differences exist, they are apparently gradual, from shallow marine to deltaic. Within the Luning allochthon in the northern Pilot Mountains, facies are laterally uniform within individual thrust nappes suggesting that thrusts formed more-or-less parallel to the facies contours of the depositional site of the Luning Formation. Estimated displacements for thrusts are based on the assumption that thrust transport was in a direction perpendicular to facies contours, even though inferred directions of thrust motion, derived in the following section, indicated oblique slip with respect to present day thrust traces. Therefore, the calculated displacement are conservative estimates.

The three nappes studied in detail (N1, N2, N4; Fig. 3) contain clastic rocks of the Luning Formation which represent fluvial flood plain, delta front, and prodelta-shallow marine environments, respectively (Oldow 1978a). The differences in thickness and granulometry of coeval segments of the Luning Formation in different nappes are compared to similar changes among rocks of corresponding environments within intact successions (Oldow 1978a) of the Devonian Catskill delta complex of New York (Friedman & Johnson 1966, Rickard 1975). Other delta complexes were also considered to establish ranges of variability; in particular, Cretaceous deltaic-marine sedimentation in the upper Mississippi embayment (Pryor 1960) and sedimentation in the Mississippi delta complex (Gould 1970). The total stratal shortening associated with nappes within the eastern domain of the Luning allochthon is estimated at about 55 km, with the greatest single shortening estimate being 40 km for the uppermost nappe (N4). It is reasonable to estimate displacements on nappe bounding thrusts to have an aggregate magnitude of 25–30 km.

Imbricate displacements. Displacements for imbricates cannot be estimated by lithofacies analysis because coeval stratigraphic units are not juxtaposed, or in those imbricates that contain coeval units no significant facies differences exist. Therefore, displacement estimates are based on length of structural overlap between imbricates. Estimates require: (1) the deduced direction of thrust motion because measurements are made parallel to the inferred transport direction, and (2) confirmation that a single unit has not been juxtaposed by a fault of small displacement. Thus, only imbricates which juxtapose different stratigraphic members of the Luning Formation, or exotic constituents of the allochthon were measured.

The transport direction for imbricate thrusts, active during first phase folding, is inferred to have been NW to SE. The relationship between imbricate thrust motion and associated first phase folding is discussed in the following section.

Estimates of contraction for the imbricates account for at least 18 km of which at least half is attributable to thrust motion. The estimated displacements are undoubtedly minimum figures, but the lack of major facies juxtaposition in coeval rocks implies that the imbricate thrusts may be of significantly smaller displacement than those bounding the thrust nappes.

Allochthon displacement

Displacement of the allochthon with respect to the autochthon is thought to be several tens of kilometres and possibly as great as 100 km. The estimate is based on the comparison of displacements attributed to facies foreshortening within the allochthon and the facies juxtaposition of rocks of the allochthon and partially coeval rocks in the autochthon. Even given the total internal shortening within the allochthon as about 70 km, only moderate differences in juxtaposed facies occur, whereas between allochthon and autochthon facies differences are dramatic.

Juxtaposition of the Luning Formation (allochthon) and Gold Range Formation (autochthon), partially age equivalent units (Oldow 1978a, 1978b), brings together rocks with marked differences in respective depositional environments. Exposures of the Gold Range Formation in the western Pilot Mountains indicate deposition predominantly in a subaerial environment characterized by volcanic and terrigenous clastic accumulation (Speed 1977). The Luning and Gold Range Formations are distinctly different facies, but the possibility of rapid changes in the character of depositional environments associated with volcanic fields and the lack of well studied present day analogues allows no specific limits to be assigned to the magnitude of displacement for the Luning allochthon. It is, however, reasonable to infer displacement on the order of at least tens of kilometres.

Thrust transport directions

Folds cogenerated with thrust faults are important in the determination of direction of thrust motion in that maximum shortening of bedding takes place in a direction normal to the fold axial surface in flexural slip folding. If folds are generated during thrusting on a subplanar surface and no significant simple shear strain occurs within the deforming mass, the principal transport direction of thrusts can be taken as more-or-less parallel to the horizontal component of maximum shortening. Additional information is necessary to assess a unique transport direction, and this information is supplied by the vergence of thrust cogenerated folds. Such folds are generally overturned in the direction of upper plate motion.

Imbricate thrusts. Contemporaneous formation of thrust imbricates and first folds in the western domain is indicated by the syn-first phase emplacement of one imbricate as discussed previously. The hypothesis is further supported by the existence of the alternating facing of stratigraphic successions of several imbricates which are thought to represent the limbs of first folds whose hinges were thrust. This alternation between upright and inverted stratigraphic successions in imbricates is found in the uppermost nappe (N2) in the western domain. Here, the imbricates were emplaced prior to the second phase of folding. In the lowermost nappe (N1), facing direction is not as systematic (Fig. 3), but the general lack of first phase major folds, occurrence of first cleavage, and demonstrable syn-first phase thrusting of one imbricate suggest an origin like that proposed for the overlying nappe. Thus, given the initial NE strike and SE vergence of first axial surfaces NW to SE transport is suggested for the imbricate thrusts.

