Preliminary Precambrian Basement Structure Map of the Continental United States – An Interpretation of Geologic and Aeromagnetic Data

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Open-File Report 2005-1029

U.S. Department of the Interior
U.S. Geological Survey

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Introduction

The Precambrian basement rocks of the continental United States are largely covered by younger sedimentary and volcanic rocks, and the availability of updated aeromagnetic data (NAMAG, 2002) provides a means to infer major regional basement structures and tie together the scattered, but locally abundant, geologic information.

Precambrian basement structures in the continental United States have strongly influenced later Proterozoic and Phanerozoic tectonism within the continent, and there is a growing awareness of the utility of these structures in deciphering major younger tectonic and related episodes. Interest in the role of basement structures in the evolution of continents has been recently stimulated, particularly by publications of the Geological Society of London (Holdsworth and others, 1998; Miller and others, 2001). These publications, as well as others, stress the importance of reactivation of basement structures in guiding the subsequent evolution of continents. Knowledge of basement structures is an important key to understanding the geology of continental interiors.

Previous studies of the basement tectonics of the continental United States have delineated the gross structural fabric (Baars and others, 1995; Marshak and Paulsen, 1996). In a significant contribution, Baars and others (1995) recognized the continental-scale orthogonal pattern and the basic similarity of the structures to the San Andreas fault system in California.

They, therefore, postulated an overall transpressional stress mechanism by analogy. Marshak and Paulsen (1996), on the other hand, suggested an intracratonic extensional mechanism for the deformation.

This map and text are an outgrowth of preparation of Precambrian basement geologic maps of several states in the western part of the United States, utilizing updated aeromagnetic data (NAMAG, 2003) as an interpretive tool: Wyoming, Sims and others, 2001b; Colorado, Sims and others, 2001a; Montana, Sims and others 2004; Idaho, Sims and others, in press; and Arizona (Sims, 2004, unpub. data). In the western Cordillera, in particular, as contrasted to interior sectors of the continent—which have been relatively stable since the end of the Precambrian—later episodic deformation focused on basement zones of weakness strongly influenced structures formed during the late Paleozoic Ancestral Rocky Mountain orogenesis, the Late Cretaceous Laramide and Sevier orogenies, and Cenozoic extensional tectonics (Sims, submitted). In addition, long-lived basement structures localized ore-bearing igneous activity, such as in the Colorado mineral belt (Tweto and Sims, 1963; Wilson and Sims, 2003), the central Idaho-Montana mineral belt (O'Neill and others, 2002), and the New Mexico structural zone (Sims and others, 2002).

Two fundamental continent-scale basement fracture systems, that formed in late Paleoproterozoic- and early Mesoproterozoic-time and thatoverlap spatially, primarily have influenced later tectogenesis. These structures abruptly formed after consolidation of the proto-continent (1.76 to 1.70 Ga), and probably represent initial lithospheric fragmentation that eventually led to continental separation in latest Proterozoic time, that is, the breakup of postulated Rodinia. The two fracture systems generally are northwest-striking transcurrent faults, formed by continent-scale transpressional deformation, and northeast-striking ductile shears.

An exception to a Paleoproterozoic age for initial shearing in the United States continent is the Vermilion fault in northern Minnesota (VF, pl. 1). This fault apparently is the southernmost structure of a regional system of dextral strike-slip shear zones within the Superior province (SP, fig. 10; Card and Poulsen, 1998, fig. 2.6) that was formed in Late Archean time (Hudleston and Bauer, 1995).

The tectonic model presented here for evolution of the continent after its consolidation accords with new geodynamic models for North and South American plate motions, motivated by seismic anisotropy (Silver, 1996; Russo and Silver, 1996; Dueker and others, 2001), that invoke mechanical coupling and subsequent shear between the lithosphere and asthenosphere such that deep mantle flow is considered a major driving force for plate movement.

Principal Basement Structures

The principal regional Precambrian basement structures shown on plate 1 are: (1) suture zones formed during amalgamation of the continent (Laurentia) in Paleoproterozoic time, (2) a wide belt of partitioned northeast-striking ductile shear zones (~1.7-1.4 Ga) that extends across the width of the continent into Canada, and (3) an even broader zone of conjugate strike-slip shears (~1.7 Ga), the principal displacement zones of which strike west-northwest to northwest. Each of these basement structures was reactivated episodically during Mesoproterozoic and later times, and accordingly they provide the building blocks for subsequent tectonic evolution of the interior of the continent.

Except for the Dillon suture zone (pl. 1) of the Trans-Montana orogen (Sims and others, 2004), suture zones generally have had a secondary role in subsequent evolution of the continent. The Trans-Montana suture zone controlled the localization of late Cretaceous igneous-related mineral deposits in the central Idaho-Montana mineral belt (O'Neill and others, 2002). Also, the zone influenced sedimentary facies patterns in the Paleozoic.

The northeast-striking ductile shears profoundly influenced the localization of ~1.4 Ga, predominantly alkali-calcic intrusions of the Transcontinental Proterozoic provinces (Sims, 2004, unpublished data; c.f. pl. 1 and Ferguson and others, 2004, fig. 9). The intrusions coincide spatially with the regional shear system, and at a detailed scale, were intruded within the preexisting shears (Nyman and others, 1994; Aleinikoff and others, 1993; Ferguson and others, 2004).

