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## Polyphase Laramide Structures and Possible Folded Tertiary(?) Sills at Dagger mountain, Big Bend National Park, Texas

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## ON THE OUTCROP

### **Polyphase Laramide Structures and Possible Folded Tertiary(?) Sills at Dagger mountain, Big Bend National Park, Texas**

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#### **LOCATION**

Dagger Mountain lies within Sierra del Carmen, a mountain range that extends southeastward from eastern Big Bend National Park in West Texas into northern Coahuila, Mexico (Figs. 1, 2). Dagger Mountain is in northeastern Big Bend National Park adjacent to US 385 (fig. 3), 13 km southeast of the northern park entrance at Persimmon Gap. At Persimmon Gap, a well-known field trip locality, Laramide thrust faults and Basin and Range high-angle faults cross-cut a map-scale overturned anticline in Paleozoic and

Cretaceous rocks (Tauvers and Muehlberger, 1988). Gasoline may be purchased at Marathon, Texas, 45 mi (72 km) north of Persimmon Gap, or at the park headquarters at Panther Junction, 20 mi (32 km) south of Dagger Mountain. Western Dagger Mountain cuesta exposures of several Cretaceous formations and Tertiary(?) sills can be reached by parking beside US 385 between national park mile markers 20 and 21 (TH1 on figure 4). Southern Dagger Mountain folds, faults, and sills can be examined by parking at mile marker 17 (TH2 on figure 5), and hiking east 0.8 km.

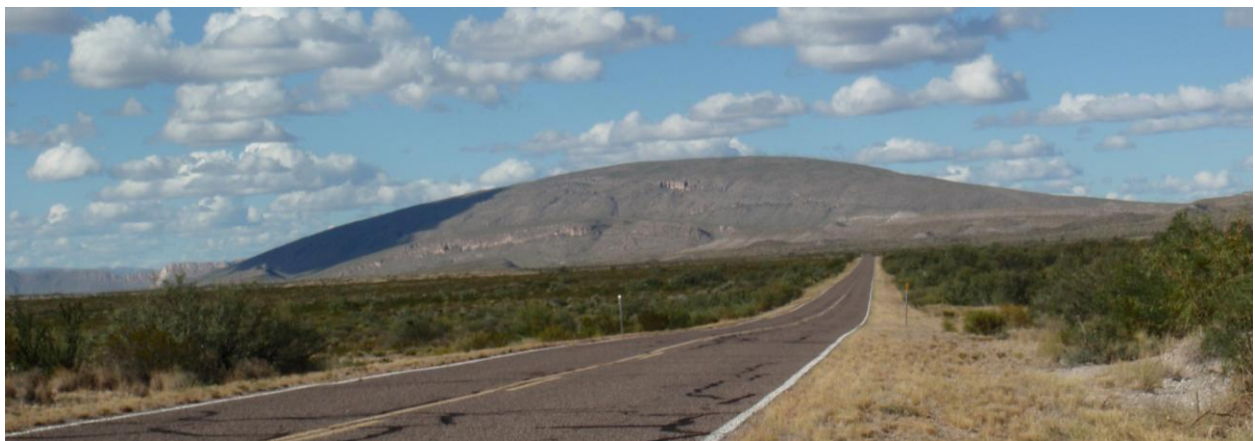
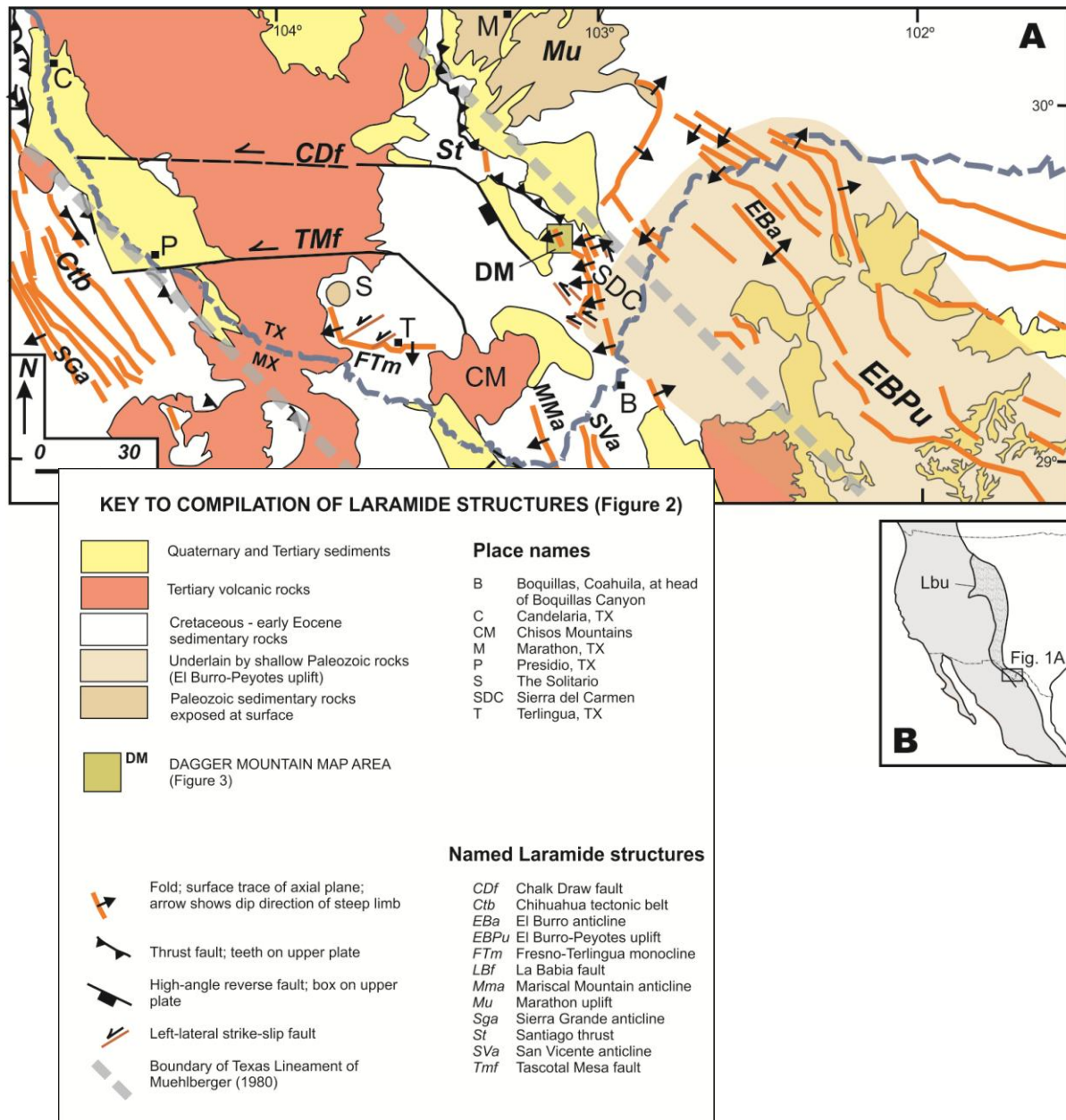


