CONTINENTAL SUBDUCTION IN THE NORTHERN U.S. ROCKIES — A MODEL FOR BACK-ARC THRUSTING IN THE WESTERN CORDILLERA

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ABSTRACT

Back-arc thrusts such as those of the western Cordillera are difficult to explain mechanically as overthrusts resulting directly from oceanic subduction, which would require transmission of tectonic stress through the weak magmatic core of the orogen. Also, increasing of basement rooting of major thrusts requires a reassessment of models of gravitational tectonics by spreading or gliding.

A model of westward subduction of the relatively heavy continental lithosphere beneath the geoclinal edge of the continent eliminates the problem of stress transmission. Eastward migration of underthrusts occurs both through the basement and along supracrustal decollement surfaces. The developing thrust belt inherits ancient transverse faults in the continental crust as well as the arcuate outlines of the old geoclinal hinge. In southwestern Montana paired thrust belts reflect paired Paleozoic hinges. Tectonic and topographic highlands in the rear of the thrust belt, to which widespread synorogenic conglomerates bear testimony, result from great uplift due to the buoyance of subducted crustal slices that became decoupled from the sinking upper mantle in the hot core of the orogen.

The petroleum potential of the foreland thrust belt in southwest Montana, and perhaps elsewhere as well, must be evaluated in terms of basement rooting of at least some of the thrusts and of significant changes in facies and structural patterns across east-west faults.

INTRODUCTION

The kinematics and dynamics of large scale "foreland" or "back-arc" overthrusting have long constituted a major problem in geotectonics. In the years preceding and shortly after World War II such thrust belts were variously seen as a by-product of (1) continental collision and underthrusting (Argand, 1924; Kober, 1923), or a related concept referred to as "Unterstromung" or underflow in the European literature (Ampferer, 1923, 1924; Kraus, 1951); (2) the final collapse of elongate crustal downbuckles or "tectogenes" (Vening Meinesz, 1933; Griggs, 1939; Umbgrove, 1947); or (3) gravitational tectonics, either by shallow gliding (Gignoux, 1948, 1950; Tercier, 1950; de Sitter, 1950) or deep mass readjustments (van Bemmelen, 1932, 1933a, 1933b).

With the advent of modern global tectonics it became possible to reassess thrust belts in terms of horizontal plate motions. Thus, continent-directed thrusting in the Tethys belt could again be understood as a product of continental collision, much as it was in the heyday of continental drift, and recognition of pre-Mesozoic plate motions made it possible to apply this model to other orogens as well, including the Alleghanian and Hercynian in North American and Eurafrica. For asymmetric situations in which a contnental mass is lacking on one side of the orogen, as in the case of the circum-Pacific belt, the new models returned to the notion of oceanic underthrusting once advocated by Umbgrove (1947) and now placed in the context of ocean spreading and subduction. This accounts well for ocean-directed thrusts on the oceanic side of the mobile magmatic arc, while the related concept of obduction can explain continent-directed thrusts involving oceanic rocks. What remained problematic, however, was the genesis of continent-directed thrust belts in the back-arc environment. Their position inland from structurally weak magmatic arcs (Fig. 1) makes it difficult to see these belts as still another product of ocean plate subduction , especially where distance from the continental edge amounts to hundreds of kilometers. The Cordilleran foreland thrust belt of western North America is a case in point. The general problem is here considered with this belt, and in particular its Montana-Idaho segment, as a test case.

BACKGROUND

More than 30 years ago, Eardley (1951, p. 311, 315, Fig. 176) pointed out that the eastern Cordilleran thrust front between Nevada and Alaska follows in a general way two great arcs with eastward convexity (Fig. 2). Elaborating on this observation and taking note of the spatial relation between the frontal thrust zone and the eastern hinge of the Proterozoic to Paleozoic geosyncline, I proposed a genetic model involving progressive underthrusting of a westward drifting North American craton beneath the eastern basement flank of the Cordilleran geosyncline (Scholten, 1956, 1957). Consideration of the problem of the transmission of forces led Misch (1960) to strong advocacy of the concept of continental underthrusting. In Canada, this concept was suggested by Bally, Gordy and Stewart (1966), who presented seismic evidence that the foreland thrusts are confined to the sedimentary strata of Proterozoic and younger age.

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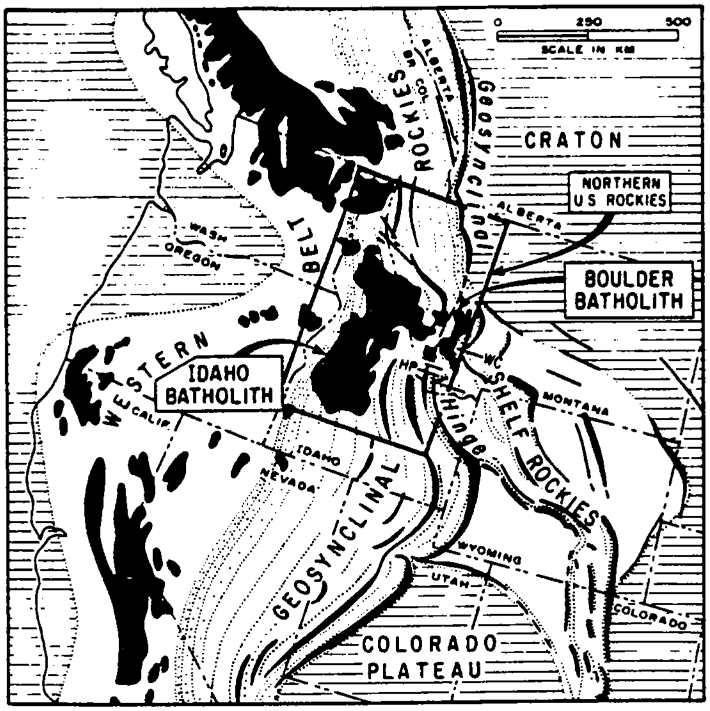

Figure 1. Tectonic map of the western Cordillera, showing deformed western belt and eastern "geosynclinal Rockies", separated from craton and "shelf Rockies" by geosynclinal hinge zone. Dotted and bold lines indicate structural trends (fold patterns and major thrust zones). Batholiths shown in black. Note some of the transverse faults in S.W. Montana (WC = Willow Creek fault zone; HP = Horse Prairie fault zone). Adapted from Eardley (1962, Fig. 21.1).

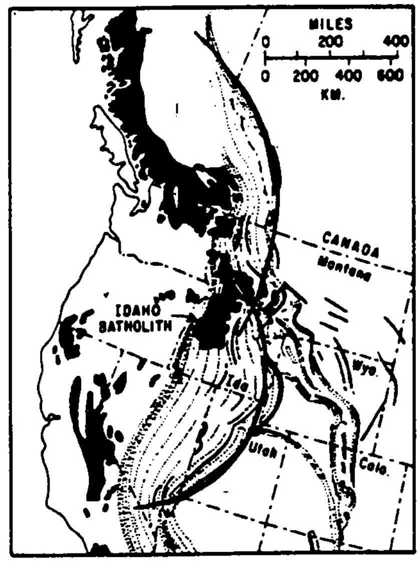

Figure 2. Double arcuate outline of back-arc (foreland) thrust front of the western Cordillera. Note spatial relation of the Idaho batholith and the transverse faults shown in Figure 1 to the arc intersection.

By contrast, Price and Mountjoy (1970; Price, 1973) argued in favor of a genesis by lateral gravitational spreading away from the high central mobile core west of the Canadian foreland thrust belt. The spreading model was supported by Elliot 1976a, 1976b) who placed it on a basis of quantitative mechanics. Hubbert and Rubey (1959; Rubey and Hubbert,1959), on the other hand, suggested a process of downslope gliding as at least a partial solution to the mechanical problem presented by major overthrusts. In both the spreading and gliding models the problem is circumvented or reduced through the application of the gravitational body force.

