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THE PUTNAM THRUST, NORTHERN PORTNEUF RANGE, SOUTHEASTERN IDAHO: STRUCTURAL COMPLEXITIES CAUSED BY UPPER-PLATE IMBRICATE THRUSTING AND NEOGENE BLOCK ROTATION

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The Putnam thrust, northern Portneuf Range, southeastern Idaho: structural complexities caused by upper-plate imbricate thrusting and Neogene block rotation

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ABSTRACT

The Putnam thrust has long been recognized as an important Mesozoic structure in the northern Portneuf Range, southeastern Idaho. At most localities, the thrust places Ordovician rocks above Permian and Pennsylvanian rocks, although near its southeastern extent, it ramps laterally downsection to the southeast. At its southeasternmost exposures, Cambrian rocks are juxtaposed above Mississippian rocks. New work indicates that the hanging wall of the Putnam thrust contains three imbricate thrust slices or subplates, which are, from structurally lowest to highest (and generally from north to south) the Lone Pine subplate, the Narrows subplate, and the Bear Canyon-Toponce subplate.

The steeply south-dipping, east-trending Narrows thrust overlies the Lone Pine subplate, underlies the Narrows subplate, and is a lateral ramp that merges eastward into the Putnam thrust. Where exposed, the Narrows thrust places Late Proterozoic quartzite of the Brigham Group over Ordovician and Cambrian rocks. The Bear Canyon thrust overlies the Narrows subplate and underlies the Bear Canyon-Toponce subplate, dips eastward along the west side of the Portneuf Range, and places lower Brigham Group quartzite above Cambrian limestone and Cambrian and Late Proterozoic upper Brigham Group quartzite and argillite. At its northern extent, the Bear Canyon thrust curves to the east, where it merges with the Putnam thrust. On the east side of the range, the intensely folded Toponce thrust places upper Brigham Group quartzite above Ordovician rocks; the Toponce is believed to be an eastward extension of the Bear Canyon thrust.

East-dipping rocks within the Lone Pine subplate were not strongly deformed during Cretaceous thrusting, in contrast to rocks within the Narrows subplate, where east-vergent recumbent folds, cleavage directions that fan about northerly strikes, and tectonic thickening and thinning of beds indicate intense, thrust-parallel shear. The deformation and thrust geometry within the Narrows subplate suggest that the Narrows subplate actually consists of several horses within a foreland-dipping duplex.

Most late Miocene and younger basin deposits occur in north-trending valleys adjacent to the northern Portneuf Range and the Bannock and Pocatello Ranges to the west. At most places, the Neogene deposits dip to the east by as much as 35°, indicating that late Miocene and younger extension and down-to-the-east rotation occurred along mostly west-dipping

listric faults that are inferred to merge on at least one regional detachment. Although large range-bounding faults account for a large component of extension and rotation, an additional large component also was contributed by numerous, relatively small-displacement normal faults within mountain ranges.

INTRODUCTION

The northern Portneuf Range lies within the Idaho-Wyoming-Utah salient of the Cordilleran fold and thrust belt, immediately south of the Snake River Plain and 20 km east of Pocatello, Idaho (Fig. 1). The range is underlain by a thick miogeoclinal sequence as old as latest Proterozoic and as young as Jurassic. It has long been recognized that the Mesozoic Putnam thrust cuts through the northern and eastern parts of the area (Mansfield, 1920, 1927; Trimble, 1982), generally placing Ordovician rocks over Permian and Pennsylvanian rocks, although the structural details have remained elusive. Much of the problem in understanding Mesozoic structures is the result of overprinting by Neogene extensional faulting in the area, as well as the widespread cover of upper Tertiary and Quaternary deposits, especially at lower elevations.

Figure 1 near here

The Putnam thrust was first described by Mansfield (1920), who did not attempt to correlate it with other thrusts described south of the northern Portneuf Range. Trimble and Carr (1976) suggested that the Putnam thrust may be a northward extension of the Paris thrust (the westernmost thrust of the Bannock thrust zone of Armstrong and Cressman, 1963), which is exposed on the east side of the Bear River Range, about 30 km southeast of the southeast corner of Figure 1. The Putnam-Paris thrust system was proposed by Trimble and Carr as the eastward boundary of an enormous klippe that extends southward into Utah and westward to the Deep Creek Mountains, although the western boundary of the proposed klippe (the Deep Creek "thrust") is probably a low-angle normal fault (K.S. Kellogg and P.K. Link, unpublished data; Rodgers and Janecke, this volume).

The Putnam thrust may not be continuous with the Paris thrust, as Trimble and Carr (1976) proposed. Rather, the two thrusts may form a thrust transfer system (Rodgers and Janecke, this volume). Evidence presented in this paper support this model.

Rocks below the Putnam thrust are placed in the Meade thrust plate. The Meade thrust system (the northern end of the Bannock thrust zone of Armstrong and Cressman, 1963) is well exposed in the Blackfoot Mountains (Fig. 1); two imbricates of the Meade thrust system there have been described (Mansfield, 1952; Allmendinger, 1978).

If the Putnam thrust represents either a northern extension of the Paris-Willard thrust system or is connected to that thrust system by a transfer mechanism, then the Putnam was active probably during Early Cretaceous time. An Early Cretaceous age for the Paris thrust is based on the age of the syntectonic Ephraim Conglomerate, which had long been thought to be Late Jurassic to Early Cretaceous in age (Armstrong and Cressman, 1963). New fossil evidence, however, indicates that the age of the Ephraim Conglomerate is entirely Early Cretaceous (Heller and others, 1986).

The Portneuf Range is typical of the ranges of the Basin and Range province. It trends north-northwest and is bounded along at least part of its west side by a major range-front fault. Valleys parallel to the range are mostly filled by locally thick late Miocene and younger sedimentary and volcanic deposits (Kellogg and Marvin, 1988); northeast-dipping Eocene volcanic rocks overlie the northeast end of the range (Trimble, 1982). The range is rugged and has about 1,200 m total relief. Mount Putnam (2,678 m), in the central part of the northern Portneuf Range, is a prominent landmark along the southeastern margin of the Snake River Plain.

The geology of the northern Portneuf Range was first investigated by Mansfield (1920, 1927) during a study of the Fort Hall Indian Reservation. Subsequently, parts of the area have been reinterpreted or mapped by Corbett (1978), Trimble (1982), Pogue (1984), Hladky (1986), Amerman (1987), Hefferan (1986), Kellogg (1990), Kellogg and others (1989), Hladky and Kellogg (1990), and Hladky and others (1991). Much of the preliminary mapping in the southeastern part of the study area (the Jeff Cabin Creek $7^1/_2$-minute quadrangle) was done by the late Steven S. Oriel of the U.S. Geological Survey during his last field season (1985).

Based on the work of Pogue (1984) in the northern Portneuf Range and LeFebre (1984) in the Pocatello Range to the west, Link and others (1985) proposed a model for the Mesozoic structural development of the region. In the northern Portneuf Range, the model incorporates two imbricate thrusts, the Jeff Cabin and Bear Canyon thrusts, above the Putnam thrust; rocks of the Jeff Cabin thrust are inferred to have deformed into recumbent folds before the younger and higher Bear Canyon thrust cut through the folds, locally ramping down section in the direction of transport. In the Pocatello Range, this model is invoked to account for upright, east-dipping beds that apparently overlie overturned beds along east-dipping thrusts (Link and others, 1985); the possible effects of regional tilting by Tertiary block faulting were not considered by Link and his coworkers.

In this paper, an alternate model for Mesozoic deformation in the northern Portneuf Range is proposed. This model relates folds directly to the mechanics of thrusting, shows that thrusts ramp up section in the direction of transport, shows that the oldest thrusts are structurally highest, and suggests that the Jeff Cabin thrust, as defined by Link and others (1985), does not exist. Two major, structurally higher imbricates of the Putnam thrust, the Narrows and Bear Canyon thrusts, define three large thrust slices within the Putnam plate. The Toponce thrust, on the east side of the range, is proposed as an eastward extension of the Bear Canyon thrust. In this paper, the term "subplate" will be used for the separate thrust slices within the Putnam plate; the term "plate" is restricted to thrust sheets bounded above and below by "major" thrust faults (Dahlstrom, 1970).

A realistic interpretation of the structural geology of the northern Portneuf Range, as well as a large part of southeastern Idaho, involves understanding the effects of Tertiary extensional faulting. The most obvious effect is down-to-the-east block faulting and a model is described whereby block rotation results from movement along mostly west-facing listric faults.

STRATIGRAPHY OF THE NORTHERN PORTNEUF RANGE

A thick sequence of Precambrian to Mesozoic miogeoclinal rocks crops out in the northern Portneuf Range (Fig. 2). Detailed descriptions of these units in the study area are given by Kellogg and others (1989), Kellogg (1990), and Hladky and Kellogg (1990). The oldest and most widely exposed sequence of rocks is the Late Proterozoic and Lower Cambrian Brigham Group (Crittenden and others, 1971; Link and others, 1985, 1987), composed of about 4,000 m of quartzite and subordinate interbedded quartzose conglomerate and siltstone. The Late Proterozoic Caddy Canyon Quartzite (Crittenden and others, 1971) of the Brigham Group is the oldest exposed unit in the northern Portneuf Range, although older rocks of the lower Brigham Group and underlying Late Proterozoic Pocatello Formation crop out in the Pocatello Range immediately to the west (Trimble, 1976).

Approximately 1,000 m of section, based on estimates from Oriel and Platt (1980), have been removed from the study area (Fig. 3a) by the Putnam thrust, although the total stratigraphic offset across the thrust at any one locality is considerably greater. This point will be discussed further in the next section.

Within the hanging wall of the Putnam thrust, the Brigham Group is overlain stratigraphically by several thousand feet of Cambrian to Lower Silurian carbonate and minor clastic rocks. The Upper Ordovician and Lower Silurian Fish Haven Dolomite is the youngest unit in the hanging wall, although the uppermost (Silurian) part of the unit is not believed to crop out in the study area (Fig. 3a). The Silurian Laketown Dolomite, however, which overlies the Fish Haven Dolomite, has been reported a few kilometers south of the area of Figure 3a (Corbett, 1978).

Figure 2 near here

Figure 3 near here

The oldest exposed unit in the footwall of the Putnam thrust, near the southeastern exposed extent of the Putnam thrust, is the Mississippian Lodgepole Limestone, above which is exposed a northeast-dipping, faulted sequence of rocks as young as the Middle Jurassic Twin Creek Formation (which crops out in the northern Portneuf Range about 8 km northeast of the area of Figure 3a; Trimble, 1982; Hladky and others, 1991). This marks the westernmost exposures in the thrust belt of rocks younger than the Lower Triassic Dinwoody Formation.

STRUCTURAL GEOLOGY OF THE NORTHERN PORTNEUF RANGE

Mesozoic thrusting

The Putnam thrust and its overlying splays, including the Bear Canyon, Narrows, and Toponce thrusts, are the dominant Mesozoic structures of the northern Portneuf Range (Figs. 3 and 4). At its leading edge, the Putnam thrust generally places Ordovician rocks above the Pennsylvanian and Permian Wells Formation, although in its southeastern exposures, the Cambrian Nounan Formation overlies the Mississippian Little Flat Formation (Amerman, 1987). Total stratigraphic offset varies across the Putnam thrust due to lateral and frontal ramping (e.g. Fig. 5), but does appear to decrease southeastward. In the northern part of the study area, approximate stratigraphic offset across the thrust, measured between the Ordovician Garden City Limestone and the Permian and Pennsylvanian upper Wells Formation, is about 3,700 m. At the southeastern exposures of the thrust, stratigraphic offset between the Nounan Formation and the Little Flat Formations is about 3,100 m. This apparent (though slight) decrease in stratigraphic offset to the southeast supports the idea that the Putnam and Paris thrusts form a thrust-transfer system (see Rodgers and Janecke, this volume).