The strike-slip fault system fragmented the continental crust into fault bounded, but coherent, blocks of varying dimensions, the boundaries of which were favorably oriented to later stress fields to be repeatedly reactivated. These structures are distributed throughout the continent, affecting both Archean and Proterozoic provinces, and arguably are the most important of the basement fault systems. These structures are discussed in the context of the regional geology in following sections.

Magnetic Map Interpretation

The recently compiled Magnetic Anomaly Map of North America (NAMAG, 2002) is an appropriate basemap for Precambrian structural interpretation. Regional-scale aeromagnetic anomaly patterns reflect the distribution of magnetic minerals, primarily magnetite and other minerals in the magnetite-ulvöspinel solid-solution series, throughout the entire crust (Reynolds and others, 1990). The relative concentration of these magnetic minerals is an indicator of geologically important factors including original lithology, metamorphic grade, and degree of geochemical alteration. Generally speaking, igneous rocks are much more magnetic than sedimentary rocks; mafic igneous rocks are more magnetic than felsic igneous rocks; magnetism may be either created or destroyed during metamorphism of sedimentary rocks; and magnetization of igneous rocks generally is diminished by metamorphism and metasomatism (Reynolds and others, 1990). Structural juxtaposition of rocks with contrasting magnetization can produce particularly sharp anomaly boundaries. Measured aeromagnetic anomalies are a complex integration of the effect of these crustal magnetic sources, most of which lie within the Precambrian basement.

Quantitative interpretation of regional-scale aeromagnetic anomalies is problematic because, in general, insufficient auxiliary information is available to overcome the inherent nonuniqueness of potential field inversion (for example, Blakely, 1995). Ideally, quantitative interpretations would be constrained by magnetic property measurements of all lithologies involved and independent depth information from seismic or other geophysical methods. Lacking these constraints, useful qualitative interpretation is possible. Building on early pioneering work by Zietz and others (1969), Hinze and Zietz (1985) examined an analog compilation of magnetic data for the conterminous United States and discussed many proposed correlations with regional geologic features. In particular, they pointed out numerous regional magnetic-anomaly provinces that characterize the Precambrian basement. These, in turn, are cut by very intense, generally linear anomaly zones that represent mafic extrusive and shallow intrusive bodies within the Midcontinent rift, southern Oklahoma aulacogen, and the Reelfoot rift (Hinze and Zietz, 1985). Kane and Godson (1989) used the same analog compilation, together with a gravity map, to define a set of geophysical "anomaly-trend zones," bounded by linear geophysical gradients, for the conterminous United States. Within their magnetic anomaly zones, they recognized and identified preferred anomaly orientation directions. In particular, they pointed out the correspondence of northwest trends in the Midcontinent with the "puzzling" trends previously identified by Bickford and others (1986). The interpretations in this report follow this general strategy, but the greater resolution of the new digital compilation (NAMAG, 2002), allows for more detailed identification of zones and trends.

Examination of the conterminous United States portion of the North American magnetic map (NAMAG, 2002), reveals a large number of linear features that fall into three broad categories: (1) boundaries of zones with common anomaly patterns, (2) continuous or discontinuous sets of steep anomaly gradients, or (3) narrow magnetic troughs. In all three cases, these linear features are postulated here to correspond with faults or fractures in the Precambrian basement. Category (1) is analogous to the zone boundaries defined by Kane and Godson (1989) and, indeed, follows or parallels many of their features. These features typically are Precambrian province boundaries, orogen margins, or rift edges. Category (2) features generally fall within the broad zones and represent structures within the broader zones. Category (3) has not been previously emphasized in regional interpretation of the conterminous United States. Within this category, basement shear zones, in particular, are readily identified because magnetite in the host rocks is apparently destroyed during ductile shearing and later alteration by hydrothermal or circulating surficial waters (Finn and Sims, in press). Accordingly, these basement structures are expressed by negative magnetic anomalies, particularly evident in terranes dominated by rocks of high magnetic susceptibly, such as most Precambrian granitic plutons.

Identification of significant geophysical lineaments and boundaries remains a subjective process, particularly at a continental scale. Various mathematical techniques exist for geophysical edge detection and enhancement (for example, Blakely and Simpson, 1986; Cordell and McCafferty, 1989), but ultimately it falls to the interpreter to edit and interpret these results. In addition to the conterminous United States studies referenced above, other examples of regional geophysical domain mapping reveal a variety of interpretive styles and techniques (for example, Cordell and Grauch, 1985; Cady, 1989; Phillips, 1990; Saltus and others, 1997). In this study, extensive prior knowledge of Precambrian geology by one of us plays a key role in determining the significance of the selected aeromagnetic features.

Structure Map Preparation

The Precambrian structure map portrays major regional structural features inherent to the basement, that is, structures known and presumed to have formed during Archean and Proterozoic times. The structures include major suture zones formed during Paleoproterozoic accretionary tectonism and regional shear zones and faults initiated in late Paleoproterozoic-early Mesoproterozoic time.