As to the specific region east of the Idaho batholith, I came to believe that the crystalline rocks exposed in the southwest Montana sector of the thrust belt were emplaced by high-angle upthrusts rather than low-angle overthrusts. Documentation of abnormal internal complexity of the thrust sheets and of an exceptionally high mid-Cretaceous uplift of Proterozoic rocks in central Idaho led to a model of gravitational gliding down the east flank of the uplift (Scholten, 1968, 1973; Ryder and Scholten, 1973). The 15-20km uplift was thought to have been caused by a combination of crustal thickening, thermal expansion and phase changes, laccolithic doming, and isostatic rebound upon erosion. In passing, plate underthrusting was suggested as the deep-seated ultimate process that triggered this unwinding sequence of shallowner mass displacements, leading to eventual re-establishment of gravitative equilibrium.

Farther south in the Cordilleran thrust belt, gravitational tectonics was invoked in models presented by Crosby (1968), Roberts and Crittenden (1973) and Hose and Danes (1973). Other writers followed Misch (1960) in viewing continental underthrusting as the direct cause of the Cordilleran thrust belt (Burchfiel and Davis, 1972, 1975; Coney, 1972, 1973; Dickinson, 1976; Lowell, 1977; Blackstone, 1977).

In recent years, attention has again been drawn to the presence of basement rocks in low-angle back-arc thrust sheets in the southern, central, and northern Rockies. Also, transverse fault zones segmenting the thrust belt have lately come to be recognized as a significant structural element controlling the development of the thrusts. This information is discussed below. It invites a reassessment of the notions of tectogenesis by rooted overthrusting, crustal underthrusting, or gravity as presented in earlier models. Such a reassessment is the purpose of this paper. It brings into focus the process of continental subduction as the fundamental lithospheric mechanism responsible for back-arc thrusting.

BASEMENT THRUSTS

In the northern U.S. Rockies the foreland thrust belt emerges with a NNW trend from beneath the thick and extensive cover of late Cenozoic volcanics in the eastern Snake River plain. In extreme SW Montana the thrust belt bifurcates into a western zone, which passes with a northerly trend between the Idaho and Boulder batholiths (Fig. 1), bounding the Sapphire thrust plate, and an eastern zone, whose trend veers to the northeast. In the region where the bifurcation occurs, crystalline (Precambrian X) basement rocks are exposed along NNW to N trending thrusts in the Tendoy and Beaverhead ranges (Fig. 3). The basement faults in the Tendoy Range were considered to be low-angle overthrusts by Kupsch (1950) and Scholten (1950: Scholten, Keenmon and Jupsch, 1955), but were later thought of as steep upthrusts (Scholten, 1973). Recent detailed work by Dubois (1981a, 1981b; this volume) has conclusively demonstrated that the basement blocks in the northern Tendoy Range are bounded by low-to medium-angle thrusts, and in places occur as klippen resting on Devonian sediments (Fig. 3). These faults are interpreted as disjointed parts or imbrications of a single folded basement ovethrust whose trace in the northern Tendoys follows the looping pattern shown on the simplified map

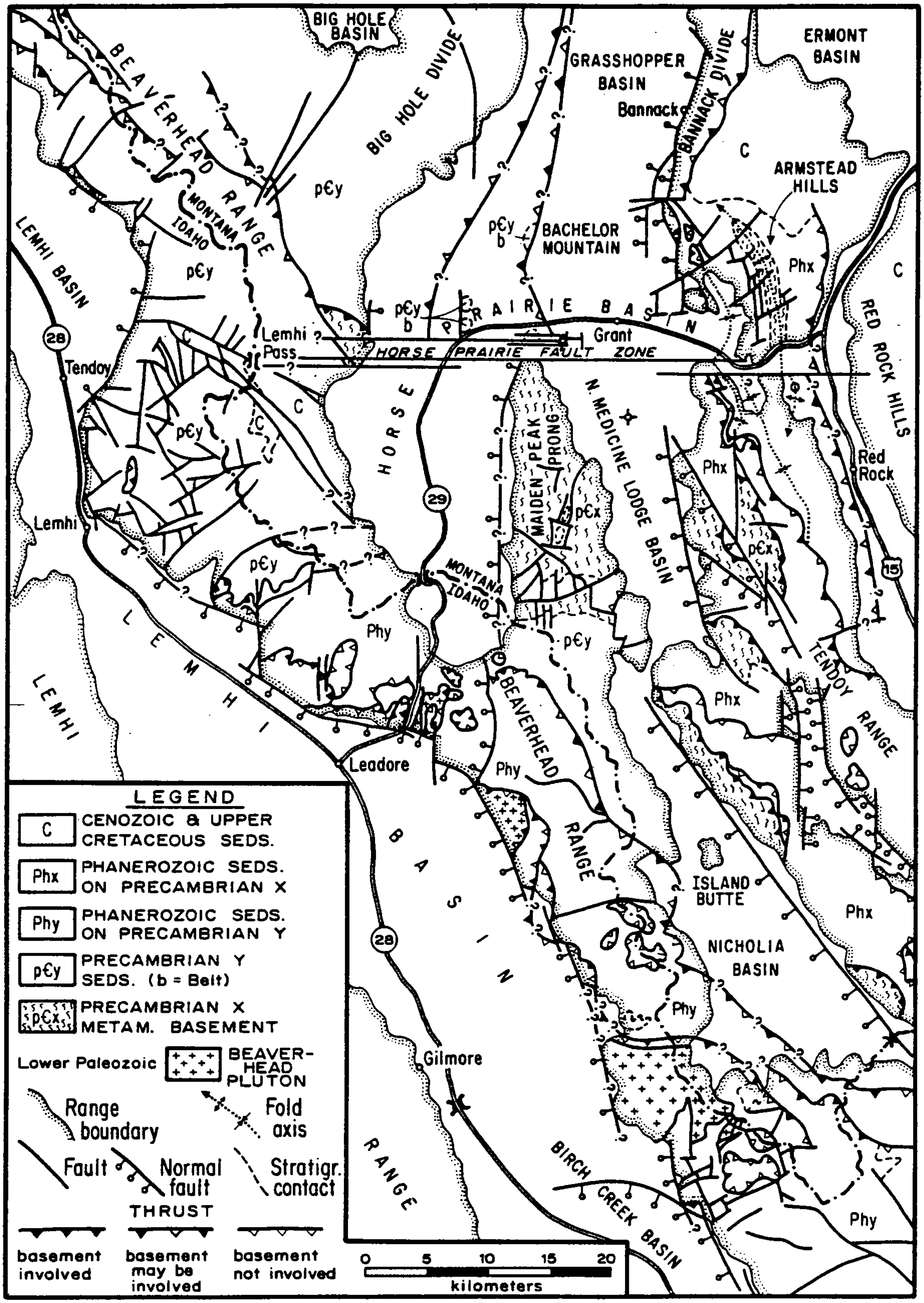

Figure 3. Simplified geologic map of the Beaverhead and Tendoy ranges in southwest Montana and adjacent Idaho.