A number of features contribute to a complex thrust geometry, including (1) at least three large subplates (or horses) overlying the Putnam thrust, (2) steep thrust ramps, both frontal and lateral, (3) east-trending Mesozoic tear faults (compartmental faults of Brown, 1984), which accommodate different styles of shortening on either side of the tear fault, and (4) locally developed, tight, nonparallel folds and well-developed cleavage.

Three principal subplates overlie the Putnam thrust in the northern Portneuf Range and are bounded by two thrusts (one of which, the Narrows thrust, is a steep lateral ramp) that appear to merge eastward with the Putnam thrust (Figs. 3a and 4). However, the branch lines, which define the joins between the two thrusts and the Putnam thrust, are not exposed. The three subplates are, from north to south and structurally lowest to highest, (1) the Lone Pine subplate, named for a canyon cutting through the subplate in the northern part of the area, (2) the Narrows subplate, named for the east-trending Narrows thrust, which dips steeply south along The Narrows of Ross Fork Creek, and (3) the Bear Canyon-Toponce subplate, named for the Bear Canyon thrust, which bounds the subplate on the west and north, and the folded and normal-faulted Toponce thrust, exposed on the east side of the range and which is believed to be an eastward extension of the Bear Canyon thrust. The Bear Canyon thrust was named by Pogue (1984) for a small canyon east of Mount Putnam and the Toponce thrust, first identified by Corbett (1978) and named and described by Kellogg and others (1989), is named for nearby Toponce Creek (Fig. 3a). Several other smaller imbricate thrust slices also have either been mapped or inferred.

Figure 4 near here

The Lone Pine subplate, which was extensively faulted and locally brecciated during Tertiary extension, contains exposed rocks as old as the Middle and Upper Cambrian Nounan Formation and as young as the Upper Ordovician and Lower Silurian Fish Haven Dolomite (Hladky, 1986). Rocks of the subplate mostly dip 20^{o}-50^{o} to the east and deformation (folding and thrust-parallel shearing) during Mesozoic thrusting was apparently minimal.

In the northern part of the map area, Tertiary extensional faults have juxtaposed rocks from the upper (Putnam/Lone Pine) and lower (Meade) plates of the Putnam thrust in a complex geometry (Figs. 3a and 5). On cross section B-B′ (Fig. 5a), restoration of Tertiary movement indicates that the Putnam thrust ramps up through the Cambrian and Ordovician section in the hanging wall. In the footwall, the thrust is a flat in the lower Wells (to the west), ramps through the upper Wells Formation and the Phosphoria Formation, and appears to flat in the Dinwoody Formation (to the east). If this interpretation is correct, the two anticlines in the lower plate may either be fault-bend folds (ramp anticlines) or fault-propagation folds (Woodward and others, 1985) that overlie a deeper (Meade?) thrust.

Figure 5 near here

The Narrows thrust, which defines the northern margin of the Narrows subplate, is not, strictly speaking, a thrust, but a steeply south-dipping lateral ramp having a large component of strike-slip movement; Trimble (1982) called it a tear fault. The Narrows subplate contains exposed rocks as old as the Late Proterozoic Caddy Canyon Quartzite and as young as the Upper Ordovician and Lower Silurian Fish Haven Dolomite. Many of the rocks within the Narrows subplate, especially those in the Brigham Group along the west side of the range, are strongly folded, sheared, and overturned. Where the Narrows thrust is exposed along Ross Fork Creek, it places Caddy Canyon Quartzite over Lower Ordovician Garden City Limestone, although beneath the covered area to the east, the thrust is inferred to ramp steeply up section eastward in both the hanging wall and footwall. The Narrows thrust probably merges with the Putnam thrust under a thick, faulted, east-dipping (by as much as about 35^{o}) sequence of mostly volcanogenic sediments (Hladky, 1986), correlated with the upper Miocene Starlight Formation of Carr and Trimble (1963).

The Bear Canyon-Toponce subplate contains rocks as old as the Late Proterozoic Caddy Canyon Quartzite on the west and as young as the Upper Cambrian and Lower Ordovician St. Charles Formation on the east. Most rocks within the subplate dip to the east less than 50^{o}, although there are several gentle, north-trending folds with wave lengths of about 1 km (Fig. 3a), suggesting ramping by an underlying thrust. Internal deformation, such as shearing, is relatively slight.

Along the west side of the range south of Mill Creek, the Bear Canyon thrust dips to the east beneath mostly east-dipping

Caddy Canyon Quartzite of the Bear Canyon-Toponce subplate. In the footwall (Narrows subplate), the thrust ramps down section to the south through the lower part of the Middle Cambrian Elkhead Limestone, the Lower and Middle Cambrian Gibson Jack Formation, and the uppermost part of the Late Proterozoic and Lower Cambrian Camelback Mountain Quartzite (Fig. 3a). One to two kilometers south of Mill Creek, excellent topographic control demonstrates that the Bear Canyon thrust dips 52^{o} eastward, about 20^{o} less steeply than beds both above and below the thrust (Kellogg, 1990). Offset of hanging-wall and foot-wall cutoffs suggests about 3-4 km of movement on the Bear Canyon thrust.

The clearly hanging-wall-down geometry rules out the possibility that the Bear Canyon thrust is a back thrust, similar to those described by Webel (1987); prior to Neogene extension and down-to-the-east rotation (to be discussed), the Bear Canyon thrust, in fact, may have been nearly horizontal or west dipping.

The Bear Canyon thrust is offset across several east-trending faults near its northern extent where it curves to the east. It is inferred to merge with the Putnam thrust under the Quaternary and Tertiary deposits of Jeff Cabin Creek (Fig. 3a). The branch line plunges to the southeast, passing east of the area of outcrop for the Toponce thrust (Fig. 3a). This branch-line geometry is mandated if the Toponce and Bear Canyon thrusts represent the same surface, as seems reasonable; strongly deformed rocks exposed beneath the Toponce thrust would therefore be part of the Narrows subplate. Separate names are retained for the Bear Canyon and Toponce thrusts to indicate that interpretations other than a single thrust surface may be viable. For example, Kellogg and others (1989) suggest a slightly different (though not now favored) interpretation in which the Bear Canyon and Toponce thrusts represented a thrust-transfer system beneath the Bear Canyon-Toponce subplate.

Just east of the inferred intersection of the Bear Canyon and Putnam thrusts, the Putnam thrust is broken by numerous Tertiary normal faults into a zone with very complicated block-faulted geometry (Fig. 3a; Amerman, 1987). At many places, upper- and lower-plate rocks are juxtaposed across Tertiary faults and the generally southwest-dipping Putnam thrust is rotated within different fault blocks into various orientations. Several major northwest-trending Tertiary faults in this zone are downthrown on their northeast side, uncharacteristic of most normal faults in the region. Toward the south, within the zone of complex block-faulted geometry, the Putnam thrust is offset westward and lower stratigraphic levels are exposed in both upper- and lower-plate rocks. The lower stratigraphic exposure is due to down-section frontal ramping toward the southeast. At its southernmost extent north of the inferred intersection with the Bear Canyon thrust beneath Jeff Cabin Creek, the Putnam thrust places Ordovician and Cambrian St. Charles Formation of the Narrows subplate above Mississippian Little Flat Formation of the Meade plate. South and east of the intersection, Cambrian Nounan Formation of the Bear Canyon-Toponce subplate is structurally above Mississippian Little Flat Formation.

The Toponce thrust is folded and is broken by numerous Tertiary normal faults (Fig. 6). The thrust places upright quartzite of the Brigham Group over locally highly sheared and overturned Ordovician Swan Peak Quartzite and Garden City Formation of the inferred Narrows subplate. Many white or tan quartzite beds immediately above the Toponce thrust are placed in the Mutual Formation of the Brigham Group, although their colors are uncharacteristic of this normally maroon-colored unit. The Toponce thrust is downdropped to the west under Toponce Creek along a west-dipping Tertiary normal fault having about 900 m of throw.

Figure 6 near here

Pogue (1984) and Link and others (1985) placed a thrust they called the Jeff Cabin thrust along upper Jeff Cabin Creek. Recent mapping (Kellogg and others, 1989) demonstrates, however, that a continuous, east-dipping section of Cambrian and Ordovician rocks exists across this area and that the Jeff Cabin thrust does not exist.

Tear or compartmental faults are common in the study area and formed concurrently with Cretaceous thrusting. Most of these faults trend east-west and are characterized by different deformational styles across them. The structural complexities are increased by recurrent movement during Tertiary extension, as shown by broad zones of brecciation along and close to the tear faults. On Figures 3a and 4, several of these larger tear faults are shown.

In Mill Creek valley, the Bear Canyon thrust is segmented (or "compartmentalized") by several generally east-trending tear faults (Fig. 3a). Across each of these tear faults different units above and below the Bear Canyon thrust are juxtaposed and the structural style commonly changes. For example, between the Mill Creek and North Mill Creek faults the Bear Canyon thrust places Proterozoic Caddy Canyon Quartzite over dolomitized Middle Cambrian Elkhead Limestone. Between the North Mill Creek and Five Points faults the Bear Canyon thrust places Caddy Canyon Quartzite over Ordovician and Upper Cambrian St. Charles Formation. Farther north, between the Five Points and Putnam Summit faults (the latter named by Pogue, 1984), the Bear Creek thrust divides into two thrust imbricates that may bound the west end of a small horse (Fig. 3b; see next section). This interpretation is favored because it accounts for an otherwise excessively thick section of Ordovician and Cambrian units in the Narrows subplate between the south flank of Mount Putnam and Jeff Cabin Creek. As an alternative explanation, the two thrusts may simply merge into a single Bear Canyon thrust within a kilometer or so east of their area of outcrop. In either case, it appears that the Bear Canyon thrust locally ramps down section in the direction of tectonic transport below a small anticline in Brigham Group rocks about 4 km west of Little Toponce Creek (Fig. 3b). This is the only locality in the study area were such aberrant thrust relations have been observed.

Evidence for a duplex in the Narrows subplate

A duplex is a family of imbricate subsidiary thrusts, each of which asymptotically curves downward to a sole or floor thrust and upward to a roof thrust (Fig. 7; Boyer and Elliott, 1982). In a hinterland-dipping duplex (probably the more commonly described type), the foreland side of a horse is uplifted as the subsequently formed horse ramps upward, causing hinterland-dipping structures. In a foreland-dipping duplex, the hinterland side of each horse is uplifted as the subsequently formed horse ramps up underneath, thereby causing both bedding and horse-bounding thrusts to rotate into a foreland-dipping orientation. Unique to a foreland-dipping duplex is that the leading-edge ramp of each horse is nose down on the floor thrust, which undergoes continued movement during thrusting.

Figure 7 near here

The strong shearing and widespread east-vergent overturing that occurs at many localities in the Narrows subplate, in comparison to the relatively unsheared rocks structurally above and below the Narrows subplate, strongly suggest that the Bear Canyon-Toponce thrust defines a roof thrust and that the Putnam thrust defines a floor thrust of the front of a foreland-dipping duplex. Lack of well developed thrust-related deformation within the Lone Pine subplate, in comparison to that within the Narrows subplate, suggests that the Lone Pine subplate is not part of the duplex and that the steeply south-dipping Narrows thrust defines the northern boundary of the duplex; the Narrows thrust can be viewed as part of the floor thrust, merging with the Putnam thrust.

The Bear Canyon and Toponce thrusts both place upright, east-dipping or gently folded, essentially unsheared Brigham Group rocks above mostly overturned, west-dipping and commonly highly sheared rocks of the Narrows subplate that are as young as Ordovician (Fig. 3a). S- or Z-shaped folds with nearly horizontal axial planes, in which west-dipping beds are overturned and east-dipping beds are upright, are characteristic of many localities in the Brigham Group quartzites (Fig. 3b) and reflect the extreme shear parallel to thrusting. Spectacular examples of nearly isoclinal folds with horizontal axial planes in Camelback Mountain Quartzite are found in the canyon of Mill Creek (Fig. 8; Pogue, 1984).