Knowledge of the accretionary history of the continent has accrued from geologic mapping and related studies, particularly geochronology, over the past century and has been summarized in the Decade of North American Geology volume on the Precambrian (Reed and others, 1993). Although fundamental shear zones in the basement rocks have been recognized in some areas since the pioneering studies of Billingsley and Locke (1941) and Mayo (1958), their extent and significance in the geologic evolution of the continent have not been fully appreciated, nor has the timing of the initial faulting been known until recently (Sims, 2002). Earlier compilation of known basement faults in the mid-continent region (for example, Kisvarsanyi, 1984; Sims, 1985; Sims and others, 1991) revealed persistent abundant northwest- and northeast-striking faults, but their age was only known at the time to be pre-1.50 Ga, the time of abundant rhyolite extrusion in southeast Missouri (see Sims and others, 1987, for discussion). Northeast-trending fundamental basement shear zones have been known for many decades to be present in the Colorado Front Range (Moench and others, 1962) and ranges to the west in the Rocky Mountains (Tweto and Sims, 1963). Later studies (Karlstrom and others, 1997) have demonstrated their existence in New Mexico and adjacent Arizona. Sims and others (2002) have demonstrated the influence of these northeast-trending basement shear zones on localization of epigenetic mineral deposits in New Mexico. Northwest-striking shear zones, however, were not recognized as fundamental basement structures of regional extent until recently (Sims, 2002). Recognition of these structures as a continent-wide integrated strike-slip fault system was largely dependent on the availability of updated aeromagnetic anomaly data (NAMAG, 2002). The magnetic data provided a means to tie together known geologic observations and extend this knowledge into the vast areas covered by younger rocks. Accordingly, the Precambrian structure map combines known geology gained from studies of exposed areas and geophysical interpretation of aeromagnetic anomaly data. We attempt to quantify relative uncertainties in mapping of the basement structures, but this is somewhat objective because aeromagnetic anomaly data commonly are a major tool in preparation of geologic maps of basement rocks at small and large scales.

Summary of Precambrian Basement Geology

The Precambrian basement in continental United States is composed essentially of a northern tract of Archean cratonic elements and enclosing pre-1.80 Ga Proterozoic magmatic terranes—which have been designated as the Hudsonian craton (fig. 1a; Van Schmus and others, 1993)—and a southern tract of diverse igneous and sedimentary rocks (1.80-1.65 Ga), known as the Transcontinental Proterozoic provinces (fig. 1b). The Hudsonian craton was consolidated during the Penokean (Sims, 1996) and Trans-Hudson (Sims and others, 1991; Peterman and Sims, 1993) orogenies. It formed the foreland against which 1.8—1.7 Ga magmatic arc rocks of the Central Plains orogen (Sims and Peterman, 1986) were accreted (fig. 1a).

The volcanic rocks of the Central Plains orogen are partly overlain by extensive rhyolite and hypabyssal granite extruded during the interval 1.76 to 1.65 Ga (fig. 1b). Penecontemporaneous quartz arenite formed locally on the rhyolite successions and locally overlapped Penokean orogenic rocks in the Lake Superior region (pl. 1; Sims, 1996; Medaris and others, 2003). Together, these rocks compose the 1.76—1.65 Ga rhyolite-quartz arenite belt of figure 1b. In Mesoproterozoic time (1.5 to 1.35 Ga), voluminous rhyolite was erupted across a broad region in the Midcontinent, and predominantly A-type intrusions were emplaced in a lengthy belt extending from southern California northeastward through eastern Canada as far north as Labrador (Sims, 2004, unpub. data). In Mesoproterozoic time, clastic sedimentary rocks (for example, Belt Supergroup (Winston, 1986) and Apache Supergroup (Wrucke, 1989) were deposited nearly contemporaneously in intracontinental structural basins in the western United States. Younger, Neoproterozoic clastic sedimentary successions were deposited along both continental margins in rift-related basins (Stewart, 1972; Thomas, 1977).

The western margin of the continent is sharply defined (figs. 1a, 1b); exotic late Paleozoic and Triassic rocks were accreted to the rifted margin in mid-Cretaceous time. The eastern and southern margins, however, are less well defined because mid-Proterozoic and older continental rocks are overridden by thrust faults along the ~1.1 Ga Grenville and Llano fronts. Intracontinental Proterozoic faults of northwest trend (Sims, submitted) strongly influenced sculpting of the continental margins during the Grenville and Cretaceous orogenies. Preexisting transcurrent faults were reactivated as transform faults to facilitate rifting.

Precambrian Basement Architecture

The Hudsonian craton consists of two Archean nuclei, the Superior and Wyoming provinces, that are circumscribed by Paleoproterozoic (pre-1.80 Ga) magmatic accretionary terranes (fig. 1a). The Trans-Hudson orogen (THO, fig. 1a) separates the two Archean nuclei, and the approximately coeval Penokean (PO) and Trans-Montana (TMO; Sims and others, 2004) orogens bound their outer margins. The Penokean orogen is juxtaposed with the southeast margin of the Superior province, and the Trans-Montana orogen is juxtaposed with the northwest margin of the Wyoming province. Accordingly, the Archean nuclei were isolated largely from later continental-margin tectonism by an outer rind of magmatic arc rocks capable of absorbing much of the subsequent strain. This can partly account for the scarce evidence of post-1.80 Ga distributed compressional deformation in Archean province rocks.

