Waves

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Timing of Deformation in Overthrust Belt and Foreland of Idaho, Wyoming, and Utah[1]

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ABSTRACT

A review of the timing and displacement evidence of the major structures of the western Wyoming Overthrust belt and foreland shows there is a progression in thrust displacement, apparent duration of motion, and palinspastic position of thrust traces from west to east. Those toward the west moved farther for an apparently longer period of time and are more widely spaced in their restored positions than those toward the east. However, average thrust velocities are all on the order of 0.5 ± 0.5 cm/yr (0.2 in./yr). Foreland events are in part synchronous with thrust belt events and had an effect on them. Although dating precision varies widely on major normal faults, present evidence does not contradict the generally held view that all normal faults postdate the youngest thrusting.

INTRODUCTION

Several developments within the last 15 years in the Overthrust belt of Idaho, Wyoming, and Utah have made a new, better defined reconstruction of events possible. First, although there still are gaps, the main features of the surface geology are largely understood. Many 7$^1/_2$-quadrangle maps, as well as the first 2° sheet (Oriel and Platt, 1980), thrust-belt-wide structure map (Blackstone, 1981), and many other important maps, have been published. Second, recent seismic profiling by Chevron, analyzed by Royse et al (1975), has provided the subsurface control that has allowed Royse et al as well as others to unravel, at least grossly, the displacements of the major thrust sheets. These data, coupled with perhaps the most refined dating on thrust faults of any thrust belt in the world, have provided an unparalled opportunity to examine in a quantitative way both the kinematics of thrusting and the relationships between tectonic activity and sedimentation in the thrust belt.

In this paper we review these developments and consider some additional problems. After a short discussion of thrust-belt geology, we review evidence for the dating of tectonic movements, both in the thrust-belt proper and in the foreland. Finally, we combine these data with other data on rotations of thrust sheets and inferences on the development of thrust-fault surfaces to produce a scenario for the development of both the Overthrust belt and the foreland to the east.

THRUST-SHEET GEOLOGY OF WESTERN OVERTHRUST BELT

The segment of the Overthrust belt in western Wyoming, southeastern Idaho, and northwestern Utah is a broad salient, convex toward the east. The region is cut by six or seven major thrust faults, numerous minor ones, and late listric normal faults. The sedimentary package affected by faulting wedges to the east. The rocks range from Precambrian metasediments and perhaps basement at the base on the west, to early Eocene synorogenic deposits at the top on the east. The youngest exposed beds, and the part of the total section composed of thrust-derived sediments, become progressively younger and greater, respectively, toward the east, which is also the direction of thrust transport. The last thrust to form, uplifted the sediments derived from earlier thrusts.

From west to east, the major thrusts are the Paris, Meade, Crawford, Absaroka, Darby, and Prospect (Fig. 1). These appear from beneath the Snake River plain trending southeastward, the most easterly three being closely spaced and complexly imbricated. The traces of the major thrusts turn abruptly south at the latitude of Jackson, Wyoming. The more easterly the thrust sheet, the more abruptly its fault trace swings southward. The southward trends continue from the well-exposed northern area nearly to the latitude of La Barge, Wyoming. There the Prospect thrust disappears, and the trace of the Darby thrust swings to the east as the fault shallows and is torn (Blackstone, 1979; Oriel and Platt, 1980); the Absaroka thrust trace swings eastward here as well. North of the Uinta Mountains, the trend back toward the west is more gentle than the swing southward at the northern end of the salient. Accepting the interpretation that the Darby and Hogsback thrusts are the same (Blackstone, 1979; Dorr and Gingerich, 1980), the Absaroka and Darby thrusts extend the full length of the salient and the other four major thrusts extend roughly down one-half of it. The Paris thrust has been extended to the south and forms one of the easternmost thrusts of Armstrong's Sevier thrust belt (Armstrong, 1968).

The Overthrust belt obeys most of the "rules" that have been developed for such belts. (1) Thrusts cut up section in the direction of transport, cutting successively younger rocks toward the east; many of the younger rocks are erosional products of older thrust sheets. (2) At any one locality, the youngest thrust is generally the lowest one structurally, although there are exceptions that we review later. (3) The deformation, in general, has been brittle, although (a) close fracturing near faults and in regions of high curvature of beds, (b) carbonate twinning (Allmen-

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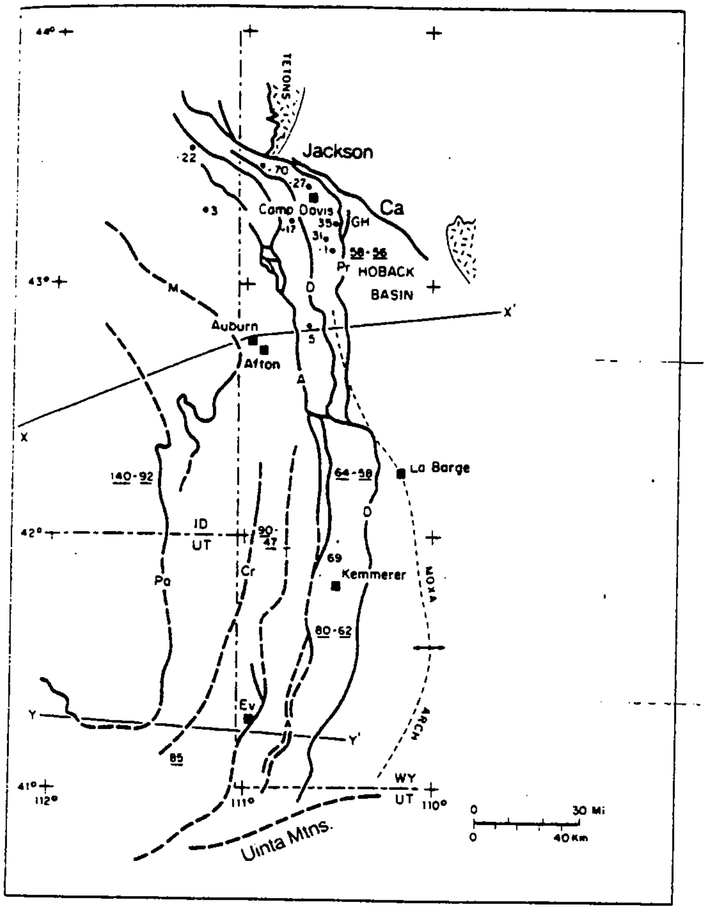


FIG. 1—Western Overthrust belt. Major faults (dashed where inferred): Pa, Paris thrust; M, Meade thrust; Cr, Crawford thrust; T, Tunp thrust; A, Absaroka thrust; D, Darby thrust; Pr, Prospect thrust; GH, Game Hill fault; Ca, Cache fault. Numbers along these faults are times (m.y.b.p.) of motion on the major thrust faults. Other symbols include EV, Evanston, Wyoming; lines XX′ and YY′ are positions of cross sections of Royse et al (1975).

dinger, 1982; Eastman and Wiltschko, 1982), and pressure solution have been reported. No regional metamorphism closely synchronous with thrusting has been observed (Armstrong and Oriel, 1965). (4) The major decollement horizons seem to follow weak horizons (Cambrian Park and Wolsey shales, Triassic Dinwoody and Woodside Formations and others such as the Mississippian Darby Formation and some Cretaceous shales) for long distances in thrust faults, to cut abruptly upward through stronger rocks (Ordovician Bighorn Dolomite, Mississippian Madison Limestone, Jurassic Nugget Sandstone, Pennsylvanian Wells Formation) (Blackstone, 1979; Rubey, 1973b; Rubey, Oriel, and Tracey, 1975; Oriel, 1969; Royse et al, 1975) although this is not true everywhere.

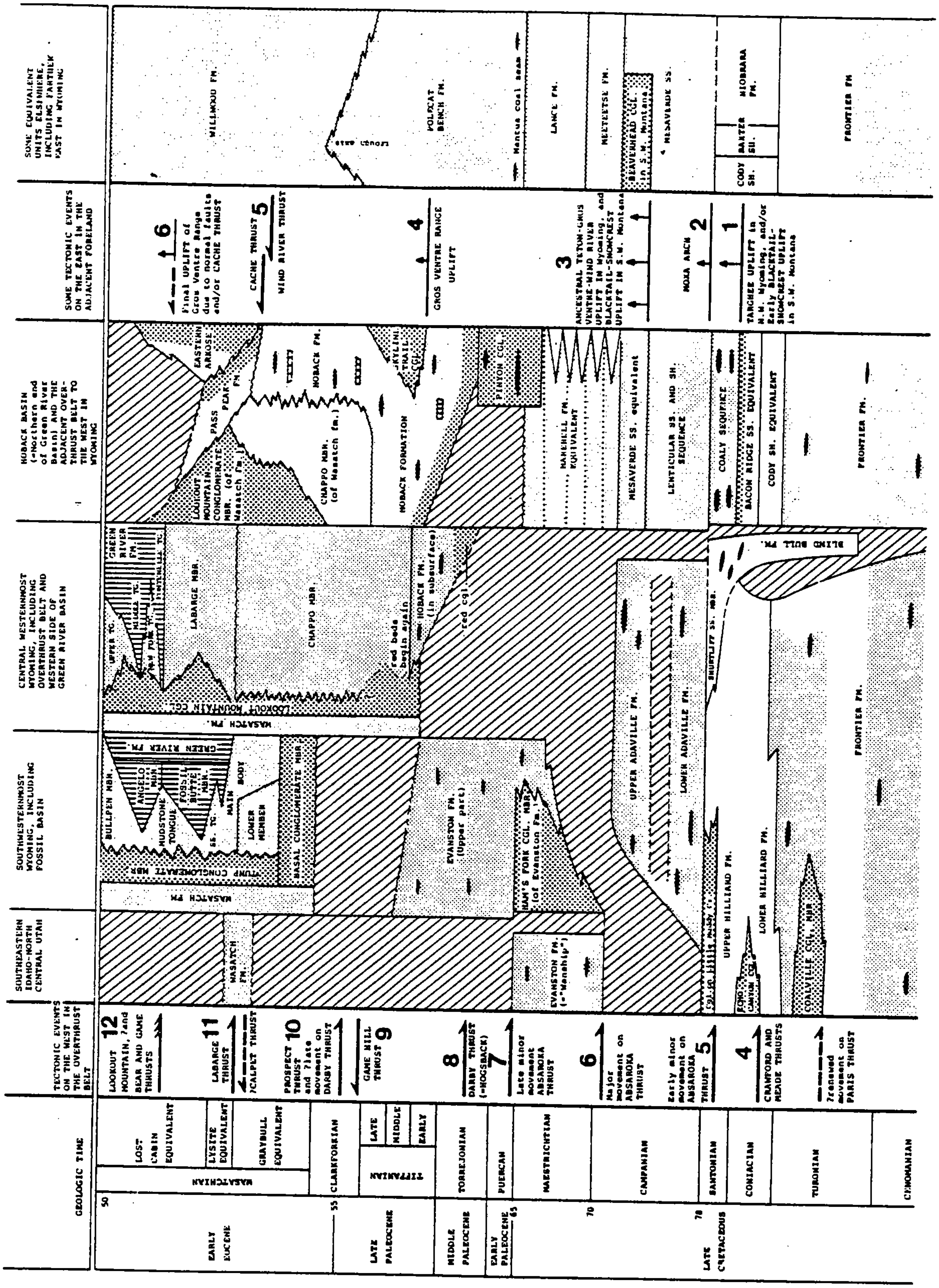
SEDIMENTATION

Armstrong and Oriel (1965) in their classic review paper clearly linked events in the thrust belt to events in the sedimentary basin to the east. This basin, which received the sediments that have allowed dating of events, has been variously called the foredeep, sedimentary moat, or, in the Cretaceous, the Cretaceous seaway. As the thrust terrain moved eastward, the basin axis moved eastward as well. The youngest thrusts sliced through the more eastward rocks that had been deposited previously on the basin's western shore, and carried them farther east. The evolution of the Overthrust belt, therefore, may be viewed as the successively eastward march of both the thrust terrain and basin, the thrusts cutting up the trailing margin of the basin as they proceeded. The erosional products that overlap, are cut by, or are produced by the thrust sheets, provide for their dating.