Figure 1. Views of Dagger Mountain from US 385. (UPPER) View from south shows Santa Elena Limestone cliffs and low cuestas of Boquillas Formation and Buda Limestone at foot of Dagger Mountain. Range-front normal faults at the foot of cuestas define the northeastern margin of the Tornillo graben. (LOWER) View from southeast shows Santa Elena Limestone cliffs broadly folded in northeast-trending  $D_2$  anticline. Fold is best seen in lower cliffs.



**Figure 2.** Tectonic map of Laramide structures in the Big Bend region. Map shows major folds, reverse faults, and left-lateral strike-slip faults. Sources of data: Muehlberger (1980), Muehlberger and Dickerson (1989), Moustafa (1988), Henry and Price (1985), St. John (1966), Charleston (1981), Smith (1970), Carpenter (1997), and Dickerson (1985). A) Dagger Mountain map area (DM) is within Sierra del Carmen (SDC) and on SW flank of a NW-trending basement uplift cored by the Marathon uplift (*Mu*) to the north and the El Burro–Peyotes uplift (*EBPu*) to the SW. B) Location map showing Cordilleran orogen (gray shades). Lbu – area of Laramide basement uplifts Modified from England and Johnston (2004).

## SITE DESCRIPTION AND PREVIOUS WORK

Dagger Mountain is named for giant daggers, a yucca variety that grows several meters tall, which are abundant on higher elevations of the peak (Maxwell, 1968). The hump-backed shape of Dagger Mountain (fig. 1), elevation 4173 feet, 1300 feet of relief, is related to the 5-km-long, north-northwest-trending, doubly plunging Dagger Mountain anticline within (figs. 3, 6). The Dagger Mountain anticline is defined by contacts and orientations of four distinctive, dominantly carbonate formations of Cretaceous age. Tertiary(?) mafic sills intruded Cretaceous strata on west and south flanks of Dagger Mountain (figs. 3, 4, and 5). Quaternary sediments fill adjacent valley floors.

Geologic maps that cover all or part of Dagger Mountain include Poth (1979, scale 1:12,000, northern flanks), Moustafa (1988, scale 1:48,000, all of US Sierra del Carmen), and Cooper (2011, scale 1:24,000, western flanks). Two geologic maps of Big Bend National Park are in print (Maxwell, 1968; Turner *et al.*, 2011). Moustafa (1988) includes detailed descriptions and kinematic interpretations of Sierra del Carmen folds and faults. He interpreted many WNW-trending structures and terminations of NNW-trending structures, including Dagger Mountain anticline, to result from reactivated Paleozoic or older WNW-trending faults within the Texas lineament, a zone of long-lived tranpression and transtension (fig. 2; Muehlberger, 1980). Morgan and Shanks (2008) described Tertiary sills and contact metamorphism in Dagger Flat, 4 km south of Dagger

Mountain, and provided the sole isotopic date (32.5 Ma) on sills similar to Dagger Mountain intrusions. Satterfield *et al.* (2009), Cullen *et al.* (2012), Knox *et al.*, (2013), and Crouch *et al.* (2013) presented preliminary results of this project. Despite excellent Chihuahuan Desert exposures, polyphase structures in Sierra del Carmen remain poorly understood, in part because few 1:12,000-scale mapping and descriptive structural analysis projects have been completed.