Nappe thrusts. The genetic relationship between major thrusts and first and second phase folds is not immediately apparent. The inferred syn-thrust origin of first folds in the medial zone and large estimated displacements for major thrusts suggest that the dominant component of motion for the thrusts was related to first phase deformation. Apparently, during transport, strain accumulated in the allochthon as thrusting, whereas in the autochthon folds and small displacement thrusts were generated. The corresponding spatial variability of second phase fold intensity in the allochthon and medial zone suggests a related origin for the folds at, or very near, the present position of the Pilot Mountains; such that the largest component of transport on major thrusts, in accordance with their relationship to first folds, was probably NW–SE.

Formation of second folds is related to late stage motion of major thrusts, which is inferred to have been in a direction different from thrust motion during first phase deformation. Axial trace truncation of second folds by thrusts occurs throughout the Luning allochthon in the Pilot Mountains. The relationship between second folds and major thrusts can be explained in two ways. In the first, basal thrusts of nappes were involved in second generation folding after emplacement of the Luning allochthon. Following the second folding the deformed major thrusts were reactivated and underwent displacement resulting in the truncation of second phase folds. During thrust reactivation, fold culminations and depressions of the original thrust surfaces would necessarily be truncated, with incorporation into the reactivated nappes of relatively small fault-bounded masses of rock. The existence of four nappes in the eastern domain of the allochthon, each consisting of uniformly different facies of Luning Formation without thrust slices of disparate facies, argues against this model. The model also fails to account for the E–W deformational gradient expressed by second phase folds.

The second explanation fits available data better and calls for second phase deformation during reactivated transport of thrust nappes. Here, major thrusts maintained their planarity after emplacement during first phase deformation. The thrusts were then reactivated or continued motion in a different direction, and during further displacement, second folds were generated. The lateral variation in the intensity of second folds is thought to be related to laterally different rates of slip on thrusts; greatest folding occurred in the parts of the nappe between areas of high and low slip rates on the basal thrust.

The second model calls for significant internal deformation of thrust nappes during thrusting, a phenomenon that has long been established for alpine-deformation. The major obstacle for acceptance of this explanation for the Pilot Mountains is whether, or not, the terrigenous clastic and carbonate rocks of the Luning assemblage could actually undergo folding yet maintain planar major thrusts. Examples found in the Jura Mountains (for example, Laubscher 1972, Weid 1960) involve detachment surfaces within ductile evaporite assemblages and as such are not directly applicable to deformation in the Luning allochthon. In the Naukluft Mountains of South West Africa, however, thrust nappes composed of late Precambrian terrigenous clastic and carbonate rocks have undergone intense internal folding during transport on a basal detachment surface (Korn & Martin 1959). Thus, it appears that decollement tectonics with nappes undergoing internal deformation during transport is not restricted to terranes underlain by evaporites. In addition, the Naukluft Mountain nappes also exhibit lateral variability in fold intensity which Korn & Martin (1959) attribute to laterally different shear stresses on the basal detachment surface.

In accordance with second fold orientations, the direction of motion for reactivated major thrusts was probably NE–SW. The magnitude of late stage displacement cannot be precisely estimated, but is thought to be small because of the great distance (10 km) over which attenuation of first folds occurs in the autochthon. The attenuation of syn-thrust folds in autochthonous rocks of other areas is variable; within about 30 m in the New Pass Range, Nevada (MacMillan 1972) and within 125 m of the base of small thrust nappes in the Naukluft Mountains, South West Africa (Korn & Martin 1959, fig. 10). Actual depth of fold penetration into the autochthon is probably controlled by many factors, but of importance here is the large apparent attenuation distance in the Pilot Mountains which suggests small additional thrust foreshortening after first phase deformation.

Acceptance of syn-thrust generation of second folds carries important implications in regard to the kinematics of second phase folding. During folding, the maintenance of an essentially planar basal thrust necessitates either homogeneous strain accumulation within the deforming mass, particularly in the western domain where second phase deformation is most intense, or heterogeneous strain accumulation above a plane of shear which remains parallel to the thrust throughout deformation. In the first situation, rigorous compliance with simple flexural slip kinematics cannot be maintained during folding. Thus, in all probability the existence of flexural slip second folds, as indicated by the recognition criteria outlined by Donath & Parker (1964) and Knopf & Ingerson (1938), suggests that either the second alternative is more realistic or that the component of homogeneous strain, of the first explanation, is relative small.