The exact nature and origin of each synorogenic deposit, however, are still subjects of dispute. What kind of event does each influx of coarse material represent? How does one explain the fluctuations of rapid sedimentation followed by lacustrine deposits swept over again by more coarse clastics? Ideas have ranged from (1) variable rates of subsidence (Suttner, 1969), to (2) sea level rise, to (3) climatic change (Eyer, 1969, p. 1368), to (4) unknown mechanisms of isostatic uplift in the source area and failure of the crust (Schumm, 1977, p. 60-62), to (5) repeated motion on thrusts. All of these models have drawbacks or uncertainties; (1) and (4) do not explain why; (3) has not been confirmed by faunal or sedimentologic evidence; (2) requires global sea level fluctuations inferred from seismic stratigraphy, which have not been shown to be synchronous with sedimentation in the foredeep in all places; and (5) is a circular argument, in a sense, because the sediments themselves are used to date the thrusts.

Thrusting, however, has been shown recently to be an important mechanism not only to form basins of the shape seen in the rock record, but also to explain basin evolution (Price, 1973; Jordan, 1981; Beaumont, 1978, 1981; Schedl and Wiltschko, 1980; Jordan, 1981). Thrusts moving toward the craton provide a large load and, in the case of the Overthrust belt, a western margin. The load consisting of thrusts and their erosional products bows the lithosphere down isostatically to form a basin with the following characteristics: (1) deepest nearest the thrust terrain; (2) asymmetrical toward the craton; (3) possessing an outer "zero crossing" that may correspond to a position of shallow water or erosion several hundred kilometers out from the load center; and (4) a basin axis which moves toward the craton as the thrust load does likewise. Accelerated influxes and basinal trapping of clastics thus reflect times of rapid uplift somewhere in the thrust terrain as a result of thrusts moving up ramps, loading the lithosphere, and causing downwarping in the adjacent foredeep. Decelerations or cessations of coarse clastic sedimentation represent times of little thrusting and correlatively slow infilling. This simple conceptual model links the known mechanism to events in the basin. Thrusting therefore explains the production of a source area and the formation of a basin to receive the sediments.

However, proposed models cannot at present account for all the fine details within the sedimentary package. The fact that studies of lithospheric deflection using infinite viscoelastic (Beaumont, 1978, 1981), infinite elastic (Jordan, 1981), and other rheologies and geometries (Schedl and Wiltschko, 1980) all properly "model" basin shape and depth, suggests that these models are not sufficiently


GEOLOGIC TIME
TECTONIC EVENTS ON THE WEST IN THE OVERTHRUST BELT
SOUTHEASTERN IDAHO-NORTH CENTRAL UTAH
SOUTHWESTERNMOST WYOMING, INCLUDING FOSSIL BASIN
CENTRAL WESTERNMOST WYOMING, INCLUDING OVERTHRUST BELT AND WESTERN SIDE OF GREEN RIVER BASIN
HOBACK BASIN (=Northern end of Green River Basin) AND THE ADJACENT OVERTHRUST BELT TO THE WEST IN WYOMING
SOME TECTONIC EVENTS ON THE EAST IN THE ADJACENT FORELAND
SOME EQUIVALENT UNITS ELSEWHERE, INCLUDING FARTHER EAST IN WYOMING
EARLY EOCENE
LATE PALEOCENE
MIDDLE PALEOCENE
EARLY PALEOCENE
LATE CRETACEOUS
50
55
65
70
78
WASATCHIAN
LOST CABIN EQUIVALENT
LYSITE EQUIVALENT
GRAYBULL EQUIVALENT
CLARKFORKIAN
TIFFANIAN
LATE
MIDDLE
EARLY
TORREJONIAN
PUERCAN
MAESTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
12 LOOKOUT MOUNTAIN, ?and BEAR AND GAME THRUSTS
11 LABARGE THRUST
?CALPET THRUST
10 PROSPECT THRUST and ?late movement on DARBY THRUST
9 GAME HILL THRUST
8 DARBY THRUST (=HOGSBACK)
7 Late minor movement ABSAROKA THRUST
6 Major movement on ABSAROKA THRUST
5 Early minor movement on ABSAROKA THRUST
4 CRAWFORD AND MEADE THRUSTS
3 Renewed movement on PARIS THRUST
WASATCH FM.
EVANSTON FM. (="Hanship")
ECHO CANYON CGL.
UPPER HILLIARD FM.
LOWER HILLIARD FM.
COALVILLE CGL. MBR.
BULLPEN MBR.
ANGELO MBR.
MUDSTONE TONGUE
FOSSIL BUTTE MBR.
SS. TG.
MAIN BODY
LOWER MEMBER
GREEN RIVER FM.
TUNP CONGLOMERATE MBR.
BASAL CONGLOMERATE MBR.
EVANSTON FM. (Upper part)
HAM'S FORK CGL. MBR. (of Evanston Fm.)
UPPER ADAVILLE FM.
LOWER ADAVILLE FM.
FRONTIER FM.
UPPER TG.
GREEN RIVER FM.
LABARGE MBR.
CHAPPO MBR.
LOOKOUT MOUNTAIN CGL.
red beds begin again
HOBACK FM. (in subsurface)
red cgl.
SHURTLIFF SS. MBR.
BLIND BULL FM.
LOOKOUT MOUNTAIN CONGLOMERATE MBR. (of Wasatch Fm.)
PASS PEAK FM.
EASTERN ARKOSE
CHAPPO MBR. (of Wasatch Fm.)
HOBACK FM.
HOBACK FORMATION
SKYLINE TRAIL CGL.
PINYON CGL.
HAREBELL FM. EQUIVALENT
MESAVERDE SS. equivalent
LENTICULAR SS. AND SH. SEQUENCE
COALY SEQUENCE
BACON RIDGE SS. EQUIVALENT
CODY SH. EQUIVALENT
FRONTIER FM.
6 Final uplift of Gros Ventre Range due to normal faults and/or CACHE THRUST
CACHE THRUST 5 WIND RIVER THRUST
4 GROS VENTRE RANGE UPLIFT
3 ANCESTRAL TETON-GROS VENTRE-WIND RIVER UPLIFT IN WYOMING, and BLACKTAIL-SNOWCREST UPLIFT IN S.W. Montana
2 MOXA ARCH
1 TARGHEE UPLIFT in N.W. Wyoming, and/or Early BLACKTAIL-SNOWCREST UPLIFT in S.W. Montana
WILLWOOD FM.
Clough gap
POLECAT BENCH FM.
Mantua coal seam
LANCE FM.
MEETEETSE FM.
BEAVERHEAD CGL. in S.W. Montana
MESAVERDE SS.
CODY SH.
BAXTER SH.
NIOBRARA FM.
FRONTIER FM.

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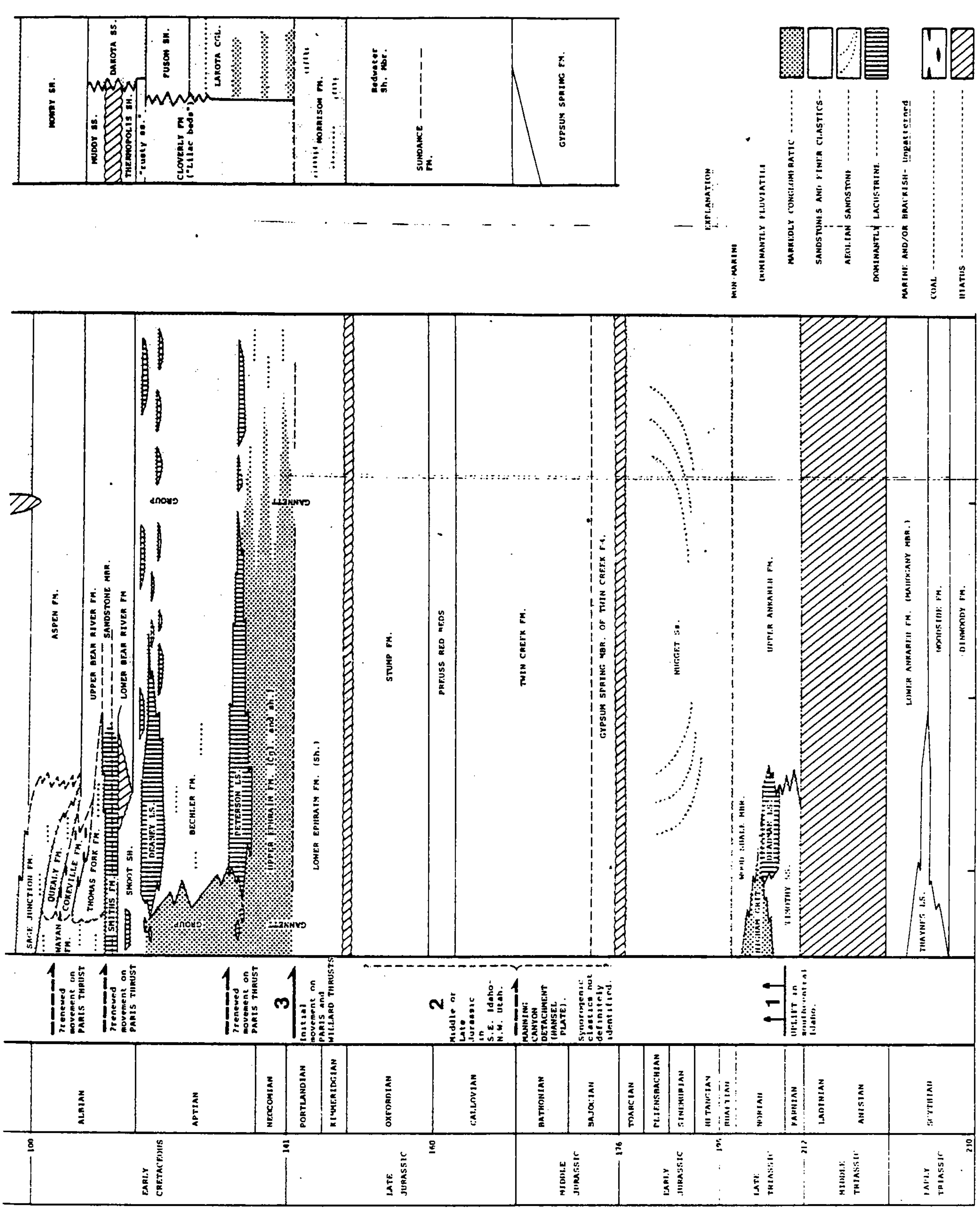

FIG. 2—Chart of major tectonic and stratigraphic events in the Overthrust belt and foreland.

constrained. Students of oceanic lithosphere flexure have found that elastic, plastic, viscoelastic, and various combinations of these models all mimic correctly the ocean-floor topography ahead of a trench (Forsyth, 1980). Independent measures of states of stress and strength are necessary to choose correctly the proper model.

However, the problem is even more complex in thrust terrain. First, the magnitudes of the original loads are not exactly known, because the overthrust plates have been partly removed by erosion, and locally downdropped by block faulting where they now lie buried beneath Neogene to Quaternary, postorogenic, sedimentary deposits. Second, sublithospheric processes, such as frictional drag exerted on the base of ~~the lithosphere by the shallowly subducting~~ Farallon plate during the Cretaceous (Dickinson, 1979), may be another potential cause of downwarping which has not yet been quantified. Third, the times of eustatic sea level changes and the ages of synorogenic sedimentary deposits in the foredeeps cannot yet in all places be time-correlated exactly enough to attribute all the changes in sedimentary thicknesses to either global eustasy or regional tectonics. Until these problems are resolved, tightly coupling thrust events to each small fluctuation in sedimentation will be difficult. However, in the following analysis we have taken the side of those who believe that episodic influxes of sediments reflect episodic motions on thrusts, knowing that this interpretation may need to be amended as more information becomes available.

TIMING

Fluctuations in sedimentation have enabled geologists to date thrusts within the Overthrust belt; these thrusts are perhaps the best dated in the world. In this section we review first the various methods that have made possible the dating of the overthrusts and significant related uplifts, and then we present the dating evidence itself. Results are summarized graphically on Figure 2.

Methods

All the methods for dating thrusts are straightforward but range considerably in precision. The simplest method is to find and date a coarse clastic deposit which can be shown to be associated with uplift. Evidence for association are: (1) significant reduction in grain size of a closely associated deposit in a direction away from the thrust sheet and toward the craton, and (2) clast composition that can be tied uniquely to the thrust or uplift. The age of the deposit gives a date for tectonic uplift. Another technique, stratigraphic bracketing, is only as precise as the bracket of ages is small. The upper limit on the bracket is the oldest date in the sediment covering the fault, and the lower limit is the youngest age from the youngest rock cut by the thrust. It yields the maximum allowable limits for the time span during which movement of a thrust or other structure occurred. Bracketing fails to be useful if the bracket of age is ambiguously long. More commonly, the ages of the bracketing strata cannot be dated because of a lack of appropriate fossils.