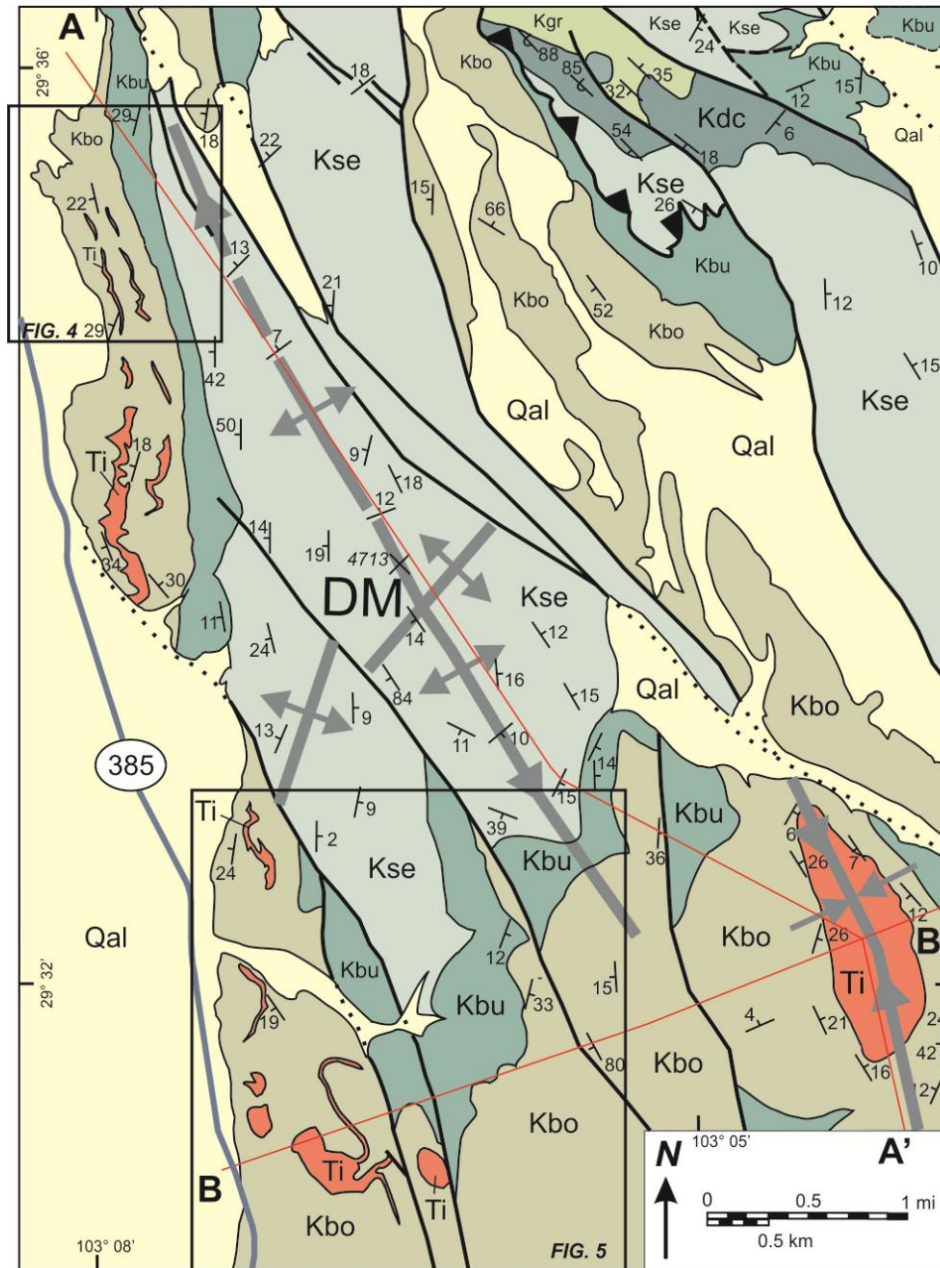
## SITE SIGNIFICANCE

The west and south flanks of Dagger Mountain contain excellent exposures of polyphase regional structures and Tertiary(?) sills. Significant features that can be seen from trailheads (figs. 4, 5) or reached with short hikes include:

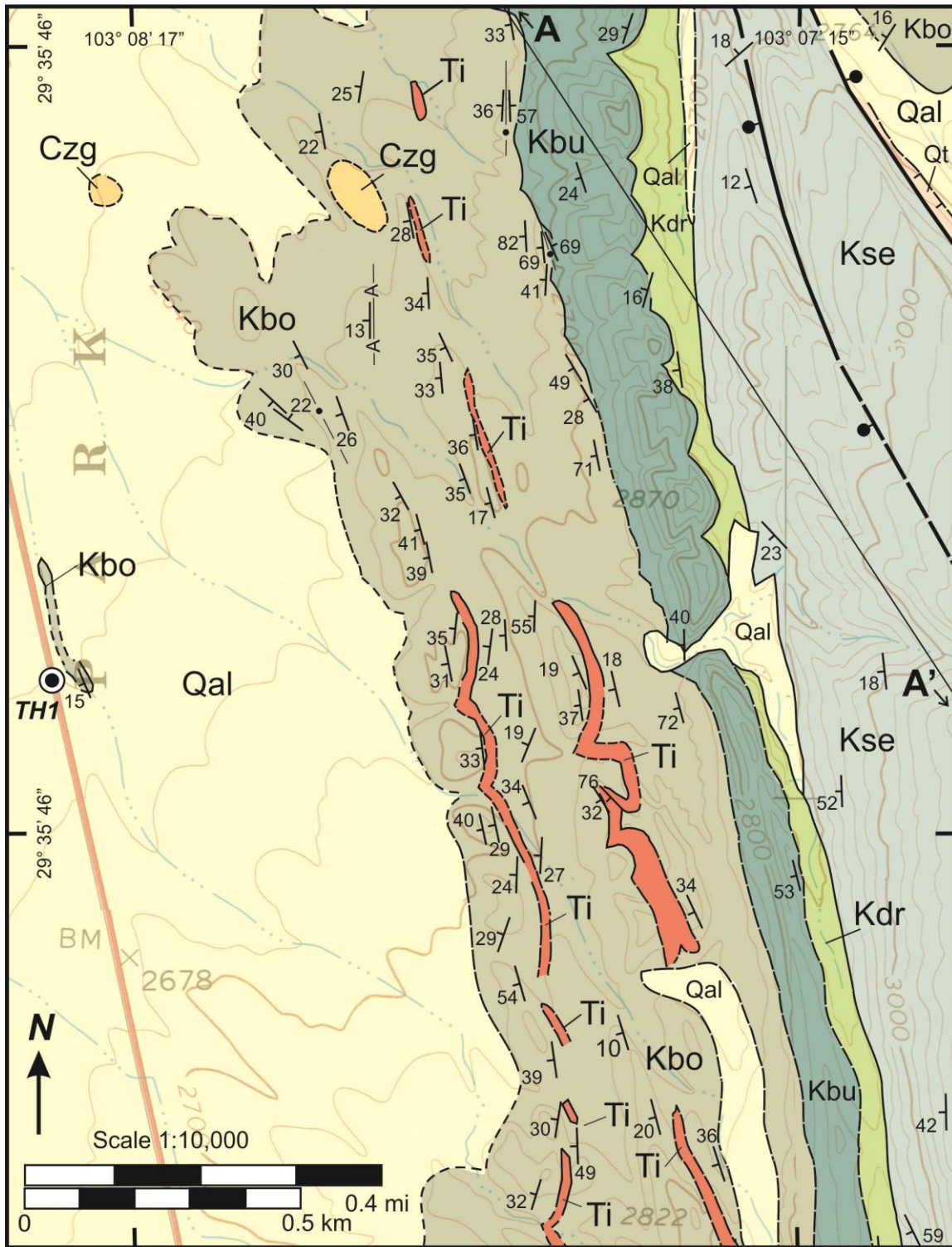
- 1) ***Dagger Mountain anticline***. This large NNW-trending anticline is interpreted to be a fault-propagation fold above a blind reverse fault on the the southwest flank of the Marathon-El Burro-Peyotes uplift, a Laramide basement uplift. This anticline and other NNW-trending folds are refolded by broad NE-trending Laramide folds. Few cases of polyphase Laramide and younger folding have been documented in Trans-Pecos Texas (e.g. Satterfield and Dyess, 2007) in spite of stratigraphic evidence of multiple late Cretaceous – early Tertiary uplift episodes (e.g. Maxwell *et al.*, 1967; Lehman, 1991).
- 2) ***Feldspathoid-rich Tertiary(?) sills***. Phaneritic mafic sills display well-exposed margins showing evidence of passive and forceful intrusion. Sills dip

moderately to steeply and one sill is found on both limbs and hinge of a map-scale Laramide anticline, apparently indicating sills were folded.

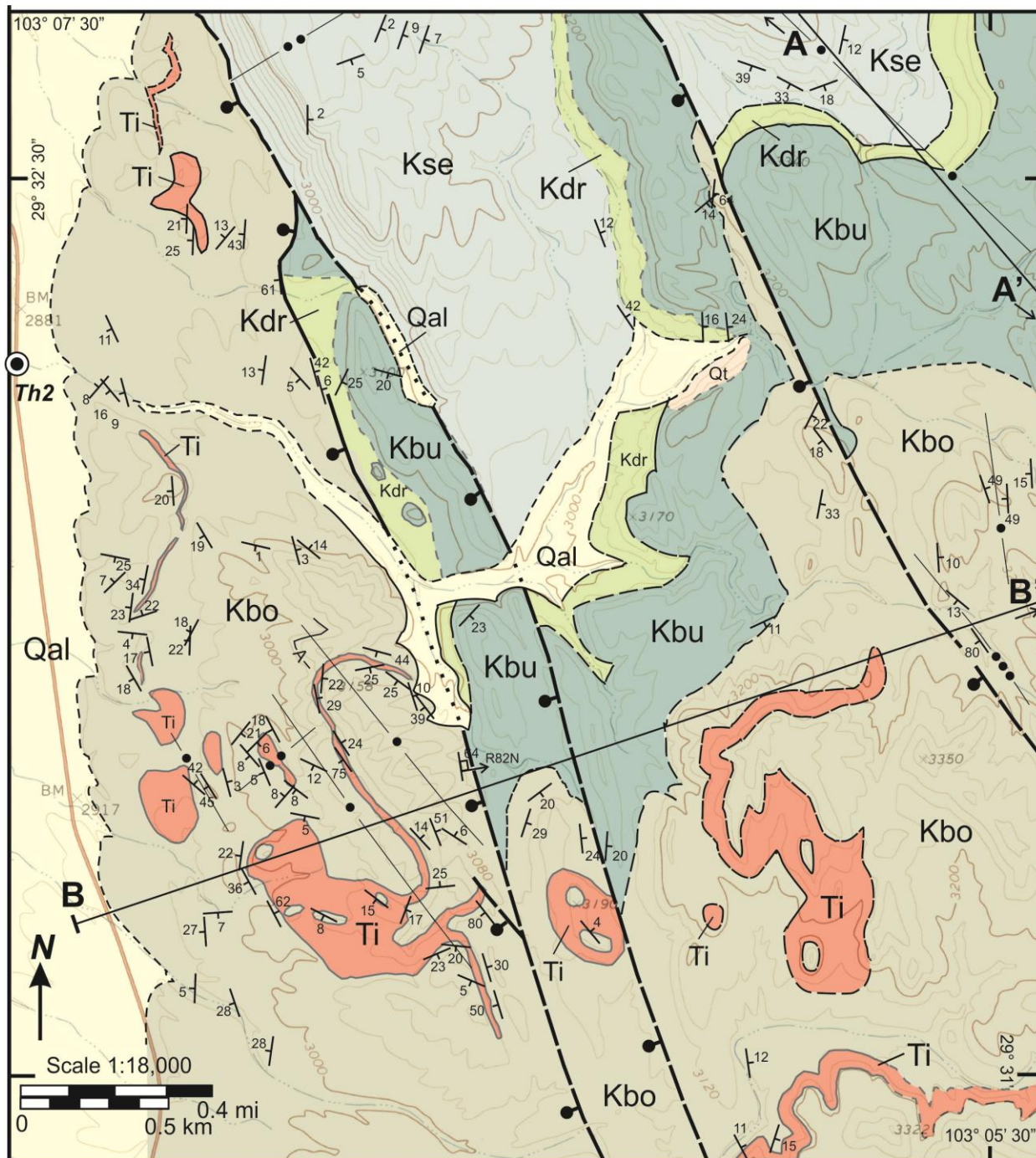
3) **Well-exposed Basin and Range faults.** High-angle faults cross-cut Laramide folds and two Tertiary(?) sills.



