CAMPANIAN PALEOSEISMITES OF THE ELK BASIN ANTICLINE, NORTHERN BIGHORN BASIN, U.S.A.: A RECORD OF INITIAL LARAMIDE DEFORMATION

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Abstract: **Paleoseismites, in the form of clastic dikes and sills and convolute bedding record syndepositional tectonism prior to lithification, fold growth, and onset of major orogenic events. The Elk Basin anticline, located in the northern portion of the Bighorn Basin, contains paleoseismites in Campanian strata along its eastern (forelimb) and western (back limb) margins. In the shallow-marine Telegraph Creek and Claggett formations, convolute bedding typically involves individual sandstone beds with vertical to overturned strata on either side of a nearly vertical vent, whereas the nonmarine Eagle Formation contains planar clastic dikes and sills, derived from liquefied sand-source beds, and convoluted bedding involving distorted laminae. Planar clastic dikes and sills were injected upward and laterally across overlying strata, and along pre-existing, nearly vertical, near-surface joints. Geographically, clastic dikes and sills are present only in the central portion of the anticline, while convoluted-bedding is present in the central and southern portions. Comparison of 145 clastic-dike measurements with 61 previously reported Laramide joint-set orientations for the Elk Basin demonstrate trends to be similar. Clastic dikes preferentially fill cross joints oriented normal to the axial trace of the anticline, while strike joints illustrate a dominant later Laramide joint set oriented subparallel to the axial trace. Paleoseismite formation is consistent with $\sim$ M 5.5 earthquakes during earliest Laramide deformation associated with development of the Elk Basin thrust fault, whereas strike joints formed during subsequent Laramide deformation after burial and cementation of Campanian strata.**

INTRODUCTION

Development of recurrence intervals and hazard risk assessments for tectonically active regions provide the primary focus of paleoseismic investigations (McCalpin 1996; Wheeler and Frankel 2000). Recent studies in pre-Neogene strata have shown that paleoseismites can also be used as indicators of syndepositional tectonism, fold growth, and onset of major orogenic events (Bartholomew et al. 2002a, 2008; Stewart et al. 2004, 2008; Bartholomew and Whitaker 2010). Unfortunately, investigations of modern seismites and paleoseismites tend to be limited by numerous obstacles. Modern (late Pleistocene–Holocene) seismite investigations are limited by the expense of trenching, difficulties in selecting appropriate sites, and the general lack of correlative stratigraphic sections (Obermeier 1996; Obermeier et al. 2002; Bartholomew et al. 2002b). Laboratory experiments provide valuable insights but are limited by the inability to account for the numerous factors (e.g., variations in grain size, lateral gradation, and porosity) which influence seismite formation (Owen 1996; Moretti et al. 1999). Investigations of paleoseismites are limited by lack of exposure and difficulties in distinguishing between earthquake-induced and nonseismic features. In addition, very few regions are documented to have paleoseismites that occur over a wide geographic area, within a narrow stratigraphic interval, and in proximity to a known fault capable of producing earthquakes with sufficiently large magnitudes (Ballantyne et al. 2004).

Over the last decade, the northern Bighorn Basin has been recognized as a region containing paleoseismites over an area of $\sim$ 1200 km^2, in Late Cretaceous–Paleogene strata and adjacent to regional faults (Stewart et al. 2004, 2008; Bartholomew et al. 2008). These characteristics provide a unique opportunity to gain insights into 3-D structural and sedimentological factors controlling seismite formation, emplacement mechanisms, and the timing of Laramide deformation. For this study paleoseismites exposed in Campanian (83.6–72.1 Ma) strata throughout the Elk Basin anticline were identified and examined to address the following topics: 1) timing, orientation, and emplacement of clastic dikes, 2) depositional controlling factors on seismite formation and development, and 3) paleo-earthquake magnitudes associated with Elk Basin paleoseismites.

Defining Paleoseismite

The term paleoseismite has been defined as a secondary deformational feature (e.g., liquefaction, landslides and slumps, clastic dikes and sills) formed in unconsolidated sediment resulting from paleo-earthquakes (Seed and Idriss 1971; Youd 1973; Seilacher 1984; Obermeier 1996). However, assigning paleoseismite features such as landslides and slumps to seismic or nonseismic events in the field proves challenging (Obermeier 1996; Wheeler 2002). To decipher between seismic and nonseismic events, paleoseismites must be shown to correspond to definitive seismic features

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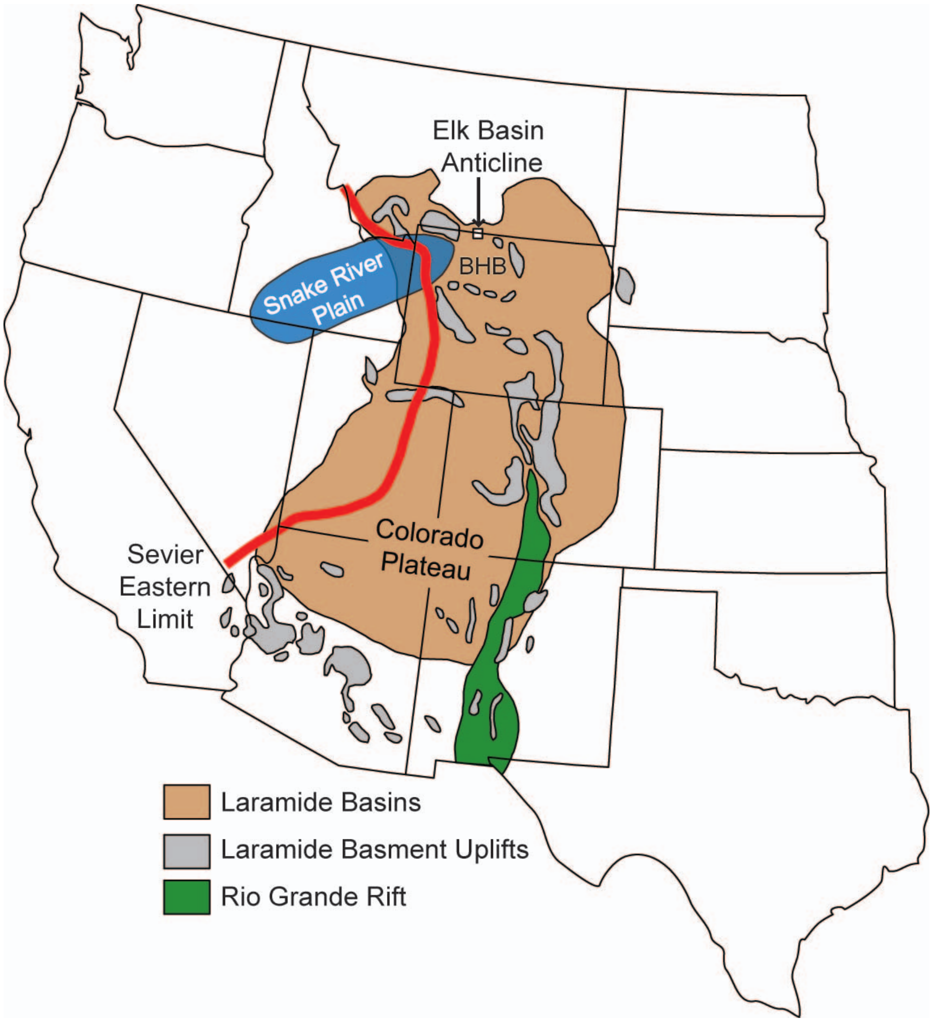

FIG. 1.—Generalized regional map adapted from Bartholomew et al. (2009) highlighting western United States geologic features related to the Elk Basin anticline, such as: Laramide basement uplifts, regional extent of Laramide sedimentary basins, the eastern limit of the Sevier Fold and Thrust Belt, trace of the Snake River Plain, and the Rio Grande Rift. The Elk Basin anticline is represented by the white box in the northern portion of the Bighorn Basin (BHB), on the Wyoming–Montana state border.

such as clastic dikes and sills, which are considered the best evidence for strong seismic shaking (Tuttle and Seeber 1991; Obermeier 1996; Bourgeois and Johnson 2001). We define paleoseismite following Stewart et al. (2002), in which the term is used to describe soft-sediment deformational features when they are in regional and/or stratigraphic association with partially fluidized beds and clastic dikes and sills.

Geologic Setting

The central Rocky Mountain Cordillera is a geologically complicated region due to the spatial and temporal overlap of the Sevier and Laramide orogenies (Fig. 1). The Sevier fold-and-thrust belt persisted from the Jurassic to Paleogene and is characterized by a traditional foreland propagating "thin-skinned" deformation sequence, totaling $\sim$ 150 km of maximum shortening (Jordan 1981; Royse 1993; Dickinson 2004). In contrast, Laramide deformation is characterized by "thick-skinned" deformation involving basement-cored uplifts (Stone 1983, 1993; Cross 1986; Erslev 1993; Neely and Erslev 2009), which persisted from the Late Cretaceous through the Eocene (Dickinson et al. 1988; Crowley et al. 2002; DeCelles 2004). Basement uplifts occur predominantly east of the Sevier fold-and-thrust belt, from southwestern Montana to northern New Mexico. Laramide "thick-skinned" deformation has been linked geodynamically to flat-slab subduction of the Farallon Plate, along the western Cordillera margin (Bird 1988; Saleeby 2003; Liu et al. 2010). However, many debates are ongoing regarding the processes, timing, and spatial extent of Laramide deformation throughout the central Rocky Mountain Cordillera (e.g., Jones et al. 2011).