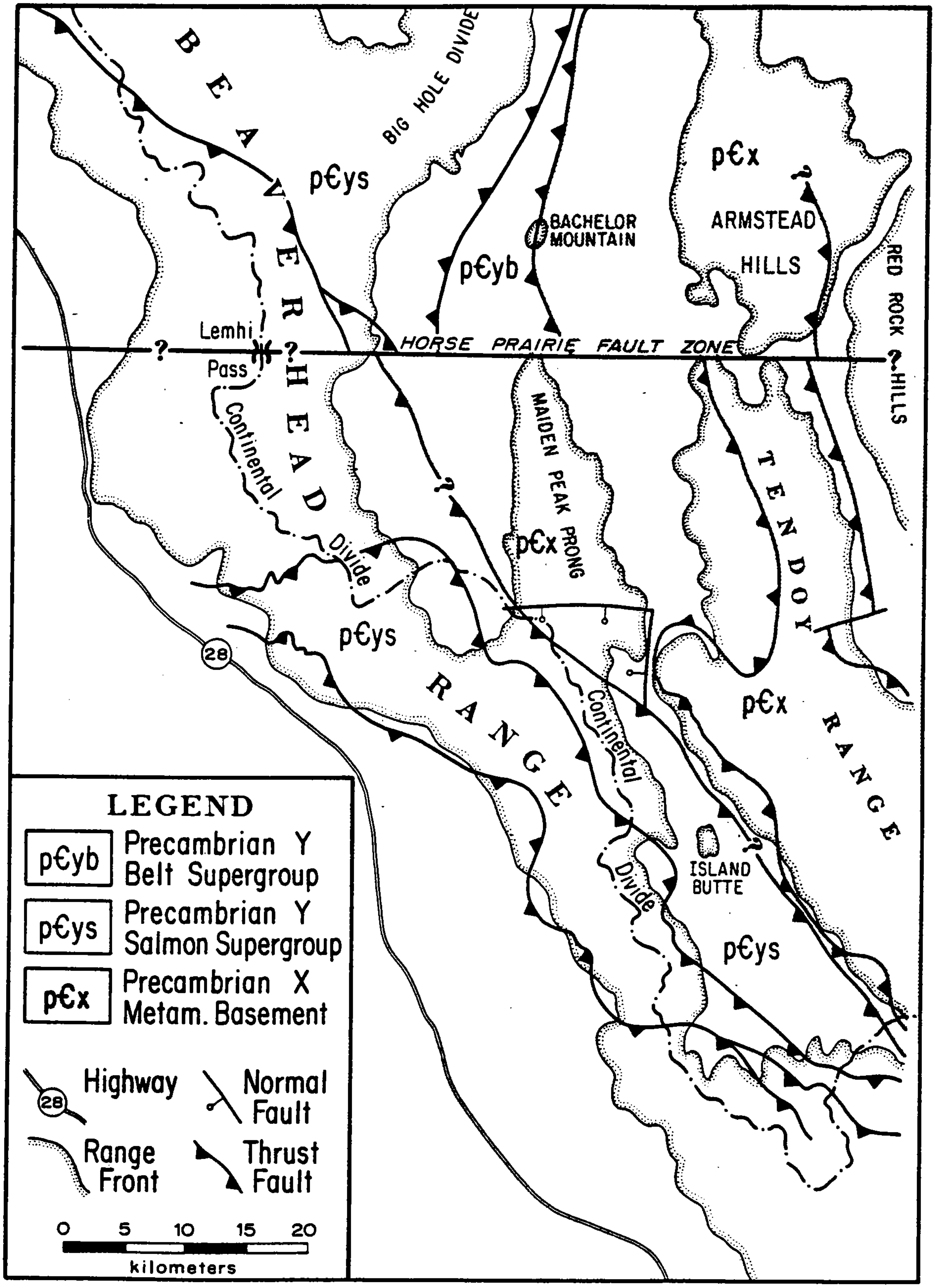

Figure 4. Stripped structure map of region of Figure 3, showing only Precambrian rocks.

of Figure 4 and whose continuation along strike is the Cabin thrust, mapped farther south in the range by Scholten, Keenmon and Kupsch (1955). In 1979 a well *(Kenneth Luff Inc. No. 1 Hansen)*, drilled in the narrow basin between the northern Tendoys and the Maiden Peak prong of the Beaverhead Range to the west (Fig. 3), passed through 700 feet of Precambrian gneiss and fault breccia below Tertiary rocks, and at 7090 feet entered into Devonian dolomite and anhydrite. The same gneiss makes up a large part of the Maiden Peak prong (M'Gonigle, 1965), and it may be concluded that the rocks of the Beaverhead Range are likewise allochthonous above the Cabin thrust in this area. The displaced rocks form part of the regional Medicine Lodge allochthon of Ruppel (1978; Ruppel and others, 1981), one of several major thrust plates in this part of the U.S. Rockies. The fundamental fault at the sole of this plate thus lies in the basement and is none other than the Cabin thrust (rather than the originally more restricted "Medicine Lodge thrust" of Kirkham, 1927, which involves Phanerozoic rocks only).

The Tendoy thrust, carrying the Tendoy allochthon, is the easternment fault in Figure 3 and the easternmost exposed NW-trending fault in this segment of the thrust belt (Scholten, Keenmon and Kupsch, 1955; Skipp and Hait, 1977). Hammons (1981) has shown its nature to be that of a low-angle overthrust. It continues northward beyond the tip of the Tendoy Range, where its rooted nature is indicated by the fact that it brings up the Precambrian gneiss of the Armstead Hills (Figs. 3 and 4). By contrast, the Cabin thrust does not project northward into the Armstead Hills, but seems to terminate at a transverse fault in the basin of Horse Prairie Creek (HP in Fig. 1). North of the basin the Grasshopper plate of Ruppel and others (1981) is emplaced upon the frontal thrust zone, and the westermost exposure of Precambrian gneiss (Fig. 3) is bounded by the Bloody Dick thrust. The faults north and south of Horse Prairie basin are not offset representatives of one another, but clearly belong to separately developed systems.

In the near absence of Precambrian X basement exposure elsewhere in the northern Rockies it is difficult to assess how many of the foreland thrusts are rooted in the crystalline crust. In the northward continuation of the thrust belt into the area between the Idaho and Boulder batholiths (Fig. 1), low-angle Philipsburg, Georgetown, Princeton, and other thrusts (Emmons and Calkins, 1913; Baken, 1981) involve Proterozoic sediments, but no metamorphic basement is exposed. In the rear of the thrust belt, however, an important thrust of continental Precambrian crystalline rocks has been reported in the Pioneer Range of central Idaho by Dover (1980). Farther north, interpretations of geophysical data led Harrison, Kleinkopf and Wells (1980) to believe that the extensive Belt terrane of northern Idaho and northwestern Montana is cut by numerous thrusts that are rooted in the crystalline crust.

The NE-trending bifurcation of the thrust belt in southwest Montana (Fig. 1) splits off as the Snowcrest-Greenhorn thrust system of Perry, Ryder and Maughan (1981), which incorporates the exposed Snowcrest thrust (Kleper, 1950) and the geophysically and stratigraphically inferred sub-Snowcrest Range thrust. Both are basement faults. Farther north, two gently NW-dipping thrusts, at least one of which involves Precambrian X metamorphic rocks, have been reported in the western flank of the Tobacco Root Mountains by Samuelson and Schmidt (1981). Northest of this, Schmidt and Hendrix (1981) describe the more easterly trending Cave and Jefferson Canyon faults in SW-central Montana, interpreted as "tear thrusts" with oblique slip. The Jefferson Canyon fault has a basement exposure on its upthrown side, and appears to be a reactivation of the Proterozoic Willow Creek fault (WC in Fig. 1), which controlled the south edge of the great Belt embayment in central Montana, and the deposition of the conglomeratic LaHood facies of the Belt Supergroup (Robinson, 1963; McMannis, 1963). The Jefferson Canyon fault is inferred to bend back to a northeast trend at its eastern end and connect with the Lombard thrust east of the Boulder batholith (Schmidt and Hendrix, 1981; Robinson, 1963). The Lombard thrust is the sole fault of the Elkhorn thrust plate of Ruppel and others (1981). It bends sharply to a northwesterly trend south of the transverse Lewis and Clark fault zone (Fig. 1). Along strike, the thrusts of the Montana Disturbed Belt trend NW-ward toward the area of the Lewis and related overthrusts and on into Canada. Neither the Lombard thrust, nor those farther north are known to be rooted in basement, though the gravity and magnetic data of Harrison, Kleinkopf and Wells (1980) suggest the Lewis thrust is.