Figure 8 near here

Postulated eastward tilting of parts of the Portneuf Range by 30^{o}-40^{o} during Neogene extensional faulting (to be discussed) certainly accounts for a large component of eastward dip of structures within the Narrows subplate, but leaves room for a large additional component of eastward dip due to the formation in Cretaceous time of a foreland-dipping duplex. Prior to Neogene eastward rotation, for example, the S-shaped folds described above were probably east-vergent recumbent folds with west-dipping axial planes. Such structures are suggestive of the overturned frontal limb of a large thrust nappe. However, the fact that a well-defined roof thrust (Bear Canyon thrust and its probable extension, the Toponce thrust) bounds the Narrows subplate makes the duplex model seem more reasonable.

The extremely sheared and overturned Ordovician rocks beneath the Toponce thrust may comprise several thrust imbricates or small, foreland-dipping horses (Fig. 6). The deformational style of these footwall rocks is very similar to that observed in the canyon of Mill Creek and elsewhere in the Narrows subplate and lends support to a model for formation of a foreland-dipping duplex within the Narrows subplate.

Beds are tectonically thickened and thinned within the Narrows subplate, reflecting extreme internal shear during thrusting. This structural style is in marked contrast to the homoclinally east-dipping beds of the Lone Pine subplate and the east-dipping to gently folded rocks of the Bear Canyon-Toponce subplate. Thickening of beds is probably due to a combination of bedding-plane slip, small-scale duplex stacking and thrust imbrication, and ductile flow. Thinning of beds is by low-angle normal faulting and, in overturned limbs of folds, by tectonic stretching. Unrecognized map-scale faults also may have contributed to apparent changes in bedding thickness.

A good example of tectonic thickening of the Camelback Mountain Quartzite and the Mutual Formation within the Narrows subplate occurs in and north of Mill Creek, where many tight to isoclinal, parasitic folds along bedding-slip planes can be seen in the canyon walls (Fig. 8). On the west side of Mount Putnam, the overturned Mutual Formation is as thick as about 820 m and the overturned Camelback Mountain Quartzite is as thick as about 510 m. These two formations have been tectonically thinned elsewhere, such as near the southern boundary of the map area (Fig. 3a), where the generally upright Mutual Formation is as thin as about 490 m and the upright Camelback Mountain Quartzite is as thin as about 270 m. It should be noted that the Camelback Mountain Quartzite is reported to be as thick as 1,000 m near Pocatello but is observed to be much thinner elsewhere (Trimble, 1976); this variation suggests that tectonically induced changes in thickness of the Camelback Mountain Quartzite may be widespread. The Mutual Formation is reported to be 800-900 m thick near Pocatello (Trimble, 1976).

Without additional subsurface data and detailed field studies, the lateral extent of the proposed foreland-dipping duplex in the northern Portneuf Range into areas adjacent to the range is, at best, speculative. One regional model for a foreland-dipping duplex, extending from the Portneuf Range westward at least through the northern Bannock Range, was suggested by Kellogg and Skipp (1988), although it is now apparent that their model did not adequately accommodate the role of Tertiary listric faulting and block rotation.

Cleavage in argillic rocks

Shear parallel to the direction of transport may cause initially formed cleavage to rotate, producing a fanning of cleavage orientations about a line perpendicular to the direction of tectonic transport. Fanning of cleavage directions is especially well developed during the extreme shear associated with duplex formation (Boyer and Elliot, 1982, Fig. 7). Limited fanning of "axial-plane" cleavage also commonly occurs in folds by refraction through beds of differing competency.

Well-developed slaty to phyllitic cleavage is present in all argillic rocks of the Brigham Group in the northern Portneuf Range. In addition, many of the Brigham Group quartzites, especially in the sheared, overturned limbs of recumbent folds, have developed a poorly developed shear-induced schistocity. Secondary minerals are tentatively identified as sericite, chlorite, and epidote, indicating greenschist-facies metamorphism. Metamorphic grade appears to be slightly higher in the Inkom Formation than in the stratigraphically higher Gibson Jack Formation, suggesting that burial metamorphism, predating Mesozoic thrusting, contributed at least partially to the metamorphic mineral assemblage.

Cleavage orientations were measured in argillic rocks of the Narrows and Bear Canyon-Toponce subplates. In both cases, the orientations are highly scattered (Fig. 9a), commonly changing by tens of degrees over distances less than 100 m within rocks of apparently similar competency. Poles to cleavage generally are scattered along an east-west line, as would be expected by progressive rollover in a west-over-east simple shear regime. The east-west spread of cleavage directions might be expected to be better defined for rocks within a foreland-facing duplex, where shear would probably be more extreme than where progressive rollover was relatively unimportant. The spread, however, appears to be as well developed in the Bear Canyon-Toponce subplate as it is in the Narrows subplate, which probably reflects the extreme ductility and resultant deformation of argillic rocks in both the Narrows and Bear Canyon-Toponce subplates. For example, abundant small-scale folds are observed in almost all argillites in the area (Kellogg, 1990; Kellogg and others, 1989).

The considerable departure of some orientations from the east-west line (Fig. 9a) is natural in any thrust system where there exists numerous, complicated, laterally varying structural domains, such as develop near lateral ramps, tear faults, and other thrust-related features (S.E. Boyer, written commun., 1989). However, except for the attempt to discriminate cleavage between the Narrows and Bear Canyon thrust subplates, no attempt was made to differentiate cleavage into different structural domains.

Cleavage also has no obviously consistent geometric relationship to bedding orientations (Fig. 9b), as would occur if cleavage developed during pre-folding, layer-parallel shear (Mitra and others, 1984); cleavage orientations are clearly highly scattered with respect to the orientation of bedding planes in both the Narrows and Bear Canyon-Toponce subplates. It may be noted, however, that the method by which cleavage was rotated--about the strike of bedding by the amount of dip--is not a unique solution to the problem of restoring bedding to horizontal.

Figure 9 near here

Neogene extensional faulting

Neogene extension has affected, to varying degrees, all of southeastern Idaho, and the northern Portneuf Range displays many of the extensional features typical for the region. A buried, linear, range-front fault is believed to bound at least part of the impressive west side of the range (Kellogg, 1990); on the east side of the range the topography is more subdued and irregular and elevations are generally lower. These features suggest that the northern Portneuf Range has the general form of a half-horst, uplifted on the west and (or) downdropped on the east. The Neogene structures are complicated by an extensive network of normal faults within the range (Fig. 3a). Much, if not most, of the regional extension was accommodated along these numerous, mostly west-dipping faults (Kellogg, 1987; Kellogg, 1990; Kellogg and others, 1989; Hladky and others, 1991).

Extensional faulting is at least as old as about 10 Ma, the maximum-known age of valley-fill deposits in the region (Starlight Formation of Carr and Trimble, 1963), although a major pulse of Basin and Range faulting may have occurred about 7 Ma (Kellogg and Marvin, 1988).

Most intermontane Miocene and younger basin-fill deposits in the region dip to the east or northeast (Hladky, 1986; Hladky and others, 1991; Link and others, 1985; K.S. Kellogg, unpublished data and Fig. 10). Dips are generally less than about 35^{o}, which is also true for Eocene volcanic rocks which bound the northeastern end of the Portneuf Range (Hladky and others, in press). Larger eastward dips in Miocene and younger rocks, though rare, are known in the northern Portneuf Range (for example, Hladky and others, 1991). In the southern Portneuf Range, down-to-the-east rotation of Tertiary beds by as much as 90^{o} along concave-westward listric faults has been described (Sachs and Platt, 1985); the rotation brought originally west-dipping Paleozoic and Proterozoic rocks into an east-dipping orientation.

At most places, the amount of Neogene rotation of pre-Tertiary rocks cannot be determined. However, based on known attitudes of tilted Tertiary beds in the northern Portneuf Range, it seems reasonable that the rotation at most localities was no more than about 30^{o} to 40^{o} eastward.

Eastward dip on Tertiary units and the existence of numerous west-dipping normal faults suggests that a regional detachment onto which concave-westward listric faults merge underlies the area. Obvious candidates for such detachment surfaces are thrust faults. Listric normal faults commonly sole into thrusts, especially near the tops of ramps (Royce and others, 1975). A good example is shown on Fig 5a (about 3 km from the left margin), where a brecciated, west-dipping normal fault zone, about 30 m across, merges with the Putnam thrust above a footwall ramp; the normal fault is not shown on the simplified map of Fig. 3a. Another example occurs one km east of Toponce Creek, where several west-dipping normal faults merge with the Toponce thrust near the top of a thrust ramp (Fig. 6).

Further evidence of widespread Neogene extensional faulting in the northern Portneuf Range is the existence of breccia zones, which are not characteristic of thrust faults of the Idaho-Wyoming thrust belt (Armstrong and Oriel, 1965). Breccia zones are particularly common in Brigham Group quartzites within several tens of meters above the Bear Canyon thrust near Putnam Peak (Pogue, 1984; Kellogg, 1990) and may be due to brittle readjustment during backsliding in the zone between the curved normal fault and the more-planar thrust plane. The brittle behavior reflects the lower pressures and temperatures that existed during extensional deformation as compared to those that existed during thrusting.

In the northern part of the study area, restoration of Tertiary movement suggests that about ten percent extension has occurred (Fig. 5b), although the amount of extension is dependent on the original dip and curvature of the fault planes, which in most cases are poorly constrained. Topographic expression of a few fault traces in this area, however, and the fact that most Tertiary faults are west side down, suggest that most Tertiary normal faults are west dipping (Hladky and Kellogg, 1990).

The existence of a thrust surface onto which the normal faults may merge is suggested by the two anticlines shown in Figure 5b--possibly fault-bend or fault-propagation folds--in the footwall of the Putnam thrust. The depth to such a surface (the Meade thrust?), which would govern the curvature of the normal faults, is conjectural. Irrespective of what curvature is chosen for the normal faults, restoring the cross section to a pre-Tertiary configuration produces large overlaps or gaps, which are largest near those Tertiary faults having the greatest offset.

The overlaps and gaps caused by Tertiary normal faulting were apparently accommodated by brecciation, which is most widespread near normal faults with the greatest throw. For example, the Fish Haven Dolomite is brecciated over an area as large as 1 by 3 km between two large north-trending faults (Fig. 5a and Hladky and others, 1991). The two faults, having vertical separations between 500 and 1,000 m, define a large graben bounded by rocks of the Putnam thrust's lower plate.

The probable influence of Snake River Plain volcanism on the Neogene tectonics of the northern Portneuf Range cannot be ignored. Rocks are downwarped toward the plain (Sparlin and others, 1982)), and the extent and complexity of normal faulting seems to increase towards the Snake River Plain margin (Kellogg, 1987; Hladky and others, 1991). There is also a striking similarity between the ages of major caldera-forming events in the plain and extensional faulting in adjacent mountain ranges (Pierce and Scott, 1986; Pierce and Morgan, this volume); both volcanism and faulting become progressively younger towards the northeast, parallel to the axis of the plain.

Faults of unequivocal Quaternary age have not been identified in the northern Portneuf Range. Immediately west of the northern part of the map area (Fig. 3a), however, northwest-trending faults, having as much as about 10 m displacement, cut basalt flows (Kellogg and Embree, 1986) that are as young as about 2.2 Ma, or late Pliocene (Kellogg and Marvin, 1988).