~~The distribution~~ of ~~sediments is another~~ way to date uplifts. Where a distinctive and datable type of sedimentary deposits occurs in one basin and not in an adjacent one, an uplifted barrier may be postulated to have existed between the two basins at the time of deposition. An example of this, to be discussed, is the ancestral Teton-Gros Ventre uplift. In this situation as in the others, the dates for the structures are only as good as those for the sediments.

Most of the dates to be reported in this study are paleontologic, founded on various fossils groups or combinations of groups. At present, terrestrial or freshwater mollusks are least precise; palynologic data are considerably more accurate and useful. Mesozoic reptiles provide some dates but are imprecise, rare, and difficult to find where needed for stratigraphic purposes. Fossil mammals, also rare, cannot always be found where they are stratigraphically significant; however, where possible in this region, they provide relatively precise dates for early Cenozoic events.

Only one radiogenically dated deposit in the relevant age range has been reported from the study region.

This paper documents how these methods were used, singly or in combination, to establish the sequence and timing of tectonic events. Two general conclusions regarding sequence and timing should be noted beforehand. (1) Although progression in time of major, datable thrusts in the Overthrust belt was from west to east, some subsidiary, back-limb splays on the western sides of major thrusts are younger than their parent thrusts. (2) Although tectonism began earlier in the Overthrust belt on the west than in the foreland on the east, there was broad temporal overlap in times of movement in those two regions after the middle Late Cretaceous.

The major tectonic events in the Overthrust belt are shown toward the left on Figure 2. Toward the right, are the major tectonic events in the adjacent foreland[3]. Significant stratigraphic units within those regions are shown between. Arrows pointing to the right indicate eastward thrust movement; left-pointing arrows indicate westward movement.

Elsewhere we discuss how the foreland uplifts exerted significant influences on the development and morphology of eastward-moving overthrusts in the Overthrust belt. It is not clear whether certain important features, such as the Moxa arch and Game Hill thrust, also shown on Figure 1, should be classified into the Overthrust belt or foreland set.

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[3] Recently some authors have substituted the term "foreland" for foredeep. Others have applied the term to any area ahead of and toward which thrusts moved. Here we use "foredeep" for a trough or basin of subsidence and sedimentation adjacent and related to an orogenic uplift, e.g., the foredeep into which eastwardly transported sediments of the Gannett and Wayan Groups, eroded from the Paris thrust uplift, were deposited. We use "foreland" in the sense defined by Eardley (1962, p. 8) for ". . . the part of the stable interior (of a continent) adjacent to a marginal orogenic belt. . ." Also see Blackstone (1980), Keefer (1970), and Prucha et al (1965) for examples of the usage we prefer. In the *Glossary of Geology* (Bates and Jackson, 1980), the terms are defined as follows. "*Foreland*—A stable area marginal to an orogenic belt, toward which the rocks of the belt were thrust or overfolded. Generally the foreland is a continental part of the crust, and is the edge of the craton or platform area." "*Foredeep*—An elongate depression bordering an island arc or other orogenic belt."

Major Events in Overthrust Belt

Major events from older to younger, include the following (numbers keyed to Figure 2).

1. Early tectonic activity occurred in the miogeosyncline. Armstrong and Oriel (1965, p. 1153) noted that Late Triassic uplift in central Idaho "shed coarse detritus into the basin on the southeast to form the Higham Grit," citing McKee et al (1959, p. 17) who indicated this grit probably was deposited in coalescing alluvial fans along a mountain front. Armstrong and Oriel interpreted this to reflect "the start of the breakup of the miogeosyncline." The Higham Grit is dated by its intercalated position within the Late Triassic, upper, nonmarine part of the Ankareh Formation. The type locality of the grit is on the Fort Hall Indian Reservation east of Blackfoot, Idaho, although the grit also occurs farther to the south. The type locality now is within the hanging wall of the Meade thrust, so it was moved eastward from the original position of deposition; its source area must have been even farther west of what, in a restricted sense, now is considered to be the Idaho-Wyoming Overthrust belt. The middle-Triassic hiatus in deposition between the paralic-marine, Early Triassic, lower Ankareh Formation and the nonmarine, Late Triassic, upper part of that formation in southeastern Idaho and western Wyoming, may also reflect partially an early phase of this tectonism. The mid-Triassic hiatus occurs throughout that portion of the Cordilleran miogeosyncline, where Early Triassic sediments had been deposited previously (Collinson and Hasenmueller, 1978, p. 177, 179, 183). Neither the specific cause of the uplift nor the exact location of the source area for the Higham Grit is yet well established.

2. There is evidence that the next episode of orogeny, involving overthrusting, occurred within the Sevier orogenic belt during Middle and/or Late Jurassic time. Oriel and Platt (1979) and Allmendinger and Jordan (1981) discussed this evidence; the latter authors postulate that a group of now separated allochthonous masses in southeastern Idaho and northwestern Utah originally were united within what they name the "Hansel plate," above a major thrust fault which they call the "Manning Canyon decollement (or detachment)" within or above late Mississippian strata. They could not restrict the time of movement more narrowly than to some time in the Middle and/or Late Jurassic (p. 310-311), as we show it on Figure 2, and they did not identify any related synorogenic coarse clastics that may have been derived from that uplift. Their dating of the time of movement is based on the inference that radiogenically dated Jurassic metamorphism in rocks west of the Hansel plate occurred after that thrusting, plus the fact that, by ambiguous stratigraphic bracketing, the thrust is post-Triassic, parts of it having overridden Triassic rocks. Unfortunately, the oldest overlapping strata may be as young as Pliocene. We suggest, however, that uplift associated with that episode of overthrusting may be reflected by the following: (1) the regressive character of the Preuss and Stump formations (late Twin Creek-Sundance sea); (2) the apparent absence of Middle to Late Jurassic (Oxfordian and Kimmeridgian) rocks in the area of Hansel plate, west of the Paris-Willard thrust in central Idaho; and (3) the presence of the latest Jurassic Morrison Formation in northeastern Utah, southwestern Montana, and southwesternmost Wyoming, which may in part be a distal facies of the nonmarine clastics which prograded westward off the eroding Hansel plate (Peterson, 1972, p. 187-188, his Figs. 1, 8; Suttner, 1969, p. 1391). Allmendinger and Jordan (1981) tentatively conclude that this episode of eastward overthrusting occurred west of and before the Paris-Willard thrust, thus also conforming to the west-to-east geographic and temporal progression of better dated major thrusts to be discussed. They admit, however, much more work must be done in this area to confirm these inferences.

3. Initial movement on the Paris-Willard thrust system produced an uplift which shed the thick, coarsely conglomeratic, synorogenic upper part of the Ephraim Formation of the Gannett Group. The upper Ephraim was followed by other progressively less coarse-grained units of the Gannett and Wayan groups and part of the Frontier Formation. Eyer (1969) cited evidence that the thin, fine-grained, pre-orogenic lower part of the Ephraim Formation contains latest Jurassic marine mollusks. He also cited reports of Early Cretaceous (Aptian) charagonites and ostracods from the synorogenic upper part of the Ephraim formation. This places the time of initial movement of the Paris thrust on the Jurassic-Cretaceous boundary. Armstrong and Oriel (1965), Oriel and Tracey (1970), and Rubey (1973a) also discussed first movement on the Paris thrust. Armstrong and Oriel (1965, p. 1859), Armstrong (1968), and Royse et al (1975, p. 45-46) reviewed evidence that the Paris and Willard thrusts were related.

The Paris-Willard system may have moved several more times. Deposition of the conglomerate of the upper Ephraim was followed by several alternations of lacustrine (or marine) and fluviatile sedimentation (Fig. 2). In the Gannett Group, the sequence of members (Eyer, 1969) is upper Ephraim conglomerate (fluviatile), Peterson Limestone (lacustrine), Bechler (fluviatile including conglomerate on the west), and Draney and Smoot (lacustrine and marginal-lacustrine, respectively). The Smiths Formation above the Smoot grades eastward and southeastward into the lower black shales and middle sandstones of the Bear River Formation. The Smiths Formation, with its fresh-water molluscan fauna (Durkee, 1979; Rubey, 1973a), carbonaceous black shales, and overlying fine-grained sandstones, is a fresh-water coastal deposit of paludal and fluviatile sediments that graded into the brackish and marine lower and middle Bear River deposits at the time of transgression of the Skull Creek seaway. The Wayan "group," above the Gannett Group, consists of several units. The color-variegated Wayan Formation of fluviatile origin (Mansfield, 1927; Dorr, in preparation) is on the northwest in the Caribou Range and vicinity in southeastern Idaho. The Wayan includes sandstones lenses with channel lag gravels, locally has yielded fragments of Early Cretaceous dinosaurs and crocodilians, and represents a braided stream, medial, wet, alluvial fan deposit. To the south and southeast, the Wayan "group" is represented in southwestern Wyoming by the Thomas Fork and Quealy Formations which resemble the Wayan and are of similar, but more distal, fan origin. The Thomas Fork and Quealy Formations are separated by the drab, finer grained Cokeville Formation which contains some thin coals, both fresh- and brackish-water mollusks, and little or no conglomerate. The Wayan "group," which thins eastward and southeastward, is the western equivalent of the upper Bear River Formation and part of the Aspen Formation (Rubey, 1973a), and represents an alluvial fan environment which prograded into a brackish coastal and marginal marine environment. The Cokeville Formation represents a brief reversal of this progradation, related to the upper Bear River marine transgression (Dorr, in preparation). The Sage Junction Formation, next above, is a fluviatile fan deposit which grades eastward and southeastward into the upper part of the Aspen Formation and possibly also into the basal part of the Frontier Formation (Rubey, 1973a). The lower part of the Frontier Formation is of fluviatile origin. The middle and upper parts of the Frontier Formation are mostly of marginal marine origin but in northeastern Utah the fan-form Coalville Conglomerate is included (Schmitt et al, 1981). Both the Gannett and Wayan groups, with their several subordinate stratigraphic units and included facies, are cut, and therefore postdated, by the Crawford thrust at Cokeville, Wyoming, and by the Meade thrust at Wayan, Idaho. For that reason the origin of those groups is attributed to the Paris thrust.

Figure 2 shows that the Gannett-Wayan-Frontier sequence was deposited during Early Cretaceous and early Late Cretaceous. This sequence reflects several episodes of accelerated progradation of alluvial-fan clastics punctuated by intervening episodes of slow, finer clastic deposition in the foredeep east of the source area uplifted by the Paris-Willard thrust. Times of marked fan expansion are represented by the upper Ephraim, Bechler, Thomas Fork, Quealy-Sage Junction, and Coalville stratigraphic units, in that order. Times of fan contraction are represented by the Peterson Limestone (lacustrine), the Draney-Smoot-Smiths sequence (lacustrine-marginal lacustrine and fresh to brackish coastal), and the Frontier Formation (except the Coalville Conglomerate in northwestern Utah to the south).

As stated earlier, the first influx of coarse clastic (upper Ephraim Formation) into the foredeep generally has been attributed to initial movement on the Paris-Willard thrust. The reasons for the subsequent expansions and contractions of coarse clastics of the fluviatile, alluvial fan environment are ambiguous because of the complexity of factors that may have interacted to produce them. Clearly the Peterson and Draney-Smoot lacustrine intervals were times when the subsidence rate of the foredeep temporarily equaled or exceeded the rate of clastic influx from the source area. However, the Smiths, Cokeville, and upper Frontier intervals were times also of transgression of Early and early Late Cretaceous seas.

Of all the possible reasons for these fluctuations, at present we favor some interaction between eustatic sea level rise and fall, thrust uplift, and thrust loading and downwarping of the lithosphere. This suggestion recently was applied by Schmitt et al (1981) and by Sippel et al (1981). They hypothesized that multiple movements of the Paris thrust, each rejuvenating the sedimentary source area, caused the episodic progradations of the coarse clastics and thick fluviatile tongues of the upper Ephraim, Bechler, and Wayan Formations and the Coalville Conglomerate of the Frontier Formation. According to their interpretation, the Peterson, Draney-Smoot-Smiths, and lower and upper Frontier intervals represent times of tectonic quiescence, after erosion had reduced the elevation of the thrust uplands, thus slowing the rate of clastic influx relative to the rate of subsidence in the foredeep. They omitted the significance of the Cokeville Formation, which is a tongue of the Bear River Formation in this sequence.