In the central to southern U.S. Rockies Precambrian metamorphic rocks in northeast Utah are carried eastward by the Taylor thrust (Crittenden, 1972). Royse, Warner and Reese (1975) suggest that, in addition, the Absaroka thrust may be rooted in basement. Burchfiel and Davis (1968a, 1972; Davis and Burchfiel, 1971), Fleck (1970, 1971), and Wright and others (1981; Wright, 1982) have described thrusting of the basement along the eastern margin of the southern Cordillera.

In other segments of the Cordilleran fold and thrust belt, in particular Canada (Bally, Gordy and Stewart, 1966), and southwest Wyoming and southeast Idaho (Royse, Warner and Reese, 1975), seismic evidence shows basement to be undisturbed. Some writers have argued that basement become involved only in special paleotectonic situations. Beutner (1977) sees such a situation in westward-jutting promontories of the craton, one of which occurs in southwest Montana. Armstrong (1975) relates the basement thrusts in that area to the postulated existence of a basement uplift, the Salom River arch, in north-cenral and east-central Idaho. Eastward rising thrusts are thought to have cut through these buttresses. If so, one must accept that décollement thrusts cut stratigraphically downward into crystalline crust in the direction of transport, and then upward again into the sedimentary pile. As to the Salom River arch, the reality of its existence has been placed into doubt by Evans (1981; Evans and Lund, 1981). In any case, a "buttress" explanation would not readily apply to basement thrusts presumed to exist in northwest Montana and northern Idaho, or known to exist in central Idaho.

That many known foreland thrusts, in the western Cordillera as elsewhere, unite into one or a few major décollement surfaces at, or above, the top of the basement remains a fact of great importance. The data available suggest, however, that basement rooting of major thrusts may be more common in this back-arc setting than generally believed, which places constraints on any overally genetic model.

TRANSVERSE FAULTS

The existence of major east-west faults has long been recognized in the structural pattern of southwest Montana, but recent field work has added to their number and elucidated their role during Cordilleran thrusting. Ruppel and others (1981) show five major faults or fault zones, all anchored in the craton but reaching westward into the thrust belt. The northernmost one is a rejuvenation of the Proterozoic Willow Creek fault zone (Schmidt and Hendrix, 1981). The Horse Prairie fault zone was studied by Scholten (1981). The two faults are labeled WC and HP in Figure 1.

Minor late Tertiary to Recent activity along the Horse Prairie fault zone (Figs. 3-5) can be seen in offsets of Tertiary beds, intrusion, mineralization and offsets of Tertiary volcanic plugs,

A

B

Figure 5. Field expression of the Horse Prairie fault zone. (A) Fault breccia of foliated Precambrian Y quartzite in hill 7 miles west of Grant (c.f. Fig. 3). (B) View looking east from the same hill (foreground). Front middle ground: right center, mineralized Tertiary lava flow; left, Tertiary sediments faulted against lava flow. Rear middle ground: right center, offset diabase plug. Spurs in distance terminate against fault zone (low wooded Armstead Hills on left, bare northern terminus of Tendoy Range on right).

decapitated drainages, changes in behavior of Horse Prairie Creek, termination of major topographic spurs, alignments of springs, tilted pediments, filled pediment channels, zones of brecciation, and slickensided east-west striking rock surfaces. Westward, the fault zone reaches into the Beaverhead Range (P. Hansen, in progress) and toward the prominent Lemhi Pass by which Lewis and Clark crossed the Continental Divide. It may be that the peculiar Z-pattern of the range crest in this area (Fig. 3) is attributable to the fault zone. Eastward, Ruppel and others (1981) suggest its continuation at the abrupt southern terminus of the Blacktail Range. Like the Willow Creek zone, the Horse Prairie fault zone shows evidence of pre-orogenic activity. A north-south stratigraphic section (Fig. 6) reveals pre-Cretaceous erosion of the entire Jurassic and much of the Triassic, followed by deposition of a coarse conglomerate facies of the Kootenai Formation (c.f. Moritz, 1951). Thick, lower Paleozoic quartzites south of the fault zone (M'Gonigle, 1965; DuBois, 1981b) are represented on the north side by a feather edge of the Cambrian Flathead Sandstone. Proterozoic sediments exposed on Bachelor Mountain on the north side (Figs. 3 and 4) show great affinity with the Belt (Mt. Shields?) sandstones, whereas those to the south belong to a unit here designated the Salmon Supergroup, and specifically to the Lemhi Group, which Ruppel (1975), and Evans (1981; Evans and Lund, 1981) show to be coeval with the Belt. Juxtaposition of these contrasting stratigraphies has been achieved in part by differential transport along thrusts, but the stratigraphic contrast is most obvious where differential motion seems to have been minor, i.e. between the frontal Tendoy thrust block and its northerly counterpart (Fig. 4), indicating the reality of initial facies changes and pre-thrust activity along the fault zone.

Most significant in the context of this paper is the evidence for a synorogenic role of the fault zone. As shown in Figures 3 and 4, thrust patterns are different north and south of the fault zone. Major thrusts, including basement thrusts, terminate against it. Within the zone, a fortuitous exposure of Proterozoic rock west of Grant (Fig. 3) provides further insight. The quartzite here occurs as a prominent fault breccia (Fig. 5), indicating fault movement under shallow overburden. Individual clasts show the quartzite is foliated, in marked contrast to its occurrence elsewhere in southwest Montana, showing deep-seated and therefore earlier synorogenic activity along the fault zone. The combination of localized foliation within, and contrasting thrust development on either side of the fault zone suggests that the ancient line of weakness in the crust and overlying sediments assumed the role of a major tear thrust during Cordilleran orogenesis, comparable to the role ascribed to the Willow Creek fault zone by Schmidt and hendrix (1981). The significance of this may be appreciated in the light of a fresh inquiry into the cause or causes of the Cordilleran foreland thrust belt.

DYNAMICS OF THRUSTING

Models of thin-skinned gravity gliding have been offered for the western cordillera by Scholten (1968, 1973), Crosby (1968), Chase and Talbot (1973), Roberts and Crittenden (1973), Hose and Danes (1973), and Hyndman (1980). The energy to create the tectonic slope required for gliding ultimately derives from the mantle and crystalline crust. It is imparted in the form of gravitational energy to the sedimentary cover, where it is converted to kinetic energy manifest in the folding and thrusting of the sediments. Thus, in such a model the force *directly* responsible for thrusting resides in the sedimentary cover alone and affects this cover alone. In view of the data presented above on basement involvement in thrusting, I now consider this an untenable hypothesis for the direct cause of the Cordilleran thrust belt as a whole, even as I continue to recognize gravity gliding on a more restricted scale for certain allochthons clearly confined to the sedimentary cover and demonstrably located at the foot of syntectonic slopes. (Kirkham's (1927) original "Medicine Lodge thrust" in the southern Tendoy Range, shown in Figure 3 with open teeth marks, is one such allochthon (Scholten, 1973). By the same token, one may accept, for certain situations, the gravity spreading model of Price and Mountjoy (1970; Price 1973) while recognizing that it is difficult to apply this model where thrusts are rooted in the basement far from the topographically high mobile core that must supply the gravitational potential for lateral translation.