During the interval 1.78—1.72, Ga magmatic ocean-arc rocks were accreted to the southern margin of the Hudsonian craton, extending southward from the Cheyenne (suture) belt (Karlstrom and Houston, 1984) in southern Wyoming, at least into northern New Mexico, across a distance of ~1,000 km. These rocks have been assigned to the Colorado province in the southern Rocky Mountains (Bickford and others, 1986), the Central Plains orogen in the Midcontinent (fig. 1a; Sims and Peterman, 1986), and the Yavapai province in Arizona (Karlstrom and Bowring, 1988). The provinces are combined in figure 1a under the Central

Plains orogen. Despite intensive studies, details of assembly of the rocks remain uncertain. Available data, however, suggest that accretion was piecemeal (Sims and Stein, 2003) and apparently was younger to the south, as suggested by the distribution of comagmatic calc-alkaline plutons (Reed and others, 1987). Seismic reflection data across the Park Range in northern Colorado (Morozova and others, 2002) suggest the presence of a possible suture zone (Farwell Mountain-Lester Mountain) within Colorado province rocks, about 50 km south of the Cheyenne belt. This zone separates predominantly (1.79—1.77 Ga) arc rocks (Green Mountain arc) to the north from 1.76—1.72 Ga arc and derivative sedimentary rocks (Rawah block) to the south (Tyson and others, 2002). At the same latitude in the Colorado Front Range, to the east, Selverstone and others (2000) have recognized an important northeast-striking Paleoproterozoic (~1.7 Ga) transcurrent boundary within the Colorado province. Rocks to the south of these tectonic boundaries have been dated in the age range 1.76—1.72 Ga. Combined, these age data indicate the probable presence of at least two distinct, accretionary arcs in Colorado— the Green Mountain and Rawah arcs. Rocks assigned to the Yavapai province in Arizona also are mainly 1.76-1.72 Ga in age (Karlstrom and Bowring, 1988). Ocean-arc rocks in the range 1.76—1.72 have been recognized from drill cores in the Midcontinent (Van Schmus and others, 1993). These rocks have been assigned to the Central Plains orogen (Sims and Peterman, 1986), which we redefine here to consist only of ocean-arc rocks formed in the approximate range 1.78 to 1.72 Ga. Rocks of the Colorado and Yavapai provinces are intensely deformed and metamorphosed generally to amphibolite grade. Consolidation and stabilization of the proto-continent at ~ 1.72 Ga were followed abruptly by intracontinent shearing of continental-scale (Sims, 2002); these fundamental basement structures guided later Proterozoic tectono-magmatic activity, discussed as follows.

The intracontinental shearing in late Paleoproterozoic time initiated alkali-calcic magmatism along the southeastern margin of the Paleoproterozoic accretionary terranes of the Central Plains orogen and areas to the west. In the southwestern United States, rhyolitic rocks, mainly ash-flow tuffs, were erupted across a broad region extending from central Arizona into the Midcontinent, and essentially penecontemporaneous quartz-arenite successions were formed in structural basins of more limited extent (Sims, 2004, unpublished data). These quartz-arenite deposits include the Mazatzal province in southeastern Arizona (Karlstrom and Bowring, 1988), the Vadito and Hondo Groups in northern New Mexico (Read and others, 1999), and the Uncompahgre Formation (Barker, 1969) in southwestern Colorado. In the northern Midcontinent region, rhyolite eruption started earlier (1.76 Ga) in southern Wisconsin (Sims, 2004, unpublished data). This magmatism was followed in the same region by local deposition of quartz arenite of the Baraboo interval (Dott, 1983). The existence of mature weathering products between rhyolite and quartz arenite successions in the northern Midcontinent (Medaris and others, 2003) and northern New Mexico (Grambling and Williams, 1985) suggests extensive crustal stability at ~1.70 Ga within the region. The rhyolite and quartz arenite successions were deformed and weakly metamorphosed at 1.65—1.63 Ga, probably during intracontinental tectonogenesis. The imposed deformational fabrics, within the rhyolite successions and contained folds, are chiefly oriented northeastward, but the quartz arenite successions occupy fault-bound basins oriented northwestward, which suggest deformation on northeast-southwest axes, as demonstrated for the Uncompahgre Formation in southwestern Colorado (Barker, 1969). The orthogonal northeast- and northwest-trending structures are interpreted to reflect partitioning of strain along kinematic fault boundaries, rather than being directly related to a regional stress field. This mode of transpression-transtension is interpreted as resulting from deformation as described by Dewey and others (1998).

Continental fragmentation across the United States was diachronous during the apparent interval 1.76—1.70 Ga. Fundamental, partitioned northeast-striking shear zones in this age range transect the Proterozoic provinces across a northeast-trending >500-km-wide belt extending from southern California into eastern Canada, and probably beyond. The northeast-striking shear zones have been interpreted as resulting from northwest-southeast shortening

(Nyman and others, 1994), probably resulting from regional transpression (Sims and Stein, 2003). Approximately contemporaneous continental-scale strike-slip faulting, chiefly oriented northwestward, segmented the Hudsonian craton as well as the Proterozoic provinces to the south. These fundamental lithospheric structures provided first-order controls on later Proterozoic tectonism, which probably took place in an intracontinental setting.