As a result, we have indicated tentatively on Figure 2 (dashed arrows and questions marks) when renewed movements of at least parts of the Paris thrust may have occurred, as reflected in the sedimentary record. We have put each tentatively suggested movement at the base (beginning) of the clastic expansion to which it would be related, rather than at the beginning of the preceding clastic contraction or possibly correlative marine transgression where it would be put according to a simple eustatic sea-level rise hypothesis. If there were several times of renewed or accelerated movement of the Paris thrust, it is significant that the Coalville Conglomerate of the Frontier Formation in northeastern Utah has no equivalent, thick, and coarse-grained counterpart farther north in western Wyoming. This might indicate that the latest movement of the Paris thrust occurred only farther south.

Whatever the history, present evidence indicates that all activity along the Paris thrust, initial and possibly later, preceded movement(s) on the Crawford-Meade thrust system to the east.

4. Movement of the Crawford-Meade thrust system came next in the sequence. Evidence geometrically linking the two thrusts is presented by Royse et al (1975, p. 45-46). The thrusts can be dated in two ways. That giving the most restricted time, if the evidence and interpretation are correct, equates movement and related uplift along the Crawford-Meade system with synorogenic deposition of the Echo Canyon Conglomerate in northeastern Utah southwest of Evanston, Wyoming. Both Royse et al (1975, p. 48-50) and Nichols (1979) have suggested this correlation, and Nichols reported middle Late Cretaceous (middle Coniacian) palynomorphs from this conglomerate. Acceptance of this correlation requires a southward transport direction for much of the Echo Canyon Conglomerate.

A less precise time for movement on the Crawford thrust is provided at Cokeville in southwestern Wyoming, west of Kemmerer. There the Crawford thrust cuts and overrides the Quealy and Sage Junction Formations (Rubey, 1973a, p. 16; Rubey et al, 1980; Oriel and Platt, 1980; Dorr, in preparation). The thrust is interpreted in the subsurface (Rubey et al, 1980, his cross sections K, L, M) to be overlapped by the Sillem Member of the Fowkes Formation west of Cokeville. Elsewhere the Sillem is underlain by the early Eocene Wasatch Formation. Above the Sillem, the Bulldog Hollow Member of the Fowkes Formation has provided a radiogenic date of 47.7 ± 1.5 m.y. (Oriel and Tracey, 1970, Table 1, and p. 37). Therefore those authors place the Sillem Member in the middle Eocene. The Crawford thrust at Cokeville thus is post-Sage Junction and pre-Sillem. Datable fossils have not yet been found in the overridden beds at Cokeville, but Rubey (1973a, p. 4, 17-23) has equated the Quealy there with the upper part of the Wayan Formation to the northwest, in eastern Idaho west of Freedom, Wyoming. One of the writers (Dorr, in preparation) has found fragmentary but identifiable reptile remains in the Wayan Formation there. These include aquatic turtles, crocodilians of two types, an iguanodontid dinosaur of the genus *Tenontosaurus*, an ankylosaurian dinosaur of indeterminate genus and species, and abundant dinosaur eggshell fragments of several different kinds and sizes. Some of this fossil material, especially *Tenontosaurus*, is similar to that found in the Early Cretaceous Cloverly Formation and Dakota Sandstone to the east in Wyoming. Rubey (1973a, p. 17-21), presented other evidence for the Early Cretaceous age of the Quealy and, indirectly, the Wayan Formations. On the basis of this bracketing evidence, the Crawford thrust is post-Early Cretaceous and pre-middle Eocene, a time span so long that it may only show that the Crawford-Meade system is younger than the initial and probably also any subsequent movements on the Paris thrust.

East of Gray's Lake and the town of Wayan, in southeastern Idaho, approximately 65 mi (100 km) northwest of Cokeville, Wyoming, the Meade thrust (frontal slice) cuts both the Wayan and Sage Junction Formations. This relationship is shown on the USGS Preston Quadrangle geologic map (Oriel and Platt, 1980) and can be seen in a roadcut along Idaho State Road 34, 0.8 mi (1.3 km) east of Wayan. At this location, highly fractured and brecciated, color-variegated beds of the Wayan Formation on the west were brought up several thousand feet and over the younger, drab beds of the Sage Junction Formation to the east. As noted earlier, newly discovered dinosaur material in the Wayan Formation a few miles east, help to establish the Early Cretaceous age of that formation. A recently acquired pollen sample, including 6 genera, from a black shale in the lower portion of the Wayan Formation about 1,440 ft (440 m) above the Wayan-Smiths formation contact along McCoy Creek northeast of Wayan, Idaho, included *Taurocusporites spackmani* and cf. *Verricosisporites obscurilaesuratus*, indicating a middle Albian (upper Bear River–lower Aspen) age for that part of the Wayan Formation (J. G. Schmitt, 1962, personal commun.). Porcelanite beds correlative with those in the Aspen Formation to the east, invertebrate fossils, and the fossil fern *Tempskya* (Rubey, 1973a, p. 19-23), establish the Early Cretaceous age of most of the Sage Junction Formation, although Rubey suggests the uppermost part of this formation may be equivalent to the lowermost Frontier Formation and thus earliest Late Cretaceous in age. Therefore, the Meade thrust, like the Crawford thrust, is post-Early Cretaceous. Although slices of the Meade thrust locally are overlapped by the Miocene-Pliocene Salt Lake Formation (Oriel and Platt, 1980), this top on the bracketed time of the Meade thrust is too young to be meaningful.

We combine the foregoing evidence, from bracketing strata and from the age of the Echo Canyon Conglomerate, to place the time of Crawford–Meade thrusting in middle-Late Cretaceous (Coniacian). Both thrusts postdate the initial and any possible subsequent movements of the Paris thrust.

5. Next in the Overthrust belt, according to Armstrong (1968) and Royse et al (1975, p. 50-52), early minor movement on the Absaroka thrust shed the "conglomerate on Little Muddy Creek," to an area approximately 15 mi (24 km) southwest of Kemmerer, Wyoming. Nichols (1979) provided a palynological date of middle-Late Cretaceous (late Santonian) for this synorogenic conglomerate and thus for this minor thrust movement.

6. In the latest Cretaceous (late Campanian or early Maestrichtian), major movement on the Absaroka thrust deformed the "conglomerate on Little Muddy Creek" (see item 5 above) and shed the Hams Fork Conglomerate Member of the Evanston Formation into the Fossil basin of southwestern Wyoming (Oriel and Tracey, 1970, p. 13-14; Royse et al, 1975, p. 50). The Hams Fork Conglomerate is dated by pollen and by the presence of the latest Cretaceous dinosaur, *Triceratops* (Oriel and Tracey, 1970, p. 12-13 and separate addendum). Armstrong and Oriel (1965), Oriel and Armstrong (1966), Armstrong (1968), Grubbs and Van der Voo (1976), and Nichols (1979) also examined the time of movement of the Absaroka thrust.

7. In a late minor movement in the very latest Cretaceous or early Paleocene, the Absaroka thrust overrode the Hams Fork Conglomerate, and then the Absaroka thrust system was overlapped by post-orogenic, middle Paleocene (Torrejonian) and younger mammal-bearing beds of the upper part of the Evanston Formation (Oriel and Tracey, 1970, p. 14 and separate addendum). This dates the event as post-Maestrichtian and pre-Torrejonian, that is, between the beginning and end of early Paleocene (Puercan) time. We show it on Figure 2 at the beginning of the Puercan, on the Cretaceous-Tertiary boundary. It might be dated slightly later in the Puercan, because no Puercan-age mammals yet have been found in the Evanston Formation.

8. The Darby thrust occurred next in the sequence. This thrust is difficult to date with certainty, and part of it may have moved more than once. Near its northern end, north and south of the Snake River in Grayback Ridge of the Wyoming Range, the youngest rocks found beneath it are the early Late Cretaceous Frontier Formation. About 20 mi (30 km) to the south-southeast, along Deadman, Blind Bull, and South Horse Creeks in the Wyoming Range, it cuts the middle Late Cretaceous (Santonian) upper part of the Blind Bull Formation. The Blind Bull Formation is a temporal equivalent of the upper Frontier and Hilliard Formations which are dated by invertebrate fossils (Rubey, 1973, a, b). No time-significant overlapping deposits have been found over the thrust trace there. Various authors, including Blackstone (1979) and Royse et al (1975), have concluded that farther to the south, just west of La Barge, Wyoming, the Darby thrust is represented by what has been called the Hogsback thrust. Dorr and Gingerich recently found precisely datable fossil mammals in structurally significant strata there and remapped that area. Their interpretation (Gingerich and Dorr, 1979; Dorr and Gingerich, 1980, p. 113) is that initial uplift along the

Darby thrust (Hogsback thrust) provided the source for the basal conglomerates in the Chappo Member of the Wasatch Formation and in the interfingering Hoback Formation (subsurface). The basal conglomerates and red beds in the Hoback Formation lie east of the Darby thrust, and both the thrust and similar basal conglomerates can be traced coextensively southward for nearly 100 mi (160 km) to the north flank of the Uinta Range (Oriel, 1969, p. 14-15). Approximately 60 mi (100 km) north of La Barge, in Monument Ridge and Game Hill along the western edge of the Hoback basin, similar basal conglomerates in the Hoback Formation crop out and overlie latest Cretaceous rocks. They are east of the Darby thrust and older than the Prospect and Game Hill thrusts which affected them. We interpret these too as synorogenic conglomerates shed from initial uplift of the Darby thrust.

The conglomerate in the Hoback basin overlies strata bearing latest Cretaceous (Lancian) pollen. The conglomerate contains reworked latest Cretaceous pollen, and is overlain by late Paleocene pollen-bearing strata in the Hoback Formation (Guennel, Spearing, and Dorr, 1973). This indicates an early or middle Paleocene age for the conglomerates in the Hoback basin area. The basal conglomerates in the La Barge area appear to be middle Paleocene (Torrejonian) in age, on the basis of unpublished subsurface pollen data (Oriel, 1969, p. 14-15).

Dating by fossil mammals from several younger levels in the Chappo Member (Dorr and Gingerich, 1980, p. 107-110) shows the initial uplift caused by the Darby thrust continued to contribute to the Chappo Member during the middle Tiffanian and Clarkforkian. The Darby (Hogsback) thrust is present in Hogsback Ridge, where its trace is overlapped by the Chappo Member. Hogsback Ridge, uplifted as a source area by the thrust was subsequently buried in its own sedimentary debris; later exhumed by erosion, it consists of steeply dipping (33°W) Paleozoic rocks deformed by movement on the Darby thrust. In Buckman Hollow, on the west side of Hogsback Ridge, these rocks are progressively overlapped by more gently dipping (17°W) Tertiary strata whose large, angular, basal clasts consist of fragments of the Paleozoic rock directly below. Mammals from the Tertiary beds of Buckman Hollow are of Clarkforkian age (Dorr and Gingerich, 1980, p. 105-109). Approximately 1 mi (1.6 km) east of Hogsback Ridge and the Darby thrust trace, at the older type locality of the Chappo Member, fossil mammals are of middle Tiffanian age (Dorr and Gingerich, 1980, p. 107). Within a short distance, these beds grade westward into a conglomerate which is their lateral facies equivalent just east of Hogsback Ridge and the Darby thrust trace. This is the evidence that the uplift (Hogsback Ridge in part), formed by the Darby thrust, continued to be a source area for sediment in the middle Tiffanian. Our interpretation, that the uplift began to shed coarse sediment in the Torrejonian, continued to do so in the middle Tiffanian, and was being overlapped no later than Clarkforkian time, indicates the time of initial movement on the Darby (Hogsback) thrust was Torrejonian, where it is placed on Figure 2. At the surface, where they can be mapped, the youngest beds that have been cut and overridden by the thrust, are in the Late Cretaceous Hilliard and Adaville Formation; this shows only that the thrust occurred sometime after the Campanian.