Recognition of basement rooting and of a secondary role of gravity tectonics goes hand in hand with reaffirmation of the view that lateral forces transmitted through the crust were directly, rather than indirectly, responsible for the overthrust belt. This leaves two models: eastward continental overthrusting and westward continental underthrusting.

The distinction between the overthrust and underthrust mechanisms was long ago recognized by alpine geologists. An exhaustive review of the alpine nappe system led Kraus (1951, p. 421) to summarize his conclusion in the phrase (as translated by me): "For time and again the evidence indicated that it is the downward forces that build mountain structures — in space as well as time the reigning process is downward construction."* Likewise, Misch (1960) recognized that the distinction is not trivial, but involves the problem of transmitting lateral forces through the weak mobile core of a developing orogen in the overthrust model as compared to their transmission through a rigid cold continent in the underthrust model (Fig. 7). This led him to advocate eastward underthrusting of the foreland beneath the mobile core. His argument seems as sound today as then.

Three additional considerations argue in favor of the underthrust model. For one, it has been shown by L. Cathles (Chevron Oil Field Research Co., La Habre, CA: pers. commun., 1982) that maximally thick, cold cratonic lithosphere, composed of approximately 25-30 km of old, relatively heavy crust and 95-100 km of upper mantle, has sufficient average density to induce it to sink into the asthenosphere (Cathles, ms in prep). In prep.). In a westward moving plate this downward body force sets up a tendency for the plate to subduct westward beneath the thinner lithosphere at the outer part of the continent. To the extent that this body force is a significant factor, it reduces the magnitude of the compressive stress that needs to be transmitted through the North American plate in the underthrust model. Such underthrusting of old cratons occurs as naturally as subduction of oceanic lithosphere. Cathles' model eliminates the oft-heard objection that continental subduction is quickly self-limiting owing to the presumed buoyancy of the subducted continental crust and the resulting uplift. Instead, the crust, though lighter than the mantle, is dragged down into it because it is part of a sinking old, thick, and dense lithospheric plate. The Cathles model suggests an answer to the question of what caused thrusting to stop. Could it be that this occurred because the thickness of continental crust to be subducted kept increasing as more interior portions of the craton arrived at the thrust belt, until the proportion of crustal material in the lithosphere finally became too great, and the average density of the lithosphere too small, to permit the plate to sink and subduct?

* The awkward term "downward construction" renders the German "Abbau" — an untranslatable word.

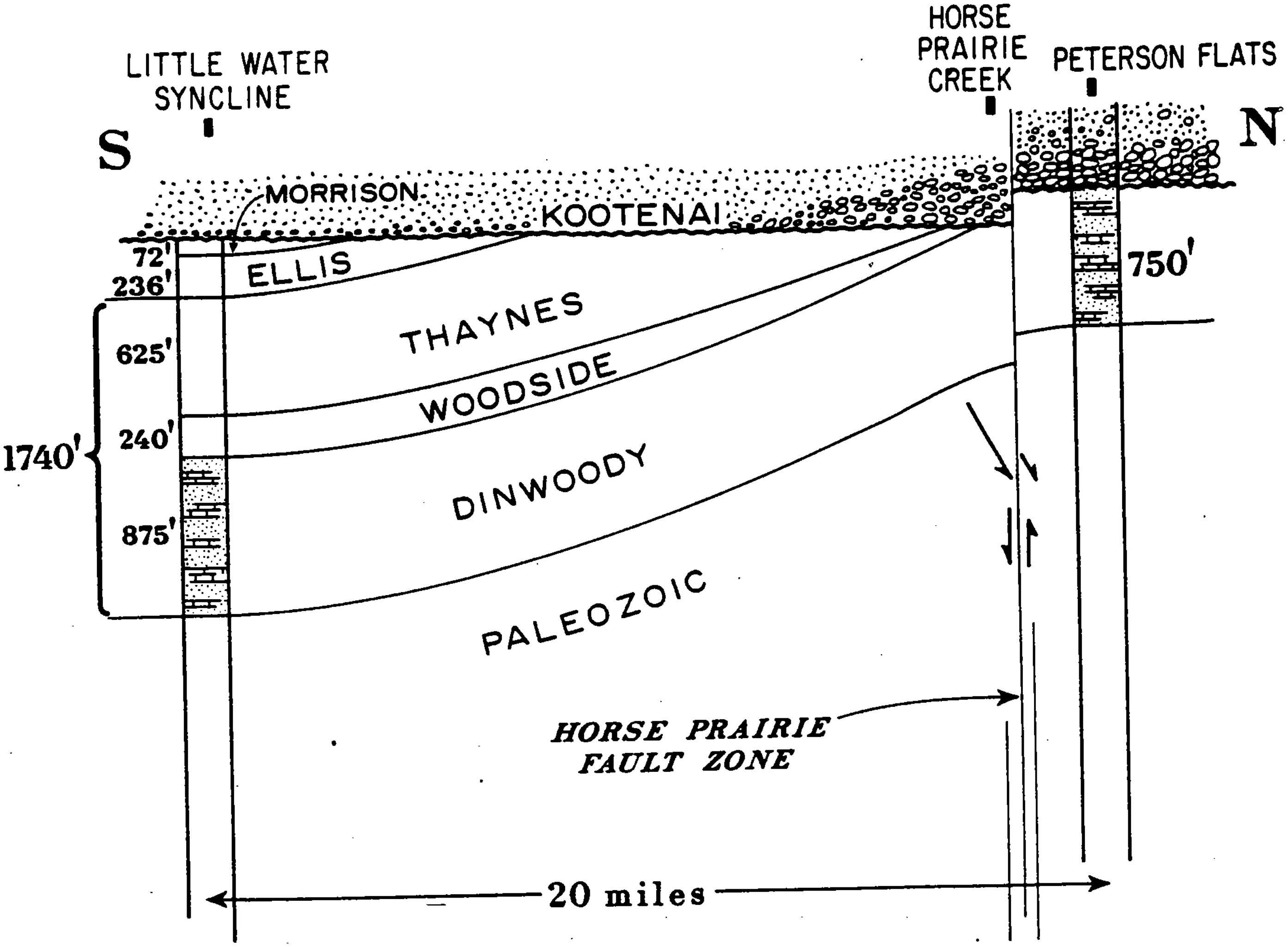

Figure 6. Stratigraphic section from the central part of the Tendoy Range (S) to the Armstead Hills (N) (c.f. Fig. 3). Note pre-Kootenai unconformity and basal Kootenai conglomerate across area of Horse Prairie fault zone, suggesting pre-orogenic fault activity.

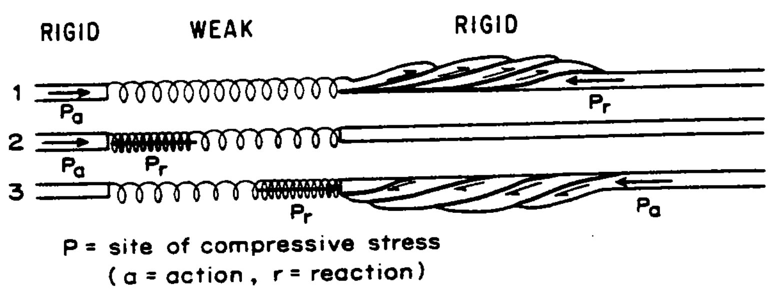

Figure 7. Three models simulating compressive stress (P) distribution between tectonic foreland and hinterland (rigid plates) and mobile core of orogen (weak coil). Only model 3 is both mechanically plausible and successful in producing foreland thrusts.