The Elk Basin anticline is a Laramide structure located in the northern portion of the Bighorn Basin. The Bighorn Basin is an asymmetric intermontane basin within the Laramide foreland containing a sedimentary package comprised of Paleozoic, Mesozoic, and Cenozoic strata exceeding 7,600 m in thickness along its western side (Pierce 1966; Pierce and Nelson 1968; Blackstone 1986, 1993). The Nye–Bowler lineament defines its northern boundary. Three Laramide uplifts, Owl Creek Range, Bighorn Range, and the Beartooth Plateau (Absaroka volcanic province) define the Bighorn Basin's boundaries to the south, east, and west, respectively.

Like many other Laramide structures throughout the Bighorn Basin, the Elk Basin anticline hosts a large amount of oil and natural gas. Jim Hurst and associates completed the first successful oil well for the Elk Basin anticline in 1915. Today, subsurface data, easily accessed exposures, and the relationship to Laramide tectonism make the anticline an ideal place for teaching many geologic field camps and conducting research.

ELK BASIN ANTICLINE

Stratigraphy

Sedimentation throughout the Late Cretaceous has been linked to thrust–belt tectonics associated with the Sevier Orogeny, in which clastic sediments from the Absaroka thrust sheet were shed eastward into the Cretaceous

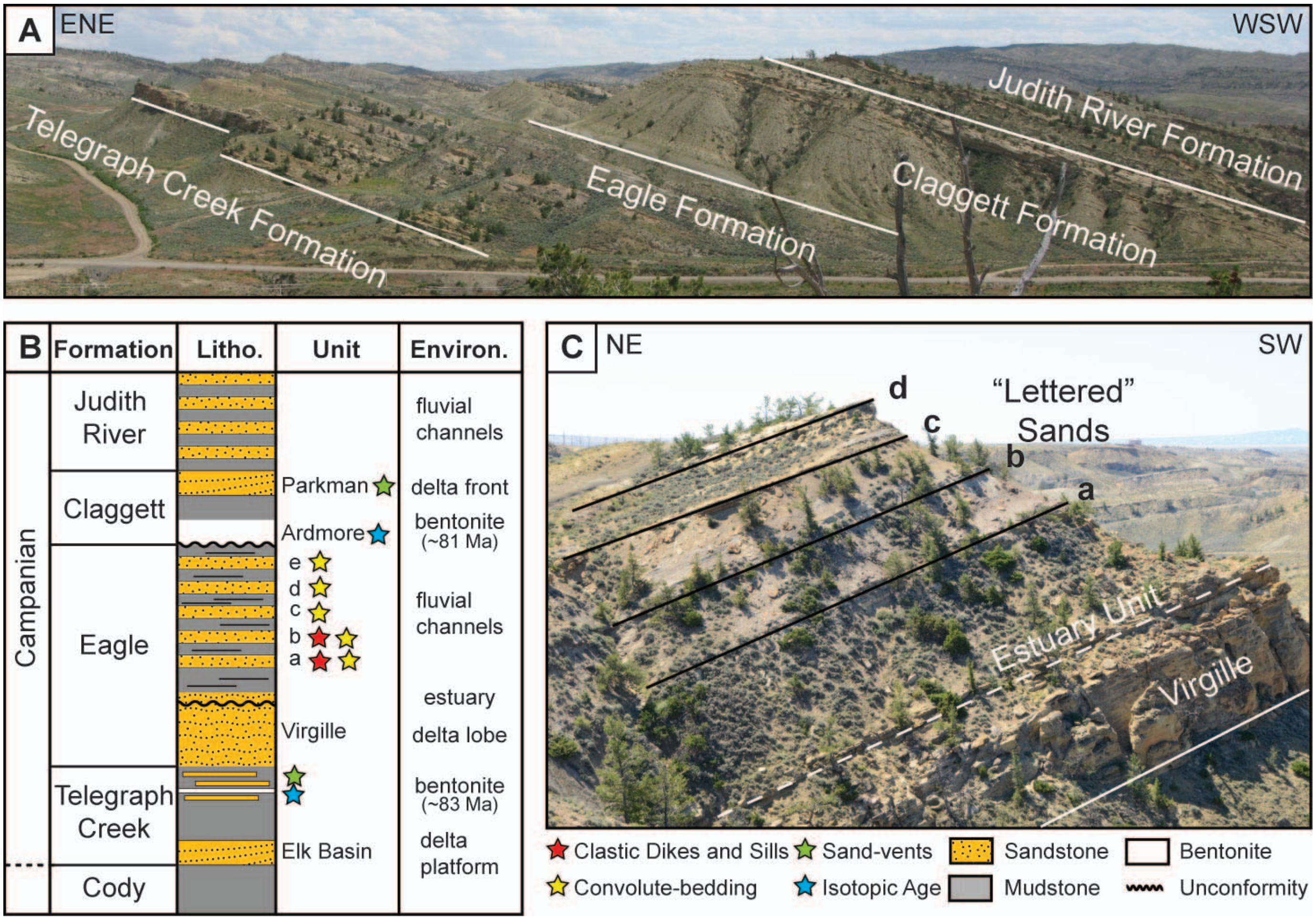

FIG. 2.—Stratigraphy of the Elk Basin anticline. **A)** Photo taken on the western flank of the Elk Basin looking SE, illustrating Campanian-age formations. **B)** Strat-column adapted from Engelder et al. (1997) demonstrating depositional environments, unconformities, position and approximate age of bentonite layers, and position of paleoseismites in the form of clastic dikes and sills and convolute bedding. **C)** Photo taken on the eastern flank of the Elk Basin looking SE, illustrating the typical "lettered" sands above the Estuary unit of the Campanian Eagle Formation.

Interior Seaway (Wiltschko and Dorr 1983). During the Late Cretaceous, the Bighorn basin also experienced tectonic loading due to the thrust sheets (Swift and Rice 1984). Rapid sedimentation, due to thrust loading, and the accumulation of thick marine mudstones (a consequence of the rate of subsidence exceeding sedimentation rate) produced a progradational shelf sequence of sediments (Swift and Rice 1984). Reflection of this cyclic sedimentation is represented at the Elk Basin by relatively few ridge-forming sandstones, separated by thick sequences of marine mudstones (Fig. 2). Today's surface morphology of the Elk Basin anticline is a breached elliptical bowl, exposing ~ 500 m of Campanian strata.

Telegraph Creek Formation.—The Telegraph Creek Formation is ~ 70 m thick. The basal Elk Basin Member is an ~ 20 m thick, loosely bonded massive sandstone, which crops out as the first ledge-forming sandstone above the Cody Shale (located in the central bowl of the anticline). The Elk Basin sandstone member is interpreted as being deposited in a delta platform environment (Swift and Rice 1984). The overlying ~ 50 m consists of sandy mudstone with a few small (~ 1 m thick maximum) sandstone lenses near the upper portion of the formation.

Eagle Formation.—The Eagle Formation is ~ 120 m thick. The basal ~ 10–20-m-thick Virgille sandstone member is a light-gray to tan, massive sandstone without interlayers, interpreted as a delta-lobe deposit. Along both flanks of the Elk Basin anticline, the Virgille Member is overlain by a massive sandstone which is interpreted (Dupré, personal communication 2012) as having formed in an estuary environment, based on the presence of a pebble conglomerate observed at the contact between the two beds. Locally, the pebble conglomerate cuts downward ~ 1–2 m into the underlying Virgille Member, consistent with the estuary depositional interpretation. Above the estuary unit, the Eagle Formation consists of interbedded mudstone, sandstone, and coal beds, which were deposited in a fluvial depositional environment. Sandstone beds range in thickness from ~ 20 cm to ~ 5 m. In previous studies, the letters A–E were used to designate resistant sandstone beds (Fig. 2C). However, more sandstone beds were mapped than the five so-called "lettered sands." Many of these sandstones are lenticular in shape, bifurcate, and pinch out throughout the formation. In hand specimen sandstones are medium grained, well sorted, and subrounded to subangular. Small coal beds ~ 15–40 cm thick are interbedded with mudstones and sandstones around the anticline, along with a locally well preserved coal bed (~ 3–5 m thick).