Royse, Warner, and Reese (1975) maintained that the Prospect thrust linked into the plane of the former Darby thrust at Snider basin and that south of there, in Cretaceous Mountain and Hogsback Ridge, movement on the Prospect thrust was taken up by a second movement on the former Darby thrust plane. However, Dorr and Gingerich (1980, p. 112-113) coupled their evidence (see preceding paragraph) that the time of initial movement on the Darby thrust was earlier than that on the well-dated Prospect thrust, with Blackstone's interpretation that the two are not geometrically linked; they concluded that movement of the Darby thrust preceded that of the Prospect thrust. They also gave evidence (Dorr and Gingerich, 1980, p. 110) that mammal-bearing strata cover the trace of (and are not cut by) the Darby thrust along the crest of Hogsback Ridge west of La Barge. Their dating by fossil mammals indicates that movement on the Darby thrust plate could have been at least as early as Torrejonian or even as late as Clarkforkian. This estimate of ambiguously long time permits movement of the Darby thrust on the crest of Hogsback Ridge to have been contemporaneous with either initial movement of that thrust or with the younger Prospect thrust, but does not prove either. There is no more firm, published, geochronometric evidence than this available at present. However, whatever the final solution to this problem in the La Barge area may be, it appears at present that in their northern parts the Darby thrust is geometrically and geographically separate from the Prospect thrust. Thus, their times of initial movement conform to the general rule that major overthrusts were progressively younger eastward.

9. The Game Hill thrust, at the western edge of the northern end of the Green River basin, is an east-dipping reverse fault or backthrust immediately adjacent to the eastern edge of the Overthrust belt. It is geographically separated by the Hoback basin from uplifts in the foreland to the east; for this reason we place it on Figure 2 in the column of Overthrust belt tectonic events. It cuts and overlies middle Late Paleocene (middle Tiffanian) mammal-bearing strata in the Hoback Formation east of Battle Mountain and west of Game Hill. East of Game Hill, at the junction of Dell Creek and the Hoback River, the steep dip of Tiffanian strata adjacent to the Game Hill thrust, is presumed to have resulted from tilting of the upthrown side of the fault. The relationships are shown and discussed by Dorr et al (1977a, map and cross sections in pocket). The Game Hill thrust had already formed and its upthrown side was present as a buttress before the Prospect (Cliff Creek) thrust moved. Therefore, the Game Hill thrust is post–late Tiffanian and pre-Prospect thrust (to be discussed), which dates it as Clarkforkian in age, like the Prospect thrust, but a little older than the latter.

Evidence that the Game Hill thrust created a preexisting buttress against which the Prospect thrust rode is twofold. Tear-fault offsets in the trace of the Prospect thrust are not cut by the Game Hill thrust where the traces of the two thrusts run together; the trace of the Game Hill thrust passes under the trace of the Prospect thrust without offsetting the latter, south of Sandy Marshall Creek (Dorr et al, 1977a, map). Secondly, in their study of paleomagnetism in Triassic red beds in the Overthrust belt, Grubbs and Van der Voo (1976) showed that the Triassic paleomagnetic declination in rocks of the Prospect thrust sheet has undergone an apparent clockwise rotation where the Prospect thrust collided with the upthrown side of the Game Hill thrust. Dorr (1952, 1958, 1978, for mammals) and Guennel, Spearing, and Dorr (1973, for pollen) also examined the dating of the sediments.

Farther to the south at La Barge, Wyoming, a similar, east-dipping fault, the Calpet thrust, was cut by the La Barge thrust. The Calpet thrust (not exposed, but known from well data) evidently preceded deposition of the Hoback Formation whereas the Game Hill thrust cut that formation (Blackstone, 1979, p. 24; Dorr and Gingerich, 1980, Fig. 3).

10. The Prospect thrust, next in the sequence, is perhaps the most closely bracketed of all. This thrust also has been called the Cliff Creek thrust in the Hoback basin area. Still farther north, near Jackson, Wyoming, its probable continuation northwestward into Idaho has been called the Jackson thrust. The Prospect thrust is best dated in its middle section, bounding the west side of the Hoback basin, at the northernmost end of the Green River basin. There, at Battle Mountain, it cut and overrode late Paleocene (middle Tiffanian) mammal-bearing beds of the Hoback Formation (Dorr, 1958; Dorr et al, 1977a, b). However, in that same area it also collided with the preexisting Game Hill thrust (see 9 above). Moreover, late-late Paleocene (late Tiffanian) mammal-bearing beds also are tilted at Dell Creek (Dorr, 1952, 1958, 1978). Therefore the Prospect thrust is post-Tiffanian here. Fifteen miles to the south the same thrust was overlapped by the Lookout Mountain Conglomerate which contains earliest Eocene (early Graybullian) mammals close to its base (Dorr and Steidtmann, 1977; Dorr et al, 1977a, pocket map and cross section). The time of Prospect thrust movement falls between those two bracketing dates, which puts it in the Paleocene-Eocene transition time known as the Clarkforkian in North American land-mammal-age nomenclature. There is still some question as to where the Clarkforkian in North America falls with respect to the Paleocene-Eocene boundary as defined in Europe. Nevertheless, in North America it is a clearly definable age between the Tiffanian and Wasatchian (Gingerich and Rose, 1977; Rose, 1979).

11. The La Barge thrust, which occurs farther to the south at La Barge, Wyoming, and is known only from subsurface data, moved eastward in the middle-early Eocene time; it deformed Graybullian—or at youngest, Lysitean—aged mammal-bearing strata of the upper part of the Chappo Member of the Wasatch Formation, and is overlapped by undeformed, late early Eocene (Lostcabinian age) strata of the La Barge Member of the Wasatch Formation (Dorr and Gingerich, 1980, p. 105, 109-111). The La Barge thrust is both the youngest and easternmost of the eastward moving major thrusts in the Overthrust belt sequence. Additional references are Gingerich and Dorr (1979) and Oriel (1961, 1962, 1969).

12. The Lookout Mountain thrust occurs north and south of the Upper Hoback River, west of the trace of the Prospect thrust. It is a subsequent imbricate splay from its parent Prospect thrust. It cut and deformed the mammal-bearing, early Eocene Lookout Mountain conglomerate, whereas the trace of its older parent, the Prospect thrust, previously had been overlapped by that same conglomerate. The relationships are shown and discussed in detail in Dorr and Steidtmann (1977) and Dorr et al (1977a); the age of the Lookout Mountain conglomerate mammals was most recently assessed in Dorr (1978).

Toward Jackson, Wyoming, at least two other similar thrusts, the Bear and Game thrusts, lie north and en echelon of the Lookout Mountain thrust. These two thrusts probably had a genesis similar to that of the Lookout Mountain thrust and thus are younger than the Prospect thrust, although neither can be dated closely by overlapping strata. The Bear thrust dies out southward into an overturned anticline south of where the Lookout Mountain thrust appears en echelon with it (Dorr et al, 1977a, map and cross sections; Royse et al, 1975, seismic cross sections).

There are several other similar imbricate splays within most of the major thrusts discussed above. However, none can be as precisely dated as the Lookout Mountain thrust, relative to its parent thrust movement. Other examples of imbricate splays, possibly or probably younger than their parent thrust, are the Fort Hill, Meridian, and Pine Ridge thrusts, west of the Darby (Hogsback) thrust in the Fort Hill Quadrangle (Oriel, 1969, p. 26-28, map and cross sections). Many imbricate splays are of relatively limited extent in a north-south direction parallel to the trace of the related principal thrust. Some, like the Bear thrust, die out into folds within the parent overthrust sheet. Armstrong (1968, p. 435) reviewed the mechanical reasons why folding, with subsequent failure into an axial-plane thrust within the major thrust plates of this region and elsewhere, could not have preceded major displacement of the parent thrusts. Thus most or all imbricate splays related to folds probably are younger than their parent thrusts, just as in the datable example where the Lookout Mountain thrust is younger but lies west of the Prospect thrust.

Thrust Kinematics

These dates on thrust motions show several broad patterns which, coupled with data on thrust sheet displacement, may be stated as kinematic "rules": (1) as has been known for a long time, the ages of thrusting generally decrease toward the craton (Armstrong and Oriel, 1965) (Fig. 3); (2) the restored spacing of major thrusts decreases toward the craton; (3) the amount of displacement on major thrusts decreases in this direction also; (4) the bracketing of thrust ages or apparent duration of motion becomes progressively tighter toward the craton (Fig. 4); (5) motion on the last thrust fault stops, or nearly so, before the next one moves, even though all previous thrust sheets move toward the craton with motion on the lowest (youngest) thrust fault surface.

These observations are not hard-and-fast in all places. For instance, there may be two reasons for the westward broadening of thrust age brackets. First, the preservation of good bracketing relationships becomes poorer toward the west. For example, although the Prospect thrust is well bracketed between 1 and 2 m.y., by its having cut the Hoback formation (age 58 to 57 m.y.) and having been overlapped by the Lookout Mountain conglomerate (age 56 m.y.), the Crawford-Meade thrust can be placed only with limited certainty at around 85 m.y. with production of the Echo Canyon Conglomerate. The youngest bed cut by the thrust may not be preserved or exposed. Likewise, the Eocene overlap of the Crawford-Meade is almost certainly too young to be important. Farther to the west, the Paris thrust has no significant overlapping sediment. Secondly, broader age brackets on progressively western thrusts may show that the times of movement were longer for thrusts which initiated earlier. We have remarked elsewhere that the Paris may have moved several times, shedding successively the Ephraim, Bechler, Thomas Fork, and Quealy Formations and the Coalville Conglomerate. This represents a remarkably long time of recurrent thrust motion—if true, about 50 m.y. At present, neither of these possibilities can be dismissed. The apparent lack of overlap in timing of major thrust faults may likewise reflect, in part, the lack of good bracketing dates in some places.

These data on displacement and timing allow one to attribute a velocity to each thrust sheet, subject to reservations stated previously. Because of the decreasing displacement and apparent decrease in duration of motion toward the craton, the velocities are similar. For the Prospect thrust, for example, the inferred average velocity is 1.0 cm/yr. (0.4 in./yr); that for the Absaroka is 0.2 cm/yr (0.08 in./yr). This range of velocities is similar to previous estimates of thrust velocities, although that for the Prospect is greater by a factor of 4 or 5. The Crawford and Paris are too poorly bracketed to yield important values, although the bounds have been indicated in Figure 4. These are average velocities and say nothing about the precise form of the displacement versus time curves for each thrust.

The Paris thrust is clearly anomalous in its documented displacement with respect to the trend of other major thrusts (Fig. 4). In the northern cross section of Royse et al (1975, their section XX′) (Fig. 1), on which these displacement numbers are based, one cannot match cutoffs across the Paris thrust. As a result, the displacement is known only to be 7 mi (11 km). However, farther south along their section YY′ (Fig. 1). the shortening on the Paris can be fixed at about 4 mi (6 km) although their section can be reinterpreted without violating either the seismic or surface data to allow for more shortening. This apparent small amount of shortening appears to contradict our tentative conclusion that the Paris thrust was responsible for large amounts of sediment over a long period of time. However, one can also argue that as the Paris brought Precambrian rock to the surface, a large component of displacement was vertical uplift. The angle of the ramp is almost lost now owing to a combination of later thrusting and extensional tectonics.