STRUCTURES WEST OF THE NORTHERN PORTNEUF RANGE

The Pocatello Range lies immediately west of the northern Portneuf Range and is underlain by a mostly east-dipping, extensionally faulted section of rocks ranging from the Late Proterozoic Pocatello Formation (the oldest exposed unit in the thrust belt) to rocks as young as the Permian and Pennsylvanian Wells Formation (Trimble, 1976; Hladky and others, 1991). The northern edge of the Pocatello Range contains exposed rocks of Silurian and Devonian age (within in area marked "a" in Fig. 10), unlike the northern Portneuf Range where exposed rocks of these ages have been removed by the Putnam thrust. A structural interpretation of parts of the Pocatello Range was made by Ludlum (1943), refined by Trimble (1976), and later reinterpreted by LeFebre (1984), Link and others (1985), and Burgel and others (1987). West of the Pocatello Range, the northern Bannock Range contains a homoclinally east-dipping sequence of Brigham Group and Cambrian carbonates, cut by numerous Neogene extensional faults (Trimble, 1976). Figure 10 is a simplified interpretation of the geology in the region between the northern Bannock Range and the northern Portneuf Range, compiled from the above sources and from unpublished observations.

Rotation by movement along Neogene west-dipping listric faults has been suggested as the cause for eastward dip of structures in the Pocatello Range and northern Bannock Range (Burgel and others, 1987; Hersley, 1988), similar to that described for the northern Portneuf Range. Concave-westward, gently west-dipping normal faults have been described cutting homoclinally east-dipping beds of the Brigham Group, immediately south of Inkom in the northern Bannock Range (Hersley, 1988). Burgel and others (1987) also have described gently west-dipping normal faults east of the Blackrock Canyon fault (shown on Fig. 10) and immediately north of Inkom (these faults are not shown on Figs. 10 and 11). A fold (Rapid Creek fold, also not shown on Figs. 10 and 11) in Brigham Group quartzites, originally with eastward vergence, is believed by Burgel and coworkers to have been rotated during normal faulting into its present position with a nearly horizontal axial plane. The Rapid Creek fold thus appears to be similar to folds observed in Mill Creek in the northern Portneuf Range (Figs. 3b and 8).

The structures underlying the area of Figure 10 are poorly known due to a lack of both seismic and deep-well control. The geometry of the subsurface structures, however, is not purely conjectural. Based on much more extensive seismic, deep-well, and magnetic control to the east, an east-west cross section, extending down to magnetic basement and drawn as far west as the Portneuf Range was suggested by Royce and others (1975, plate IV; the west end is approximately at 112°03′ W., 42°30′N., about 25 km south of the southern border of Fig. 10). Their cross section, although in large measure interpretive, deserves careful study and serves to make the following points: (1) depth to magnetic basement, immediately above which is an inferred basal decollement, is about 25,000 ft (7,600 m) below sea level under the Portneuf Range, (2) the basal decollement dips to the west about 7^{o} under the Portneuf Range, (3) the Absaroka thrust soles into the basal decollement immediately east of the Portneuf Range, (4) the Paris thrust (which may be a southern extension of the Putnam thrust) and the Meade thrust also merge together immediately east of the southern Portneuf Range, (5) major down-to-the-west range-bounding faults merge with the Absaroka thrust or the basal decollement, (6) structures are inferred to be rotated into the major normal faults with a significant component of drag, such that synclines as much as 10 km wide form on the west side of the normal faults, and (7) the Meade thrust has moved about 20 miles (32 km), based on offset of the Nugget Sandstone.

Figure 10 near here

Figure 11 near here

Based on surface outcrops and the guidelines suggested by Royce and others (1975), a schematic cross section can be drawn across the Bannock, Pocatello, and Portnuef ranges (Fig. 11). Accepted conventions of thrust faulting (e.g. Royce and others, 1975; Boyer and Elliott, 1982) have been followed and the cross section, as much as possible, is area balanced. A stratal wedge, tapering about 2^{o} to the east, is assumed.

The Pocatello and Bannock Ranges, similar to the Portneuf Range, are shown rotated down to the east along west-dipping Neogene listric faults that bound the ranges (including the east-bounding valleys) on their eastern sides. These major faults are inferred to sole in the basal decollement above crystalline basement and account for the regional eastward dip of pre-Tertiary beds and the generally eastward dip of Miocene and Pliocene basin-fill deposits. The dip on the Neogene beds is, however, generally less than that on the pre-Tertiary beds and structures.

In contrast to the above interpretation, Trimble (1976, p. 69) believes that the mountain block that forms the Bannock Range is not tilted. He notes the existence in the range of a nearly horizontal, "pre-basin-and-range" erosional surface that truncates east-dipping quartzites. Nonetheless, rotation of the range is favored because (1) the inferred erosional surface is not dated, so may postdate block rotation, (2) Neogene basin fill flanking the Bannock Range generally dips to the east, and (3) pre-Tertiary sedimentary rocks dip nearly homoclinally eastward.

Numerous, mostly west-side-down normal faults, smaller than the range-bounding normal faults, are found throughout the Portneuf, Pocatello, and Bannock Ranges (e.g. Kellogg, 1990; Hladky and others, 1991). Most of these within-range faults (not shown on Fig. 11) are generally west-dipping listric faults, similar to the range-bounding faults, but may sole on a detachment surface (Putnam or Meade thrust?) significantly above the basal decollement; such an interpretation is made in Figure

3b. Royce and others (1975) avoid interpreting the subsurface geometry of the within-range normal faults in the Portneuf Range, which are drawn on their cross section simply as steep, straight lines that terminate at a depth of several thousand feet. The within-range normal faults may, in fact, account for a large part of the eastward dip of structures and may also explain the observed high variability in the amount of eastward rotation, which is particularly evident in the northern Portneuf Range.

Neogene extension and rotation of range-sized blocks accounts for the surface geometry of structures in the Pocatello Range inferred to be westward projections of the Putnam and Bear Canyon thrusts. The Putnam thrust is believed to strike westward or southwestward across the northern Pocatello Range, juxtaposing Late Proterozoic rocks of the Brigham Group and Pocatello Formation to the south above middle and upper Paleozoic rocks to the north (inferred lower-plate rocks occur within the area marked "a" in Fig. 10). The precise location of the thrust is unknown due to thick, extensive deposits of Tertiary diamictite (Trimble, 1976; Hladky and others, 1991). Similar deposits in the northernmost Portneuf Range were interpreted as debris flows that formed during rapid basin-and-range uplift in late Miocene time (Kellogg and Marvin, 1988). The exposed lower-plate rocks comprise a homoclinal, east-dipping sequence as old as the Ordovician and Silurian Fish Haven Dolomite (Trimble, 1976) and as young as the Mississippian Monroe Canyon Limestone (Hladky and others, 1991; previously mapped as Wells Formation by Trimble, 1976). The generally southwestward strike and southeastward dip of the inferred Putnam thrust is believed due to tens of degrees of down-to-the-east Neogene block rotation.

The Bear Canyon thrust is believed to have been downdropped on the west by at least 2.5 km along a major Neogene fault that extends along the west side of the Portneuf Range (Figs. 10 and 11). In the Pocatello Range, the inferred westward extension of the Bear Canyon thrust is a curved east- and north-dipping surface that juxtaposes Caddy Canyon Quartzite of the lower Brigham Group and Pocatello Formation above Brigham Group rocks with about 1.2 km of stratigraphic throw (from reinterpretation of Trimble, 1976). Total movement on the Bear Canyon thrust, determined from offset of the base of the Brigham Group, is about 4.5 km (Fig. 11), in good agreement with about 3-4 km of movement observed across the Bear Canyon thrust in the Portneuf Range.

The above interpretation implies that rocks in the Pocatello Range and Bannock Range underlying the inferred Bear Canyon thrust are westward extensions of the Narrows subplate. Although these rocks are mostly homoclinally east dipping, many structures are similar to those found in the Narrows subplate of the northern Portneuf Range. For example, west of the town of Inkom, both north and south of the Portneuf Narrows (Fig. 10), overturned, cleaved beds within east-vergent recumbent folds in rocks of the Pocatello Formation are bounded above by at least one east-dipping, older-over-younger thrust (Blackrock Canyon fault) (LeFebre, 1984; Link and others, 1985; Fig. 10); rocks above the thrust dip homoclinally to the east. These relationships are similar, on a smaller scale, to those observed across the Bear Canyon thrust in the northern Portneuf Range.

East-dipping thrusts above overturned and folded beds may be roof thrusts to small duplexes or horse-bounding thrusts within a duplex.

The inferred extension of the Bear Canyon thrust into the Pocatello Range requires in the Bannock Range that the deeply buried Bear Canyon thrust juxtapose Pocatello Formation above either Pocatello Formation or Brigham group rocks. This in turn indicates a minimum of 5 km total west-side-down movement along the normal faults that front the west side of the Pocatello Range.

One small subplate, underlain by a low-angle fault in the west-central part of the Pocatello Range, places Brigham Group quartzite over the older Pocatello Formation (Fig. 10; Trimble, 1976). Link and others (1985) concurred with Trimble (1976) that this structure is a younger-over-older thrust and point out that younger-over-older flat faults have been observed in several places in the region. Alternatively, I suggest that this structure may be an extensional fault that formed considerably later than during Cretaceous thrusting but prior to Neogene high-to moderate-angle normal faulting.

CONCLUSIONS

The northern Portneuf Range and surrounding mountain ranges have undergone two major periods of deformation: Early Cretaceous compressional deformation and Neogene (mostly late Miocene) extensional faulting. Although the Putnam thrust has long been recognized as the major compressional feature in the area, the detailed structure of the complexly deformed upper plate is only now beginning to be understood.

The Putnam thrust juxtaposes Ordovician rocks above Permian and Pennsylvanian rocks along most of the thrust front. Along its southeastern exposed extent, the thrust ramps downsection toward the southeast; at its southeasternmost exposures, the thrust places Cambrian rocks above Mississippian rocks.

Two major and several minor imbricate thrusts have been identified above the Putnam thrust. From north to south and structurally lowest to highest, two of the major imbricates in the northern part of the area are the steeply south-dipping Narrows thrust and the mostly south- to east-dipping Bear Canyon thrust. The Toponce thrust, in the southeastern part of the area, is believed to be a southeastward extension of the Bear Canyon thrust.

In the northernmost part of the area, the Lone Pine subplate underlies the Narrows thrust and overlies the Putnam thrust. Where exposed, the Narrows thrust is a steep, east-striking lateral ramp, probably having a large component of strike-slip movement, that merges eastward with the Putnam thrust.

The Narrows subplate has undergone tremendous internal shear, producing recumbent folds, cleavage directions that fan about northerly strikes, east-dipping contraction faults, and tectonic thickening and thinning of beds. These features strongly suggest that the Narrows subplate forms at least part of a foreland-dipping duplex in which the Bear Canyon (and its inferred extension, the Toponce thrust) form a roof thrust and the Putnam thrust forms the main floor thrust; the east-trending Narrows thrust, which merges with the Putnam thrust, defines the northern floor-thrust boundary. Rocks within the Lone Pine subplate, structurally beneath and north of the Narrows thrust, are upright and not significantly sheared, suggesting that the Lone Pine subplate was not part of the duplex.

The extent of the proposed duplex within the Narrows subplate is unknown and its extension into the ranges west of the northern Portneuf Range is also unknown. However, east-dipping thrusts and overturned, folded beds beneath thrusts in the Portneuf Narrows area near the southwest side of the Pocatello Range suggest that local duplex formation may have affected this area.

The formation of a foreland-dipping duplex cannot account for all the apparent rotation of structures within the Narrows subplate. Regional eastward dips, generally less than 35°, of Tertiary rocks throughout a large part of southeastern Idaho strongly suggest that Neogene extensional faulting caused widespread down-to-the-east rotation along concave-westward listric faults that probably merge onto a regional detachment surface or several such surfaces; these surfaces are most likely reactivated thrusts (Royce and others, 1975) along which Neogene movement was approximately opposite to that during Cretaceous thrusting.

