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Fault-controlled pluton emplacement in the Sevier fold-and-thrust belt of southwest Montana, USA

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Abstract

Problems associated with syncompressional pluton emplacement center on the need to make room for magma in environments where crustal shortening, not extension, occurs on a regional scale. New structural data from the Pioneer and Boulder batholiths of southwest Montana, USA, suggest emplacement at the top of frontal thrust ramps as composite tabular bodies at crustal depths between 1 and 10 km. Frontal thrust facilitated pluton emplacement was accommodated by: (1) a magma feeder zone created along the ramp interface; (2) providing 'releasing steps' at ramp tops that serve as initial points of emplacement and subsequent pluton growth; and (3) localizing antithetic back-thrusts that assist in pluton ascent. A model of magma emplacement is proposed that involves these elements. This model for syntectonic ramp-top emplacement of plutons helps explain how space is made for plutons within fold-and-thrust belts.

1. Introduction

Emplacement of silicic magmas in convergent settings presents the apparent paradox that horizontal compressional stresses, contractional strains, and regional shortening seem at variance with the requirement that space has to be created for emplacement of magma. An excellent place to examine this problem is the Rocky Mountains of southwestern Montana (Fig.1), where large volumes of Late Cretaceous calc-alkaline magma intruded at shallow crustal levels (1–10 km) into the developing Sevier fold-and-thrust belt.

Many case studies have documented emplacement of silicic plutons in contractional settings within the continental crust (for a review, see Hutton, 1997). Most models, however, call upon mechanisms whereby magma is emplaced in space created by tensional or dilational jogs along transcurrent fault zones within magmatic arcs (e.g. Hutton, 1982; Tikoff and Teyssier, 1992; Castro and Fernandez, 1998). These models are not applicable to typical conditions found in convergent zones, such as the Late Cretaceous North American Cordillera, where contractional deformation was dominantly dip-slip instead of strike-slip. Examples of syncompressional magma emplacement have been reported from thrust terranes, but these generally formed under deep crustal conditions of 10–20 km depth and <350°C (Karlstrom et al., 1993; Ingram and Hutton, 1994; Rosenberg et al., 1995). The plutons described in this paper were all emplaced at shallow structural levels within a foreland fold-and-thrust belt, suggesting that similar processes can operate at shallow crustal levels during brittle deformation.

In western Montana, the Mesozoic magmatic arc spatially overlapped the Sevier orogenic belt, unlike areas to the north and south where the Sevier orogen developed in a distinctly back-arc foreland setting. Recent and ongoing field studies suggest that many Late Cretaceous batholiths of southwestern Montana were emplaced as tabular bodies at the top of frontal thrust ramps between the hinterland and foreland portions of the Sevier orogen (Burton et al., 1998; Lageson et al., 1994). These shallow-level composite batholiths were apparently emplaced by episodic intrusion and deformation, during overall regional contractional deformation.

In this paper, we propose a model of magma emplacement in the southwest Montana fold-and-thrust belt that takes into account thrust fault geometry, structural siting of plutons, and apparent timing of shortening and pluton emplacement. Fundamentally, emplacement occurs due to a propensity for magma to exploit and follow anisotropies, such as brittle fault zones, in the upper crust. Our examples

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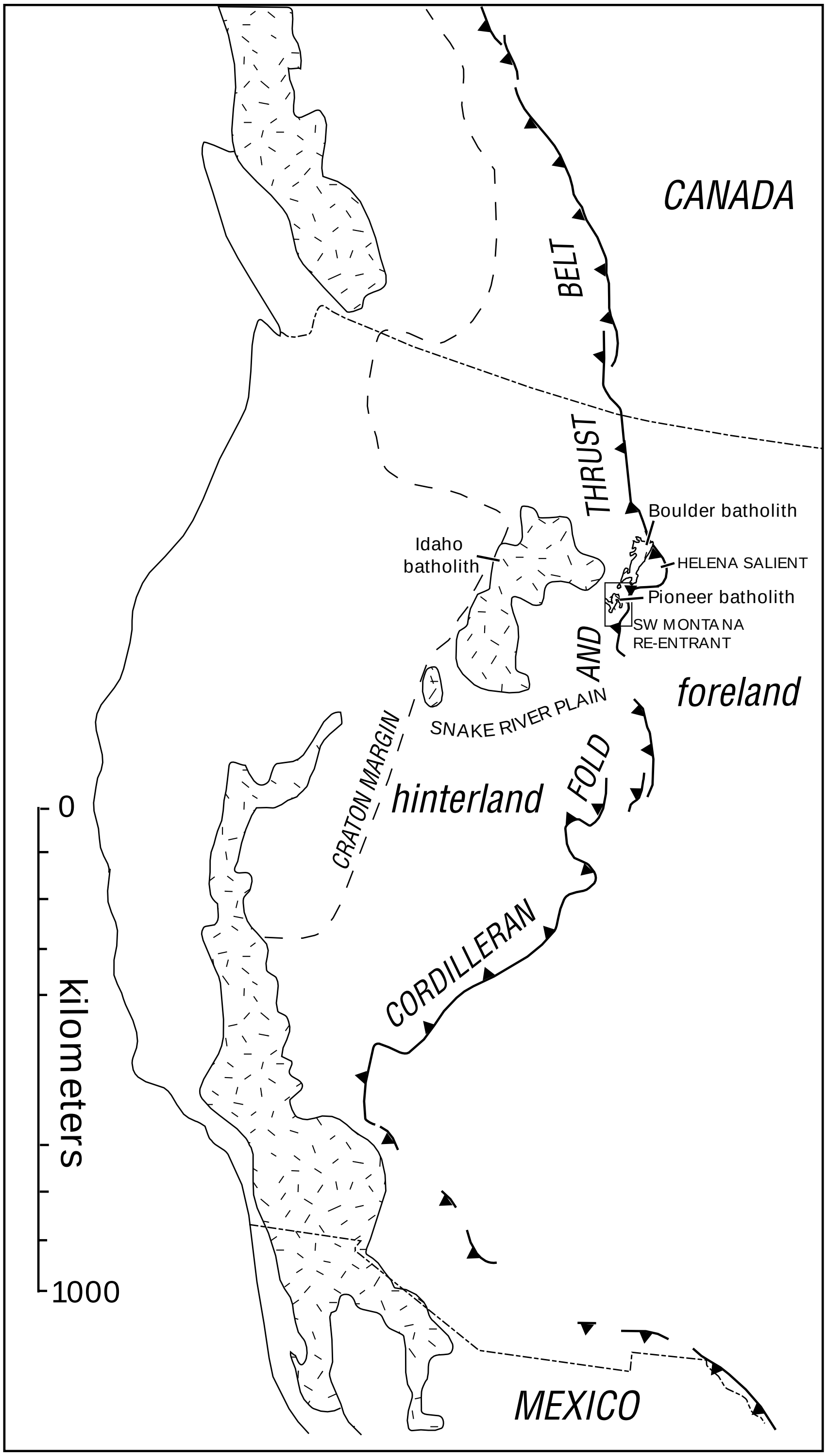

Fig. 1. Simplified geologic map of the Cordilleran Sevier fold-and-thrust belt in North America showing the position of the frontal thrust zone and late Cretaceous magmatic arc.

show that dilational space, sufficient for pluton emplacement, can be created near a vertical bend in a thrust fault system (i.e. a ramp to flat interface). This mechanism is accomplished through synmagmatic dip-slip translation of hanging wall material over a thrust ramp. Emplacement is also assisted by vertical lift of a thrust fault hanging wall during the intrusion of silicic magma. We focus specifically on the well-exposed relationships between thrust faults in the McCartney Mountain thrust salient and the Pioneer batholith and its satellite plutons.