Although these dates for the major thrusts of the Overthrust belt answer many important questions, many are left unanswered. No thrust has been well dated at two localities. As a result, nothing is known about the propagation history of thrust traces or the possibility of diachronous motion of the same fault surface in two or more locations. Yet, the propagation of thrust sheets is responsible for the overall architecture of a thrust terrain. One of the writers (Wiltschko) has speculated that thrusts may localize at some basement warps or highs such as basement normal faults, or in the cores of preexisting folds, or at facies changes and subsequently propagate away from these "break points" along strike (Wiltschko and Eastman, in press). The first mechanism can be documented in the Overthrust belt. The Moxa arch is a broad basement warp, locally faulted on the west flank (Dixon, 1982), which trends north from the Utah border along the east flank of the thrust belt turning into it west of La Barge, Wyoming. Here, the trace of the Darby thrust, which trends generally north-south, turns abruptly eastward and trends about S70E for 19 mi (30 km) before resuming abruptly a north-south trend (Fig. 1). The trace of the Absaroka thrust fault, as well as the stratigraphy in both the Darby and Absaroka plates, show a similar change in trend, though less dramatically. In addition, the Darby thrust surface forms a ramp in this area, shallows beyond the top of the ramp (see Blackstone, 1979, section CC′), and is torn by the Thompson fault (Blackstone, 1979, Fig. 4). Finally, the Prospect thrust, which trends along the west flank of Hoback basin (Dorr et al, 1977a) and then past the southwest termination of the Tetons, appears from beneath the Darby thrust sheet in this locality. Blackstone (1979) infers that the Prospect thrust's southern termination lies about 6 mi (9 km) south of the east-west trend of the Darby thrust trace (Fig. 1). The close associa-

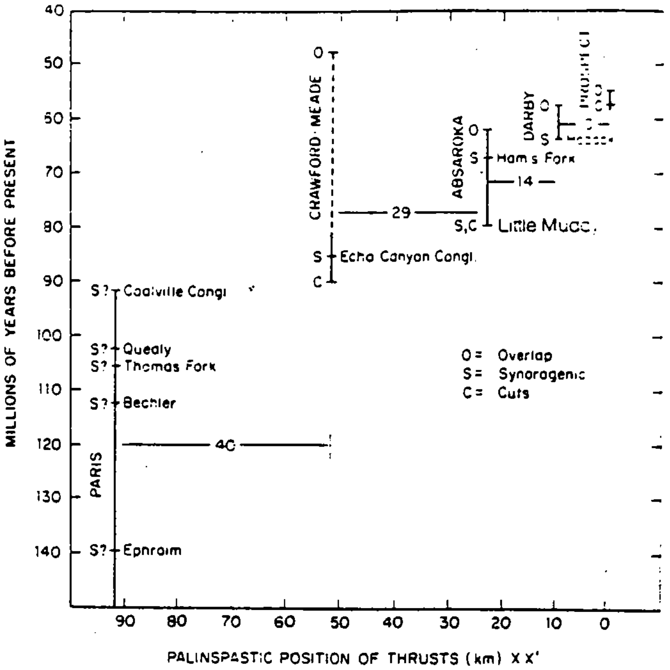

FIG. 3—Times of motion versus palinspastic position of major thrusts. Basis of dating motion is shown as overlap by younger beds (O), association with a synorogenic deposit (S) or crosscutting relationship (C). The palinspastic position is based on reconstruction of cross section XX′ of Royse et al (1975); see also Figure 1.

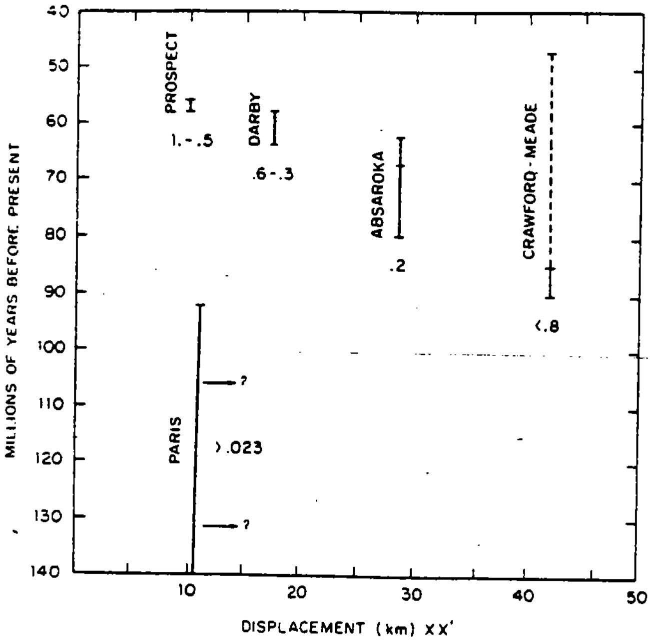

FIG. 4—Times of motion versus displacement of major thrusts. Shown below each bracket for times of motion are velocity constraints, in cm/yr for each thrust. Displacements are based on reconstruction of cross section XX′ of Royse et al (1975). Displacement on Paris thrust is a minimum estimate.

tion of structural changes—ramping, shallowing, tearing, and termination—in one or more thrust sheets is perhaps the most salient aspect of the geology of the central-western Wyoming thrust belt.

The photoelastic experiments of Wiltschko and Eastman (in press) show that an average stress concentration of about 1.5 occurs over such a basement arch, and that the principal stress directions are "deflected" toward the surface. The Moxa arch—and other localities of abrupt changes in curvature of basement—could have acted as places where thrusts localized.

To test these and other ideas of thrust propagation, precise dates at several places of the youngest rocks cut in the subsurface by thrusts are needed. Coupled with the assumption that thrusts cut up section into active basins, these dates should reflect closely the times of initiation of thrusting along strike.

Other Structural Features in Overthrust Belt

The foregoing analyses dealt only with major and reasonably well dated thrusts. Numerous others, as well as normal faults and folds, not depicted on Figure 2, are present in the Overthrust belt. For most of these there has been too little detailed, published information available from which to determine their structural relationships and ages. Now, however, the U.S. Geological Survey geologic maps and cross sections for the Fort Hill (Oriel, 1969), Afton (Rubey, 1973b), Sage and Kemmerer (Rubey, Oriel, and Tracey, 1975), and Cokeville (Rubey, Oriel, and Tracey, 1980) quadrangles provide remarkable detail on surface and subsurface geometrical relationships for many of these.

In our analyses of these data, strata that are shown on the cross sections to be cut, overridden, or folded by thrusts or normal faults were assumed to predate those structures. Rocks which at one time clearly would have lain with angular unconformity above fault traces or folded strata were assumed to postdate those structures even in places where, because of erosion, the younger, undeformed rocks no longer extend over the structures. Deformed and undeformed strata thus were treated as beginning and ending time-bracketing units. Normal faults which cut thrusts were dated as younger than those thrusts.

The time spans within which times of movement of the lesser thrusts and normal faults can be constrained are longer and less well established than for the major thrusts. Commonly, too, either a beginning or ending date cannot be established, so it can be determined only that the structure is before or after a certain time. Only the Prospect, Darby, and Absaroka (including Tunp) overthrust plates were considered. Numerous lesser thrusts and normal faults occur also in the hanging walls of the Crawford-Meade and Paris thrusts, but detailed structural cross sections for those areas have not yet been published so those structures are not included in the following analyses.

For minor thrusts, we found the following.

1. In the Prospect overthrust plate, the Lookout Mountain thrust has been definitely dated as younger than the Prospect thrust; the Bear and Game thrusts probably are younger as well (see earlier discussion).
2. In the Darby overthrust plate, the best available beginning and ending dates for the Pine Ridge, Meridian, and Fort Hill thrusts allow ambiguously long time spans within which those movements can be constrained—so long that the thrusts could have moved before, during or after the time of movement of the Darby (Hogsback) thrust to which they appear geometrically related. Moreover, their bracketed ages also embrace the times of movement of all the major thrusts in the region, Paris through La Barge, inclusive.
3. In the Absaroka overthrust plate, we found the following. (a) The South Fork and Porcupine Ridge thrusts are constrained only by beginning times, which fall after initial movement on the Paris thrust, and their ending times are not dated. Thus, it cannot be determined if they moved before or after the Absaroka thrust. The published cross sections do not show if they cut or merge into the Absaroka thrust at depth. (b) The Commissary and Beaver Creek thrusts appear to have moved before major movement on the Absaroka thrust, but the data do not prove if they moved before or after initial movement on that thrust. They are, however, constrained to times after initial movement on the Paris thrust and before the major Absaroka, Darby, Prospect, and La Barge thrust movements. They are imbricate splays off the Absaroka thrust. (c) The Tunp thrust trace appears on published maps between those of the Crawford-Meade on the west and Absaroka on the east. Published data do not show how the Tunp thrust relates to the Absaroka and Crawford thrusts at depth. Time constraints are sufficiently ambiguous to allow movement on the Tunp thrust to fall anywhere from before the Crawford-Meade (but after initial Paris) to a

time contemporaneous with major movement on the Absaroka thrust. All times of thrust movements subsequent to major Absaroka are excluded from the allowable time span for the Tunp thrust movement. (d) The Stoffer Ridge thrust trace lies within the Tunp thrust plate, between the traces of the Tunp thrust on the east and the Crawford-Meade on the west. Constraints on its time of movement are too ambiguous to exclude the times of movement of any major thrusts except those of Paris.

In summary, only the Lookout Mountain thrust can be shown by stratigraphic-paleontologic dating definitely to have moved after movement on its parent (Prospect). Dates for all the others are ambiguous enough in that regard to allow for movements before, during, or after their apparent geometric parents, or any one or more of the other major thrusts in the region. Therefore, age relationships to parent thrusts are indeterminate for most.

Few of the many normal faults which occur within the Overthrust belt can be narrowly dated, although some can be shown to cut and therefore postdate certain thrusts. A few are listric normal faults on which movement occurred along a reactivated part of an earlier thrust plane, but in the opposite direction. A well-documented and dated fault of this type (but not shown in the quadrangles mentioned) is the Hoback fault at the southernmost end of Jackson Hole (Dorr et al, 1977a; Royse et al, 1975). It is similar to, but smaller than, the Star Valley and Grand Valley faults in the Absaroka plate. The Hoback fault began to move in the late Miocene or early Pliocene. It moved along a reactivated portion of the common plane of the Bear and Prospect (Cliff Creek) thrusts. Seismic profiles have shown (Royse et al, 1975) that the Bear thrust is a subsidiary slice within the Prospect overthrust sheet. The Hoback fault cuts down through the Bear thrust plate, joins the Bear thrust plane where the latter ramps up from the Prospect thrust, and continues down along the Bear thrust plane into the Prospect thrust plane (Dorr et al, 1977a, Fig. 18; Royse et al, 1975). The Hoback fault shed the Camp Davis Formation, the lower part of which is dated as late Miocene or early Pliocene by a fossil horse tooth (Dorr et al, 1977a, p. 34-38). The Stoffer Ridge and Muddy Ridge faults in the Cokeville Quadrangle are other examples of listric normal reversal of movement along earlier thrust planes.

As noted by Armstrong and Oriel (1965, p. 1862-1863), these normal faults have a wide range in age. Those authors concluded that the normal faults all moved after overthrusting had ceased, but that some were as old as Oligocene (post-Eocene and pre-Miocene–Pliocene). However, fewer than one-third of the normal faults can be bracketed by both beginning and ending dates. Stratigraphic units, whether affected or not, provide most of the beginning and ending dates. Some exceptions, where the method of stratigraphic bracketing was modified, were those normal faults which are shown by surface mapping to cut the surface traces of major, well dated thrusts. In those instances, the beginning time for the normal fault was taken to be no older than the age of the thrust which was cut. In most places the normal faults cannot be directly correlated with well-dated, derivative, clastic deposits. The exceptions are the Hoback fault, and two faults which first produced and later were overlapped by the Salt Lake Formation in the Afton and Sage-Kemmerer Quadrangles. Those three faults can be placed in the Miocene-Pliocene.

Many of the allowable time spans for normal faults could be shortened considerably if the following dating method were accepted. All the normal faults cut folds in the overthrust sheets. The fact that the normal fault traces do not appear to be folded indicates that the normal faults postdate the folds. In one class of normal faults, the cross sections suggest that the folds began to form before the thrusts and subsequently were cut and displaced by the thrusts. For these situations, the folds being older than the thrusts could have been normal faulted before thrusting. Although this is improbable it is not impossible; for these the dating problem cannot be resolved. However, in a second class of normal faults the thrust plane is shown to be folded conformably with the strata in the hanging wall above the thrust plane. In this class, the folds are younger than the thrusts so the normal faults which offset the folds must also be younger. If this is so, then the times of movement of the normal faults in the second class fall after the dated time of movement of the major thrust plate. In our analyses, the beginning times of normal faults were not calculated according to this principle because we were not certain the data (from wells and seismic profiles) used in construction of the cross sections were sufficient to prove these relationships. If a reader wishes to accept the cross sections at their face value, analyses can be modified accordingly by moving the beginning dates for the allowable time spans for each normal fault of the second class up past the time of movement of the major overthrust plate within which the normal fault occurs. However, if this were done, then it would become circularly illogical to conclude that all normal faults occurred after thrusting had ceased because, a priori, some normal faulting would have been dated as post-thrusting. Contrarily, if any folds are older than the thrust plates within which they occur, then some normal faults which cut such folds also could be older than those thrusts.