Major range-bounding faults may sole into the basal decollement immediately above crystalline basement, which is inferred to be about 9-10 km beneath the Portneuf Range. Smaller, within-range normal faults probably merge on higher-level reactivated thrusts, a view supported by observed normal faults that merge with the Putnam and Toponce thrusts and the existence of extensive zones of brecciation immediately above the Bear Canyon thrust.

Neogene block rotation also accounts for reasonable westward projections of the Putnam and Bear Canyon thrusts into the Pocatello Range.

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CAPTIONS

Figure 1. Index map of part of southeastern Idaho showing location of study area, area of Figure 10 , and Fort Hall Indian Reservation (short-dashed line).

Figure 2. Generalized stratigraphic column of rocks exposed in study area (Fig. 3a). Upper part of Fish Haven Dolomite, which contains rocks as young as Silurian, is not believed to crop out in map area.

Figure 3. (a) Simplified geologic map of part of the northern Portneuf Range, showing total known extent of the Putnam thrust. Geologic symbols, except for QTu (Quaternary and Tertiary deposits, undivided), are defined in Figure 2. Map based on Corbett (1978), Hladky and Kellogg (1990), Kellogg (1990), Kellogg and others (1989), and Hladky and others (1991). (b) Cross section along line A-A′ on Figure 3a.

Figure 4. Diagrammatic tectonic map covering area of Figure 3a showing the major structural elements. Cross section along A-A′ shows relationships between subplates of the Putnam thrust and the Meade plate. Scale of cross section is reduced one-third from that of map. Note that bend in cross section causes opposing sense of movement on Putnam thrust on each side of bend.

Figure 5. (a) Cross section along B-B′ (shown on Fig. 3a), adapted from Hladky and Kellogg (1990). Cross section shows considerably more stratigraphic and structural detail than appears on Figure 3a. (b) Cross section B-B′ after all Tertiary faults have been restored to their pre-faulting positions. Cross-hatched areas are zones of overlap and horizontally lined areas are gaps. Dotted lines represent present ground surface.

Figure 6. Enlarged geologic map and cross section of Toponce Creek area. Location of map area shown on Figure 3a.

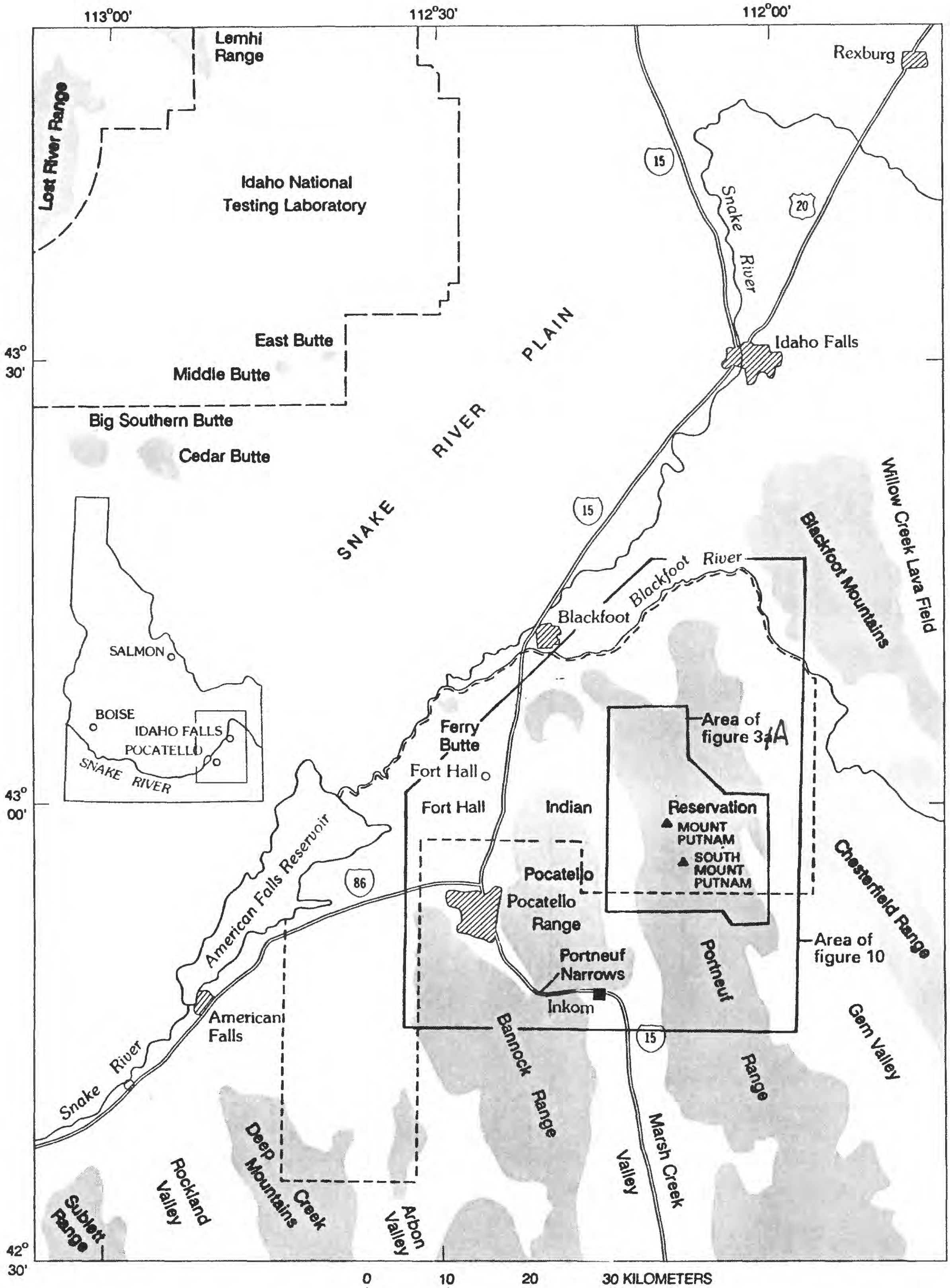
Figure 7. Schematic diagrams showing the development of (a) hinterland-dipping duplex, (b) antiformal stack (a situation intermediate to a hinterland- and foreland-dipping duplex), and (c) foreland-dipping duplex. Relative order of formation of horses is indicated by numbers, 1 being first formed; note that relative order in hinterland-dipping and foreland-dipping duplexes are reversed. Also note that any simple shear transferred to rocks above the floor thrust during both initial ramping and continued movement along the floor thrust will increase the leading-edge cutoff angle within each horse by thrust-parallel slip. Adapted from Boyer and Elliott (1982).

Figure 8. View, facing north, of recumbent syncline in Camelback Mountain Quartzite of the Narrows subplate near bottom of Mill Creek canyon. The nearly horizontal axial plane was probably west-dipping prior to Neogene rotation. Distance across outcrop is approximately 15 m. Photograph by P.K. Link.

Figure 9. Equal-area projection of cleavage orientations measured in the Narrows and Bear Canyon-Toponce subplates. All poles are lower hemisphere projections. (a) Poles to cleavage measured in the Narrows subplate (circles) and Bear Canyon-Toponce subplate (triangles). (b) Poles to cleavage, where bedding orientations were measured in same outcrop, after rotation by an amount necessary to restore bedding to horizontal (and upward facing).

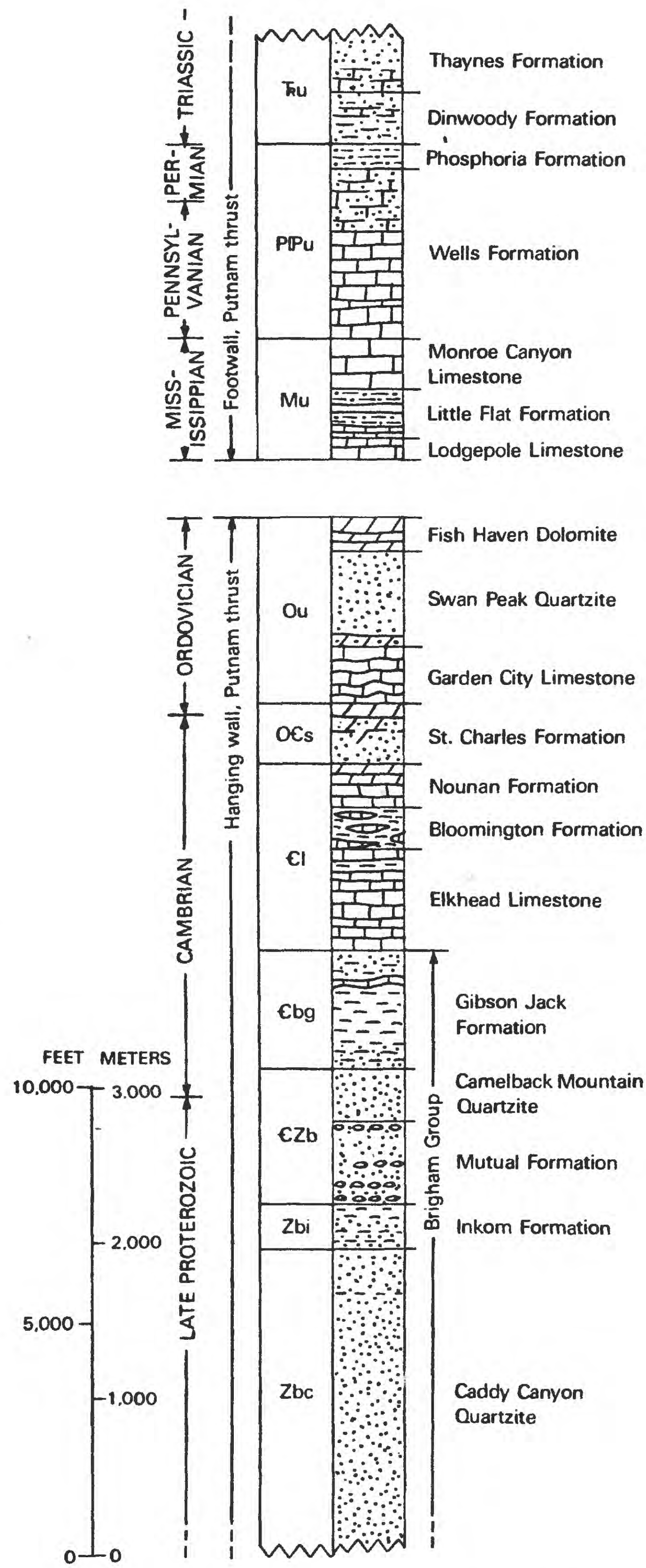
Figure 10. Generalized geologic map of northern Portneuf Range, Pocatello Range, and northern Bannock Range. Adapted from Mansfield (1952), Trimble (1976, 1982), Corbett (1978), Link and others (1985), Hefferan (1986), Kellogg and Marvin, 1988), Kellogg (1990), Kellogg and others (1989), and Hladky and others (1991). Blackrock Canyon Limestone of Trimble (1976) is included with Pocatello Formation. Strike and dip are shown for Tertiary units only. BCF is Blackrock Canyon fault. Area of outcrop labeled "a" is referred to in text. Area of Figure 10 shown on Figure 1.

Figure 11. Cross section along line A-A′ of Figure 10. All but the largest front-range Tertiary faults have been removed. The cross section is largely schematic, due to lack of seismic and deep-well data for area, although depth to Meade thrust, Absaroka thrust, and magnetic basement are approximately known from Royce and others (1975). BCT is Bear Canyon thrust, PMT is westward extension of Putnam and Meade thrusts, pЄu is Precambrian undivided, and random dash pattern is crystalline basement.