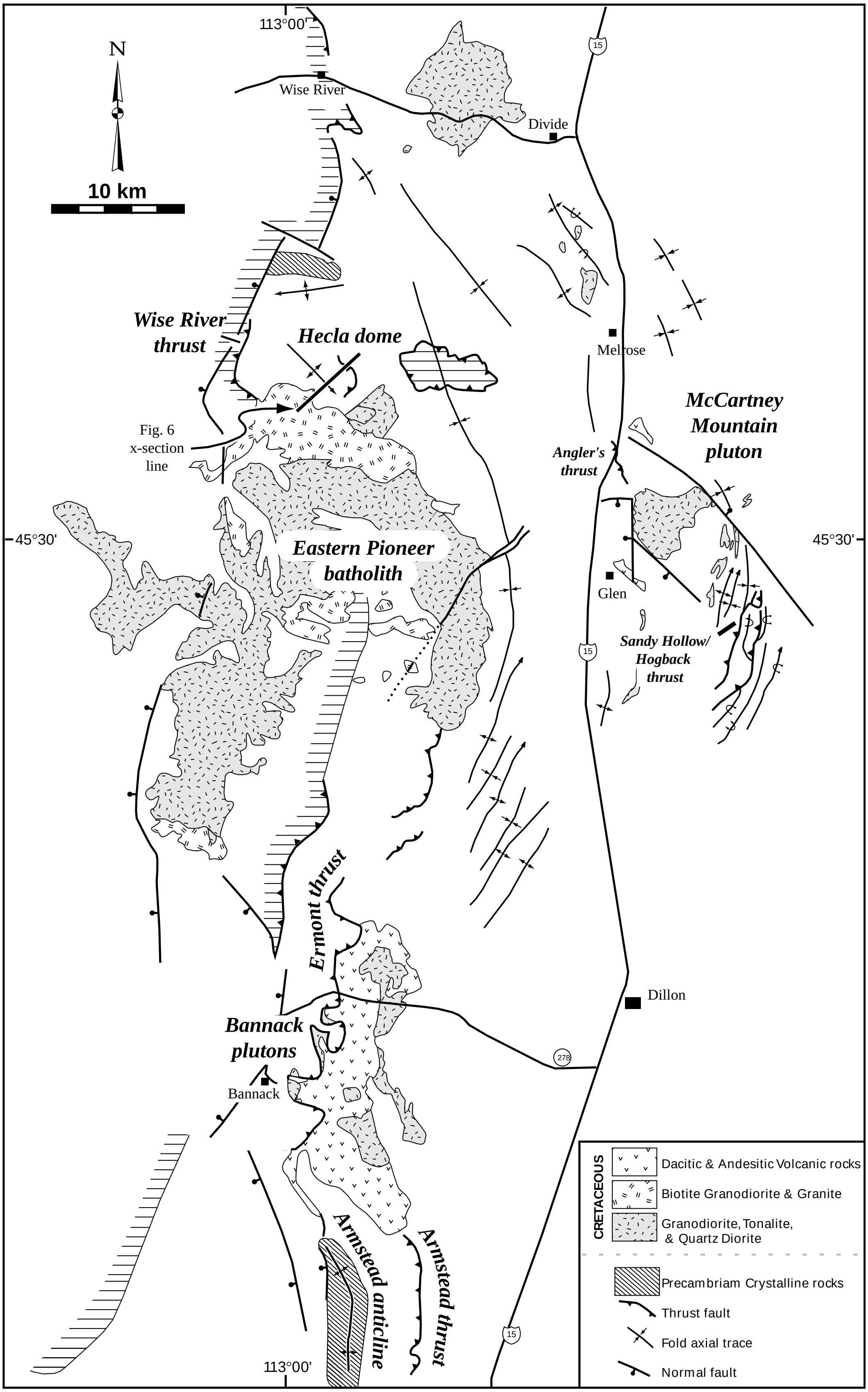

Fig. 2. Generalized geologic map the Pioneer batholith and major structures of the McCartney Mountain thrust salient (modified from Ruppel et al., 1993). Horizontal line pattern indicates leading eastern edge of areas underlain by Proterozoic Belt Supergroup rocks.

2. Regional geology

The Late Cretaceous–Paleocene Sevier orogenic belt of southwest Montana is characterized by three overlapping tectono-magmatic components: (1) the dominantly thin-skinned Sevier fold-and-thrust belt, (2) a belt of silicic intrusive and extrusive igneous rocks, and (3) Laramide-style, basement-cored uplifts (Fig. 2). The pronounced spatial and temporal coincidence of these features makes southwest Montana unique when compared to sections along strike to the north (i.e. northwest Montana and eastern Canadian Rockies) and to the south (Wyoming, Idaho, and Utah). More typically, the Sevier orogen has a distinct western magmatic arc and metamorphic hinterland, separated from the eastern foreland characterized predominantly by thin-skinned folds and thrusts (DeCelles and Mitra, 1995).

In southwest Montana the three-dimensional configuration of thin-skinned contractional deformation was inherited from the geometry of the Middle Proterozoic Belt basin (Winston, 1986; Boyer, 1995). The Middle Proterozoic Belt Supergroup forms an eastward-tapering sedimentary wedge (Winston, 1986), which is overlain by Phanerozoic strata that thin eastward. Thrust sheets generally follow this trend and ramp upward from thick successions of Belt and younger strata in the west, into thinner successions to the east. Such a ramp system bisects what is known as the southwest Montana re-entrant.

The southwest Montana re-entrant (Fig. 1) extends south from the Highland Mountains to the Snake River Plain, and is bound on the east by Archean crystalline rocks and Paleozoic strata uplifted in the Ruby and Tobacco Root Mountains (Ruppel and Lopez, 1984). A major thrust ramp system, placing Belt strata over Paleozoic and Mesozoic rocks, bisects the re-entrant from north to south. This system has previously been described as the leading edge of three thrust plates, the Sapphire, the Grasshopper, and the Medicine Lodge plates (Ruppel and Lopez, 1984; Skipp, 1988). Along the ramp system, thrust surfaces step up from a basal décollement in Proterozoic Belt rocks to stratigraphically higher levels in Mississippian carbonates due to the eastward tapering Belt succession. Crystalline rocks, observed along the ramp system trace, are most likely duplexed footwall slivers of basement translated short distances up the ramp in a dominantly thin-skinned setting (Coryell and Spang, 1988; Kipf et al., 1997). Immediately east of the ramp system, Paleozoic rocks lie directly on crystalline basement (Coryell and Spang, 1988; Pearson, 1996) with no intervening Belt succession.

The McCartney Mountain thrust salient forms an eastward bulge within the southwest Montana re-entrant (Fig. 2), and is delineated by the convex-east curvature of Late Cretaceous thrust faults and fold hinge lines (Brumbaugh and Hendrix, 1981). The eastern and southeastern margins of the salient are covered unconformably by post-Sevier Cenozoic basin-fill deposits. The northeastern boundary is defined by the Highland Mountains foreland uplift (Ruppel et al., 1993). Intrusive contact with the Late Cretaceous Pioneer batholith marks the western margin. Deformed rocks of the salient include Middle Proterozoic quartzite and argillite, Cambrian through Triassic platform deposits, Jurassic through Late Cretaceous foreland basin sediments, and Late Cretaceous volcanic and intrusive rocks (Brumbaugh and Hendrix, 1981).

Calc-alkaline magmatism throughout southwest Montana was widespread during the Late Cretaceous and early Tertiary and propagated eastward through time from the hinterland into the foreland fold-and-thrust belt (Constenius, 1996). In general, plutonism was synchronous with a major pulse of crustal thickening between 85 and 55 Ma based on K–Ar geochronology of crosscutting felsic dikes (Robinson et al., 1968; Hoffman et al., 1976), paleomagnetic and K–Ar isotopic data (Harlan et al., 1988), and ^{40}Ar/^{39}Ar geochronology and thermochronometry (Fillipone and Yin, 1994). Major composite plutonic centers include the Idaho, Boulder, and Pioneer batholiths, emplaced between 80 and 53 Ma (Foster and Fanning, 1997). The Boulder batholith and associated Elkhorn Mountains volcanic field, the Pioneer igneous complex, the Flint Creek plutons, and numerous smaller bodies form an expansive belt of Late Cretaceous magmatic rocks that lie 80–100 km east of plutonic centers in the Idaho batholith. Unlike mid-crustal magmatic systems exposed in the Idaho batholith, plutons within the eastern magmatic belt were emplaced within the evolving fold-and-thrust belt and foreland basin at relatively shallow depths (1–10 km) apparently as thin (meter- to kilometer-scale) tabular sheets or laccoliths (Hyndman et al., 1988; Sears et al., 1989). Many intrusive bodies spatially overlap with major contractional structures. Regional cross-sections have depicted the granitoid sheets as occupying major thrust zones (e.g. Hyndman et al., 1988) or superjacent to major thrust surfaces (Burton et al., 1998). The specific genetic link between thrust faulting and magmatism is the subject of this paper.