A second major episode of predominantly alkali-calcic A-type magmatism, commonly called the "Transcontinental anorogenic province" (Silver and others, 1977; Anderson, 1983) occurred in Mesoproterozoic (1.5—1.35 Ga) time. It followed the same general path as the earlier (1.76—1.65 Ga) rhyolitic magmatism (rhyolite-quartz arenite belt, fig. 1b), extending from southern California diagonally across the United States to Labrador. The felsic magmatism was not associated spatially with significant clastic sedimentation. The felsic magmatism consists of coeval and apparently cogenetic volcanic and mesozonal plutonic rocks that overlap spatially. The volcanic and associated hypabyssal rocks (fig. 1b) have been referred to (Van Schmus and others, 1993) as an Eastern granite-rhyolite province (1.47±30 Ga) and a southern granite-rhyolite province (1.37±30 Ga) (fig. 1b); they blanket much of the Midcontinent (Van Schmus and others, 1996), apparently mostly as a thin veneer. The mesozonal plutonic rocks form isolated or circumscribed intrusions that are widely spaced throughout the belt of Transcontinental Proterozoic provinces (Van Schmus and others, 1993); they lack possible associated volcanic rocks. Although generally granitic in composition, some plutons contain anorthosite (for example, Wolf River batholith in Wisconsin (Anderson and Cullers, 1978) and the Sherman batholith in southern Wyoming (Frost and others, 2002). A few plutons in Colorado are composed of foliated granodiorite (e.g., Mt. Evans batholith; Aleinikoff and others, 1993).

The designation of the mesozonal Mesoproterozoic plutons as anorogenic (Anderson, 1983) has been disputed because some bodies are partly deformed (Nyman and others, 1994; Aleinikoff and others, 1993; Ferguson and others, 2004). The recognition that the shear zones that host the intrusions are intracontinental structures is a key to understanding this tectonic enigma. These structures have partitioned strain imposed by a regional stress field during and subsequent to emplacement of the plutons, resulting in alternating compression and extension caused by transpressional-transtensional deformation. In this tectonic environment, kinematic boundary conditions along fault-bound blocks are more important than the regional stress field in determining local tectonism. The shear zones that host the plutons probably were formed in late Paleoproterozic (~1.70 Ga; Sims and Stein, 2003) time. Extension concurrent with magma emplacement at ~1.4 Ga provided openings for magma emplacement (Sims and Stein, 2003). Continued or subsequent transpression along the preexisting shear zones caused local deformation of the intrusive bodies. In a continental setting, preexisting zones of weakness are preferentially reactivated during tectonism at the expense of development of new, pristine fractures (Holdsworth and others, 2001).

Basement Structural Controls

The continental-scale shears and faults that formed in late Paleoproterozoic time, after consolidation of the protocontinent have provided the primary structural controls for later Proterozoic tectonism and magmatism in this part of the North American continent. The close spatial relationship of the Transcontinental Proterozoic provinces (Van Schmus and others, 1993) with the belt of northeast-striking fundamental, intracontinental shear zones shown on plate 1 is interpreted to indicate that these structures provided first-order controls on localization of the igneous activity in the provinces as a whole (Sims, 2004, unpublished data), as well as at a local scale (for example, Ferguson and others, 2004).

Petrogenetic studies of the igneous bodies (Anderson and Cullers, 1979; Stein, 1985; Frost and others, 2002) localized by the northeast-trending structures indicate remelting of lower crustal rocks as a major component of the magmas, stimulated by ponding of basaltic magma at the base of the crust.

The northwest-trending late Paleoproterozoic transcurrent fault system (pl. 1) was superposed on, and extends beyond the belt of northeast-striking shear zones along the southern margin of the Hudsonian craton (fig. 1b). It provided second-order controls on tectono-magmatic activity within the broad Transcontinental Proterozoic provinces. Specifically, it provided structural openings for igneous intrusions and structural basins for rhyolitic extrusions and quartz-arenite successions. Mid-Proterozoic tectonism involved kinematic interactions among the northeast-striking shear zones and individual strands of the northwest fault system.

Continental Margins

Both the western and eastern continental margins (pl. 1) are characterized by angular bends (promontories and embayments) that can be attributed to reactivation of intracontinental basement structures during the rift to drift transition in the interval Late Proterozoic-Cambrian period, which eventually led to continental separation on both margins. During rifting, intracontinental northwest-trending strike-slip shear zones, initiated chiefly in late Paleoproterozoic time (~1.70 Ga), were reactivated as transform faults, which accommodated differential lateral displacements. The rifted margins likewise follow preexisting structural fabrics, which acted as zones of weakness during extension accompanying the rifting (Sims and others, in press).

The trace of subsequent passive-margin sedimentary successions and orogenic belts on both continental margins are inherited from the shape of the earlier late Neoproterozoic rifted margin. On the western margin, stratigraphic facies patterns of Neoproterozoic through Devonian successions (Poole and others, 1992) trend north-northeast from southern California to Idaho, where they abruptly turn to a northwest orientation, extending into northeast Washington, where they resume a northerly trend into Canada (pl. 1; fig. 1a). The northwest-trending segment in Idaho coincides with the Salmon River arch (Armstrong and others, 1977), which is now known (Sims and others, in press) to be a horst formed during reactivation of the mid-

Proterozoic Clearwater fault (CF, fig. 1a) zone that shed clastic sediments into adjacent northwest-trending structural basins. The deformed belt has been called the “Central Idaho disturbance” (Sims and others, in press).