113°00'
112°30'
112°00'
43° 30'
43° 00'
42° 30'
Lemhi Range
Lost River Range
Idaho National Testing Laboratory
East Butte
Middle Butte
Big Southern Butte
Cedar Butte
SNAKE RIVER PLAIN
Rexburg
Snake River
Idaho Falls
15
20
Willow Creek Lava Field
Blackfoot Mountains
Blackfoot River
Blackfoot
SALMON
BOISE
IDAHO FALLS
POCATELLO
SNAKE RIVER
Ferry Butte
Fort Hall
Area of figure 3A
Fort Hall Indian Reservation
MOUNT PUTNAM
SOUTH MOUNT PUTNAM
American Falls Reservoir
86
Pocatello
Pocatello Range
Chesterfield Range
Area of figure 10
Portneuf Narrows
Inkom
Portneuf Range
American Falls
Gem Valley
Snake River
Bannock Range
Marsh Creek Valley
Rockland Valley
Deep Creek Mountains
Arbon Valley
Sublett Range
0 10 20 30 KILOMETERS

Fig. 1.



TRIASSIC
PER-MIAN
PENNSYL-VANIAN
MISS-ISSIPPIAN
Footwall, Putnam thrust
Ʀu
PIPu
Mu
Thaynes Formation
Dinwoody Formation
Phosphoria Formation
Wells Formation
Monroe Canyon Limestone
Little Flat Formation
Lodgepole Limestone
ORDOVICIAN
CAMBRIAN
LATE PROTEROZOIC
Hanging wall, Putnam thrust
Ou
O€s
€l
€bg
€Zb
Zbi
Zbc
Fish Haven Dolomite
Swan Peak Quartzite
Garden City Limestone
St. Charles Formation
Nounan Formation
Bloomington Formation
Elkhead Limestone
Gibson Jack Formation
Camelback Mountain Quartzite
Mutual Formation
Inkom Formation
Caddy Canyon Quartzite
Brigham Group
FEET
METERS
10,000
3,000
2,000
5,000
1,000
0
0

Fig. 2

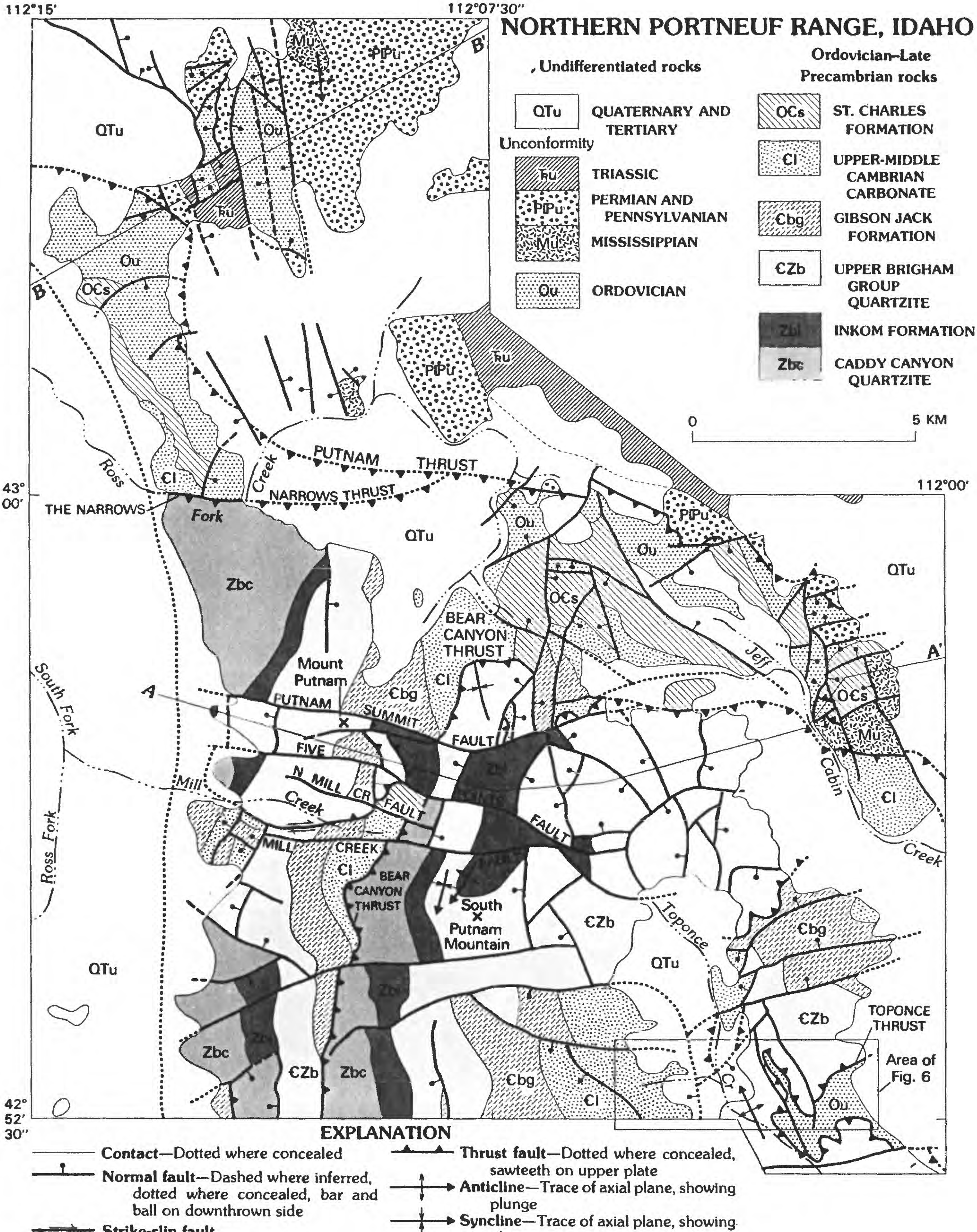

NORTHERN PORTNEUF RANGE, IDAHO
Undifferentiated rocks
QTu QUATERNARY AND TERTIARY
Unconformity
₸u TRIASSIC
PIPu PERMIAN AND PENNSYLVANIAN
Mu MISSISSIPPIAN
Ou ORDOVICIAN
Ordovician–Late Precambrian rocks
OCs ST. CHARLES FORMATION
Cl UPPER-MIDDLE CAMBRIAN CARBONATE
Cbg GIBSON JACK FORMATION
CZb UPPER BRIGHAM GROUP QUARTZITE
Zbl INKOM FORMATION
Zbc CADDY CANYON QUARTZITE
0 5 KM
112°15′
112°07′30″
112°00′
43° 00′
42° 52′ 30″
B
B′
A
A′
PUTNAM THRUST
NARROWS THRUST
THE NARROWS
Ross Fork Creek
South Fork
Ross Fork
Mill Creek
BEAR CANYON THRUST
Mount Putnam
PUTNAM SUMMIT FAULT
FIVE
N MILL CR FAULT
POINTS FAULT
MILL CREEK
South Putnam Mountain
Jeff Cabin Creek
Toponce Cr
TOPONCE THRUST
Area of Fig. 6
EXPLANATION
Contact—Dotted where concealed
Normal fault—Dashed where inferred, dotted where concealed, bar and ball on downthrown side
Strike-slip fault
Thrust fault—Dotted where concealed, sawteeth on upper plate
Anticline—Trace of axial plane, showing plunge
Syncline—Trace of axial plane, showing plunge

Fig. 3a.

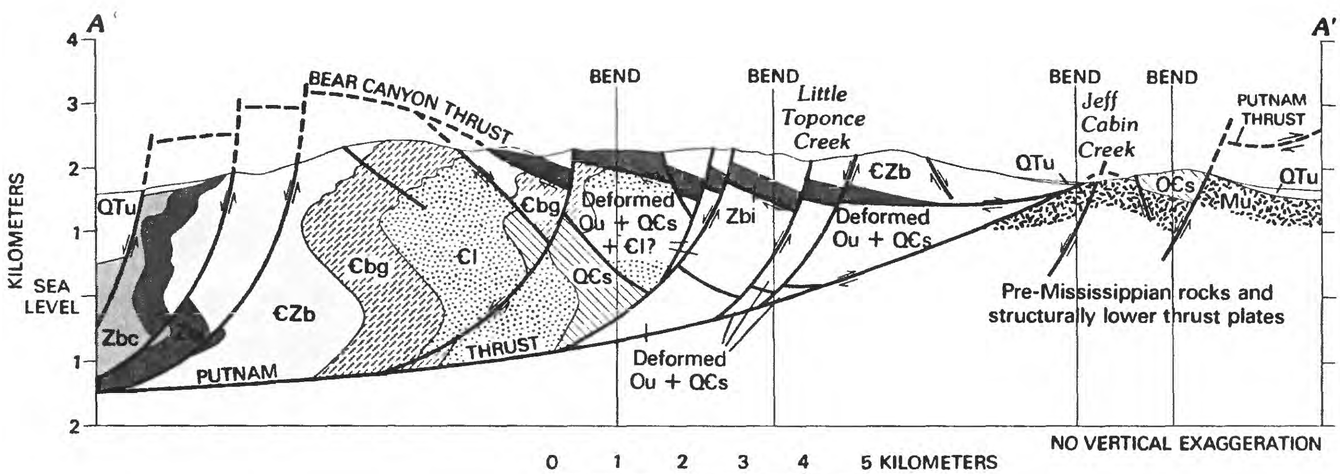
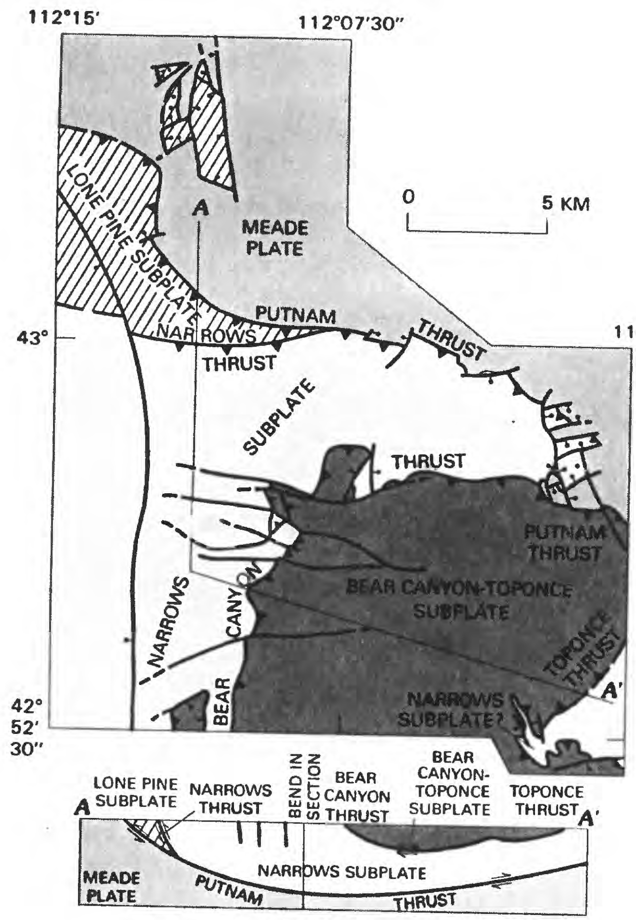

A
A'
BEAR CANYON THRUST
BEND
BEND
Little
Toponce
Creek
BEND
Jeff
Cabin
Creek
BEND
PUTNAM
THRUST
KILOMETERS
SEA
LEVEL
QTu
Zbc
€Zb
€bg
€l
QCs
€bg
Deformed
Ou + Q€s
+ €l?
Zbi
€Zb
Deformed
Ou + Q€s
QTu
Q€s
QTu
Mu
Pre-Mississippian rocks and
structurally lower thrust plates
THRUST
PUTNAM
Deformed
Ou + Q€s
NO VERTICAL EXAGGERATION
0 1 2 3 4 5 KILOMETERS

Fig. 3b.