We present data from the eastern Pioneer Mountains and McCartney Mountain thrust salient, an area where intrusive rocks and their relationships to deformed country rocks are particularly well-exposed. The following descriptions depict three separate areas where recent mapping and detailed structural analyses reveal important new aspects of the precise spatial relationships and geometry by which Late Cretaceous magmas were emplaced within contractional fold-thrust environments.

3. Bannack area

3.1. Structural geology

The major frontal Sevier thrust faults in the Bannack area are the Ermont and Armstead thrusts (Fig. 2). In general, the Ermont thrust places Mississippian carbonates on Late

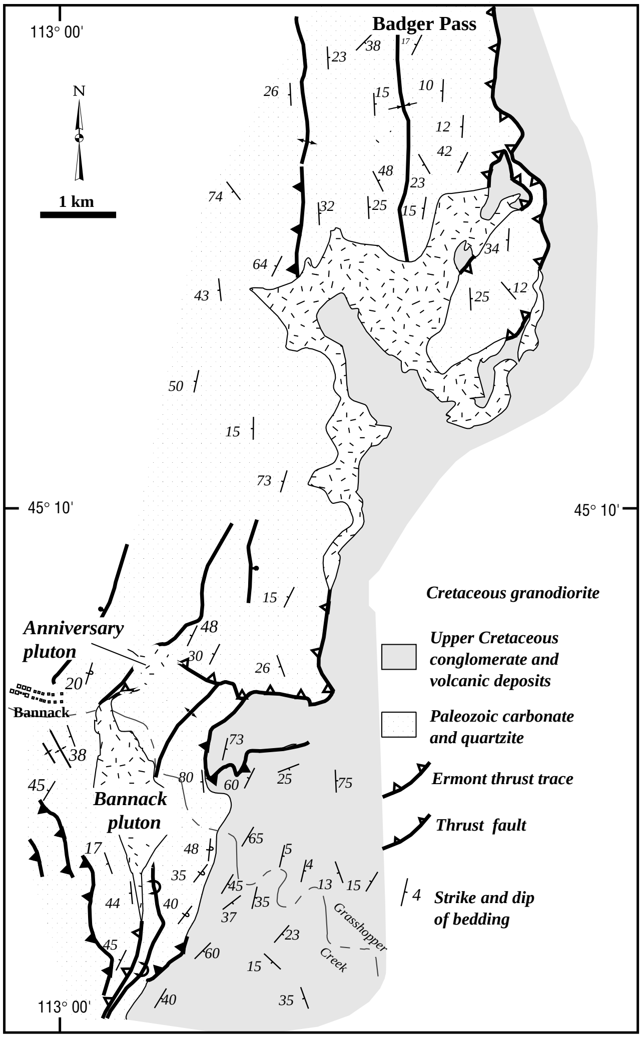

Fig. 3. Geologic map of the area near Bannack, Montana (from Kalakay, unpublished mapping).

Cretaceous Beaverhead conglomerates and associated volcanic rocks. The sinuous fault is traceable for nearly 30 km along strike, from just south of Bannack north to the margin of the Pioneer batholith where it strikes into a complex of north-plunging folds (Brandon, 1984; Pearson, 1996). Along its eastern trace the fault has a gentle west-dip up to 20° forming a hanging wall flat above truncated footwall strata. To the west, the fault dip steepens to 20–40°, forming a footwall ramp beneath a series of west-dipping imbricate thrusts in the hanging wall. Kinematic analyses of mineral fiber lineations on shear planes within the fault zone indicate that thrust motion was dominantly dip-slip. Hanging wall fault rocks are characterized by complicated interconnected fracture networks. Most fractures range from 0.5 to 10 cm in width, and are oriented at various angles to the fault plane.

South of Bannack, the Ermont thrust merges into another fold-thrust system, which includes the basement-cored Armstead anticline. The Armstead anticline is in the hanging wall of the Armstead thrust, which like the Ermont thrust places Mississippian carbonates on Late Cretaceous Beaverhead strata. Coryell and Spang (1988) interpreted the Armstead anticline as a basement-cored duplex structure. Their model portrays an intensely imbricated fault-bend fold. Imbrication is mostly in the form of back-thrusts formed by rotation and translation of basement rocks above a ramp in the Armstead thrust.

New structural data suggest a linkage between the Armstead area and structures exposed at Bannack. We propose that the Ermont thrust steps down laterally (southward) to a deeper structural level that involves duplexed basement rocks in the hanging wall at the Armstead anticline. Therefore, the Ermont and Armstead thrust faults are geometrically linked, with the Armstead anticline representing an antiformal stack from deeper structural and stratigraphic levels than the Ermont thrust.

3.2. Geology of intrusive rocks in the Bannack area

Numerous granodiorite stocks and sills intrude deformed Paleozoic and Mesozoic strata near Bannack (Fig. 3). In the north, near Badger Pass, granodiorite bodies occur as thin (3–50 m) sheets that intrude into the nearly flat lying, eastern Ermont thrust system. To the west, the intrusive sheets thicken in an area of imbricated hanging wall back-thrusts above a west-dipping footwall ramp. Narrow (30–50 cm thick), subvertical granodiorite dikes fill fracture zones in the highly deformed hanging wall of the Ermont thrust at several localities. Magmatic foliations within the sheet-like bodies vary from steep dips (50–90°) in interior zones, to shallow contact-parallel orientations near their margins. High-temperature, solid-state deformation fabrics are scarce to non-existent within the intrusive rocks. Metamorphic aureoles in surrounding carbonates are narrow (2–20 m thick) and undeformed, showing textures of statically recrystallized carbonate and calc-silicate hornfels. South of Badger Pass, the granodioritic Bannack and Anniversary plutons exposed along Grasshopper Creek display a slightly deeper level of the intrusive system. In contrast to the sill-like sheets of Badger Pass, the Bannack and Anniversary plutons range from 200 to 600 m in thickness and were emplaced between the Ermont thrust and a subsidiary hanging wall imbricate fault to the west (Fig. 3). These pluton-bounding faults contain Mississippian carbonates and mudstones in both their hanging wall and footwall. Wall rock xenoliths are abundant within the Anniversary pluton and comprise angular blocks of Mississippian carbonate representative of brecciated hanging wall rocks found within the intruded fault zone (Mack et al., 1999). Some xenoliths are composed of granitic gneiss similar to rocks found less than 5 km south of the pluton in the core of the Armstead anticline. We interpret the gneissic xenoliths as blocks that were stopped from the Ermont fault where it cuts crystalline basement beneath the pluton. This involvement of basement rocks provides further evidence for the geometric link between the Ermont and Armstead thrust