A second reason for favoring the underthrust rather than the overthrust model relates to the evidence, provided by the synorogenic conglomerates, for synorogenic uplift in the rear of the thrust belt. In the region of the present Idaho batholith, rocks initially 10 to 12 km deep were placed at least 5 km above sea level and subjected to erosion (Scholten, 1973; Ryder and Scholten, 1973). Creating a "high" of such magnitude, which is both tectonic and topographic, conceivably could have been achieved by eastward lateral translation and piling up of overthrust sheets onto the continent. However, overthrusting must then have proceeded at an exceedingly rapid rate to overcome the simultaneous effects of isostatic subsidence (which counteracts the raising of deep rocks along low-angle thrusts) and erosion (which counteracts the raising of the topographic surface). In all probability, great tectonic and topographic elevation can be attained only by vertical rise of the crust, that is, by isostatic uplift. Isostatic uplift implies that too much continental crust exists at depth, which,

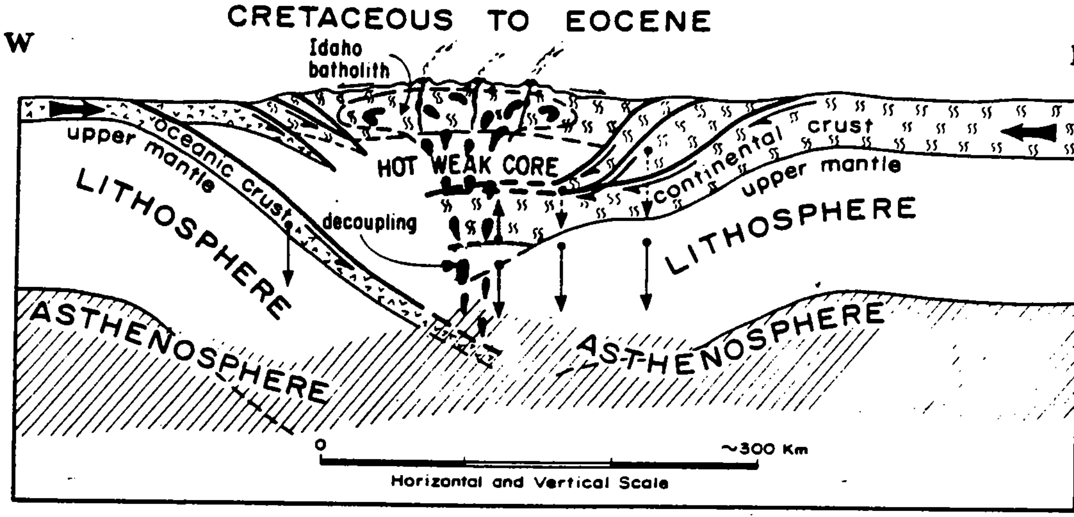

Figure 8. **Model for Cretaceous through Eocene tectonic-magmatic events in the western Cordillera of the United States. Arrows and half-arrows indicate movements of lithosphere. Partial melting of subducted oceanic lithosphere creates hot, weak core or orogen and related intrusion and extrusion. Westward drift and sinking of continental lithosphere cause continental subduction. At depth in hot core, decoupling of subducted continental crust from upper mantle creates great buoyant uplift of underridden lithosphere behind thrust arc. Energy potential of central orogenic highland leads to gravitative adjustments, adding to lateral translation.**

in a model of plate motions, can only be produced by continental subduction.

The question naturally arises how the same crust that was subducted by gravity can cause uplift once it has been subducted. Cathles (pers. comm., 1982) suggests that the upper, lithospheric laminae represented by the crust, once they are heated up, are likely to disengage from the heavy remainder of the lithosphere, which continues to sink. Heating of the subducted slab occurs at depth in the core of the developing orogen, rendered hot and mobile upon eastward subduction and partial melting of oceanic lithosphere. In the northwestern Corillera of the United States this was initiated at least as far back as Permo-Triassic time (Onasch, 1977; Scholten and Onasch, 1977). Once released, the light crustal material begins to exert an upward gravitative pressure on the overlying lithosphere, and rapid isostatic rise ensues (Fig. 8). Continued subduction places new continental lithosphere beneath already subducted and uplifted crust, and the process of underplating and uplift is repeated. Because it takes time for sufficient heating to occur, the crust succeeds in "sneaking" downward and laterally to some distance behind the thrust belt before it decouples from the mantle. Thus, the Cathles model explains why great uplift occurs in the rear of the fold and thrust belt. The opposing sense of thrust motion on the two sides of the core implicit in the dual subduction model of Figure 8 is in good accordance with known field relations and with Burchfiel and Davis' (1968b) notion of the "two-sided orogen".

A third reason for preferring the underthrust model relates to the transverse fault zones in southwestern Montana. As discussed above, at least two of these are ancient fractures used as tear thrusts during Cordilleran tectonogenesis. Because the fault zones are anchored in the craton, it seems more plausible to consider that the thrust sheets inherited them from the craton in the course of continental subduction than that they were imparted to the craton from a set of overriding thrust sheets.

On the basis of the distribution of seismic, volcanic, and tectonic activity and of topographic patterns, Suppe, Powell and Berry (1975) propose the existence since late Cenozoic time of a Western U.S. plate between the North American plate on the east and the Gorda and Pacific plates on the west. The eastern boundary of the Western U.S. plate is portrayed as a zone of extension repeatedly transformed toward the west. Furthermore, they suggest that a belt of seismicity may extend westward from Yellowstone Park as far as central Idaho, possibly defining one of several transforms that segment the plate into subplates. I note that the eastern boundary of their Western U.S. plate coincides closely with the earlier Cordilleran thrust front, and that the east-west belt of seismicity would encompass the Horse Prairie fault zone and the Centennial fault zone south of it. In view of this, I suggest that the Western U.S. plate of Suppe, Powell and Berry, once part of the North American plate, became a separate entity when the North American plate began to subduct beneath its western edge along a set of lithospheric underthrusts, in the process imparting pre-existing east-west fractures onto the new Western U.S. Plate.

CONTINENTAL SUBDUCTION IN MONTANA

Figures 9 through 11 illustrate a model for the development of a paried thrust belt in southwest Montana by continental subduction. Underthrusting of the crust begins in the flank of the geocline (Scholten, 1956, 1957), probably, as suggested by Burchfiel and Davis (1975), at the locus of greatest ductility contrast between cold, rigid lithosphere of the craton and the more mobile lithosphere at its western fringe.

On a continental scale the geocline is composed of a northern and a southern segment, and the arcuate intersections of these two geoclinal segments with the sphere of the Earth predetermines the evolution of the thrust belt in the form of a northern and a southern arc (Fig. 2), meeting at a set of transverse east-west faults (Fig. 1). Crustal subduction causes a scraping off of the sedimentary cover along a décollement at the top of the basement, and eastward migration of upward cutting thrusts. The development of décollement displacements over wide areas may be aided by gravitational spreading away from the high central core of the orogen. Such a combination of processes has been proposed for the Canadian Rockies by Price (1981). Eventually, additional basement underthrusts develop farther east, in particular at (but not necessarily confined to) the