EXPLANATION

Thrust fault—Teeth in upper plate; dashed where approximately located

Tertiary-reactivated Cretaceous tear fault—Dashed where approximately located

Normal fault—Bar and ball on downthrown side; dashed where approximately located

Fig. 4.

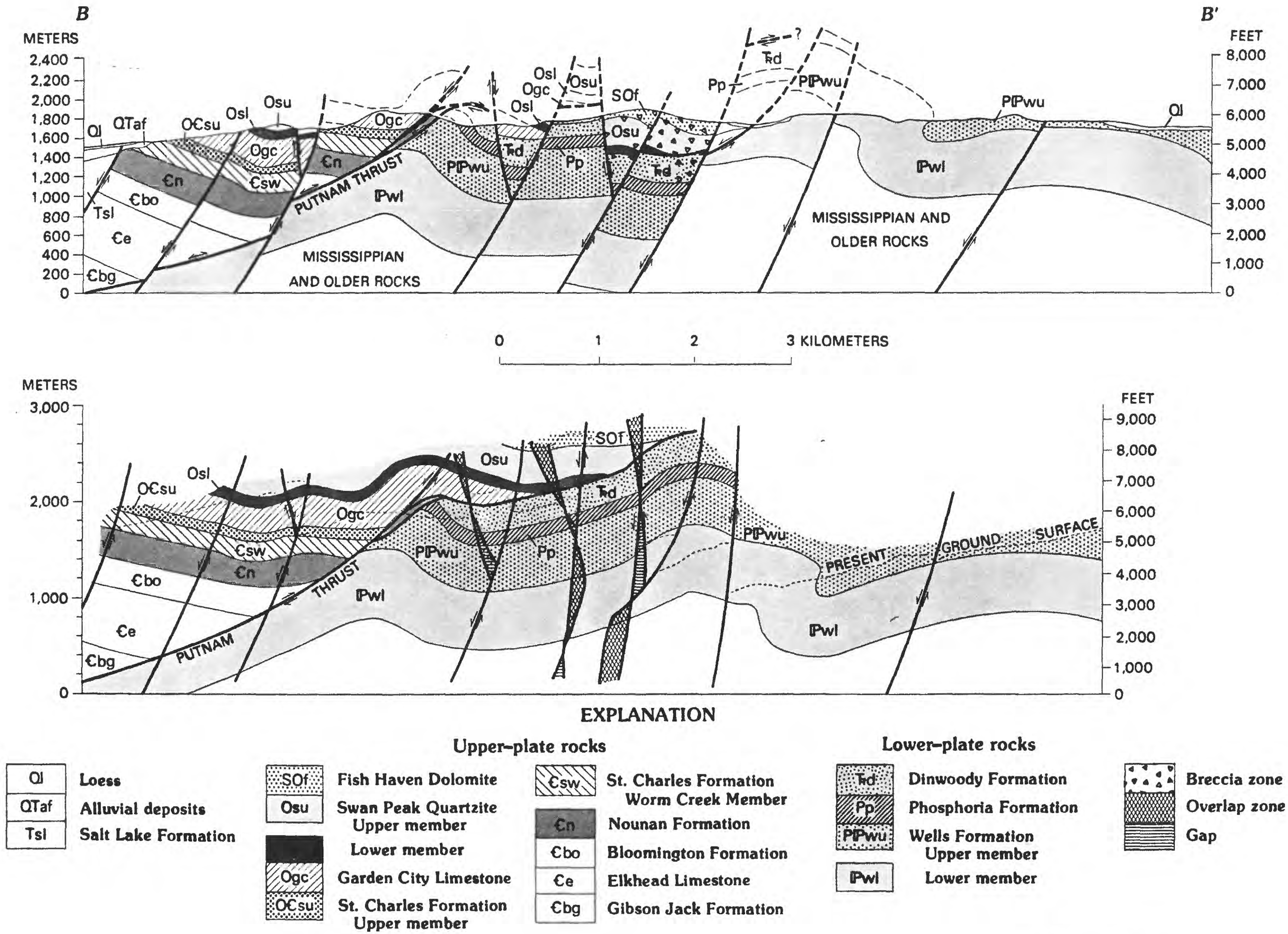
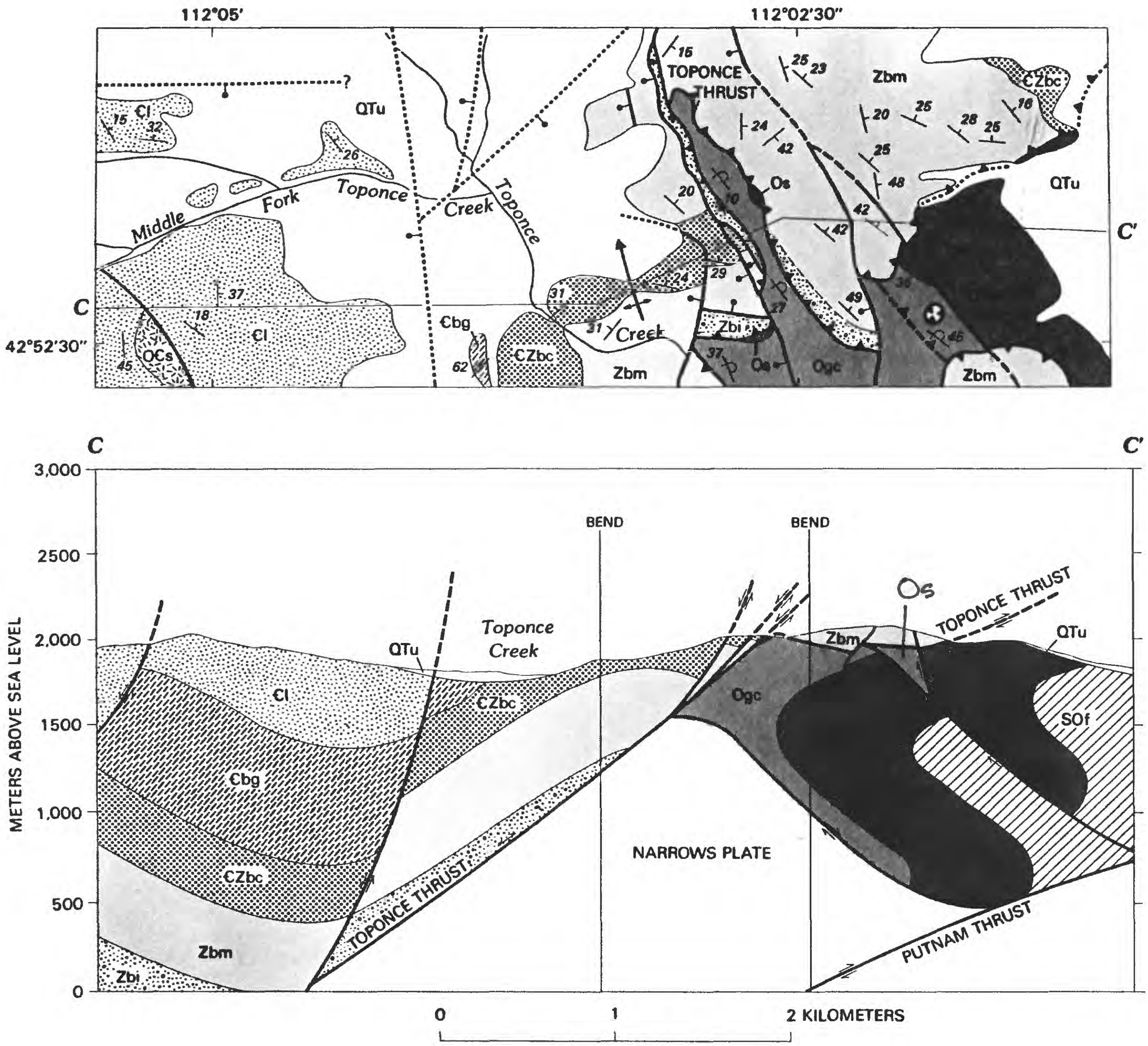

B
B'
METERS
FEET
PUTNAM THRUST
MISSISSIPPIAN AND OLDER ROCKS
MISSISSIPPIAN AND OLDER ROCKS
0 1 2 3 KILOMETERS
PRESENT GROUND SURFACE
EXPLANATION
Upper-plate rocks
Lower-plate rocks
Ql Loess
QTaf Alluvial deposits
Tsl Salt Lake Formation
SOf Fish Haven Dolomite
Osu Swan Peak Quartzite Upper member
Lower member
Ogc Garden City Limestone
OЄsu St. Charles Formation Upper member
Єsw St. Charles Formation Worm Creek Member
Єn Nounan Formation
Єbo Bloomington Formation
Єe Elkhead Limestone
Єbg Gibson Jack Formation
ₜRd Dinwoody Formation
Pp Phosphoria Formation
PIPwu Wells Formation Upper member
IPwl Lower member
Breccia zone
Overlap zone
Gap

Fig. 5.



EXPLANATION

Symbol	Description
QTu	Quaternary and Tertiary, undifferentiated
	Unconformity
SOf	Fish Haven Dolomite
	Swan Peak Quartzite
Ogc	Garden City Limestone
OCs	St. Charles Formation
€l	Upper and Middle Cambrian carbonates
€bg	Gibson Jack Formation
€Zbc	Camelback Mountain Quartzite
Zbm	Mutual Formation
Zbi	Inkom Formation
20	Strike and dip
45	Strike and dip, overturned beds
	Normal fault—Bar and ball on downthrown side
	Thrust fault—Teeth on upper plate
	Anticline—Trace of axial plane, showing plunge
	Tertiary-reactivated thrust fault

Fig. 6.

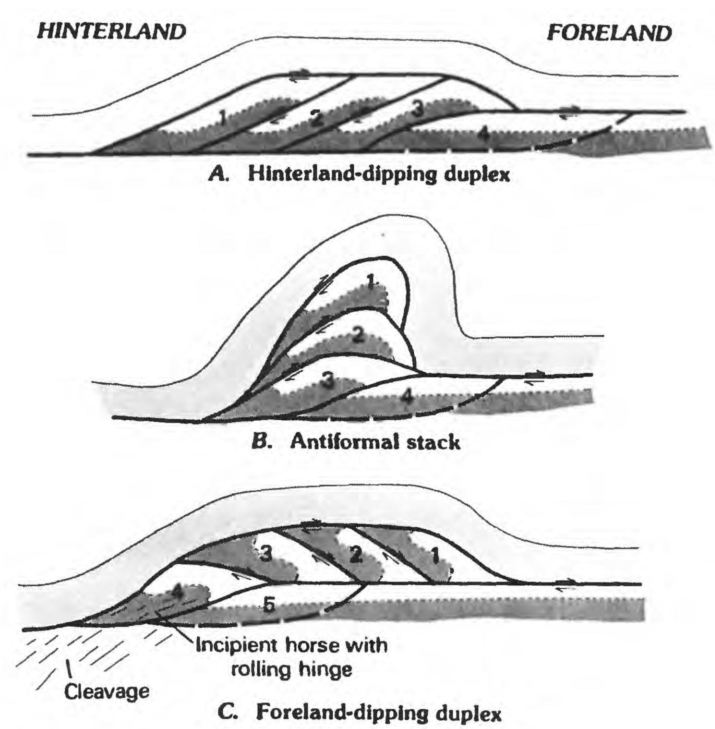

HINTERLAND
FORELAND
1
2
3
4
A. Hinterland-dipping duplex
1
2
3
4
B. Antiformal stack
3
2
1
4
5
Incipient horse with
rolling hinge
Cleavage
C. Foreland-dipping duplex

Fig. 7.

Fig. 8.