Claggett Formation.—The Claggett Formation is ~ 60 m thick. The base of the Claggett Formation is an ~ 4–6-m-thick bentonite which appears to unconformably truncate stratigraphy in the upper Eagle Formation. Above the bentonite, the Claggett Formation is predominantly

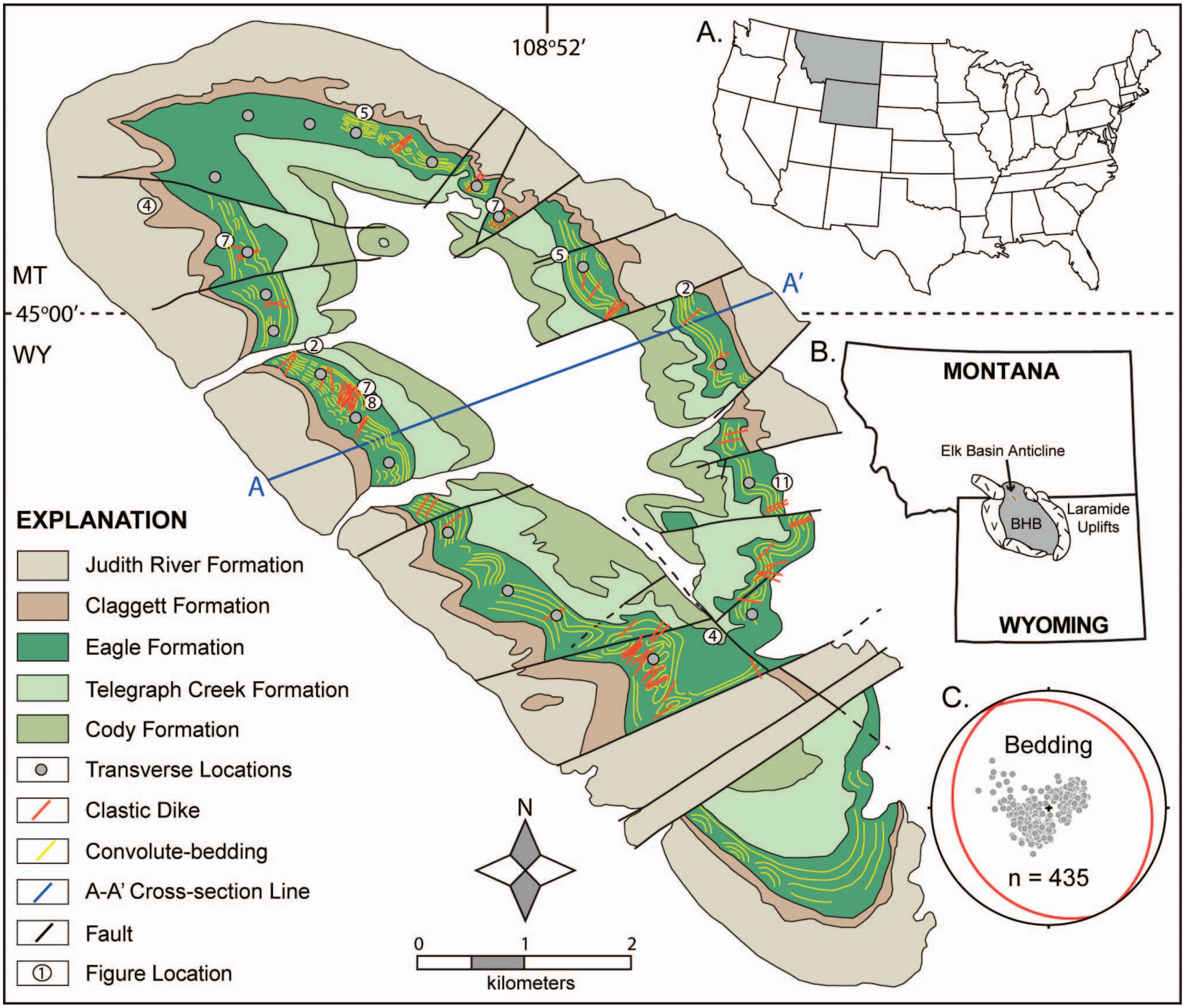

FIG. 3.—Geologic map of the Elk Basin anticline illustrating the distribution of paleoseismites in the form of clastic dikes and convolute bedding exposed in the Campanian Eagle Formation (Clastic-dike orientations are expressed after local structural unfolding), Elk Basin faults, location of measured-section traverses (Fig. 6), location of A–A′ cross section line, and location of specific paleoseismites highlighted in later figures. **A)** U.S. state border map highlighting Wyoming and Montana, of which the Elk Basin anticline is geographically continued. **B)** Generalized geographical outline of the Bighorn Basin (BHB), with surrounding Laramide basement uplifts, illustrating the location of the Elk basin anticline. **C)** Steronet demonstrating collective NW–SE-striking bedding measurements from Campanian strata throughout the Elk Basin anticline.

mudstone (∼ 35–45 m thick) which is capped by the Parkman (sandstone) Member. The Parkman Member is a delta-front sandstone ∼ 5–10 m thick.

Judith River Formation.—The Judith River Formation is ∼ 270 m thick. It consists of interbedded ∼ 2–10-m-thick sandstones and mudstones, with a few small (∼ 1 m thick) coal beds. Sandstones in the Judith River Formation are fine- to medium-grained, gray, argillaceous sandstones. These sandstones were deposited in a deltaic–fluvial environment (Obradovich 1993).

Structure

The Elk Basin anticline is a fault-propagation fold (Woodward et al. 1985; Mitra 1986) in that the fold developed as the thrust propagated upward. In Laramide structures, like the Elk Basin anticline, the propagating thrust fault originated within the basement. Its measureable offset dissipates up-section, as shortening is transferred to a fold that grows at the fault tip as displacement increases. These fault-propagation folds have also been termed drape folds (Stearns 1971), forced folds (Stearns 1978), and basement-involved thrust-generated folds or thrust folds (Stone 1991).

Bally (1983) and Stone (1983, 1993) used seismic and well-log data to map an ∼ NW–SE striking basement thrust beneath the Elk Basin anticline, which is expressed at the surface by the axial trace of the fold. However, the axial trace changes to a more WNW–ESE trend in the northern nose and to a more N–S trend in the southern nose. The forelimb and back-limb dip ∼ 28° and ∼ 23°, respectively. Stone (1993) showed ∼ 1900 m of net (thrust fault) displacement of the nonconformable contact

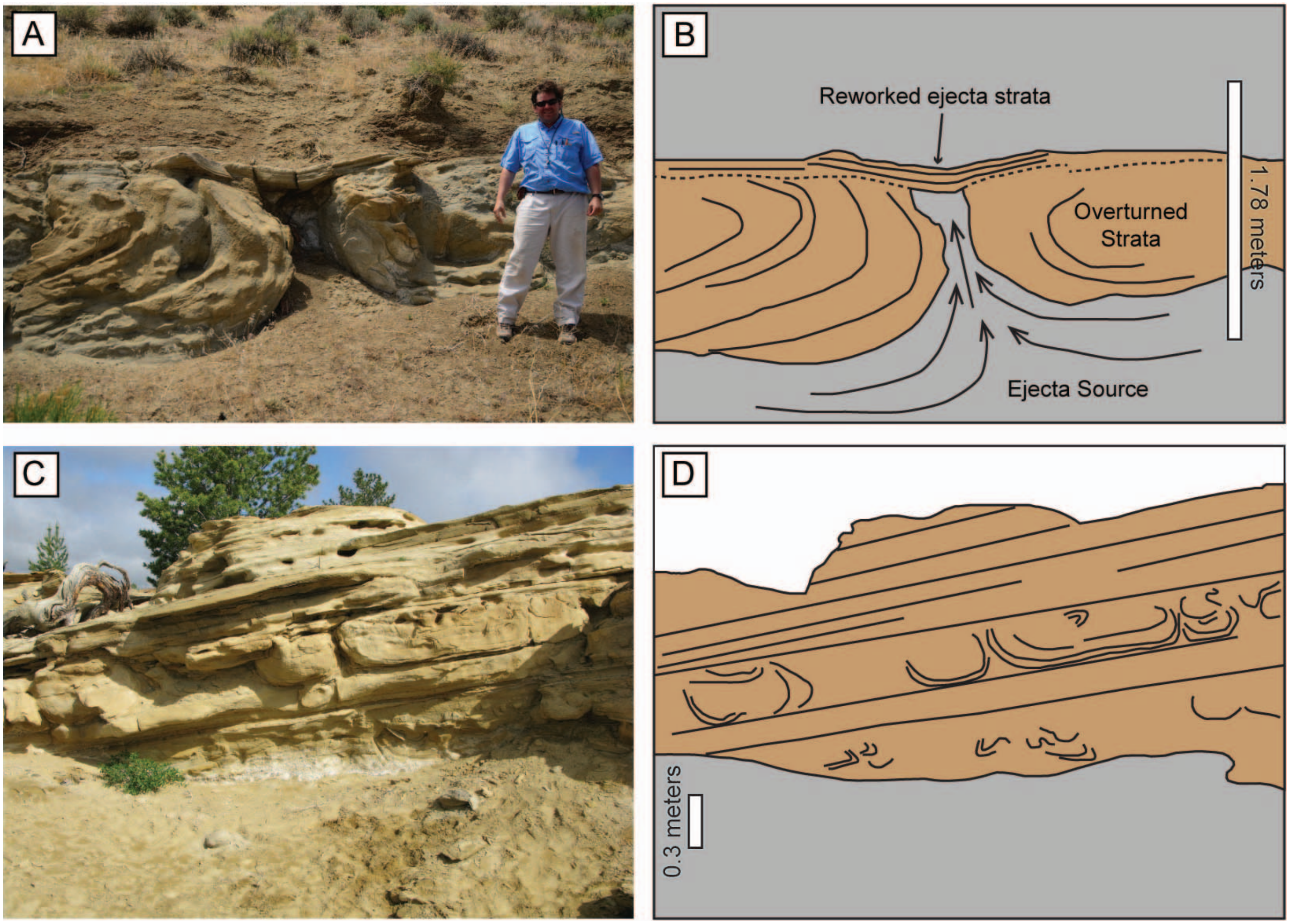

FIG. 4.—Typical paleoseismites expressed as sandblow vents in the shallow marine Telegraph Creek and Claggett formations. Note overlying undisturbed strata, indicating that vent material was reworked by water action.

between the Precambrian basement and overlying Paleozoic strata. Displacement decreases upsection to zero, so that no fault displacement is mapped in the Campanian strata exposed at the surface.