On the eastern continental margin, angular bends along the margin (Thomas, 1977, 1983) are grossly similar in orientation and shape to those on the western margin. Rifted margin segments that generally trend north-northeast are offset by northwest-striking transform faults (pl. 1). Crustal separation of the eastern continent margin occurred penecontemporaneously with that on the western margin, as indicated by passive-margin volcanic-sedimentary successions of late Neoproterozoic to Early Cambrian age, followed by formation of a Cambrian-Ordovician carbonate bank.

Orogenesis along both continental margins was prolonged and episodic but culminated at widely different geologic times. Tectonic transport on each margin was directed craton-ward. On the western margin, orogenesis during the middle Paleozoic (Antler orogeny) and late Paleozoic (Sonoma orogeny) terminated with the Cretaceous Sevier orogeny (Burchfiel and others, 1992). These orogenic episodes did not materially change the zig-zag shape of the continental margin. On the eastern margin, west-vergent orogenesis began in the Ordovician, as indicated by earliest clastic-wedge sediments (Thomas, 1977) and terminated in the late Paleozoic with development of the Appalachian-Ouachita system.

Dynamics

The assembly of the Hudsonian craton (fig. 1a) in Paleoproterozoic time (Van Schmus and others, 1993) and the addition of the Central Plains orogen (Sims and Peterman, 1986) and its general equivalent, the Colorado province (Bickford and others, 1986) to the craton previously have been generally attributed to plate tectonic processes, mainly the suturing of accretionary arcs to Archean nuclei—the Superior (Card, 1990) and Wyoming (Sims and others, 2001b) provinces. The nature, origin, and significance of the post-assembly Proterozoic shear zones and faults have not been well understood previously. Yet it is these structures that provided the prevailing architecture for subsequent geologic evolution within the continent.

Model for Subcontinental Mantle Deformation

The systematics of major regional post-assembly Precambrian basement structures throughout the United States continent point to a common causal mechanism for their development. The model presented here accords with new geodynamic models for North and South American plate motions, based on seismic anisotropy beneath the continents (Silver, 1996), that invoke mechanical coupling and subsequent shear between the lithosphere and asthenosphere such that a major driving force for plate movement is deep-mantle flow. The model of subcontinental mantle deformation has been proposed to explain the Andes Cordillera in South America and by analogy the Rocky Mountains (Russo and Silver, 1996), and also deformed mantle peridotite xenoliths in the Slave craton in northwest Canada (Kennedy and others, 2002). The inadequacies of plate tectonic theory to explain continental deformation have been pointed out previously by Molnar (1988).

Two orthogonal sets of shear zones and faults are predominant in the continent: (1) northeast-striking, partitioned ductile shear zones, and (2) northwest-trending strike-slip ductile-brittle faults. The northeast-striking shear zones are interpreted as resulting from northwest-southeast shortening (Nyman and others, 1994; Karlstrom and others, 1997; Sims and Stein, 2003), apparently formed during the interval 1.76 to 1.70 Ga (Shaw and others, 2001). The northwest-trending (1.7—1.5 Ga) transcurrent fault system consists of west-northwest to northwest synthetic faults and northerly-trending antithetic transfer faults; it is attributed to transpressional-transtensional deformation (Dewey and others, 1998), that is, strike-slip deformation that deviates from simple shear because of a component of shortening or extension orthogonal to the deformation zone.

The northeast- and northwest-oriented shears and faults mimic orthogonal teleseismic images of the upper mantle (van der Lee and Nolet, 1997; Dueker and others, 2001). The northwest-trending fault system mirrors northwest-oriented high-velocity seismic anomalies, indicative of cool mantle; the northeast-striking shears chiefly mirror low-velocity anomalies of the same trend, indicative of warm mantle (or melts). These data support the postulate of Karlstrom and Humphreys (1998) that the mantle structure in the Rocky Mountain region was formed in Proterozoic time and has been modified little subsequently. Possibly, this postulate is applicable to the stable interior of the United States as well. The northwest-oriented mantle fabric guided later mechanical crustal dislocations, and the northeast-oriented fabric guided episodic magmatic activity as well as crustal shortening.

The general coherence of regional lithospheric structures and mantle anisotropy within the continent strongly suggests that the overall continental lithosphere is coupled to the upper mantle, and that deformation within the continent is chiefly the result of subcontinental deformation, as discussed by Silver (1996). The absolute motion of the continent is demonstrably southwestward (for example, Schutt and Humphreys, 2001). Russo and Silver (1996) have shown that drag resulting from subcontinental mantle convection is a more powerful driving force for deformation than plate-generated forces (that is, ridge-push and slab-pull). As stated previously, they proposed that the Andes Cordillera and, by analogy, the Rocky Mountains are products of subcontinental mantle deformation.

The kinematics of regional basement structures within the United States continent suggest that deformation since at least early Proterozoic time has been predominantly transpression. Transcurrent lithospheric structures formed during Proterozoic mantle deformation are oriented obliquely to the southwestward (absolute) motion of the North American plate. Stress caused by traction between the asthenosphere and lithosphere during the southwestward drift focused on preexisting block boundaries repeatedly have reactivated basement zones of weakness, thus localizing sedimentation, magmatism, and generation of ore deposits (Sims and others, 2002).