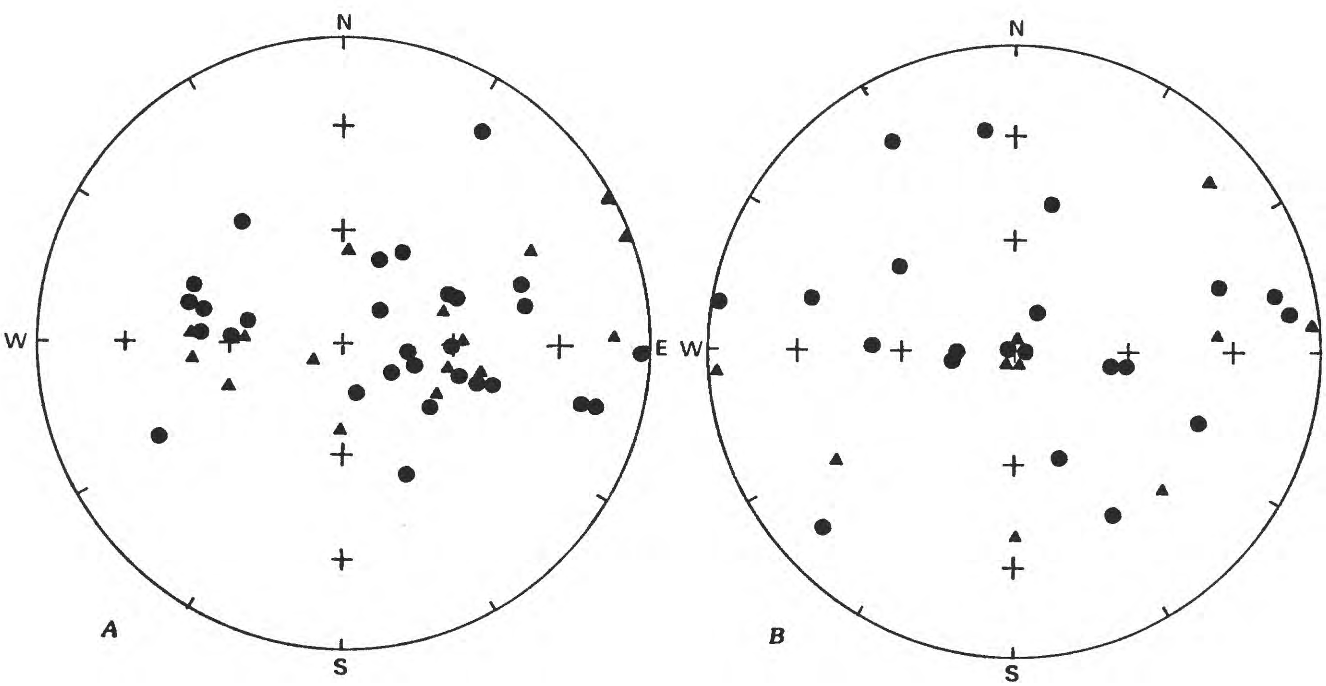
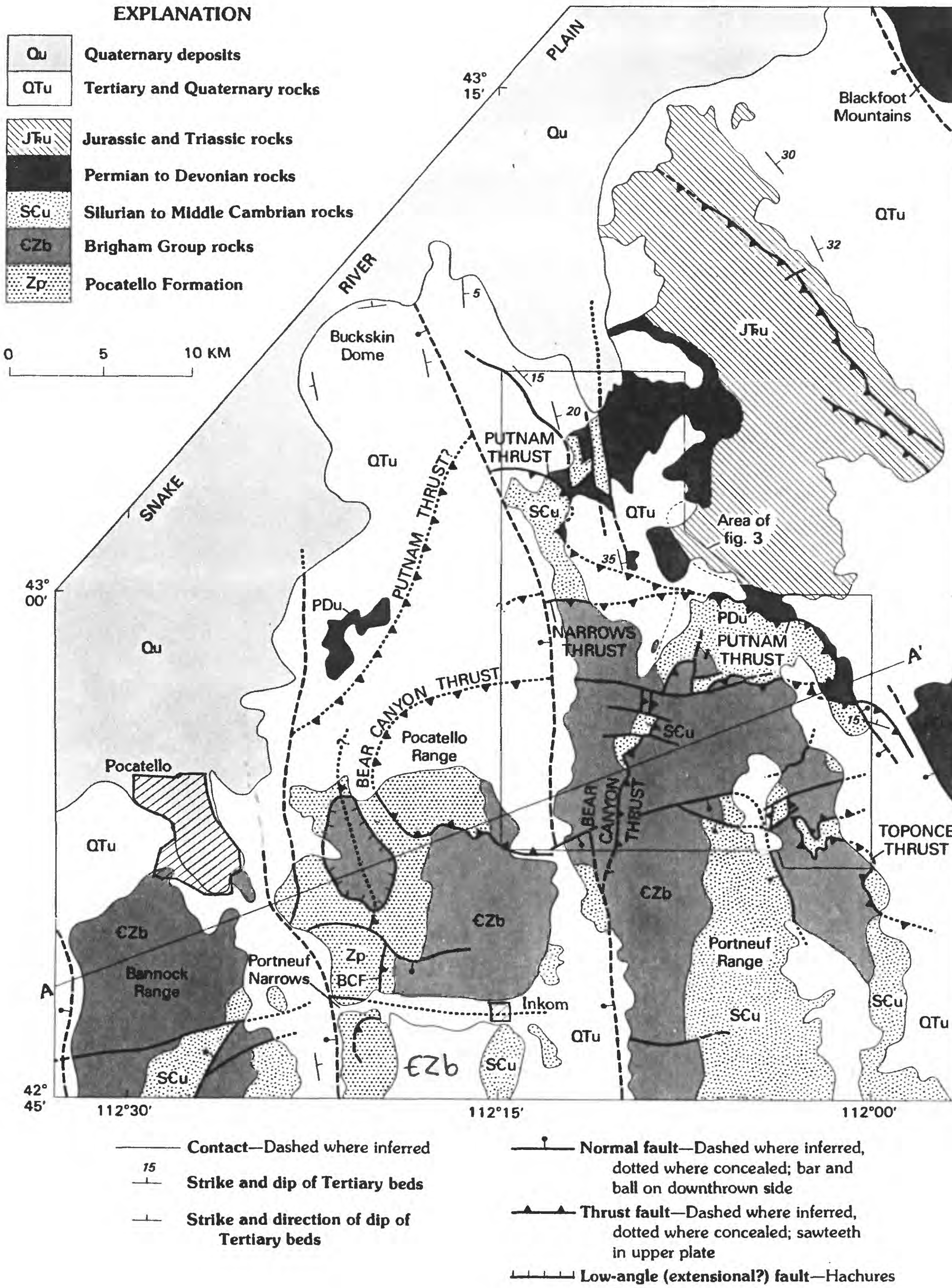


Fig. 9.



EXPLANATION
Qu
Quaternary deposits
QTu
Tertiary and Quaternary rocks
JŦu
Jurassic and Triassic rocks
Permian to Devonian rocks
SЄu
Silurian to Middle Cambrian rocks
ЄZb
Brigham Group rocks
Zp
Pocatello Formation
0
5
10 KM
SNAKE
RIVER
PLAIN
43°
15′
43°
00′
42°
45′
112°30′
112°15′
112°00′
Blackfoot Mountains
30
32
5
15
20
35
15
Buckskin Dome
PUTNAM THRUST
PUTNAM THRUST?
NARROWS THRUST
BEAR CANYON THRUST
TOPONCE THRUST
Area of fig. 3
PDu
Pocatello
Pocatello Range
Portneuf Narrows
BCF
Inkom
Bannock Range
Portneuf Range
A
A′
ЄZb
SЄu
QTu
Qu
Contact—Dashed where inferred
Strike and dip of Tertiary beds
Strike and direction of dip of Tertiary beds
Normal fault—Dashed where inferred, dotted where concealed; bar and ball on downthrown side
Thrust fault—Dashed where inferred, dotted where concealed; sawteeth in upper plate
Low-angle (extensional?) fault—Hachures in upper plate

Fig. 10.

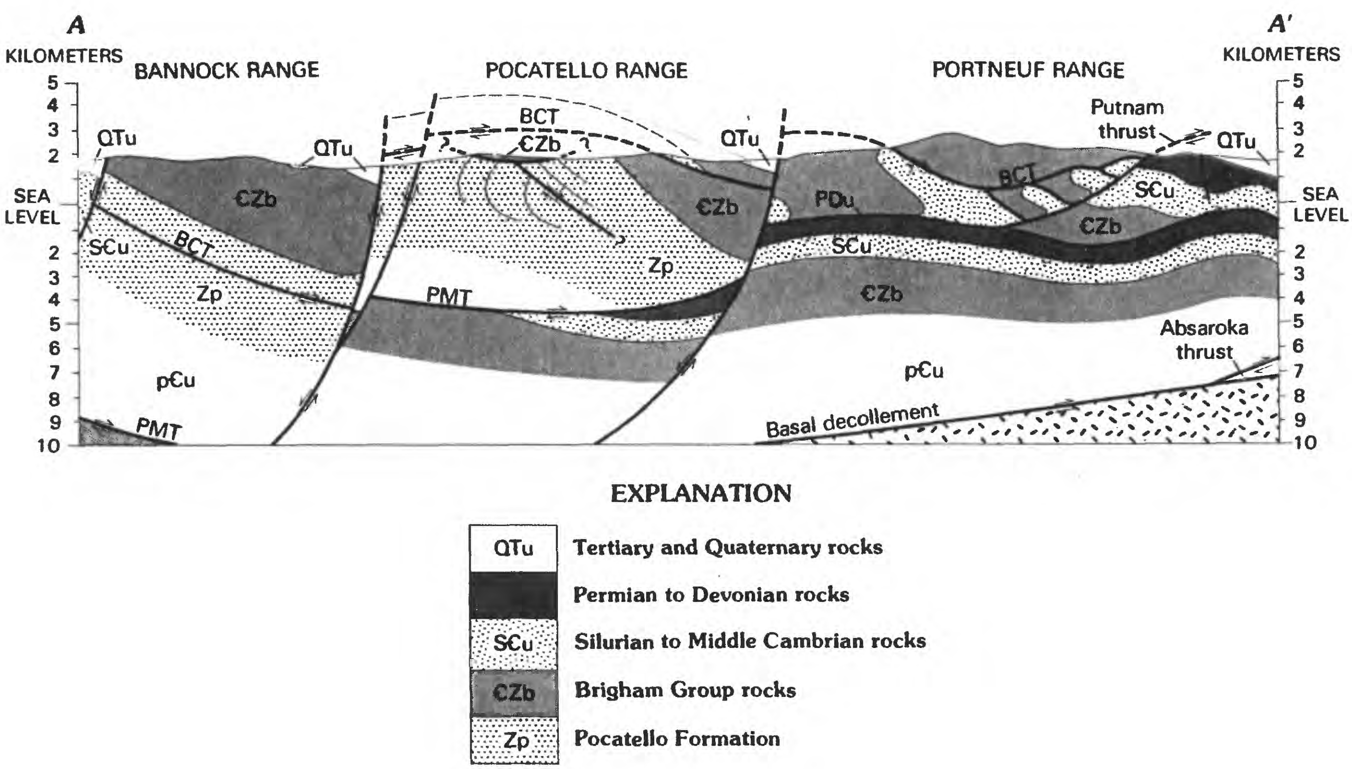

A
A'
KILOMETERS
BANNOCK RANGE
POCATELLO RANGE
PORTNEUF RANGE
KILOMETERS
SEA LEVEL
QTu
ꞒZb
SꞒu
BCT
Zp
PMT
pꞒu
Putnam thrust
PDu
Absaroka thrust
Basal decollement
EXPLANATION
QTu Tertiary and Quaternary rocks
Permian to Devonian rocks
SꞒu Silurian to Middle Cambrian rocks
ꞒZb Brigham Group rocks
Zp Pocatello Formation

Fig. 11.