High-Angle Faults.—The Elk Basin anticline is cut by three sets of normal faults (Estabrook 1923; McCabe 1948). Two NE–SW-trending sets of oblique-slip normal faults (near the northern and southern noses) strike across the axial trace of the fold. The third set of oblique-slip, normal faults strike parallel to the axial trace of the fold. Estabrook (1923) showed the sequence of normal faults to be: a) NE-trending, down-to-south faults on southern nose; b) NE-trending, down-to-north faults on northern nose; and c) NW-trending faults. Dips on faults range from $\sim 40°$ to $\sim 85°$, with offsets ranging from nearly 0 to $\sim$ 55 m. All faults are interpreted as post-Paleocene in age (McCabe 1948).

Joints.—Engelder et al. (1997) identified two prominent joint sets in Campanian strata on the flanks of the anticline. The dominant joint set strikes subparallel to the fold axis (strike joints) and the less prominent joint set strikes normal to the fold axis (cross joints). Their study showed that strike joints formed first, whereas in most compressional settings, cross joints form first (e.g., Narr and Suppe 1991, 1994). Most of the strike joints trend parallel to the anticlinal fold axis. Strike-joints in the forelimb of the anticline are not as uniformly oriented as those within the backlimb, possibly due to disruption by local faulting. Other more recent joint studies throughout the Bighorn Basin (which include site locations within the Elk Basin anticline) have described multiple joint sets related to Sevier (S-I, S-II, and S-III) and Laramide (L-I, L-II, and L-III) deformation in the region (e.g., Bellahsen et al. 2006; Ambrouch et al. 2010; Weil and Yonkee 2012; Beaudoin et al. 2012, 2014). These studies show that the oldest Laramide joint set (L-I) throughout the northern Bighorn Basin results from Laramide LPS in the $\sim$ NE direction.

PALEOSEISMITES

Paleoseismites throughout the Elk Basin anticline are expressed in three forms: convolute bedding (vents) in marine strata, convolute bedding (contorted lamina) in nonmarine strata, and planar clastic dikes and sills in nonmarine strata (Fig. 3). Characteristics of paleoseismites observed in this study, specifically nonmarine convolute bedding and clastic dikes, are similar to those observed in other pre-Neogene strata, geographic locations, and tectonic settings, such as Mississippian strata of the Appalachian fold-thrust belt in Virginia and West Virginia (Stewart et al. 2002; Bartholomew and Whitaker 2010), Triassic strata of the Deep River rift basin in North Carolina (Wooten et al. 2001), Paleocene strata along the

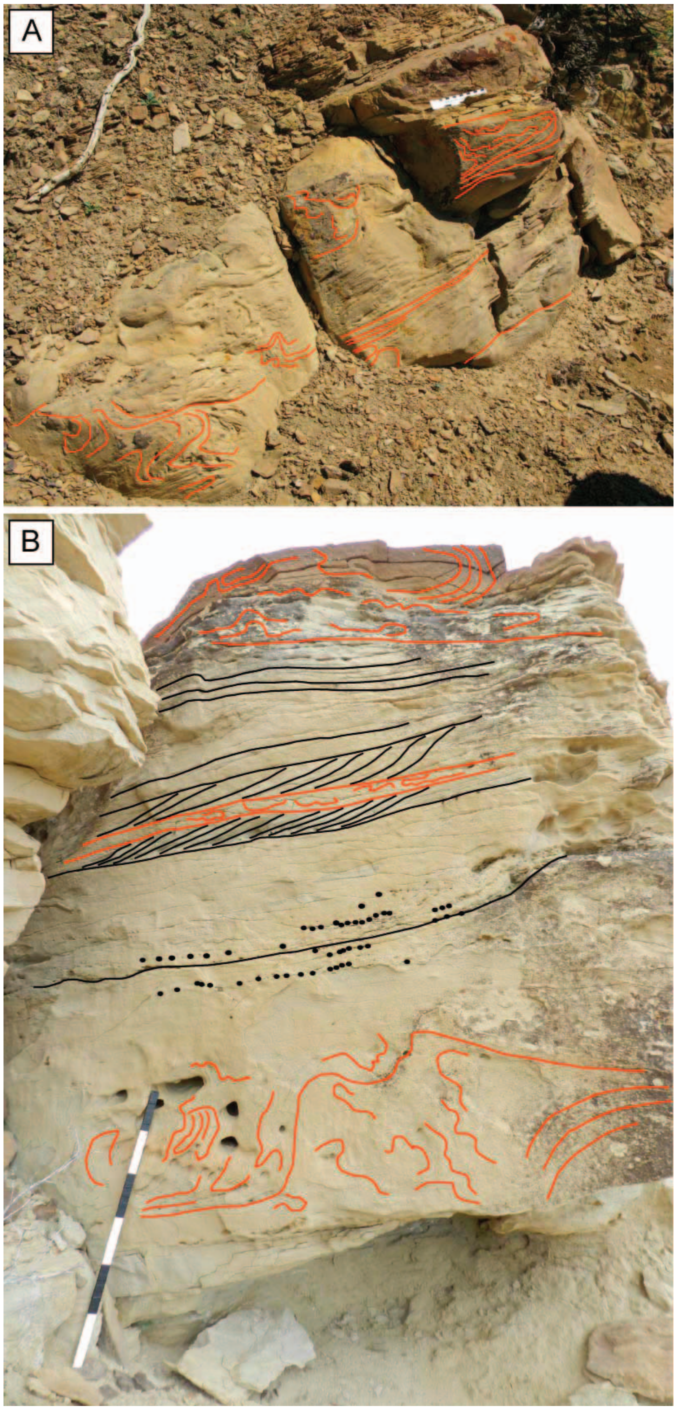

FIG. 5.—Typical paleoseismites expressed as convolute bedding in the non-marine Eagle Formation. **A)** Characteristic dewatering structures (i.e., overturned or recumbent layers) found throughout sandstones. **B)** Second sandstone bed above the Estuary unit, located on the eastern flank of the Elk Basin anticline (Figs. 3, 6). In the sandstone, three horizons (interlayers) of convolute bedding are present (red outlines) separated by horizons of undisturbed bedding (black outlines), illustrating the sensitivity to local controls (i.e., cohesion and time) for the occurrence of seismites (sediment liquefaction). Black dots indicate local stratigraphic pebbles.

eastern margin of the Laramide–Beartooth Uplift (DeCelles et al. 1991; Bartholomew et al. 2008; Stewart et al. 2008), and Eocene strata of the Atlantic Coastal Plain in South Carolina and Georgia (Bartholomew et al. 2002a; Bartholomew et al. 2007; Bartholomew et al. 2009).

Convolute Bedding in Campanian Marine Strata

Convolute bedding in sandstone beds in marine formations (Telegraph Creek and Claggett) are well exposed on both the eastern and western flanks along the entire length of the Elk Basin anticline. Convolute bedding is commonly associated with multiple sand-blow vents in individual sandstone beds ranging in thickness from ~ 1–5 m. These vents typically have vertical to overturned bedding along their flanks (Fig. 4). At most locations these steeply dipping beds are then truncated upward by an unconformable surface at the base of overlying undeformed strata. The absence of identified ejecta from vents coupled with frequent stratigraphic recurrence of deformed beds (with sand-blow vents and convolute bedding) alternating with normally bedded strata on meter-scale stratigraphy suggest that the top of each deformed bed represented the sediment–water interface at the time of paleo-earthquake events, where the ejecta was quickly reworked by wave or current action.

Convolute Bedding in Campanian Nonmarine Strata

Stratigraphic and geographic distribution of convolute bedding in the nonmarine Eagle Formation is common in the central and southern portions of the anticline, along both the western and eastern flanks, while absent in the northern nose of the anticline. In the Eagle Formation, convolute bedding formed as dewatering structures (i.e., contorted lamina). Dewatering structures are characterized by highly contorted bedding with oversteepened fold limbs (Fig. 5). Identification of oversteepened fold limbs was determined by laminae which exceed a dip angle of 30° (i.e., $>$ angle of repose) and lacked secondary diagenetic weathering processes such as liesegang bands and boxwork structures (Obermeier 1996). Convolute bedding typically occurred in laterally extensive sandstone beds 1 to 5 m thick. The ratio of convolute bedding outcrop length to bed thickness exceeds 100:1 throughout the entire Eagle Formation. This ratio suggests that each of these liquefied beds exhibited high pore fluid pressure over a large area, with ever-present overburden pressure. The absence of paleo-sand blows in the Eagle also suggests that convolute bedding was confined to sandstone source beds, thus permitting escape of fluidized sediment only through clastic dikes and sills.