Despite all these difficulties, the data are sufficient to support the following conclusions regarding the movement times of normal faults in the quadrangles considered:

1. With one possible exception, all the normal faults considered could be younger than the youngest (La Barge) well-dated overthrust. The data allowed this because of the uncertainty of the ending dates for most of the normal faults. The possible exception is a normal fault east of Slate Creek Ridge, in the southwestern corner of the Fort Hill Quadrangle. Oriel (1969, cross section G) shows this fault offsetting, and therefore post-dating, the Darby (Hogsback) thrust and overlapped by the Conglomerate Member of the Wasatch Formation. In the stratigraphic system used by Oriel in his cross sections, that conglomerate was correlated with the La Barge member of the Wasatch Formation. The La Barge thrust was overlapped by the La Barge Member (Dorr and Gingerich, 1980). Therefore, the fault along Slate Creek Ridge and the La Barge thrust both are shown to have been overlapped by Tertiary deposits of the same age. The normal fault, there-

fore, could be dated as having formed during, shortly before, or after movement on that youngest thrust. This ambiguity is even more equivocal than it seems, however, because the Wasatch Formation also contains basin-margin conglomerates which are younger than the La Barge Member. Oriel's (1969) correlation of the conglomerate, which overlaps the fault at Slate Creek Ridge with the La Barge Member, is not supported by a paleontologic date for the conglomerate. Therefore, it is possible that the normal fault was overlapped by a younger conglomerate than that which overlapped the thrust; consequently, the normal fault could be younger. This problem cannot be resolved at present.

2. About one-half of the normal faults have beginning dates which definitely limit their time of movement to after movement on the last (La Barge) thrust.

3. Because most of the normal faults lack ending dates, all but two could be young enough to fall within the mid-Cenozoic to Holocene (17 m.y. or less) episode of "basin and range" faulting as discussed by Stewart (1971, p. 1019, 1038), but at least two moved before or during the middle early Eocene. This conclusion would not change if all normal faults were dated, a priori, as post-thrusting.

4. It follows from 3 that although some tensional faulting may have begun early, at or shortly after the end of compressional thrusting, most of it could have, or in fact did, begin long afterward.

Events in Foreland

Certain tectonic events produced uplifts, with resultant high-standing Precambrian basement, along the southwestern edge of what we regard as the foreland (see footnote 3) east of the Overthrust belt. These constituted arches or buttresses, over or against which certain of the later, eastwardly moving overthrusts rode, thus controlling the late development of the thrust belt. One of these features, the Moxa arch, lies along the western edge of the Green River basin. It is questionably placed within the foreland structural class on Figure 2. Seismic evidence (Dixon, 1982) shows that the west flank of the arch is faulted. The fault predates the Absaroka thrust (Dixon, personal commun.). The remaining foreland uplifts lie along the structural axis which trends northwestward through the Wind River and Gros Ventre Ranges and beyond, to form the northeastern structural boundary of the Green River basin; these clearly belong in the foreland set. These features developed in an area which throughout the Paleozoic and early Mesozoic lay along or northeast of the sedimentary hinge line between miogeosyncline and shelf. Therefore, this part of the foreland is an area in which sedimentary deposits of those ages become 75% or more thinner than their miogeosynclinal temporal equivalents to the west, where the structures of the Overthrust belt later developed. A review of these relationships was presented by Armstrong and Oriel (1965, p. 1849-56) and will not be repeated here. However, it should be emphasized that prior to overthrusting from the west, the Precambrian basement stood higher in the foreland than in the miogeosyncline (future Overthrust belt), rising eastward to the hinge line between those two areas. This was the case even before substantial Laramide uplifts raised parts of the foreland farther to produce significant arches and buttresses which the subsequent thrusts ramped over or impinged upon from the west. The sequence of foreland events discussed below is summarized from papers by Dorr et al (1977a, b) and Dorr (1981), except as otherwise noted.

The orientation of uplift axes and thrust traces in the foreland is roughly northwest-southeast. This is in contrast to the orientation of overthrust traces and fold axes in the Overthrust belt, which trend north-south except on the north where structures in those two provinces converge. This convergence and impingement had important mechanical effects which we discuss later.

The sequence of events in the foreland was as follows (numbers keyed to Figure 2).

1. Tectonism in the foreland region was initiated, possibly as early as the middle-Late Cretaceous (Coniacian) by uplift west of Yellowstone Park and possibly to the west and/or northwest of the modern Teton Range, in southwestern Montana, northeastern Idaho, and northwestern Wyoming. The area of uplift constituted a source area for coarse clastics, and remained high-standing through the latest Cretaceous into the middle Paleocene time. Evidence for time of initiation of this uplift is the appearance of late Precambrian (Beltian) metaquartzite roundstones, first in small quantities near the top of the Bacon Ridge Sandstone of Coniacian age, later (middle to late Campanian) in the Beaverhead Conglomerate of southwestern Montana, and still later and in great quantities in the Harebell Formation (Maestrichtian, dinosaur-bearing) and Pinyon Conglomerate (latest Cretaceous to middle Paleocene, mammal-bearing) in the Jackson Hole, Mt. Leidy Highland, and northern Wind River basin areas. Love (1973) and Love et al (1973) called this the Targhee uplift, and by inference placed it west or northwest of the modern Teton Range, in an area now covered primarily by volcanic rocks of the Snake River downwarp. McGookey (1972, p. 223) identified the source area for much of the conglomerate as the Blacktail-Snowcrest uplift in southwestern Montana which rose in middle to late Campanian time and shed the Beaverhead Conglomerate. Lindsey (1969) also placed the source area in southwestern Montana and attributed the Harebell and Pinyon conglomerates to reworking and farther southeastward transportation of the Beaverhead Conglomerate. Wherever the uplifted source area may have been located, note that although this uplift occurred after the initial and possibly renewed movements of the Paris thrust, the first evidence for it is approximately contemporaneous with the initial movement of the Crawford-Meade thrust system; thereafter, events in the Overthrust belt and the foreland overlapped through time.

2. The Moxa arch appears at the northern boundary of the Uinta Range, its axis trending northward from there along the western edge of the Green River basin to just north of La Barge, Wyoming; there it curves northwestward to pass beneath the upper plates of the Darby (Hogsback) and Prospect thrusts at the northern end of Hogsback Ridge and Snider basin (Blackstone, 1979, 1980, 1981). According to Royse et al (1975), the arch con-

tinues in the subsurface beneath those thrusts for some distance to the northwest. Thomaides (1973) and Wach (1977) have shown that the upper part of the Hilliard Formation (Santonian) and older rocks were truncated by erosion across this arch, but that the arch was unconformably overlapped by the Ericson (Mesaverde, Campanian) Formation. Although there may have been earlier, minor uplifts of the arch, this puts the time of major arching at the Santonian-Campanian boundary, or in early Campanian (Fig. 2), antedating major movement of the Absaroka thrust and later movements of the Darby, Prospect, and La Barge thrusts.

3. In the Late Cretaceous (middle Campanian and Maestrichtian), uplift along the edge of the Foreland produced the ancestral Teton-Gros Ventre-Wind River uplift. Note the use of "ancestral," because the modern Teton Range, a normal fault block, did not begin to rise until late Pliocene; the Gros Ventre Range did not begin to form as a separate structurally entity until late Paleocene; and substantial movement on the Wind River thrust also occurred later, in middle-early Eocene (Fig. 2). The adjacent Wind River basin on the northeast, and Green River basin on the southwest subsided rapidly as this ancestral uplift rose (Keefer, 1970, p. 1-2, 10). Partial evidence for location and time of this uplift is that its presence is required to explain that southeastwardly transported Precambrian metaquartzite roundstones, from the Targhee and/or Blacktail-Snowcrest uplifts to the northwest, were excluded from entry into the northern Green River basin. This occurred at a time when they were contributing greatly to the Harebell Formation and Pinyon Conglomerate in the closely adjacent Jackson Hole-Mt. Leidy highland-northern Wind River basin area of deposition and elsewhere to the north and northeast of the Green River basin (Dorr et al, 1977a, b; Love et al, 1973; item 1, above). This uplift led to erosional unroofing of the Wind River Range area, down to the Precambrian rocks, and filling of the adjacent Wind River and Green River basins with thick deposits including the latest Cretaceous Lance and the Paleocene Fort Union and Hoback Formations. Minor early movements on the Wind River thrust may also have been involved in this uplift, although major movement on that thrust occurred in the early Eocene (Fig. 2; item 5, below).

4. Next in the Foreland, the Gros Ventre Range was markedly and independently uplifted, shedding the Skyline Trail Conglomerate southwestward into the margin of the Hoback basin where it intertongued with the Hoback Formation. The time of uplift is determined by the age of the conglomerate which has been relatively dated. Late Paleocene snails occur below the conglomerate, but the conglomerate was deformed and overridden by the Prospect thrust during the Clarkforkian. Thus, the uplift, which may or may not have involved early movement on the Cache thrust, is late Paleocene in age (Dorr et al, 1977a, pocket chart, text).

5. In middle-early Eocene, the Cache and Wind River thrusts moved southwestward. The Cache thrust cut the Skyline Trail Conglomerate (item 4, above) and the resulting uplift shed the Pass Peak Formation (middle to late Wasatchian) which overlapped the thrust trace. Along the structural front of the Gros Ventre Range, immediately adjacent to the Cache thrust, the Pass Peak Formation is diamictitic. The Wind River thrust simultaneously shed the "early Eocene arkose" southwestward into the northern Green River basin where it interfingered with middle and late early Eocene mammal-bearing beds of the Pass Peak Formation. Both thrusts cut, overrode, and

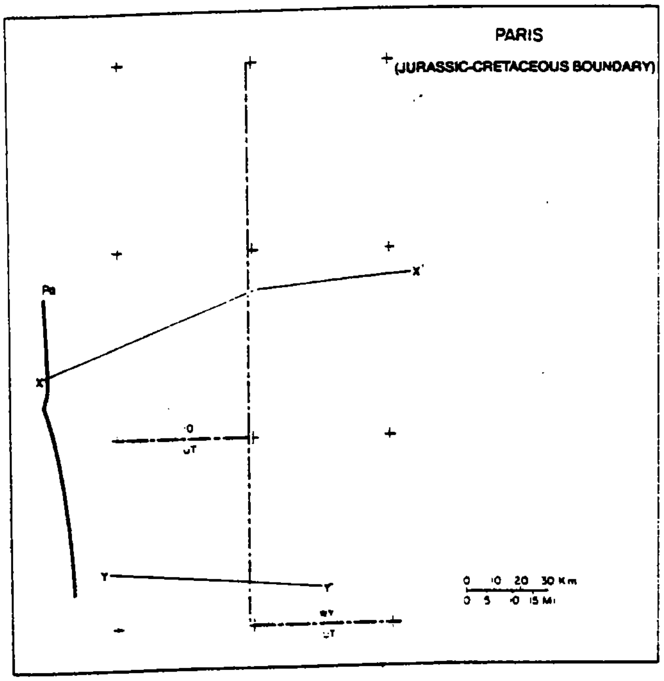

FIG. 5—Reconstruction of western Overthrust belt during Paris thrust time.

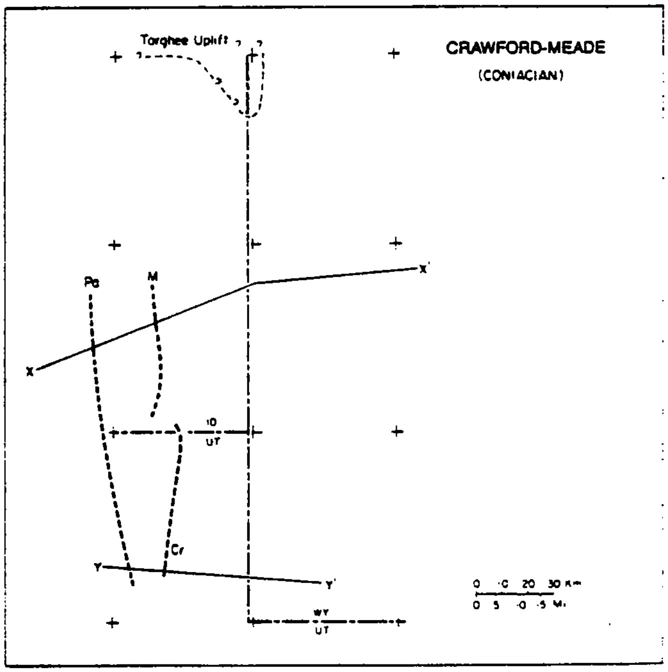

FIG. 6—Reconstruction of western Overthrust belt during Crawford-Meade thrust system time.

deformed the Paleocene Hoback Formation but did not deform the Pass Peak Formation (Dorr et al, 1977a, text, pocket map and chart, p. 47; Dorr, 1969, 1978; Steidtmann, 1969, 1971). Therefore, the time of thrusting can be dated in two ways: first, by the age of the derived Pass Peak Formation; second, by the fact that along the trace of the Cache thrust, in the upper Dell Creek area of the Hoback basin, the deformed Hoback Formation lies with angular unconformity beneath the Pass Peak Formation.