Suggestions for Future Research

Geologic investigations in the Archean Superior province in the Canadian Shield (Peterman and Day, 1989; Kamineni and others, 1990; Bauer and Hudleston, 1995; Card and Poulsen, 1998; Park, 1981) have disclosed a system of right-lateral transcurrent shears and faults in Archean rocks that is similar kinematically to the ductile-brittle faults in the United States sector of the continent. Shear zones in the southern part of the province have been interpreted as being late Archean in age (Bauer and Hudleston, 1995), whereas those in the western part of the Superior province are interpreted as being Paleoproterozoic (~2.3 Ga) (Kamineni and others, 1990). These structures, and others in the Superior province, deserve further study.

As a working hypothesis, we suggest that intracontinental shearing, driven by subcontinental mantle deformation, was initiated in Archean time in the cratonic nucleus within the Superior province and that it progressively affected younger accreted rocks to the south as they became coupled to the mantle below. An implication of this postulate is that continent-scale transpression had a dominant role during the early evolution of the North American continent.

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Figure Captions

Figure 1. Generalized Precambrian geologic map of continental United States. *A*, Archean and Paleoproterozoic accretionary crustal provinces assembled prior to 1.70 Ga. *B*, Late Paleoproterozoic and Mesoproterozoic provinces formed during intracontinental deformation. CB, Cheyenne belt; CF, Clearwater fault; DS, Dillon suture, GF, Grenville front; GL, Great Lakes tectonic zone, LF, Llano front; MCR, Midcontinent rift; Nd, Nd line of Van Schmus and others, 1996; Nf, Niagara fault; SAF, San Andreas fault; VF, Vermilion fault; WL, Walker Lane.

Plate 1. Preliminary Precambrian basement structure map of the continental United States—An interpretation of geologic and aeromagnetic data.

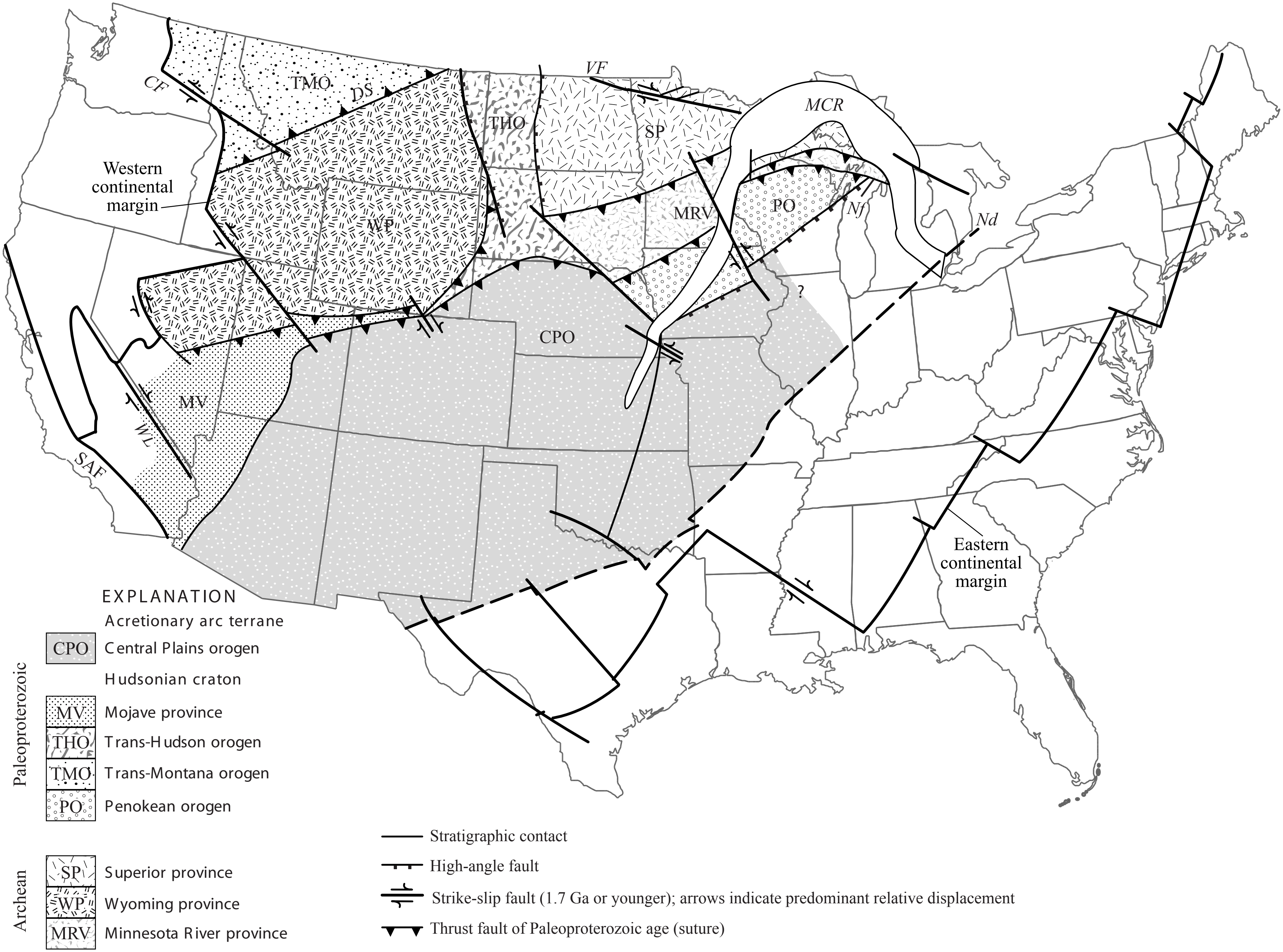
CF
TMO
DS
THO
VF
SP
MCR
Western continental margin
WP
MRV
PO
Nf
Nd
?
CPO
MV
WL
SAF
Eastern continental margin
EXPLANATION
Paleoproterozoic
Acretionary arc terrane
CPO Central Plains orogen
Hudsonian craton
MV Mojave province
THO Trans-Hudson orogen
TMO Trans-Montana orogen
PO Penokean orogen
Archean
SP Superior province
WP Wyoming province
MRV Minnesota River province
Stratigraphic contact
High-angle fault
Strike-slip fault (1.7 Ga or younger); arrows indicate predominant relative displacement
Thrust fault of Paleoproterozoic age (suture)

Figure 1a.