Clastic Dikes and Sills in Campanian Nonmarine Strata

Planar clastic dikes and sills were identified only in the nonmarine river-deposited Eagle Formation, represented by interbedded sandstone, mudstone, and coal beds. Stratigraphically, the sand source beds for most clastic dikes appear to have been confined to the first or second sandstones above the estuary unit (Fig. 6). Geographically, dikes and sills occur in the central portion of the anticline and are absent near the northern and southern noses. The planar dikes and sills range in length from ~ 30 cm to ~ 50 m, and their widths range from 2 cm to ~ 45 cm (see Supplemental Material for all clastic-dike measurements).

No sand-blow vents or ejecta were identified in the Eagle Formation; however, upward terminations of dikes exhibit multiple expressions. The majority of the nearly vertical, planar dikes cut upward through several meters of mudstones and/or coal beds, typically thinning and ending upward before reaching the next overlying sandstone. Several end at the base of the next overlying sandstone (Fig. 7A). Multiple clastic-dike segments have an *en echelon* relationship (Fig. 7C), indicating that the liquefied sand filled Mode II joints. A few dikes cut upwards into the next overlying sandstone (Fig. 7D, 7E), then thin and end upwards ($<$ 0.5 m) above the second sandstone. Several nearly vertical, planar dikes change to lower-angle dips ($<$ 45°) upward within 0.5 m beneath the capping sandstone (Fig. 7D). One nearly vertical dike cuts upward through coal beds changing to an ~ 15°-dipping sill where it penetrates across thin sandstone beds separating the coal beds (Fig. 8). Presumably, all dikes originated from sand source beds (Fig. 8A, 8B), which are now part of the

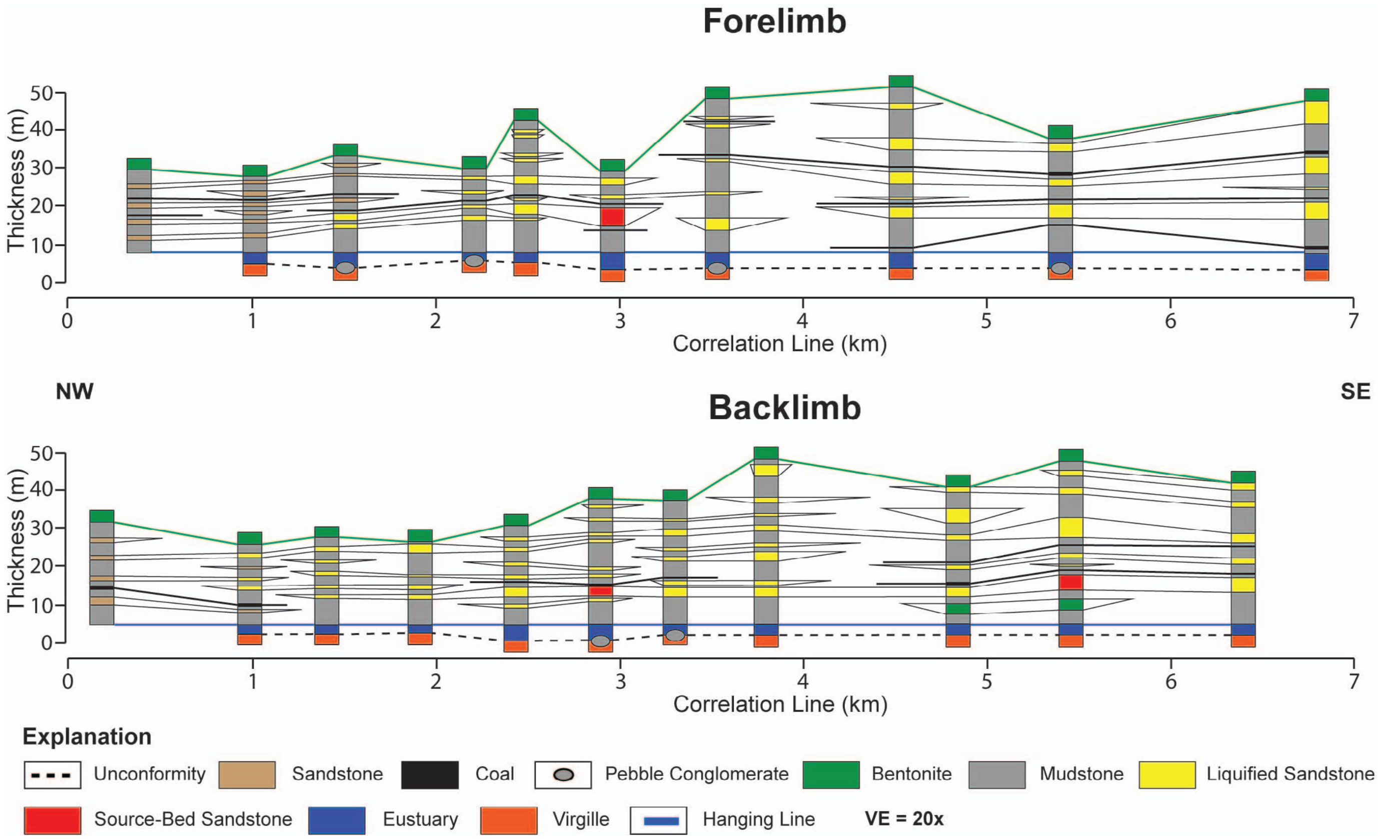

FIG. 6.—Stratigraphic correlation of the western (back limb) and eastern (forelimb) flanks of the Eagle Formation, Elk Basin anticline. Traverse (i.e., measured sections) locations can be found in Figure 3.

sequence of fluvial sandstones of the Eagle Formation; unfortunately, only three dikes could be traced downward to their sand source beds.

Measurements of 71 clastic dikes, containing 145 segments, throughout the Eagle Formation show three principal trends (Fig. 9): a predominant NE–SW ($n = 76$) trend, an ENE–WSW ($n = 43$) trend, and a NNE–SSW ($n = 26$) trend. Each dike trend has an associated, less dominant, orthogonal trend. The dominant orientations of clastic dikes are normal to the axial trend of the Elk Basin anticline and suggest that the majority of clastic dikes are Mode I cross joints. The central NW-trending (~ 315°) axial trend is consistent with the dominant NE–SW dike set; the northern WNW-trending (~ 290°) axial trend is consistent with the ENE–WSW dike set; and the N–S-trending (~ 350°) axial trend is consistent with the NNE–SSW dike set. Comparing orientations of clastic dikes and Laramide joint sets from Engelder et al. (1997) shows they contain similar orientations. While clastic dikes are oriented normal to the axial trace of the Elk Basin anticline, joint sets from Engelder et al. (1997) are dominantly oriented parallel to the axial trace. While these orientations between clastic dikes and joints suggest that they may be related, it should be noted that the clastic dikes must have formed in unconsolidated sediment near the time of deposition, while measurements by Engelder et al. (1997) represent Mode I (opening) joints formed in response to tangential longitudinal stretching (i.e., layer curvature during folding) of Elk Basin strata, during a later post-lithification time.

DISCUSSION

Timing, Orientation, and Emplacement of Paleoseismites

The distribution of liquefied beds (central and southern portions), nonliquefied beds (northern portion), and clastic dikes and sills (central portion) indicate that liquefaction was related to earthquakes associated with the growth of the main thrust fault directly beneath the Elk Basin anticline. When the anticline is retrodeformed so that the Eagle Formation is horizontal, as it was during Campanian deposition (a basic assumption for liquefaction of pre-lithified sediment; Obermeier 1996), the thrust fault has no discernible displacement of the basement-sediment nonconformity (Fig. 10). A small angular unconformity found in one outcrop near the base of the Eagle Formation (uppermost Telegraph Creek Formation), along the eastern flank of the anticline (Fig. 3), supports an interpretation that deformation and sedimentation of Campanian Elk Basin strata were penecontemporaneous. Therefore, seismite-producing Campanian earthquakes are associated with the earliest stage of basement faulting.

One implication of this is that all of the Campanian paleoseismites represent initiation of Laramide thrusting beneath the anticline. Elk Basin stratigraphic ages have been relatively well dated and correlated through biostratigraphy, paleomagnetics, and isotopic ages of bentonite layers (e.g., Obradovich 1993). The contact between the Eagle and Claggett formations is defined by an ~ 4–6 m thick bentonite layer, regionally termed the Ardmore bentonite. The Ardmore bentonite has been dated at various locations throughout South Dakota, Montana, and Wyoming, demonstrating results similar to the age obtained by Hicks et al. (1995) from the Elk Basin anticline of 80.71 ± 0.55 Ma. Another bentonite layer identified in the upper portion of the Telegraph Creek Formation was dated to an age of 83.1 ± 0.5 Ma (Hicks 1993). The two bentonite ages bracket the duration of Eagle Formation strata deposition to ~ 2.5 m.y., within the Campanian.