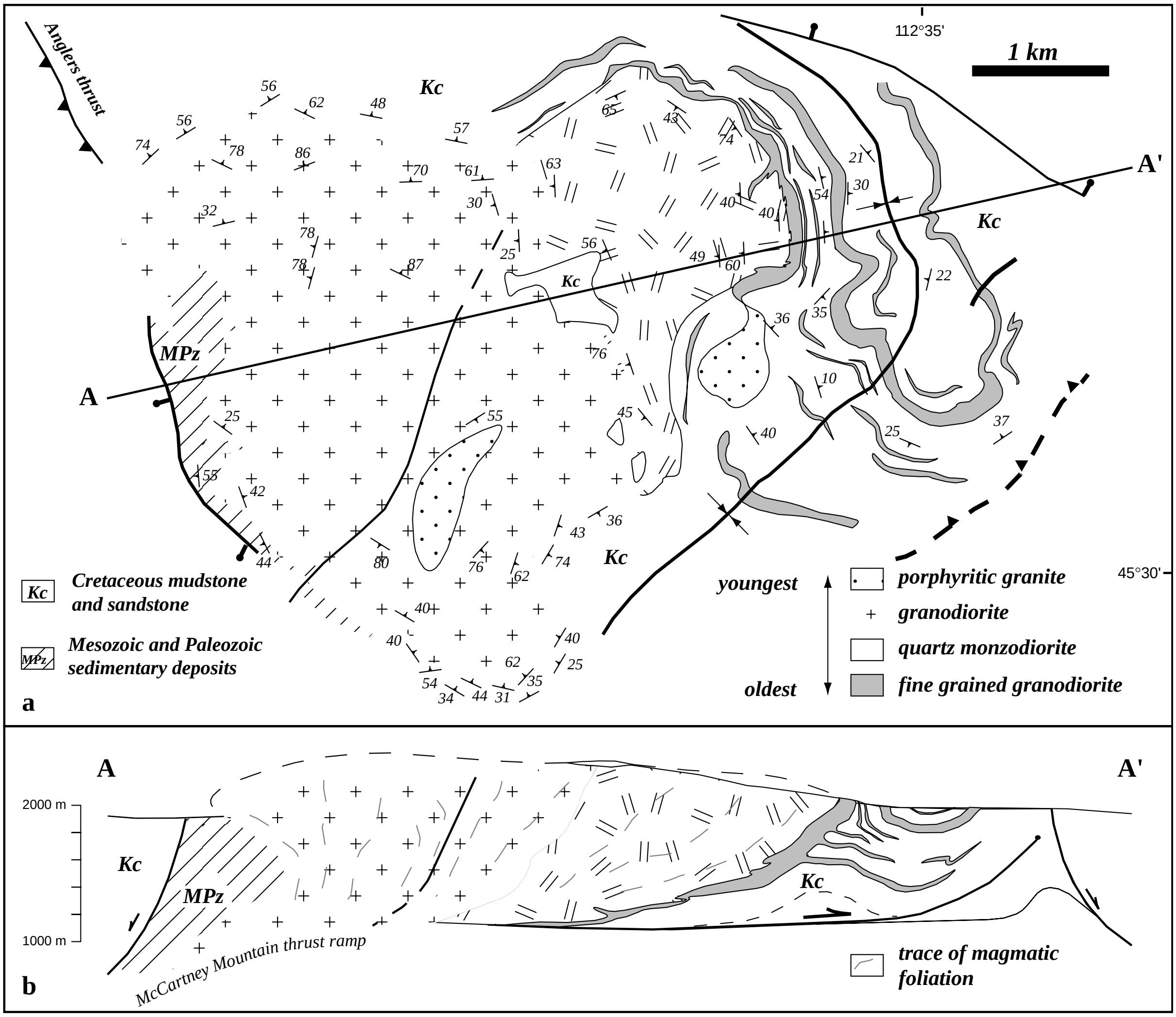

Fig. 4. Geologic map and cross-section of McCartney Mountain pluton and adjacent wall rock structures. Note fine-grained granodiorite sills are folded with axial planar magmatic foliation (compiled from unpublished mapping of Kalakay and also of Gunckel, 1990).

systems. Both the Bannack and the Anniversary plutons show a moderate to steep west-dipping magmatic foliation, defined by aligned hornblende that is subparallel to the intrusive contact and the overall fault geometry.

4. McCartney Mountain

4.1. Local thrust system

Thin-skinned deformation in the McCartney Mountain area consists of a multi-tiered system of east-directed imbricate thrusts and folds within Paleozoic and Mesozoic strata. Thrust faults sole into a common décollement in the Pennsylvanian section (Brumbaugh and Dresser, 1976; Brandon, 1984; Lopez and Schmidt, 1985). Individual thrust sheets are locally well-exposed and show intense internal shortening through well-developed cleavage, tight disharmonic folding, and internal duplexing (Brumbaugh and Dresser, 1976; Brandon, 1984; Geiger, 1986). From structurally highest to lowest, major thrusts in the McCartney Mountain area are the Anglers thrust, McCartney Mountain thrust, and Sandy Hollow/Hogback thrust (Brumbaugh and Dresser, 1976; Brandon, 1984; Gunckel, 1990) (Fig. 2). Kinematic analyses by Brumbaugh and Dresser (1976) show thrust displacements in the McCartney Mountain as mostly dip-slip.

The McCartney Mountain pluton was intruded into the McCartney Mountain thrust sheet along a footwall ramp-hanging wall flat system located between the Anglers thrust to the west and structurally lower Sandy Hollow-Hogback thrust to the east. These tectono-magmatic relationships are described in more detail in Section 4.2.

4.2. Geology of McCartney Mountain pluton

The McCartney Mountain pluton is the easternmost intrusive body of the McCartney Mountain salient, and is roughly pear-shaped in plan view (Figs. 2 and 4a). Around its northern perimeter, the pluton is surrounded by a concordant aureole of metamorphosed Cretaceous sedimentary rocks. The contact with the metasedimentary rocks is sharp. Magmatic foliation within plutonic phases intensifies toward the margin, becoming very strongly developed at distances up to 50–100 m from the contact. The present topography of McCartney Mountain exposes both the roof and floor of the pluton.

Along the northern boundary, both compositional layering within the aureole and foliation within the plutonic phases dips moderately (40–50°) away from the pluton. These orientations together with roof pendants exposed in the area suggest a level of exposure near the pluton roof. In contrast, along the southern margin both wall rock and pluton magmatic foliations dip 25–40° inward toward the body, indicating an exposure level close to the base of the pluton. Along the western contact, Pennsylvanian quartzite beds dip steeply away from the pluton. However, detailed mapping shows that both the contact and pluton magmatic foliations dip inward, toward the pluton.

Friberg and Vitaliano (1981) originally described the pluton as a composite, subvertical body comprising three plutons fed from a common source. Our study recognizes four distinct and mappable intrusive phases ranging in composition from granodiorite to granite (Fig. 4a). Cross-cutting relationships indicate a younging of plutonic phases from east to west. The oldest phase, a fine-grained granodiorite, occurs as a series of sills within deformed Cretaceous metasedimentary rocks. The sills are characterized by a strong magmatic foliation defined by alignment of hornblende and biotite. The sills also contain abundant cm-scale xenoliths almost entirely composed of the adjacent wall rock. The xenoliths possibly represent stoped material derived from the intruded McCartney Mountain thrust fault.

The fine-grained granodiorite is intruded in the west by a texturally coarser quartz monzodiorite. The contact between fine-grained granodiorite and quartz monzodiorite is sharp. Xenoliths of foliated fine-grained granodiorite are common within the quartz monzodiorite indicating a younger relative age for the quartz monzodiorite. The quartz monzodiorite, thus far the only isotopically dated pluton of the McCartney Mountain suite, yields a single K/Ar biotite cooling age of 74 ± 1 Ma (Brumbaugh and Hendrix, 1981). Moderate to steep magmatic foliations within the quartz monzodiorite consistently dip westward, away from the fine-grained granodiorite. The quartz monzodiorite is, in turn, structurally overlain and intruded by a medium-grained granodiorite that forms the largest body of the McCartney Mountain intrusive suite. The contact between quartz monzodiorite and medium-grained granodiorite is gradational in the pluton center and sharp near wall rock contacts. A flat-lying roof pendant of Cretaceous metasedimentary rock obscures a portion of the contact. Magmatic foliations in the medium-grained granodiorite generally dip west toward the inferred thrust ramp along the western side of McCartney Mountain. The youngest rocks of the intrusive suite are unfoliated porphyritic granites that form small stocks in the southern half of the pluton.

Fig. 4(b) is an east to west cross-section illustrating the sill-like geometry of the McCartney Mountain pluton. Overall pluton thickness is ~700–800 m, estimated from the elevation difference between pendants at the top of the pluton and low angle inward dipping wall rocks near the pluton base. Along the west side of the McCartney Mountain, plutonic rocks are in contact with steeply west-dipping quartzite of Pennsylvanian age. The eastern contact is within Cretaceous Colorado Group sedimentary rocks. An east-to-west stratigraphic discontinuity, with older rocks structurally above younger rocks, arises if the pluton is removed from the cross-section. This discontinuity has been explained as a thrust fault system with Pennsylvanian rocks to the west folded above a footwall ramp that connects flats in the Pennsylvanian and Cretaceous sections (Gunckel, 1990). The flat–ramp–flat system has subsequently been obscured by intrusion of the McCartney Mountain pluton.