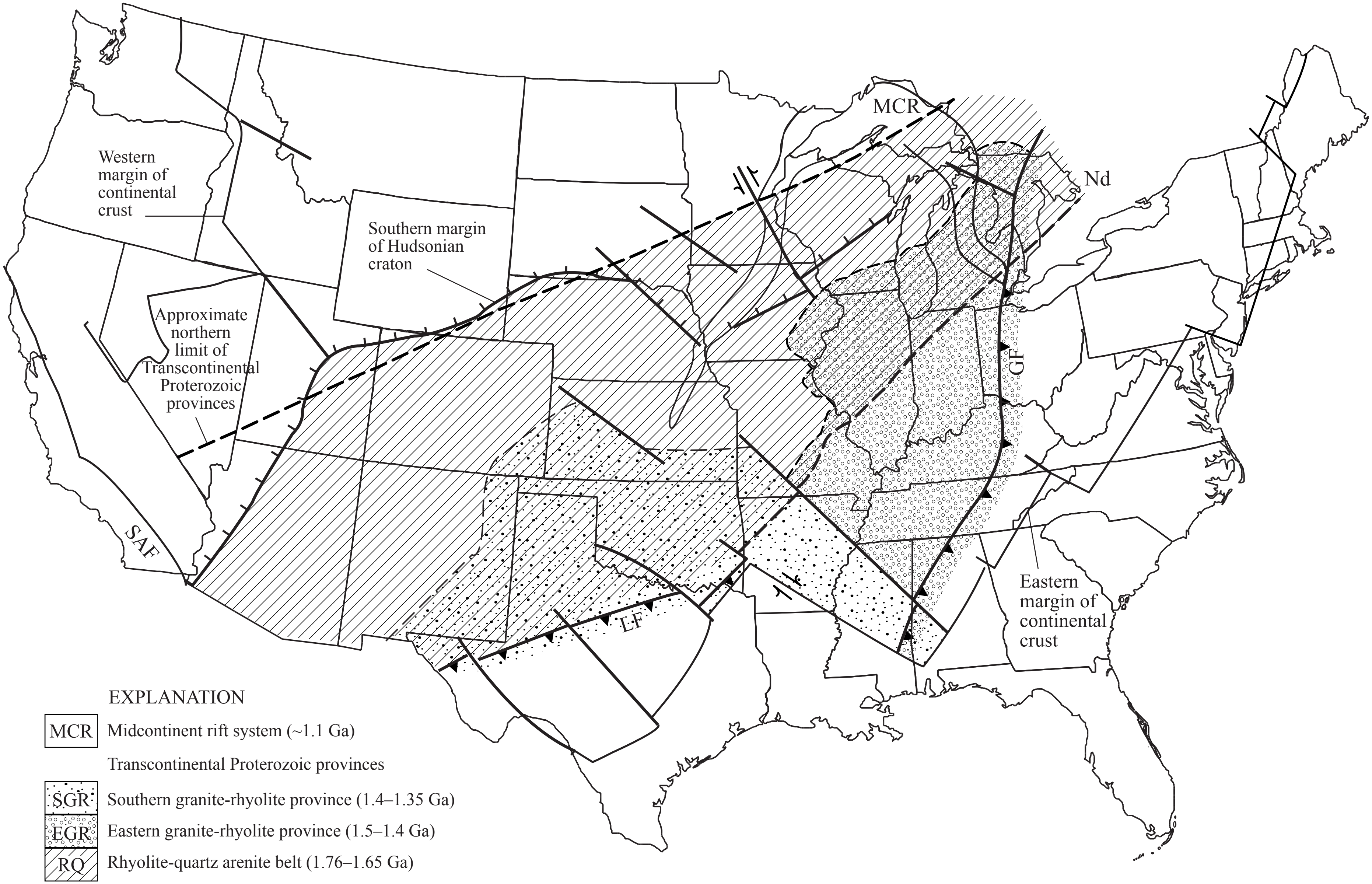
MCR
Nd
Western margin of continental crust
Southern margin of Hudsonian craton
Approximate northern limit of Transcontinental Proterozoic provinces
SAF
GF
LF
Eastern margin of continental crust
EXPLANATION
MCR Midcontinent rift system (~1.1 Ga)
Transcontinental Proterozoic provinces
SGR Southern granite-rhyolite province (1.4–1.35 Ga)
EGR Eastern granite-rhyolite province (1.5–1.4 Ga)
RQ Rhyolite-quartz arenite belt (1.76–1.65 Ga)
Approximate contact
Grenville thrust fault
Strike-slip fault

Figure 1b.