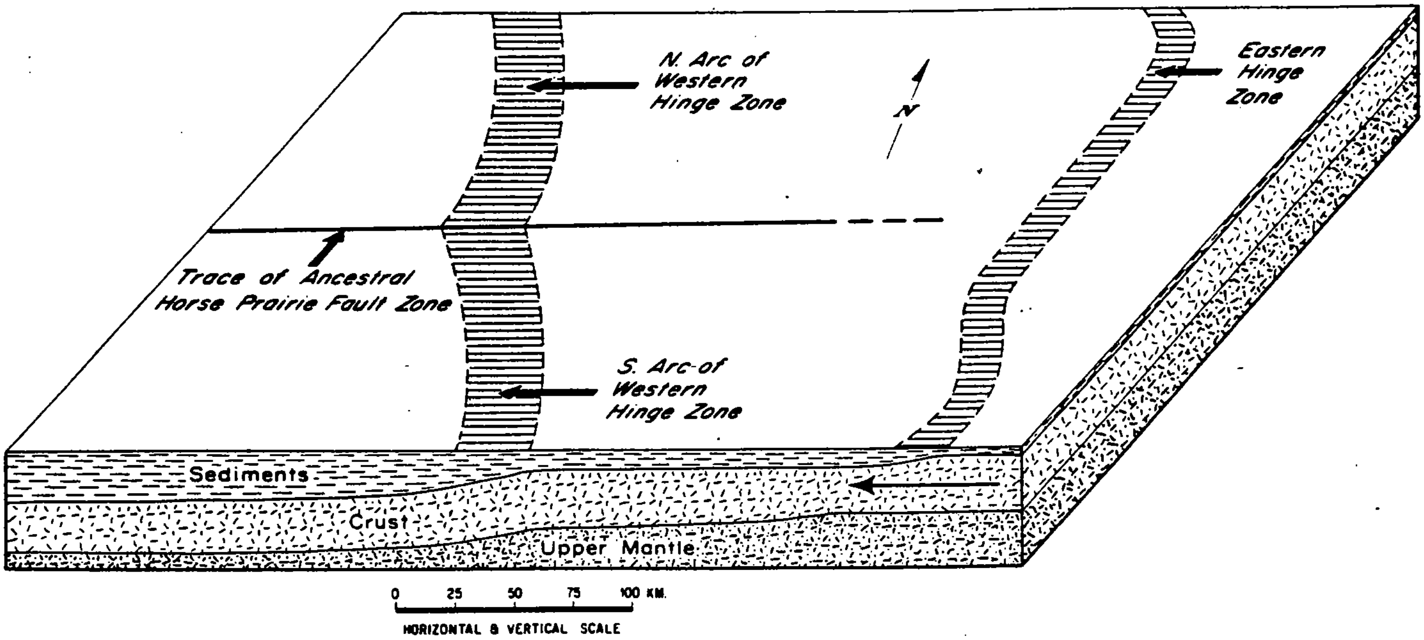

Figure 9. Palinspastic reconstruction of geoclinal hinge zones in southwest Montana. The arcuate outline of the geoclinal flank predetermines the later thrust fronts.

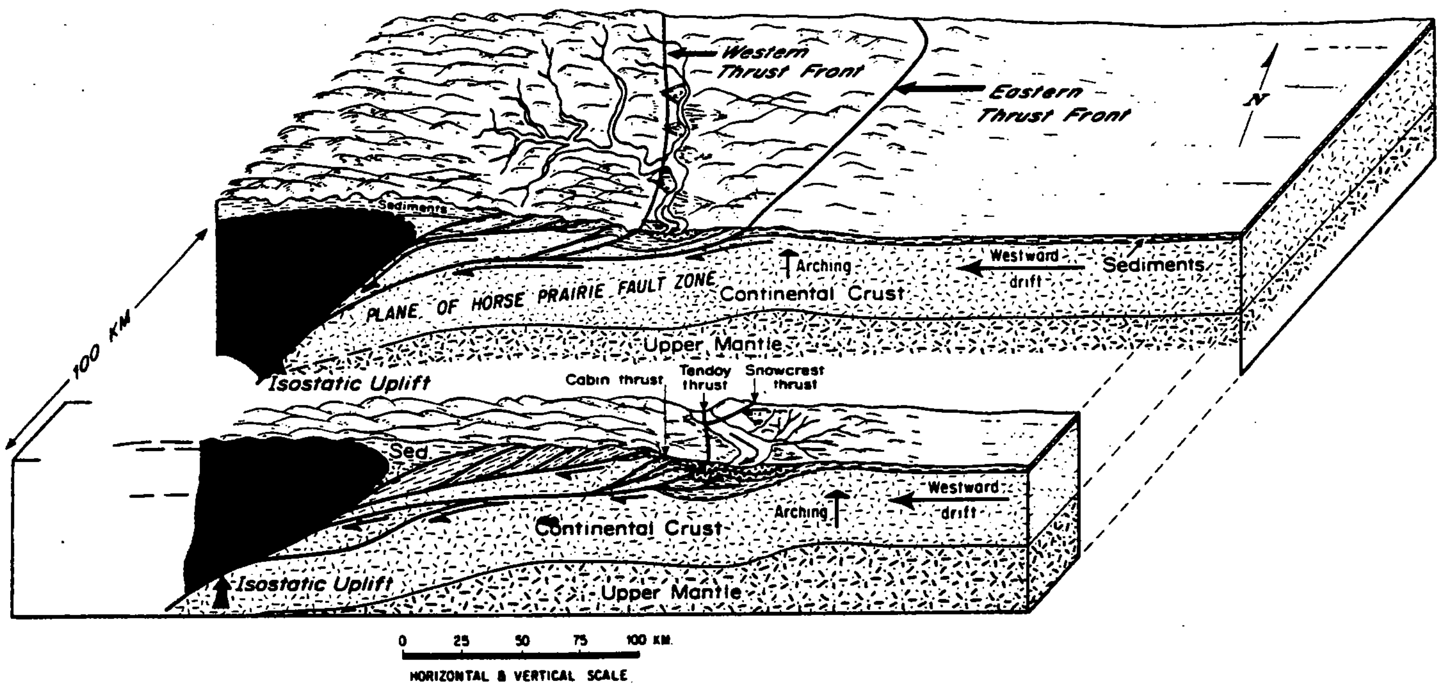

Figure 10. Tectonic, magmatic and sedimentary events in southwest Montana and central Idaho triggered by westward subduction of continental lithosphere into the hot, mobile core of the orogen.