**Figure 3.** Simplified geologic map of Dagger Mountain area. Dagger Mountain (DM; elevation 4713 ft.) and adjacent area contains NNW- and NE-trending map-scale folds. Axial traces are shown as broad gray lines. Thick black lines are high-angle Basin and Range faults. Kbu map unit includes Buda Limestone and Del Rio Clay. **For other symbols see key on separate page.** Map is compilation of 1:12,000-scale mapping by Angelo State University students and faculty.

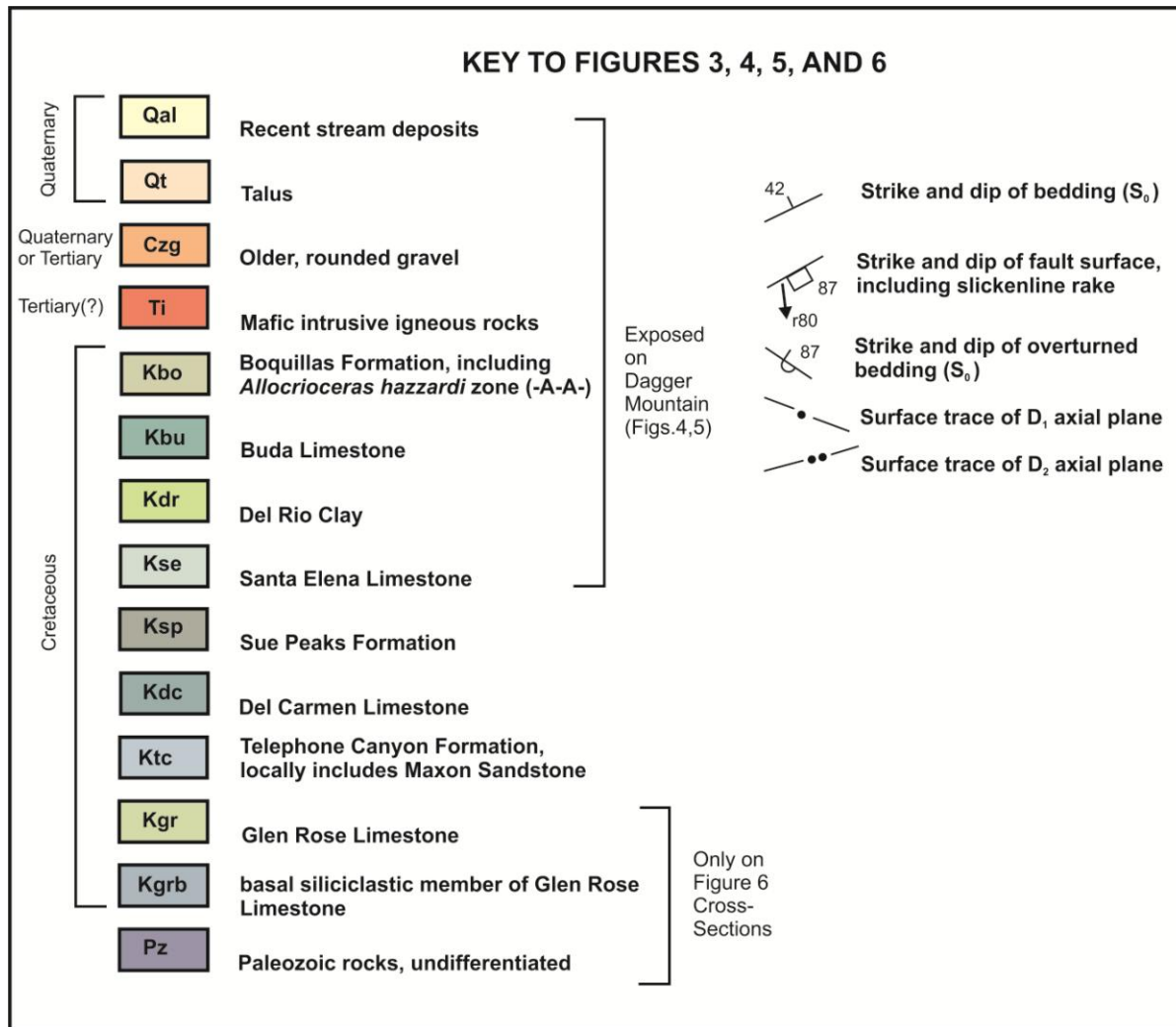


**Figure 4.** Geologic map of northwest flank of Dagger Mountain. Map shows steep dips in Santa Elena limestone and two sills intruding but not deforming the Boquillas Formation. TH1-Trailhead 1. **Key on separate page.**