A second implication is that clastic dikes throughout the Eagle Formation formed as fluidized sand injected along pre-existing joints in unconsolidated sediment still prone to liquefaction. Emplacement of clastic dikes into pre-existing joints is a significantly different process from

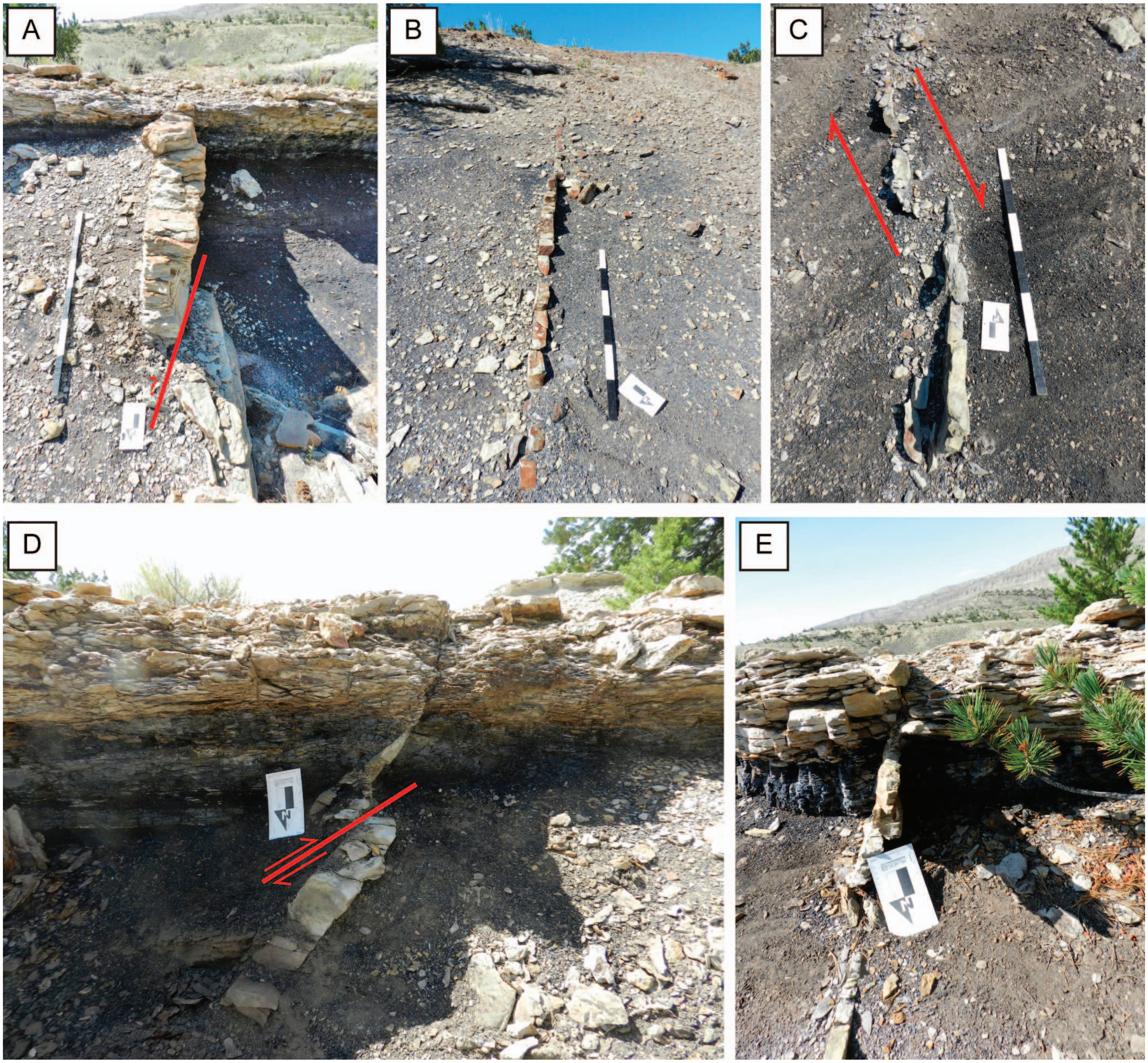

FIG. 7.—Typical paleoseimites expressed as clastic dikes in the nonmarine Eagle Formation. **A**, **E)** Note abrupt termination at base of overlying sandstone, **B)** planar dimensions, **C)** *en echelon* relationship, and **D)** shallowing of dip near base of overlying sandstone. Red lines in Parts A and D represent small faults which die out in interbedded mudstone and coal layers. True sense of motion could not be precisely determined for Part A. Red arrows in Part C indicate sense of shear associated with *en echelon* segments.

forcible hydraulic injection (i.e., hydro-fracturing) processes, caused by large differences in pore-fluid pressures (Obermeier 1996). The vast majority of clastic dikes throughout the Eagle Formation have similar orientations, are planar in shape, and contain *en echelon* segments, all indicating injection along Mode I (opening) and Mode II (sliding) joints. In previous paleoseismite studies (Wooten et al. 2001; Stewart et al. 2002; Bartholomew et al. 2002, 2008; Bartholomew and Whitaker 2010), injection of fluidized material into pre-existing joints has been suggested to demonstrate seismite formation in an environment associated with a near-surface stress field, in which orthogonal sets of joints may form by "stress switching." The concept of stress switching was well summarized by Dunne et al. (2003) with regard to the formation of coeval orthogonal joint sets associated with minimum (Sh) and maximum (SH) horizontal stress orientations. Three mechanisms have been associated with stress switching: 1) switching in response to small stress fluctuations when Sh and SH are nearly equal; 2) localized switching at the scale of individual joints or abutting joint sets; and 3) switching at a regional scale due to stress relaxation (i.e., uplift and/or exhumation) and/or changes in the tectonic setting (Lachenbruch 1962; Hancock 1985; Engelder 1985; Dunne and North 1990; Caputo 1995; Olson 1996; Dunne et al. 2003). Regional switching in exhumed bedrock might include both tectonic and relaxation components as Nadan and Engelder (2009) showed that "excess horizontal

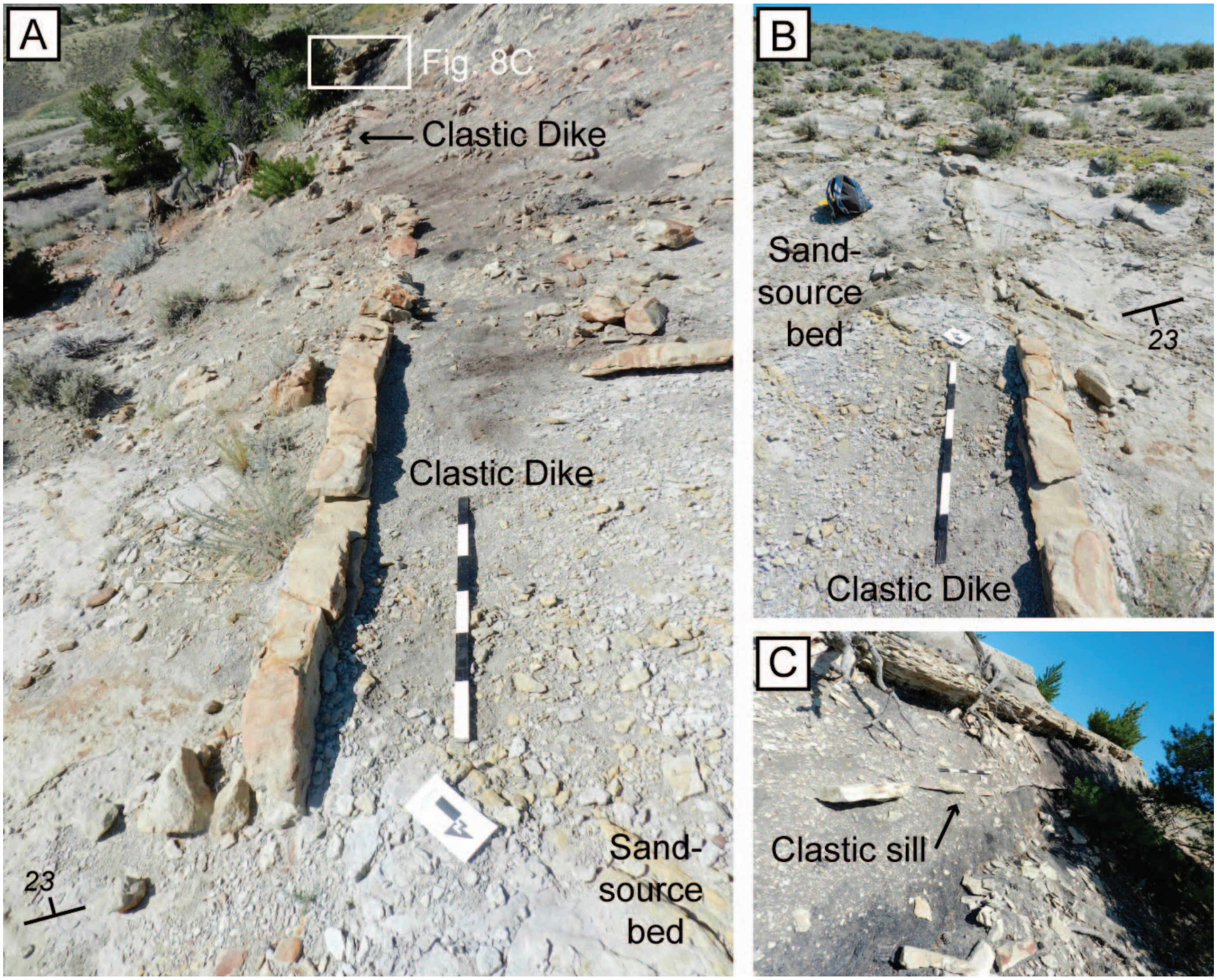

FIG. 8.—Large (~ 50 m total length) clastic-dike located on western flank of the Elk Basin anticline (Fig. 3). **A)** Clastic-dike is shown looking eastward and **B)** looking westward, directly injecting upwards from a sand source bed. **C)** Same clastic dike as in Parts A and B, farther to the west. Notice change in clastic dike from a nearly vertical to subhorizontal dip angle due to exceeding overburden pressure.