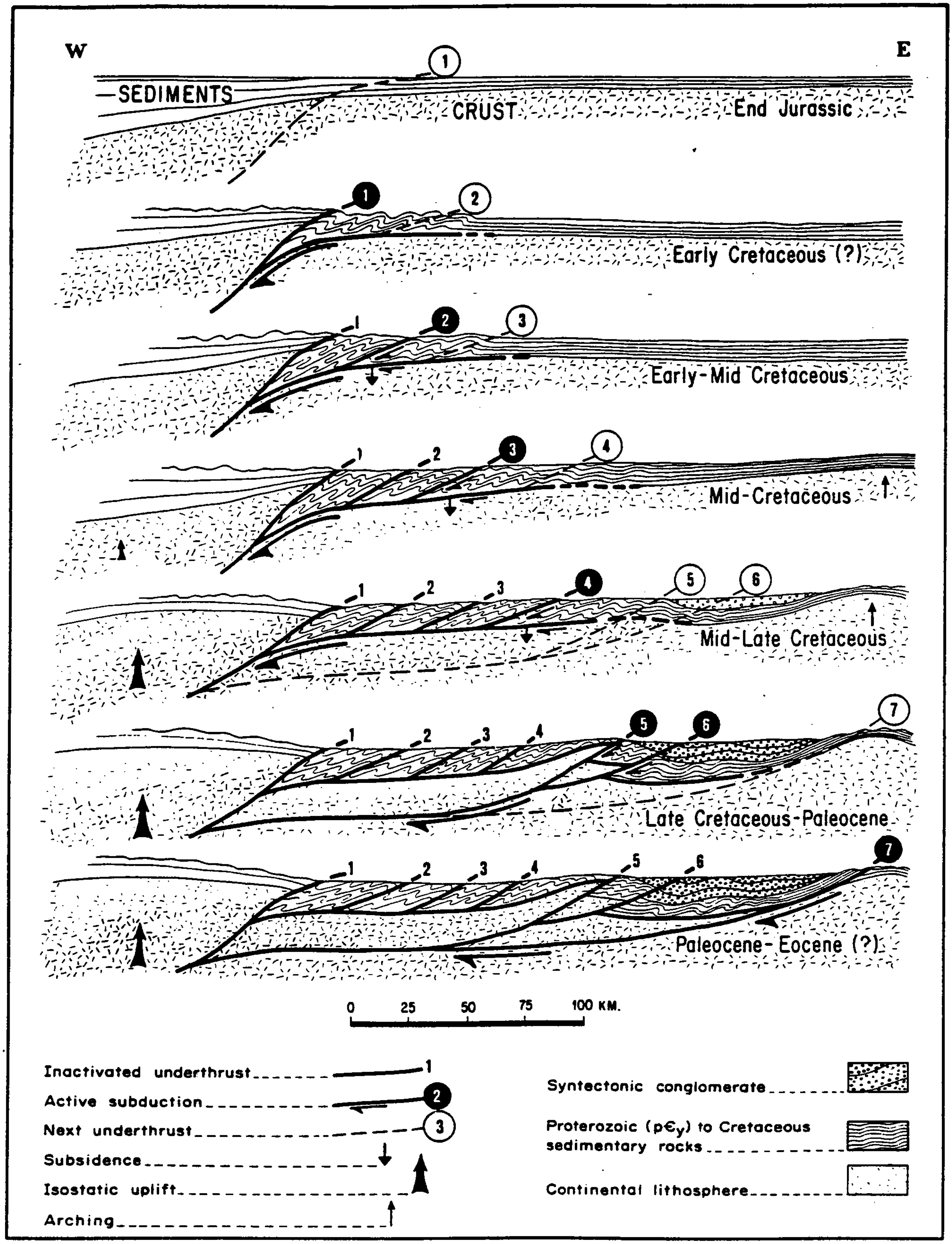

Figure 11. Model for sequential development of back-arc thrusts and synorogenic uplift and sedimentation east of Idaho batholith.

locus of the geoclinal hinge. Immediately east of the subduction front the crust will have a tendency to be bowed up, giving rise to the early uplifts that created locally derived facies of synorogenic conglomerates (Ryder and Scholten, 1973). Finally, continental underthrusting in southwest Montana jumps to a second hinge with a NNE trend, developed during the Paleozoic (Scholten, 1956, 1957). Depending on how far away this new set of thrusts is rooted in the crystalline crust, it may expose basement at the present thrust trace or stay above basement for some distance back of the thrust trace. South of the intersection between the northern and southern thrust arcs, the eastern bifurcation of the northern arc goes into the subsurface beneath already subducted continental lithosphere. Consequently, there is no expression of the NNE trend south of this intersection.

A by-product of continental subduction is developed some time after subduction begins, continuing as it proceeds. Great and rapid isostatic uplift is initiated and maintained by the emplacement of new lithospheric slices below earlier ones, ultimately giving rise to prominent tectonic and topographic highlands in the rear of the thrust zone, and to floods of syntectonic conglomerates.

Finally, the question may be raised whether there is perhaps a genetic relation between continental subduction and the intrusion of the Idaho batholith. Its peculiar position much farther inside the continent than the other great batholiths of the American West has been noted by many, and Eardley (1951) observed that it is located directly west of the intersection between the two great Cordilleran arcs (Fig. 2). The petrologic-geochemical signature of the Eocene phase of the Idaho batholith suggests a partial derivation from continental crust (Rehm and Lund, 1981). The question can be sharpened: Is it plausible that burial of mutally subducting lithospheric slices into the mantle in the region of the hot mobile core could have permitted heating of the continental crust sufficient not just to cause its decoupling from the mantle, but in addition a partial melting of that crust, followed by batholitic intrusion into the underridden plate (Fig. 8)? It should be easier to initiate partial melting in continental crust subducted into the mantle than in continental crust that has not been subducted.

IMPLICATIONS FOR OIL AND GAS EXPLORATION

With regard to oil and gas occurrence, the most important aspect of the model presented in this paper is that it encourages a critical review of the possibility that certain Cordilleran foreland thrusts may be rooted in the crystalline crust, so that sedimentary units may lie structurally below basement.

In southwest Montana the major thrusts are believed to be basement rooted both along the NNW to N-trending bifurcation of the thrust belt and along the NNE-trending one. Granite gneiss exposed in the thrust belt is underlain by sedimentary rocks, and the same may be true for basement occurrences encountered or seismically interpreted at depth. A case in point is the Cabin basement thrust system in the Tendoy Range, the sole fault of Ruppel's (1978) Medicine Lodge allochthon (Figs. 3 and 4), which almost has to occur as well beneath the Beaverhead Range to the west. The basin behind the Cabin thrust trace and between the Tendoy and Beaverhead ranges (Medicine Lodge-Nicholia basin) therefore seems to offer attractive exploration prospects, for the Precambrian Y sediments or Precambrian X gneisses which here lie directly below the Tertiary, themselves should rest on Paleozoic sediments. The *Kenneth Luff Inc. No. 1* Hansen well in North Medicine Lodge basin (Fig. 3) has confirmed what was strongly indicated by field work. The reinterpretation of the frontal fault in the NNW-trending thrust zone, the Tendoy thrust, as a low-angle thrust rather than a high-angle upthrust implies that the terrain directly west of its trace also constitutes a favorable prospect.

In assessing the temperature regime to which potential source rocks have been subjected, it is not adequate to base conclusions on analyses of induration indices, such as the conodont alteration or carbon preference index, obtained from samples collected at the surface. Oil and gas potential must be assessed by estimating indices in rocks below the thrust sheets, which may be lower than those in the thrust sheets. Thus, the Paleozoic sediments below the Cabin thrust system west of the Tendoy Range belong to the Tendoy allochthon and should have indices intermediate between surface samples collected in the Tendoy Range and those collected in the Beaverhead Range.

Finally, interpretations of seismic data aimed at understanding subsurface structural patterns conducive to oil or gas accumulation in southwest Montana should take into account the east-west faults. Thrust patterns on the two sides have developed independently and cannot be correlated, and the paleotectonic activity along the faults has influenced sedimentation, so that significant facies changes may be expected across the faults.

SUMMARY

Theoretical as well as field evidence suggests that the fundamental cause of Cordilleran and, by analogy, probably all back-arc thrusting is subduction of old continental lithosphere beneath its own margin. In an ultimate sense the impetus for subduction is gravitational, combined with lateral drift. Arcuate out-lines of thrust belts reflect the intersection of the geocline with the sphere of the Earth. Where arcuate segments meet, subperpendicular fault zones may develop, which may later function as tear thrust along which continental subplates move side by side into the subduction zone. Underthrusting migrates eastward partly through the crystalline crust and in part along supracrustal décollement surfaces.

Underthrust crustal segments are heated in the hot mobile core of the developing orogen, where, disengaged from the upper mantle, they produce rapid isostatic uplift. Partial melting of subducted continental crust may perhaps contribute to batholithic intrusion. As a large topographic gravity potential develops behind the thrust arc, a process of gravitational spreading of the sedimentary cover is superposed on the subduction process. At a smaller scale, and more superficial level, local high uplifts cause downward gravity gliding or sediments. At all scales and levels the tectonic process is in the final analysis a lithospheric response to a gravitative disequilibrium and an attempt to re-establish equilibrium. It is sobering to read how much of this scenario was anticipated three quarters of a century ago by Bailey Willis (1907, p. 123-133).

Implications for petroleum occurrence reside in the probable existence of sedimentary rocks below thrusts of crystalline rocks. Also, significant changes in facies and structural patterns may be expected along the old east-west fault zones.

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