**Figure 5.** Geologic map of the southwest flank of Dagger Mountain. Map shows D<sub>1</sub> and D<sub>2</sub> Laramide folds, including one apparently folded Tertiary(?) sill that can be traced from one limb, the hinge, and the adjacent limb. TH2 – Trailhead 2. **Key on separate page.**





## REGIONAL SETTING

Sierra del Carmen contains folds and reverse faults of the easternmost Cordilleran orogen cross-cut by easternmost Basin and Range normal faults and drag folds. Mafic sills in and near Dagger Mountain are within the eastern Trans-Pecos igneous province, composed of magmas that crystallized during the end of Cordilleran contraction and beginning of Basin and Range extension (Barker, 1977; Henry and McDowell, 1986). Figure 2 shows Laramide structures of southern Trans-Pecos Texas and northern

Mexico, also termed the Big Bend region. Page *et al.* (2008), Henry and Price (1985), and Muehlberger and Dickerson (1989) provide overviews of the tectonic setting of the Big Bend region.

The Dagger Mountain anticline is part of the Laramide orogen, the easternmost and youngest part of the Cordilleran orogen (fig. 2-lower). In northern Sierra del Carmen northeast-dipping reverse and thrust faults cross-cut and are folded by gentle to tight map- and outcrop-scale folds, some overturned (fig. 2; Satterfield and Dyess, 2007). Laramide folds and faults in Sierra

del Carmen define the southwest flank of a Laramide basement uplift that contains two of three regional Laramide deformation phases (Satterfield *et al.*, 2012). Cross-cutting relations and syn-uplift sedimentation pulses constrain Laramide deformation in the Big Bend region to 70 – 47 Ma (Lehman, 1991, 2004; Erdlac, 1990; Erdlac and Henry, 1994). Middle Eocene strata unconformably overlie Laramide folds in Late Cretaceous units near Sierra del Carmen (Lehman, 2004). Long-lived subduction at the convergent plate boundary between the North American Plate and several plates to the west produced the Cordilleran orogeny (Dickinson and Snyder, 1978; Oldow *et al.*, 1989; Burchfiel, *et al.*, 1992). Competing plate-tectonic models summarized in English and Johnson (2004) seek to explain Laramide mountain-building mechanisms.

Sierra del Carmen intrusions fall within the Trans-Pecos magmatic province, a broad, northwest-trending belt of alkali-rich felsic and mafic lava flows, pyroclastic flows, and intrusions that mostly lies in northern and western Mexico (red map unit on figure 2; Barker, 1977). Both passively and forcefully emplaced intrusions are found in and near Sierra del Carmen. The Rosillos Mountains, prominently visible across HW 385 7 km southwest of Dagger Mountain, consist of a “sloppy pancake stack” of passively emplaced syenite sills (Scott *et al.*, 2004). However the felsic McKinney Hills laccolith, 19 km SE of Dagger Mountain, strongly deformed its margins (Martin, 2007). In Dagger Flat, 3 km SE of Dagger Mountain, sills overlie a ~75 km<sup>2</sup> oval intrusion in the shallow subsurface

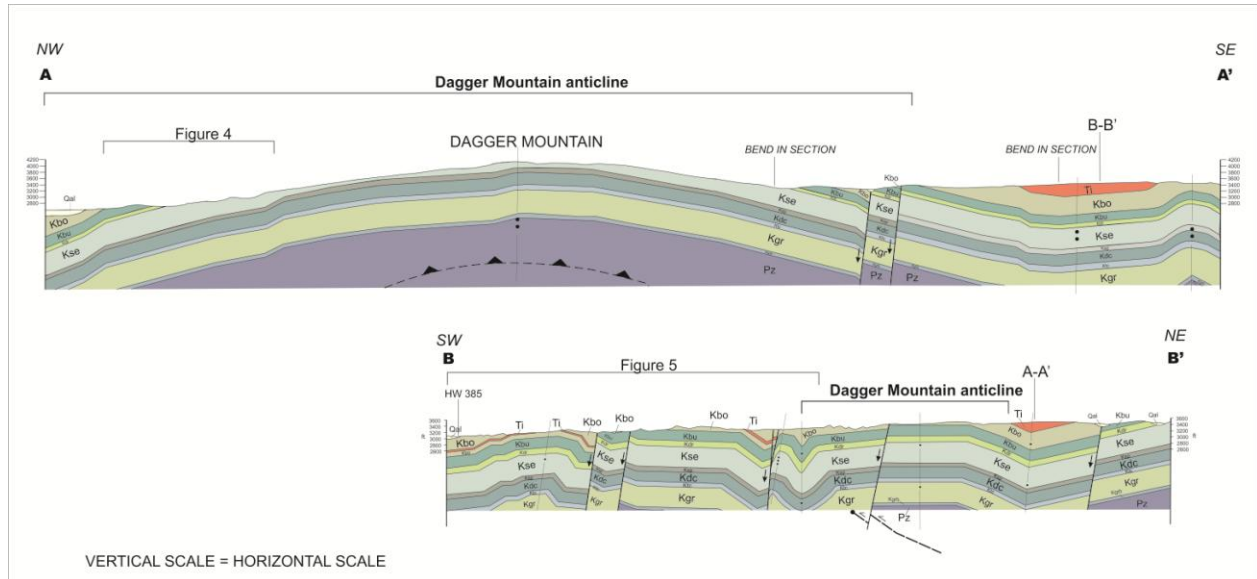
identified by a positive aeromagnetic survey anomaly (Morgan and Shanks, 2008).