In either case, the previously deduced initial orientations for first folds are not thought to be significantly affected and inferred displacement directions for syn-first phase thrusting are reasonable. In homogeneous strain, it is doubtful that significant reorientation of second folds would occur. If homogeneous strain is the product of the same stress system responsible for development of second folds the most probable orientation of the homogeneous strain axes ($X:Y:Z$ where $X > Y > Z$) is the following: the plane (XY), normal to the maximum compressive strain component (Z), is parallel to second phase axial surfaces. Thus, the effect of synchronous homogeneous strain during second phase flexural slip folding probably would not significantly reorient second generation axial surfaces. For heterogeneous strain accumulation above a shear plane, sparse data suggests that significant rotation of second and first generation structures, possibly by simple shear or a significantly noncoaxial second phase strain history, occurs only in the immediate vicinity of basal thrusts. The lack of significant reorientation of first and second generation structures is supported by the uniform mean orientation of first and second axial surfaces throughout the Luning allochthon.

The last motion of the major thrusts is related to third phase folding. Third folds are both cut by and fold major thrust surfaces. Fault plane lineations on the basal thrust of the structurally lowest nappe (N1) indicate that the last motion was essentially parallel to the strike of the prefold fault surface. Even though the thrust is folded in major third folds in the western domain, the general strike of the fault across the northern Pilot Mountains is nearly E–W. Thus, when considered with the dominant westerly vergence of third generation folds, the last motion was ostensibly E to W. Displacements were probably quite small as suggested by the very sparse distribution of third folds.

DISCUSSION

In the following discussion, a scenario for the structural evolution of the Luning allochthon of the northern Pilot Mountains is presented. Constraints are derived from preceding sections of this paper.

Motion and imbrication of thrust faults occurred throughout the first episode of deformation with thrust transport in an approximately NW–SE direction. The onset of deformation consisted of major folding and thrust imbrication at a distance of possibly as great as 100 km or more from the present location of the Pilot Mountains. Initial folding culminated in major overturned to recumbent folds which, with continued compression, had their hinges thrust, resulting in the emplacement of the thrust imbricates. During imbricate thrusting, exotic rocks, Permo–Triassic volcanic and sedimentary rocks, were incorporated into the allochthon, which otherwise is composed of a homogeneous assemblage of carbonate and terrigenous clastic rocks. The Permo–Triassic units probably represent thin thrust slices of topographic irregularities or up-folds of the infrastructure incorporated within the allochthon during inception of a detachment surface. Existence of the detachment surface is indicated by lithologic homogeneity among relatively thin thrust nappes which have undergone large displacements.

Displacements of thrusts are varied but are divisable as either large or small. Small displacement thrusts (imbricate thrusts) were emplaced and locally folded in first folds and then transported *en masse* on large displacement thrusts (nappe thrusts). Maintenance of planarity of major thrust faults throughout first phase deformation suggests nappe imbrication similar to that described in the eastern Rocky Mountains of Canada by Dahlstrom (1970). There, progressive deformation resulted in younger thrusts cutting under older thrusts, which allowed nappe imbrication and maintained the planarity of older thrusts surfaces. Thus, thrusts in the Pilot Mountains are thought to represent segments of listric thrust faults associated with detachment tectonics.

Upon encroachment of the allochthonous terrane the subjacent autochthon underwent folding and some small displacement thrusting, possibly a premonitory event to what would result in detachment and incorporation of the autochthonous rocks into the allochthon if first phase deformation had continued. After emplacement and related first generation folding of the medial zone in the Pilot Mountains, the allochthon underwent additional motion and folding (second phase). The timing between first and second phase deformation is not currently known and may represent a continuum or two discrete events; nonetheless, reorientation of thrust motion between the first and second episodes of deformation is thought to be the result of local crustal downwarp. The projection of the northerly trending eastern margin of a Mesozoic basin proposed for the medial zone in the western Pilot Mountains coincides with the boundary between eastern and western domains in the allochthon. The suggestion is that the basin underwent a phase of accelerated subsidence and the allochthon slid into the forming depression resulting in the second phase folding.

Two mechanisms for basin downwarp are proposed. In the first, subsidence is simply a response to crustal loading by emplacement of the Luning allochthon during the first deformation. As stated above, basin subsidence was probably active from Triassic(?) to at least Early Jurassic times, as indicated by the distribution and lithology of the Gold Range and Dunlap Formations. Thus, if during first phase deformation the Luning allochthon encroached upon the basin it is reasonable that load-generated subsidence would result and continue until a state of equilibrium was reached. Another possibility is that the downwarp is the product of major crustal flexure. If after allochthon emplacement during first phase deformation, the region was subjected to regional compression with resultant formation of very large crustal flexures within the autochthon (second generation folds), it is not unreasonable to expect a pre-existing basin to be the site of a major synform.

The final stage of allochthon emplacement consists of third phase folding and associated motion on major thrusts. The spatial correspondence between intense second folds and third phase fold development suggests a related origin. Conceivably, continued or late stage reactivation of basin subsidence may be called upon and simply may be local adjustments to equilibrium between the allochthon and underlying basin. Flexural deformation of major thrusts in third generation folds indicates cessation of slip.

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