The extent of the aureole surrounding the McCartney Mountain pluton is determined by the occurrence of porphyroblasts in pelitic wall rocks. High-temperature, low-pressure metamorphism is indicated by mineral assemblages containing biotite, andalusite, and muscovite. The aureole is approximately 100–200 m wide along the northern contact and as much as 1200 m wide around the eastern and southern parts of the pluton. On the basis of wall rock mineral assemblages and pluton geobarometry, Alonso and Friberg (1985); Friberg and Vitaliano (1981) estimated that the plutons were intruded at a depth between 1 and 3 km (≤1 kb).

A well-developed stretching lineation, formed by elongate andalusite porphyroblasts, is observed in the southeastern and southern parts of the aureole. The lineation lies within the wall rock foliation and plunges to the east-northeast. Porphyroblast–matrix relationships in pelitic wall rocks provide information regarding the relative timing of metamorphism and deformation. Within core regions, porphyroblast inclusion trails are at high-angles to external foliation. From core to rim, inclusion trails curve in a continuous pattern into parallelism with external biotite and muscovite foliations. This indicates that porphyroblasts overgrew an external foliation during a period of progressive deformation (Barker, 1994). Thus, metamorphism and deformation were coeval. These microscopic fabrics coincide with mesoscopic and macroscopic high temperature developed east-vergent folds in the wall rocks. Wall rock bedding is folded into a km-scale syncline that lies subparallel to the northeastern, eastern, and southeastern contacts. Sills of fine-grained granodiorite contain magmatic foliations that are axial planar with the overall synclinal structure (Fig. 5) suggesting that folding related to shortening was synchronous with sill emplacement.

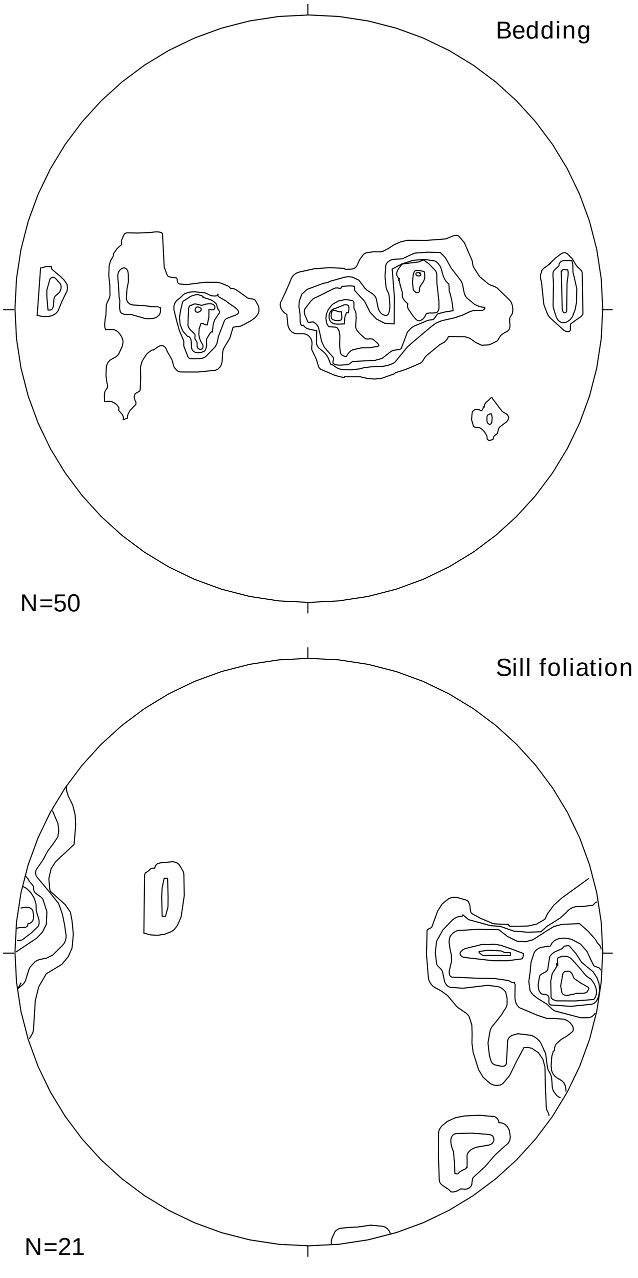

Fig. 5. 1% area contoured stereograms of poles to bedding in country rock and magmatic foliation in fine-grained granodiorite sills as shown in Fig. 4. Note axial planar relationship between folded bedding and magmatic foliation.

5. Pioneer batholith

5.1. Geology of the Pioneer batholith and adjacent country rocks

The Pioneer batholith is exposed over an area of ~800 km^2 and forms the largest intrusive body in the McCartney Mountain thrust salient (Fig. 2). Snee (1982) and Zen (1988) previously described it as a calc-alkaline suite containing five major intrusive phases ranging in composition from potassic ultramafic rocks and melagabbro, through granodiorite, quartz monzonite, granite and syenite. Pluton composition varies as a function of age from hornblende gabbro and hornblende-biotite quartz diorite (Keokirk quartz diorite) with cooling ages of ~80 Ma, to hornblende-biotite tonalite at ~77–74 Ma, to biotite-hornblende granodiorite and biotite granite at ~72 Ma, and biotite granodiorite and two-mica granite at ~67–65 Ma (Snee, 1982; Marvin et al., 1983).

East of the Wise River, in the eastern Pioneer Mountains, contacts are typically steep, except where adjacent to local roof and/or floor zones (Snee, 1982; Zen, 1988; Kalakay and John, 1997). The largest pluton, the Uphill Creek granodiorite, comprises over 75% of the exposed batholith and is considered to have been emplaced ~75 ± 1 Ma (Snee, 1982). Alignment of internal plutonic contacts, the general elongation of the plutons, and the locally developed magmatic fabric within the batholith led Snee (1982) and Zen (1988) to suggest that translation along WNW-striking faults continued during pluton emplacement and solidification.

The eastern contact of the Pioneer batholith extends N–S for over 70 km and forms the western boundary of the McCartney Mountain thrust salient (Fig. 2). Sedimentary rocks north, east, and south of the batholith consist of Cambrian through Mesozoic strata that exhibit east-verging, nearly isoclinal, and reclined folds to the north, that become progressively more open and upright to the south (Brandon, 1984; Zen, 1988). Plastic deformation is more intense in the north (Geiger, 1986; Kalakay and John, 1997), while in the south deformation is dominantly brittle, manifested mostly as thrust faults with heave displacements up to several hundred meters, and only local penetrative strain (Brumbaugh and Dresser, 1976). Estimates of paleotemperature obtained from clay mineralogy and conodont alteration indices range from 50°C in the south near Dillon, to 250–350°C in the north near Melrose (Geiger, 1986; Sharkey, 1986; Sweet et al., 1981). The north-to-south changes in thermal regime and deformation mechanisms are likely a reflection of progressively deeper levels of exposure to the north. This concept is corroborated by a preserved sequence of volcanic rocks, coeval and geochemically cogenetic with the Pioneer batholith, that lie unconformably on deformed Mesozoic and Paleozoic strata near Bannack. The sequence is conspicuously missing in the north.