compressive stress, a remnant of incomplete (thermoelastic) relaxation, carries upward right to the bedrock surface…," and where inversion of σ_2 and σ_3 from earthquake focal mechanisms in the upper crust is attributed to relaxation. Bartholomew and Whitaker (2010) illustrated how orthogonal joint sets and normal faults might develop in local extensional regimes related to fault-bend folding above a thrust fault. They also illustrated how a preexisting basement fault might be reactivated as a steeply dipping reverse fault producing an arched region in the near-surface uplifted area. Such an arch will produce a local extensional stress regime with orthogonal joint sets developing during cycles of deposition alternating with cycles of earthquakes along the primary basement fault. It is this tectonic mechanism that is envisioned at depth along typical Laramide basement faults while a growth fold, such as the Elk Basin anticline, develops during deposition. One clastic-dike, along the Elk Basin's eastern flank (location shown in Fig. 3), illustrates the emplacement differences between injections along pre-existing joints verses hydro-fracturing in the Eagle Formation (Fig. 11).

Depositional Controlling Factors on Seismite Development

From a sedimentological perspective, the intriguing presence of sandblow vents in the shallow-marine depositional environments (Telegraph Creek and Claggett formations) but not in the nonmarine fluvial environment of the Eagle Formation requires explanation, if both are indeed paleoseismites. Obermeier (1996) proposed that nonmarine surface-rupturing liquefaction, in the epicentral region of an earthquake, is dependent mainly upon the thickness of the sand source bed and the thickness of the overlying stratum which caps the sand-source bed. This suggests that if sand-source-bed thickness is too thin then insufficient pressure will be generated to overcome the overburden pressure. Likewise, if overlying strata are too thick, then the overburden pressure may greatly exceed pressures required for liquefaction. In the Campanian marine strata of the Elk Basin anticline, overlying beds are typically < 1 m thick and liquefied beds typically range from 0.2 to 1 m thick. Thus, the ratio of overburden thickness to sand-source-bed thickness is on the order of $\sim$ 1:1 to 5:1. But in a water-saturated marine environment, for the underlying

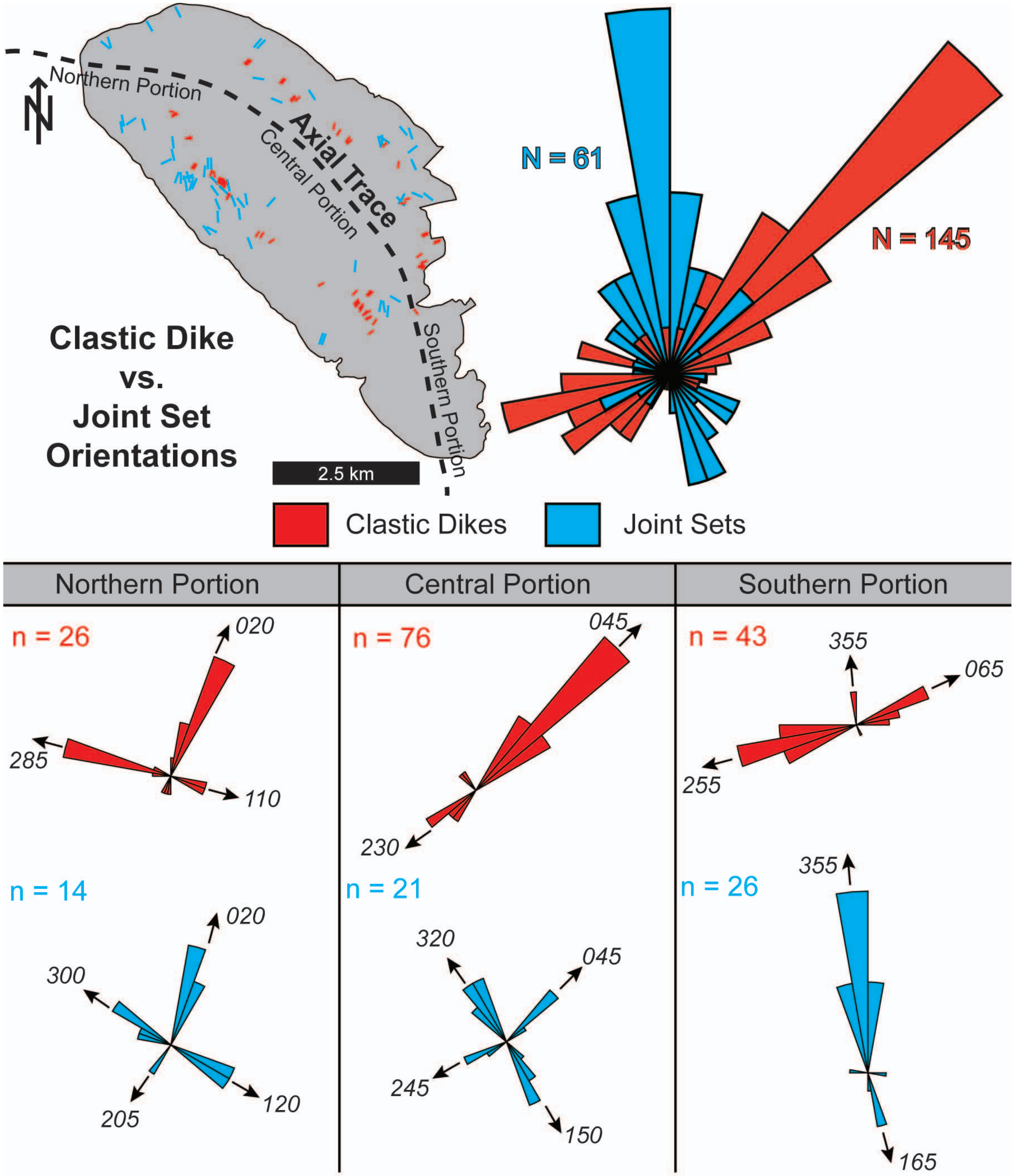

FIG. 9.—Comparison of orientations of clastic dike and Laramide joint sets (Engelder et al. 1997) throughout the Elk Basin anticline. The northern portion (trend of axial trace ~ 290°) relates to NNE–SSW clastic dike orientation and WNW–ESE Laramide joint set orientation. The central portion (trend of axial trace ~ 315°) relates to a prominent NE–SW clastic-dike orientation and a NW–SE Laramide joint set orientation. The southern portion (trend of axial trace ~ 345°) relates to an ENE–WSW clastic-dike orientation and a prominent ~ N–S Laramide joint set orientation. All rose diagrams are equal-area projections produced in Rick Allmendinger's Steronet 7 software (http://www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet.html).