6. The last distinguishable and datable early Cenozoic event in the foreland occurred in late early Eocene or shortly after, when minor uplift of the southern end of the Gros Ventre Range locally deformed the Pass Peak Formation, the upper part of which is dated late early Eocene on the basis of mammals (Dorr, 1969, 1978; Dorr et al, 1977a, b; Steidtmann, 1969, 1971). This was the last of three independent tectonic movements of the Gros Ventre Range. At least the middle one involved movement on the Cache thrust. The last may have occurred along minor, subsidiary faults stemming from the thrust (Dorr et al, 1977a, p. 46). The last movement, which was relatively minor, occurred after early Eocene time, although it is not bracketed at the late end by any undeformed, overlapping strata older than Pleistocene; the exact time of movement is ambiguous.

Uplifts of the foreland had an important effect on the thrust belt. As early as the study of Horberg et al (1949), it was recognized that complexity of the thrust belt increases near the Gros Ventre Mountains. Mapping by Dorr et al (1977a) showed that the Prospect thrust, where it is closest to the Game Hill fault and Gros Ventre Range, is torn, complexly faulted, folded, and in places brecciated. The foreland provided a buttress which blocked thrust motion. Grubbs and Van der Voo (1976) show further that in the northern Overthrust belt the thrust sheets closest to the foreland have rotated, perhaps as much as 70°. These rotations are counterclockwise where the frontal thrusts trend northwest-southeast but are clockwise where the thrusts turn southward (Fig. 1). The rotations also decrease away from the foreland. Clearly, the deformation was not confined to cross sections that trend across the strike of the thrust belt. As a result, cross sections drawn through this portion of the thrust belt must consider the third dimension.

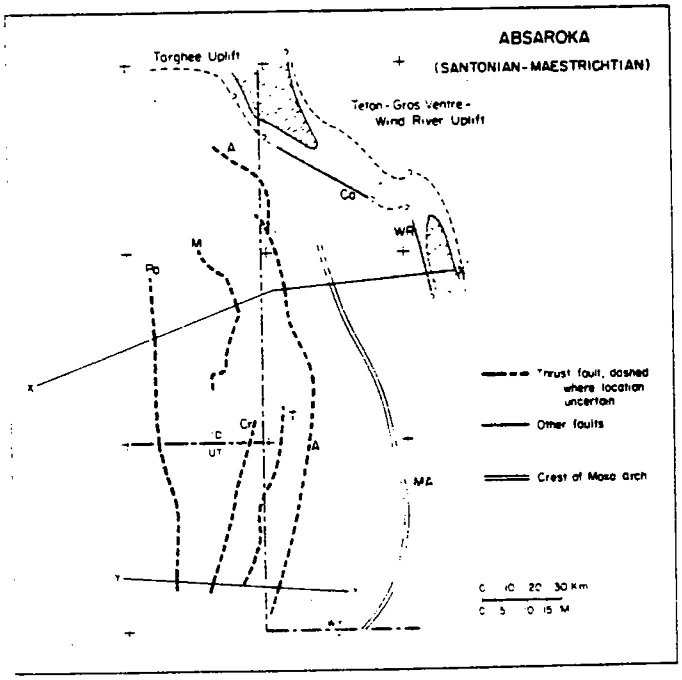

FIG. 7—Reconstruction of western Overthrust belt during Absaroka thrust time.

RECONSTRUCTIONS

Figures 5 through 9 show our reconstructions of events in the foreland and Overthrust belt from the time of initiation of the Paris thrust onward. Data for these figures come from several sources. The dating evidence as well as the kinematic implications for the major thrusts and other structures has been presented. The positions of the major thrusts are based on our restoration of the seismically controlled regional cross sections of Royse et al (1975, Plates 1, 2; their Fig. 1), including both thrust displacement and large-scale fold shortening. Shortening due to body deformation such as solution cleavage, and small-scale folding and faulting has not been included because these, with a few exceptions, have not been mapped in the thrust belt. The geographic base in all of these figures is present political boundaries, drawn as if etched on post-thrusting basement.

Paris (Jurassic-Cretaceous Boundary)

The Paris thrust had begun by latest Jurassic–earliest Cretaceous about 60 mi (100 km) west of its present position along the latitude of Afton, Wyoming (Figs. 1, 5). Evidence for initial movement is age of the westward-thickening of the Ephraim Conglomerate. Recurrent motion over 50 m.y. may be recorded by other units (Bechler, Thomas Fork, and Quealy Formations and Coalville Conglomerate). If so, the Paris thrust has the longest history of movement, the smallest amount of horizontal displacement, and the largest associated amount of erosional products. To explain the small displacement yet large sediment production, it may be necessary to postulate a steep ramp along which most of the displacement was due to uplift, possibly in part due to geometries imposed by miogeosynclinal thickening.

Crawford-Meade (Coniacian)

During this time the Crawford-Meade system (Fig. 6) ramped to the surface as evidenced by the Echo Canyon Conglomerate. As a result of movement on the Crawford-Meade, the Paris thrust ramp was moved between 26 and 22 mi (42 and 35 km) to the east. The Targhee uplift had begun to form at this time, its existence inferred from the presence of Precambrian metaquartzite cobbles in the Coniacian Bacon Ridge Sandstone.

The Crawford-Meade system may herald a change in mechanics of the thrust belt. The Crawford-Meade, on present evidence, did not move until the Paris thrust's long movement history had ended. Therefore, it is tempting to postulate that for some reason the Paris thrust fault reached a point where it could not accommodate further displacement and therefore the displacement was transferred to a new thrust surface.

Absaroka (Santonian-Maestrichtian)

The Absaroka thrust was the next major thrust in the sequence, forming closer to the Crawford-Meade than the latter did to the Paris (Fig. 7). It did not overlap in time with the Crawford-Meade. Further, it did not move for as long a time and did not move as far. The Moxa arch (and associated faulting) had formed by the time the Absaroka thrust moved and may have had an effect on the Absaroka plate west of La Barge, Wyoming. In the foreland, the ancestral Teton–Gros Ventre and Wind River uplift had risen. The Paris and Crawford-Meade ramps were moved between 29 km (18 mi) (along XX′, Fig. 1) and 19 km (12 mi) (YY′) eastward as a result of motion on the Absaroka thrust.

Darby (Mid-Paleocene)

Influenced by the Moxa arch and perhaps the Targhee uplift, the Darby thrust formed next (Fig. 8). Where the Darby and Moxa arch meet, the Darby thrust shallows, its trace turns abruptly eastward, and it is torn. The Darby thrust most probably began to rotate counterclockwise to impinge with the Targhee uplift to the north and ancestral Teton–Gros Ventre uplift to the northeast. Although the timing of the rotations is known no more precisely than post-Triassic (Grubbs and Van der Voo, 1976), it is probable that the parts of the Darby thrust that have rotated did so in part when the thrust was active. Therefore, we choose to attribute some of the Darby plate rotation to the time of motion of that plate. The remainder of the rotation would occur by "piggy-back" rotation of the Darby thrust on the Prospect thrust.

The Darby thrust continues the trend of moving less, over a shorter period of time and forming closer to the Absaroka than the latter did to the Crawford-Meade. The velocity of movement of the Darby thrust is of the same order as the Absaroka, however. Following earlier speculation, the Darby thrust zone may have strengthened more quickly than that of the Absaroka, resulting in a more expeditious transfer of displacement to the next most cratonward thrust.

Prospect (Paleocene-Eocene Boundary)

The Prospect thrust was the last major thrust to form in the thrust belt (Fig. 9). In addition, it is the thrust most affected by the foreland. In the northern Overthrust belt, its motion was apparently accompanied by perhaps as much as 70° of counterclockwise rotation into the ancestral Teton–Gros Ventre trend and as much as 35° clockwise into the Game Hill thrust (Fig. 1). The Gros Ventre Range had been uplifted as an independent block just before this time, shedding the Skyline Trail Conglomerate which the Prospect thrust subsequently deformed. The nature of the link between the Gros Ventre Range and the area of the ancestral Teton Range to the northwest is not well understood. The Game Hill thrust, a west-verging thrust fault had likewise formed before the Prospect thrust arrived, and it was overridden by the Prospect. Farther south, the Prospect thrust terminates where the Moxa arch impinges on the thrust belt.

The Prospect thrust moved the least distance (10 km, 6 mi) over the shortest period of time (1 to 2 m.y.) of all the

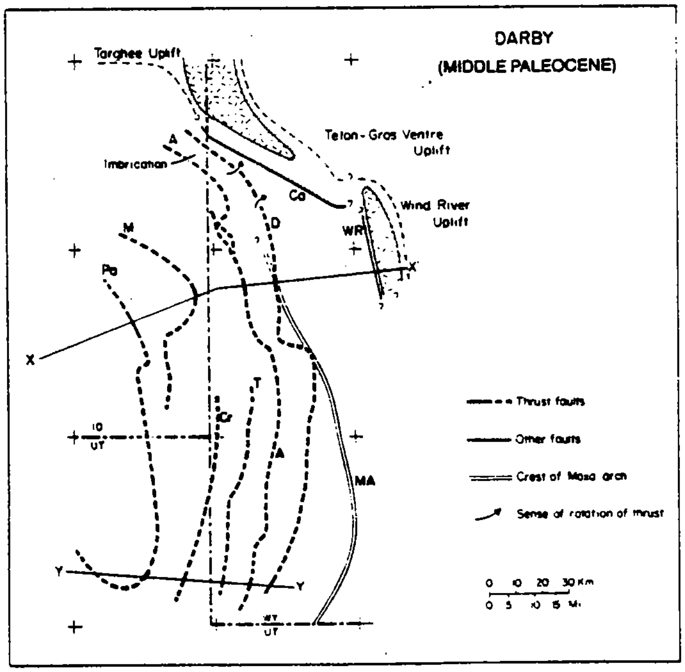

FIG. 8—Reconstruction of western Overthrust belt during Darby thrust time.

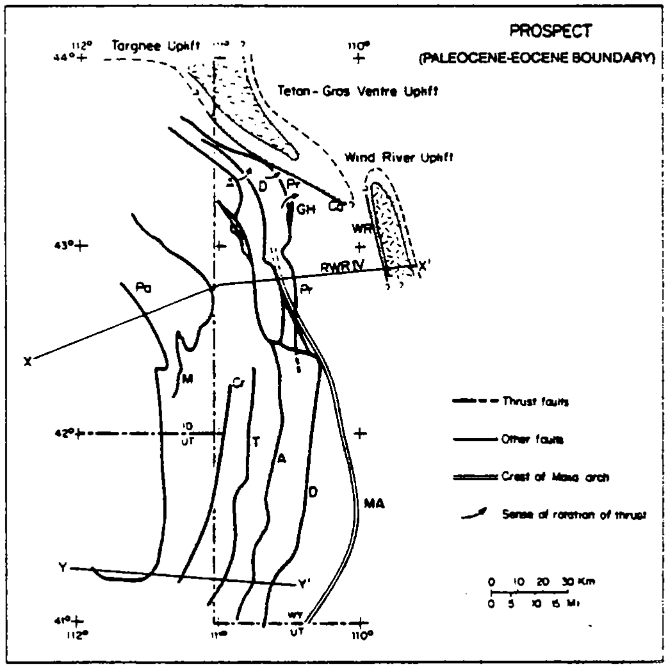

FIG. 9—Reconstruction of western Overthrust belt during Prospect thrust time.

major thrust sheets. It is also the most conclusively dated. Although there are thrusts farther east of the Prospect in the subsurface (e.g., the La Barge thrust), they are minor in extent and throw.

After the thrusting had ceased, at the end of early Eocene, the Green River basin and presumably much of the thrust belt were nearly completely buried. The level of the fill is now represented by the vestiges of a pediment called the Sub-Summit Surface, high on the Wind River Range (Dorr et al, 1977a). Post-Pliocene uplift and exhumation account for the present spectacular relief.

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