Isotopic dates of Trans-Pecos Texas igneous rocks range from 64 to 17 Ma; magmatism peaked at 38 – 32 Ma (Gilmer *et al.*, 2003; Henry and McDowell, 1986). Mafic extrusive igneous rocks interstratified with Late Cretaceous sedimentary rocks have been recently documented at two locations in the Big Bend region, including in the SE Rosillos Mountains, 10 km southwest of Dagger Mountain (Breyer *et al.*, 2007; Befus *et al.*, 2008). Most Trans-Pecos magmas were generated by mantle upwelling above a foundering subducted Farallon plate at the end of the Laramide orogeny (Parker *et al.*, 2012; Parker and White, 2008).

Dagger Mountain and Sierra del Carmen are dramatic topographic highs because of recent uplift on Basin and Range range-front normal faults. Sierra del Carmen is a horst separating easternmost basins: the Tornillo graben to the southwest and the Black Gap graben to the northeast (Dickerson and Muehlberger, 1994). NNW-, NW-, and WNW-striking high-angle faults dissect Sierra del Carmen; some show right-lateral strike-slip offset (Moustafa, 1988; Mahler, 1990; Tauvers and Muehlberger, 1988). Sparse kinematic indicators on Basin and Range faults in the Dog Canyon area north of Dagger Mountain show dominantly normal slip (Satterfield and Dyess, 2007). Basin and Range extension in the Big Bend region began at 31 Ma (Henry and Price, 1986) and continues today. Most earthquakes occur on graben-bounding faults along the Rio Grande River from the southern tip of the Big Bend, through El

Paso, and into New Mexico (Dumas, 1980). Several Basin and Range faults in or near Sierra del Carmen offset Quaternary

sediments (Maler, 1990; Collins, 1994; Stevens, 1994).



**Figure 6.** Cross-sections across Dagger Mountain anticline and adjacent structures. Locations shown on Figure 3. A-A' shows broad, northeast-trending D<sub>2</sub> anticline and syncline. B-B' shows several NNW-trending D<sub>1</sub> anticlines and synclines. An inferred blind thrust fault is shown below the west-vergent Dagger Mountain anticline. Two Tertiary(?) sills (Ti) are apparently folded in D<sub>1</sub> and D<sub>2</sub> folds. High-angle D<sub>3</sub> faults showing normal separation cross-cut D<sub>1</sub> and D<sub>2</sub> folds. **Key on separate page.**

## CRETACEOUS STRATIGRAPHY

Four distinctive Cretaceous formations widespread throughout the Big Bend region crop out on Dagger Mountain: Santa Elena Limestone, Del Rio Clay, Buda Limestone, and Boquillas Formation (each described in detail in Maxwell *et al.*, 1967). The stratigraphic section exposed on Dagger Mountain totals 450 m (fig. 6). The Santa Elena Limestone consists of medium gray-weathering, thick-bedded lime mudstone and wackestone exposed as dramatic cliffs on the west flank of Dagger Mountain and

as dip slopes on higher elevations and other flanks. Sparse horizons within contain abundant chert nodules, silicified fossils, and rudistid bivalves. The overlying Del Rio Clay contains poorly exposed red-orange-weathering mudstone and sandstone that forms slopes. Loose pieces of red-orange fine-grained quartz sandstone commonly contain the characteristic agglutinated foraminifer *Cribratina texana*. The Buda Limestone above consists upper and lower cliff-forming members of ivory-white-weathering thick-bedded wackestone and lime mudstone separated by a slope-

forming nodular wackestone member containing abundant bivalve and gastropod casts. The sharp contact between upper Buda Limestone and the overlying slope- and cuesta-forming Boquillas Formation is a regional unconformity (Maxwell *et al.*, 1967). The Boquillas Formation consists of distinctive tan-weathering sandy limestone beds 5 cm to 3 m thick separated by tan-weathering calcareous shale intervals several centimeters to several meters thick.

### **TERTIARY(?) MAFIC SILLS**

Mafic sills stand out from a distance against tan Boquillas Formation limestone and shale. Two thick, fairly continuous sills map out as numerous separate exposures that include scalloped stripes and ovals. Complex map patterns result from Laramide folding and a complex network of cross-cutting draws (figs. 4, 5). On the west flank of Dagger Mountain two sills traced over four kilometers intrude the lower Boquillas Formation near and below the *Allocrioceras hazzardi* zone (fig. 4). Sills are typically exposed on steep sides of cuestas. Sills thicken from 6.4 and 12.8 m to the north to 15.9 and 33.4 m respectively in the south. The large oval Tertiary(?) intrusion southeast of Dagger Mountain is interpreted to be a sill within the core of a doubly plunging syncline. Evidence supporting sill geometry include its lower Boquillas stratigraphic position similar to other sills, similar mafic composition, and margins parallel to adjacent Boquillas Formation bedding. This sill is most easily reached by

Inoceramid bivalves are common throughout the Boquillas Formation. The middle Boquillas Formation contains the *Allocrioceras hazzardi* zone, characterized by spiny open-coiled ammonites and baculitids at the top of a brown-weathering, 1 – 3-m-thick interval (Maxwell *et al.*, 1967; Cooper, 2011). Figures 4 and 5 show this zone only where *A. hazzardi* ammonites have been found.

hiking north from the termination of the Dagger Flat Auto Trail. Another sill near the southern trailhead (TH2 on figure 5) can be traced continuously from one limb, through the hinge, and along the other limb of a map-scale Laramide D<sub>1</sub> fold.