Country rock deformation along the east-central contact zone is dominated by the Cherry Creek syncline (Fig. 2). The axial trace of the syncline is continuous and roughly contact-parallel for nearly the entire length of the eastern contact. Brandon (1984) and Zen (1988) originally mapped the synclinal hinge as a fault. However, subsequent mapping by Tysdal and others (1994) lead to its reinterpretation as an east-verging asymmetric syncline. The vertical to overturned west limb of the syncline is interpreted as the east limb of a fault propagation fold. In this interpretation, the Cherry Creek syncline is a footwall syncline beneath a structurally higher hanging wall anticline to the west. Metamorphosed Cretaceous sedimentary rocks in the core of the

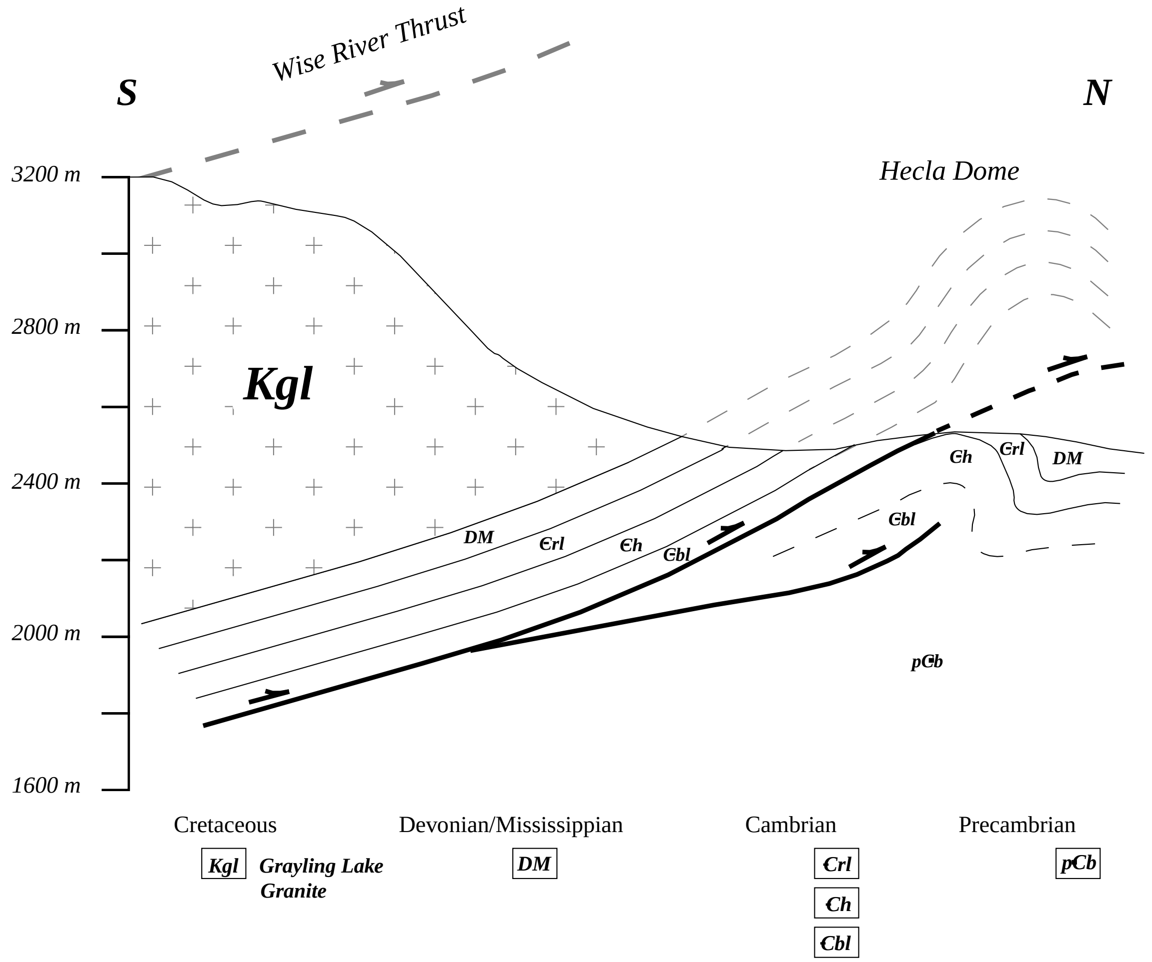

Fig. 6. N–S geologic cross-section through the Hecla region, northern Pioneer batholith showing relationships of concordant intrusion and parallelism with subjacent and superjacent thrust plates. Line of cross-section shown on Fig. 2.

fold contain a well-developed, steeply dipping axial planar cleavage, formed by synkinematic growth of white mica. The geometry and distribution of cleavage is subparallel to the margin of the Pioneer batholith, suggesting a synchronous relationship between batholith emplacement and major folding in the country rocks. Therefore, we interpret the Cherry Creek fault/fold complex as a ramp anticline where the ramp portion of the thrust was synkinematically intruded by the Pioneer batholith.

The eastern contact of the batholith strikes roughly N–S with a gentle to moderate east dip and concordant intrusive relationships with the country rock. These geometric elements, exhibited on maps of Pearson and Zen (1985) and Zen (1988), are well exposed at many localities. In these locations, Mississippian carbonates forming the upper contact or roof of the batholith, dip gently (5–15°) to the east away from the batholith. Plutonic rocks concordantly underlie the Mississippian strata. Near the eastern margin of the batholith, the contact steepens to dips of 20–35°, lending an overall domal shape to the pluton–wall rock contact.

Approximately 10–15 km north of Rock Creek, the contact turns abruptly west and cuts down section from an exposure of the pluton roof to an exposure of the pluton floor. West of this bend, near Hecla, country rocks dip toward the Grayling Lake granite, a 74.1 Ma border pluton of the Pioneer batholith (Marvin et al., 1983). Several kilometers of exposure display the granite lying concordantly above gently south-dipping Paleozoic carbonates. Magmatic foliations and flattened mafic enclaves within the granite are subparallel to the underlying contact. Roof pendants of Paleozoic limestone are found a few kilometers to the south and are in stratigraphic order with those beneath the pluton. Local maximum pluton thickness, estimated from differences between roof and floor elevations, is approximately 350 m.

The cross-section in Fig. 6 correlates structural data from roof and floor regions of the intrusive contact. The cross-section clearly illustrates the concordant and tabular geometry of the batholith. West of Hecla, the contact intersects the Wise River thrust, which places Middle Proterozoic Belt strata on Paleozoic rocks. The fault strikes NW with a gentle southerly dip before terminating against the Grayling Lake granite. Where the two coincide, the Wise River thrust and

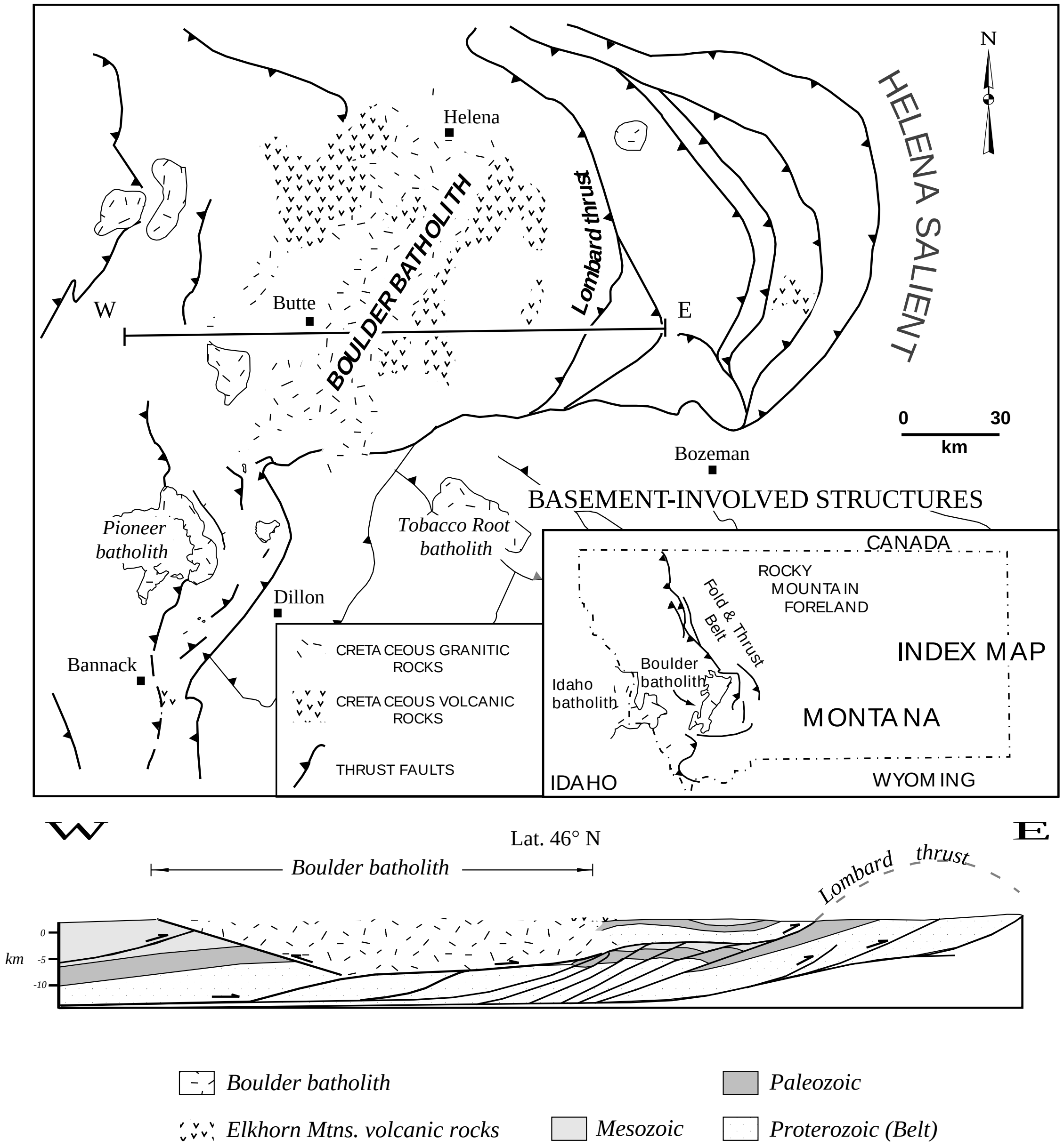

Fig. 7. Map and cross-section of Boulder batholith and Helena salient of western Montana thrust belt. Map and cross-section modified from Burton et al. (1998).