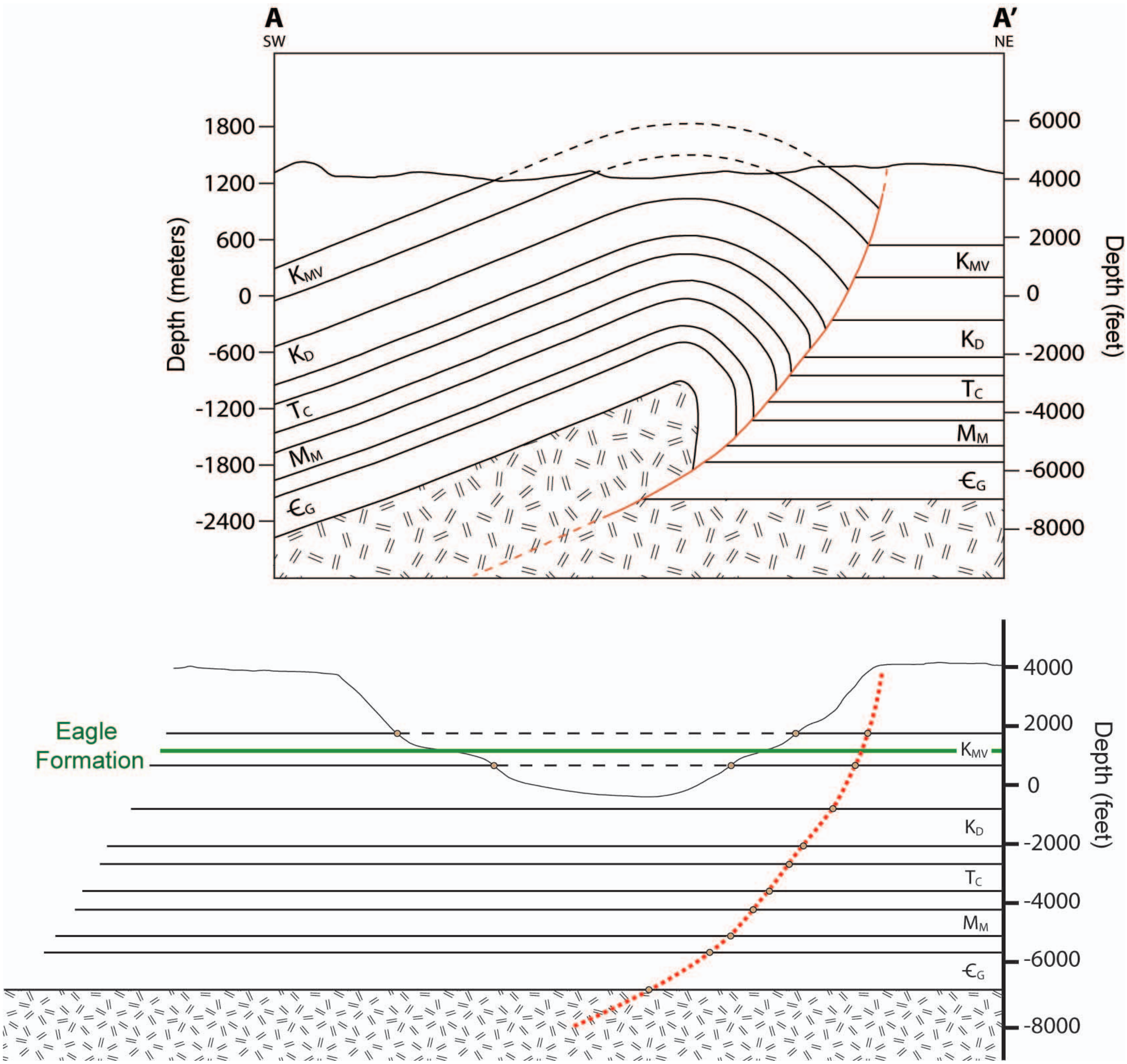

FIG. 10.—Elk Basin anticline A–A′ cross section and retrodeformed section (to time of Eagle Formation deposition). Cross section (Fig. 3) adapted from Engelder et al. 1997 and Stone 1993. K_{MV}, Cretaceous Mesa Verde Group. K_D, Cretaceous Dakota Formation. T_C, Triassic Chugwater Group. M_M, Mississippian Madison Formation. C_G, Cambrian Gallatin Group. Note no observable offset on the thrust beneath the Elk Basin at the time of deposition of the Eagle Formation (green line).

sand-source-bed to liquefy and not the thin overburden suggests that other factors are equally important. Cohesion, a factor dependent upon both grain size and composition, is essential for the overburden not to liquefy, but instead to be folded upward (and even overturned) around the numerous sandblow vents. Yet, too much cohesion or cement may also prohibit venting.

A large sand source bed (Fig. 5), on the eastern flank (forelimb) of the anticline illustrates at least three distinct beds with convolute-bedding features throughout its $\sim$ 5 m thickness. The convoluted laminae interbedded with undisturbed bedding suggests that sediments have an interval of time during which they can be liquefied before they either are dewatered or acquire sufficient cohesion or cement to inhibit liquefaction. Previous work (Tinsley et al. 1985; Dupré and Tinsley 1989; Dupré, personal communication 2012) along the San Andreas Fault showed, that for sand-sized sediment, the time period for liquefaction is on the order of thousands of years.

Another factor that can influence upward injection of liquefied sand is the aforementioned presence of pre-existing joints. Such joints may actually be generated by the same earthquake or by previous earthquakes. But the essential thing is that pre-existing joints permit upward injection of liquefied material for significant distances through overburden, which has cohesion even if the overburden pressure exceeds the liquefaction-generated fluid pressure. In the latter case, no surface venting will occur unless joints extend upward to the surface.

FIG. 11.—Example of clastic dike in the nonmarine Eagle Formation, located on the eastern flank of the Elk Basin anticline (Fig. 3). The large basal portion of the clastic dike is planar in shape (Part A), suggesting emplacement into an early-formed, nearly vertical, near-surface joint. Injection by means of hydro-fracturing is suggested by sills which follow horizontal bedding planes (Parts A and B), tapering laterally away from the source dike, and the irregular shape of the clastic-dike up section before the dike pinches out. Note that the horizontal injections are smaller in scale to the main upwardly injected liquefied sand dike from which they originate. Hydraulic injections propagate within bedding planes, thinning laterally away from the main dike, suggesting that overburden prevented dike propagation beyond the upsection extent of the joints.

Although paleoseismites occur throughout the Eagle Formation, they are unlikely to represent all of the earthquakes which were $M \geq 5.5$ because of the special conditions, noted above, for seismites to occur. In the central and southern portions of the Elk Basin every major sand bed was liquefied, with measured sections containing liquefied beds throughout the entire formation. Thus, the preserved record is limited to the stratigraphic occurrences of sand source beds, not the occurrence of earthquakes with $M \geq 5.5$.

Thus, the five major factors which influence development of clastic-dikes and surface vents are: 1) proximity to the epicenter of an earthquake, 2) thickness of sand source bed, 3) thickness of overburden, 4) cohesion of overburden and source strata, and 5) the presence of pre-existing joints in overburden.

Magnitudes and Epicenters of Paleo-Earthquakes

Magnitudes of paleo-earthquakes are often reconstructed based on the regional extent of paleoseismites and sand-dike size (i.e., thickness) (Obermeier et al. 1993). Retrodeformation of the Elk Basin illustrates that paleoseismites were documented over an area of ~ 35 km^2. However, the size distribution of clastic dikes in the Eagle Formation shows no discernible spatial trend. Another method by Ishihara (1985) estimates ground acceleration based on source bed thickness for paleoseismites and length of associated clastic dikes. Unfortunately, this method is incompatible with this study, due to its assumption that clastic dikes are entirely injected by hydraulic fracturing. Obermeier (1996) proposed that the minimum magnitude for an earthquake to produce clastic dikes is $M \geq 5.5$. However, due to the lack of paleoseismites present near the northern nose of the anticline, and the previously discussed local controls on paleoseismite formation, the magnitudes were likely $<$ M 5.5. Magnitudes larger than M 5.5 would presumably have overridden local controls, generating pervasive paleoseismite occurrences throughout the entire anticline.

Assuming that the orientations and distribution of the clastic dikes throughout the Eagle Formation are partially if not entirely controlled by various segments along the thrust fault beneath the Elk Basin, a presumable epicenter for paleo-earthquakes would have been located at or near segment breaks between the northern, central, and southern portions of the Elk Basin thrust. This suggests that three segments would have developed (uplifted) coeval with respect to one another during anticline fold growth. In addition, an epicenter near the segment break could explain the lack of clastic dikes and other paleoseismites in the northern nose of the anticline. As slip of the fault segment was initiated during thrusting, intensity of shearing would have dissipated in the direction of the northern fault segment, owing to a less likely initiation of liquefaction.

CONCLUSION

The Elk Basin anticline in the northern Bighorn Basin, provides an ideal laboratory to conduct a paleoseismic investigation due to its geographic and stratigraphic exposure of paleoseismites, their relation to Laramide tectonism, and the vast amount of geologic data compiled over the past century (on account of the anticline's large accumulation of oil and gas). From this study the following conclusions were drawn:

Paleoseismites throughout the Elk Basin stratigraphy demonstrate different forms in varying depositional environments. Vertical to overturned sandblow vents occur in shallow-marine environments of the Telegraph Creek and Claggett formations. Whereas, the nonmarine Eagle Formation contains paleoseismites of convoluted bedding (contorted lamina) and planar clastic dikes and sills.

Retrodeformation of the Elk Basin cross section suggests that paleoseismites record initial Laramide basement deformation of the Elk Basin anticline. Isotopic ages from bentonite layers, biostratigraphy, and paleomagnetics bracket the deposition of strata to earliest Campanian time. The presence of paleoseismites throughout the anticline's stratigraphy illustrates tectonic activity throughout deposition of Campanian strata.

Long planar shapes, upward tapering, *en echelon* segments, and vertical orientation of clastic dikes at the time of their formation indicate upward injection along pre-existing near-surface Mode I and Mode II joints. Near-surface hydro-fracturing is indicated in upper parts of dikes by injection of narrow sills along low-angle fractures and bedding planes. The relationships between dikes and joints to the northern, central, and southern axial trends of the anticline suggest that the Elk Basin thrust developed coevally.

Estimating paleo-earthquake magnitudes for the Elk Basin during Campanian time remains elusive. However, due to the paleoseismite stratigraphic and geographic distribution, type, and size, paleo-earthquakes responsible for seismite formation here were likely $\sim$ M 5.5.

SUPPLEMENTAL MATERIAL

Supplemental data is available from JSR's Data Archive: http://sepm.org/pages.aspx?pageid=229.

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