sheet-like Grayling Lake granite have a strikingly similar geometry. The spatial and geometric coincidence of these two features leads us to infer that the Grayling Lake granite intruded the Wise River thrust zone. This corroborates the findings of Fraser and Waldrop (1972) who described granitoid intrusions emplaced along the same thrust system approximately 30–40 km to the north. It also agrees with fault/pluton relationships observed near Rock Creek (see previous description).

North of the contact, within the contact aureole of the Grayling Lake granite, Paleozoic metasedimentary rocks and Cretaceous sills of Keokirk quartz diorite are plastically deformed in the Hecla dome. Hornblende K–Ar ages of ~80.1 Ma for the Keokirk quartz diorite (Zen, 1988) suggest that it predates the Grayling Lake granite. Both metasedimentary rocks and quartz diorite sills show plastic deformation in the form of parasitic folds and meter-scale reverse-sense shear zones. A strong biotite cleavage exists in pelitic metasedimentary rocks, which host biotite, andalusite, and cordierite mineral assemblages. The cleavage is axial-planar to folds and subparallel to the mesoscopic thrust surfaces. The sills of Keokirk quartz diorite are generally folded along with bedding in the surrounding sedimentary units. Weak solid-state fabrics within the sills, formed by aligned biotite and hornblende, overprint earlier magmatic textures and are subparallel to axial planar fabrics in pelitic rocks.

Previous workers have suggested that the Hecla dome and associated deformation formed during forceful emplacement of a quartz diorite body inferred to exist beneath the structure (Karlstrom, 1948; Gunckel, 1990). However, due to overprinting high-temperature solid-state fabrics observed in the quartz diorite sills, it is more likely that cleavage development and folding were concurrent with emplacement of the Grayling Lake granite. K–Ar ages of 71.6 and 72.2 Ma (Zen, 1988) on cleavage-forming biotite from pelitic wall rocks coincide with the age of the Grayling Lake granite and further strengthen the argument for major metamorphism and synmagmatic deformation of wall rocks during its emplacement.

5.2. Boulder batholith

Recent investigations suggest strong similarities between the geometry and structural position of the Boulder batholith and the somewhat smaller intrusive bodies described in previous sections. The Boulder batholith is a composite body over ~100 km long in a north to south direction, spanning the entire eastern margin of the Helena salient of the Sevier fold-and-thrust belt (Fig. 7). The batholith is a composite of 15 major plutons with an aerial extent of over 6000 km^2. The largest volume pluton, the Butte quartz monzonite, was intruded directly beneath a cogenetic volcanic carapace, underscoring its very shallow depth of emplacement (Tilling et al., 1968). Magmatic emplacement of the batholith (from ~80 to 70 Ma) broadly overlapped in time with major phases of contractional deformation within the thrust salient (Tilling et al., 1968; Robinson et al., 1968; Hamilton and Meyers, 1974; Burton et al., 1998).

For decades there has been debate over the geometry, structural position, and mode of emplacement of the Boulder batholith. Hamilton and Meyers (1974) described the batholith as a 5-km thick sheet, emplaced by lateral spreading between a down-warped floor of Middle Proterozoic Belt through upper Cretaceous rocks and a roof of volcanic ejecta. Klepper et al. (1971, 1974) disagreed, arguing that the batholith is as much as 50 km thick and thereby cross-cuts stratigraphy and major contractional structures in its vicinity.

Hyndman and Chase (1979) reinterpreted the gravity and magnetic data used by Hamilton and Meyers (1974) and arrived at a thickness of 10 km for the Boulder batholith. He further suggested that the floor of the batholith was once connected to a western magma source in the Idaho batholith. In his interpretation, the two batholiths are coeval and connected via a sill that intruded at the base of a huge allochthon while it slid eastward from the roof of the Bitteroot lobe of the Idaho batholith. However, recently published thermochronologic and geochronologic data (Hodges and Applegate, 1993; Foster and Fanning, 1997), have shown the timing of emplacement and unroofing of the Bitteroot metamorphic core complex to post-date emplacement of the Boulder batholith by 10–15 m.y. Given this new information, the emplacement model of Hyndman and Chase (1979) seems no longer tenable.

An often cited model involves emplacement of the Boulder batholith into a pull-apart space that developed within a segment of a thin-skinned thrust sheet during eastward translation in the Helena salient (Schmidt et al., 1990). The hypothesis involves an elaborate kinematic scenario, whereby the Lombard thrust sheet, a major thin-skinned allochthon of the Helena salient, underwent periodic mechanical coupling to eastward-moving, thick-skinned, basement blocks located north and south of the salient. Coupling caused the Lombard allochthon to split into a forward propagating eastern sheet that left behind a stationary western sheet. The trailing edge of the eastern Lombard sheet became the boundary of a progressively opening 'pull-apart' cavity that was subsequently intruded by the main phases of the Boulder batholith. We find the kinematics and timing of complicated coupling mechanisms assumed by this model to be fundamentally untestable. Furthermore, it borrows the model of transtensional basin development from strike-slip environments and unjustifiably applies it to a fold-thrust salient. These defects together with results of recent seismic and structural investigations (Lageson et al., 1994; Vejmelek and Smithson, 1995; Burton et al., 1998), render the model of Schmidt et al. (1990) geometrically and kinematically unsound.

Balanced regional cross-sections, deep seismic reflection data, data from deep boreholes, and tectonic reconstructions suggest that the Boulder batholith, like plutons in the McCartney Mountain thrust salient, was emplaced as a composite tabular body at the top of a frontal thrust ramp (Lageson et al., 1994; Vejmelek and Smithson, 1995; Burton et al., 1998).

6. Summary and conclusions

6.1. Summary

From our detailed study of the emplacement history of the Pioneer batholith and its satellite plutons, the following summary can be made:

(a) Plutons were emplaced *within* shallow level thrust zones, between hanging wall and footwall sections, into a ramp-top setting.
(b) Intrusive bodies are generally tabular and concordant with both hanging wall and footwall rocks.
(c) Where exposed, roof rocks are domed above a concordant subjacent pluton.
(d) In cases of the large-volume plutons (e.g. McCartney Mountain pluton and Pioneer batholith) wall rock deformation along their eastern (foreland-facing) margins is characterized by kilometer-scale folds and an accompanying axial-planar cleavage.
(e) Plutons contain abundant xenoliths interpreted as stoped fault rocks derived from an intruded fault zone.

Previous models that attempt to explain the emplacement

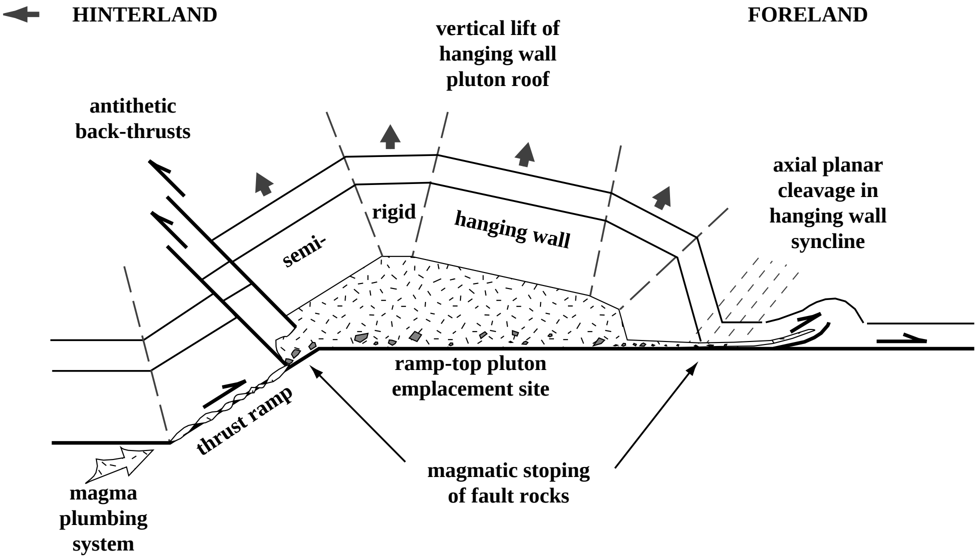

Fig. 8. Proposed emplacement model for magmatism in the southwest Montana thrust belt.

of batholiths in western Montana invoke transtensional ‘pull-apart’ zones along reactivated Proterozoic faults (Schmidt et al., 1990), gravitational detachment from the roof of the Idaho batholith to the west (Hyndman et al., 1975), or compound sill-like intrusions of magmatic sheets (Hamilton and Meyers, 1974; Hyndman et al., 1988). However, these models do not take into account the ramp-top structural setting of the two largest volume batholiths (i.e. Pioneer and Boulder batholiths) as well as smaller satellite plutons discussed in this paper.

6.2. Emplacement model

Our model (Fig. 8) for emplacement of Late Cretaceous silicic plutons in the Sevier fold-thrust belt of western Montana is based on the detailed field mapping and structural relations between plutons and their wall rocks recorded above. In all cases, field data show a clear spatial correlation between the plutons and the top of major frontal thrust ramps. Frontal thrust ramps demonstrate many key elements that may facilitate pluton emplacement: (1) extensional strains along the ramp interface produced by incremental plane-strain simple shear; (2) a dilatant space or ‘releasing-step’ at the top of the ramp; and (3) antithetic back-thrusts that may assist in pluton emplacement. Regardless of whether the pluton is synkinematic (sensu stricto) or post-kinematic, or some combination thereof, we found evidence that frontal ramp tops create an environment where plutons are initially emplaced and grow. This is evidenced by the progressive size-increase of plutons from Bannack to McCartney Mountain to the Pioneer batholith to the Boulder batholith, all located at ramp-top structural positions.

Frontal ramps are, by definition, dominantly dip-slip fault zones that accommodate plane-strain displacement of the hanging wall up-and-over the footwall block (Coward et al., 1992, p. 115; Mosar and Suppe, 1992; Zoetemeijer and Sassi, 1992). Plane-strain deformation incorporates local environments of shortening and extension that are manifest through an array of well-documented secondary structural features (e.g. Ramsay and Huber, 1987). Locally developed and connected extensional structures such as interconnected dilatant (e.g. fractured hanging wall rocks in Bannack), could provide pathways for the migration of magma to ramp-top structural positions. We envisage a model similar that of Collins and Sawyer (1996), but under shallow crustal (i.e. brittle) conditions. Also, antithetic back-thrusts that emanate from the ramp interface (Serra, 1977; Morse, 1977; Wiltschko, 1979) could also facilitate the ascent of magma. Additionally, a brecciated fault zone could be part of the magmatic plumbing system, as evidenced by the spatial proximity of pluton floors and roofs to subjacent and superjacent thrust systems and fault zone xenoliths found in most of our cases studied.

The tops of frontal ramps are often observed as areas of intense imbrication and disharmonic folding (Royse et al., 1975; Harris and Milici, 1977; Serra, 1977). As the hanging wall is rotated up-and-over a ramp interface, the inherent rigid to semi-rigid behavior of the upper plate, as determined by dominant structural-lithic units in the stratigraphic succession (Lageson et al., 1994) creates a dilatant zone at the top of the ramp that, in the absence of magma, collapses to form an imbricate fan. This dilatant zone can similarly be the site for emplacement of a silicic pluton, either syn-kinematically (magma taking the place of an imbricate fan) or post-kinematically (magma emplacement aided by pre-existing imbricate faults).

Finally, once initial pluton emplacement has occurred at the top of a ramp interface (exemplified by the small plutons at Bannack), growth and amplification of such shallow plutons can occur through several mechanisms such as roof lifting (the roof in this case being the thrust fault hanging wall) driven by magma overpressure (Correy, 1988). Again, these mechanisms can either be synkinematic or post-kinematic with respect to the subjacent thrust system. The distinctive east-dipping western flank of the Boulder batholith (Vejmelek and Smithson, 1995) and McCartney Mountain pluton (this study) suggests that antithetic thrust faults and other hinterland-vergent structures of the type described by Serra (1977) and Gabrielse (1992) facilitated the upward growth and amplification of the pluton following initial ramp-top emplacement.

Thus, we see a spatial and temporal progression from south-to-north in Late Cretaceous granitoid bodies of southwest Montana. Plutons at Bannack would represent small, incipient intrusive bodies that were emplaced at the top of a frontal–ramp interface in a dilatant zone with co-mingled imbricate thrust faults in wall rocks. The McCartney Mountain pluton represents a further stage of pluton development in that the pluton is much larger and thicker, but it is still concordant to the subjacent footwall and superjacent hanging wall of the intruded thrust system. Also, the McCartney Mountain pluton shows a clear younging-to-the-west, with the youngest pluton situated at the top of the subjacent thrust ramp. The Pioneer and Boulder batholiths are much larger composite bodies, but both are located at the top of regional thrust ramps that separate the 'western' Sevier fold-thrust belt from its 'eastern' or foreland portion. The greater thickness and east-dipping west-flank of the Boulder batholith suggests that magma ascent either followed or was aided by antithetic structures common to major ramp interfaces.

6.3. Pre-kinematic, synkinematic, or post-kinematic pluton emplacement

Recently, authors have questioned the compatibility between rates of faulting and plutonic processes (Yoshinobu et al., 1998). This punctuates the need to clarify whether emplacement was pre-kinematic, synkinematic, or post-kinematic with respect to adjacent structures. In our cases, including McCartney Mountain and the Pioneer batholith, relationships between wall rock metamorphic fabrics, folds, and magmatic fabrics show clear evidence for synkinematic emplacement processes. However, on a regional scale the evidence is not conclusive that all magmatic pulses were accompanied by synkinematic intrusion of magma, despite a consistent observation of plutons lying within thrust zones. A case in point lies in Bannack, where plutons were intruded between hanging wall and footwall sections and thus occupy the fault zones (a one-to-one *geometric* relationship). We also conclude that there has not been significant thrust fault motion since the plutons were emplaced (i.e. plutons are not pre-kinematic). However, field data do not fully demonstrate that plutons were emplaced during slip along adjacent fault zones (i.e. not a one-to-one *kinematic* relationship). In Bannack, plutonism may have post-dated thrusting, yet utilized contractional structures during emplacement.

In overview, we present several examples where pluton emplacement occurred during deformation. However, some plutonism may have occurred after thrust motion had ceased. In all our cases, magma exploited either developing fault zones (synkinematic example) or preexisting fault zones (post-kinematic example) during some stage of emplacement. Either scenario allows for fault zone stoping and roof lifting to serve as important emplacement processes. Furthermore, these mechanisms can be purely post-kinematic, thus removing the need for rates of plutonic processes to keep pace with fault translation rates (Yoshinobu et al., 1998).

In its simplest form our model for pluton emplacement in a ramp-top 'releasing step', is required to be synkinematic and therefore bound by relative rates of pluton emplacement and fault displacement. This relationship is less important if we acknowledge that some translational strain is induced by magma pressure and contemporaneous forceful emplacement processes as suggested by Tikoff et al. (1999). Thus, we favor an emplacement model similar to that of Benn et al. (1998), whereby pluton space is created by a combination of tectonic forces and magma pressure.

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