Two Boquillas Formation measured sections on the western flank of Dagger Mountain show changes in sill spacing. In the northern section, 11.4 m of Boquillas Formation separate sills, while in the southern section 35.4 m separate the same sills. Sill spacing changes show sills are not perfectly parallel to bedding.

At the outcrop scale, speckled dark gray to black sills weather dark brown and commonly display spheroidal weathering (fig. 7). Although weathered, sills are fairly resistant, forming moderate to steep slopes. Mafic sills also contain sparse, several-centimeter-thick grayish-white felsic sills. Felsic sills consist of 1 mm subhedral feldspar (95%) and biotite (5%). Similar felsic segregations within mafic sills are common throughout the Big Bend region (Carman *et al.*, 1975; Shanks and Morgan, 2008). Sills do not contain a primary foliation. Intrusive contacts are sharp and

typically well exposed (fig. 7). Rare 3-m-thick chilled margins are present. Relatively thin, up to 3-m-thick contact metamorphic zones contain lighter-colored, locally spotted, recrystallized more-resistant limestone that retains sedimentary laminations. Other rare contact-

metamorphic features include calcite veins, warped laminations, and hematite mineralization. Contact metamorphic zones also contain sparse boudins of flaggy limestone surrounded by shale; fissility wraps around boundins.



**Figure 7.** Typical intrusive contact between mafic sill (Ti) and Boquillas Formation (Kbo). Well-exposed sharp contact on west flank of Dagger Mountain separates sill above from Boquillas Formation below. Contact parallels bedding in the Boquillas Formation limestone. Contact metamorphic zone is less than 50 cm thick.

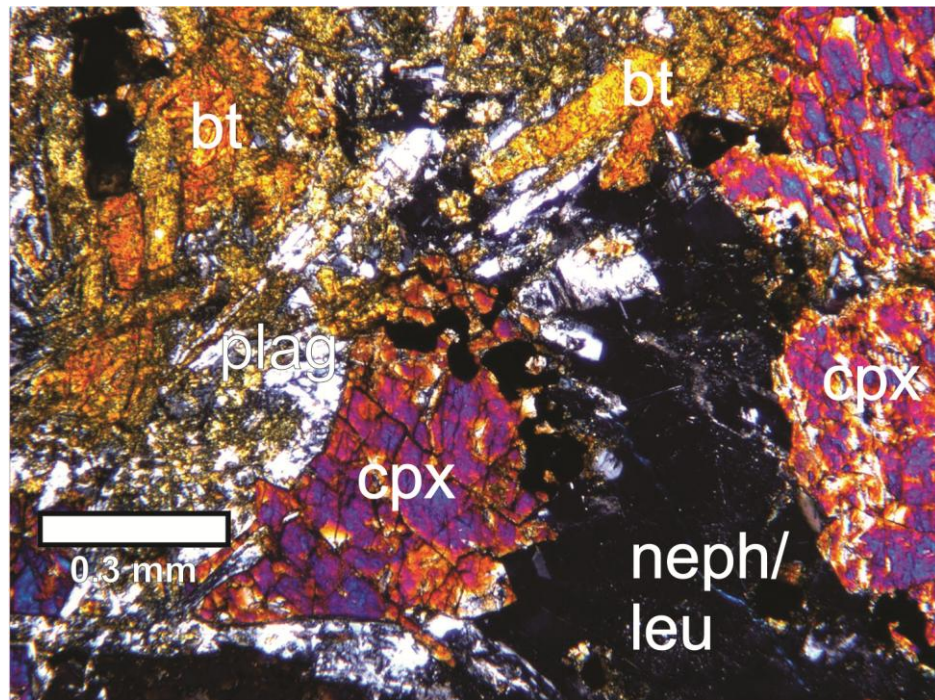
Seven thin sections from Dagger Mountain show sills contain abundant feldspathoid minerals leucite and probable nepheline (fig. 8). Subhedral and anhedral crystals range from 0.2 to 1.0 mm. Sills contain 30 – 80% mafic minerals, dominantly amphibole, clinopyroxene, and biotite mica. Felsic minerals are plagioclase feldspar, leucite,

and probable nepheline. CIPW norms calculated from ICP-MS major element data indicate nepheline should be present (Cullen, unpublished data). Accessory minerals include apatite and oxide minerals. Sills are classified as clinopyroxene amphibole biotite gabbro, clinopyroxene biotite leuciteolite or nephelinite,

clinopyroxene biotite amphibole leuciteolite, and clinopyroxene amphibole biotite leucite or nepheline monzosyenite (IUGS phaneritic igneous rocks classification modified by Winter (2010), Fig. 9). Maxwell *et al.* (1967) classified Dagger Mountain sills as diabasic anlacite gabbro. Geochemical data from five Dagger Flat samples plot in the alkali gabbro field on a total alkali versus silica (TAS) diagram (Morgan and Shanks, 2008).

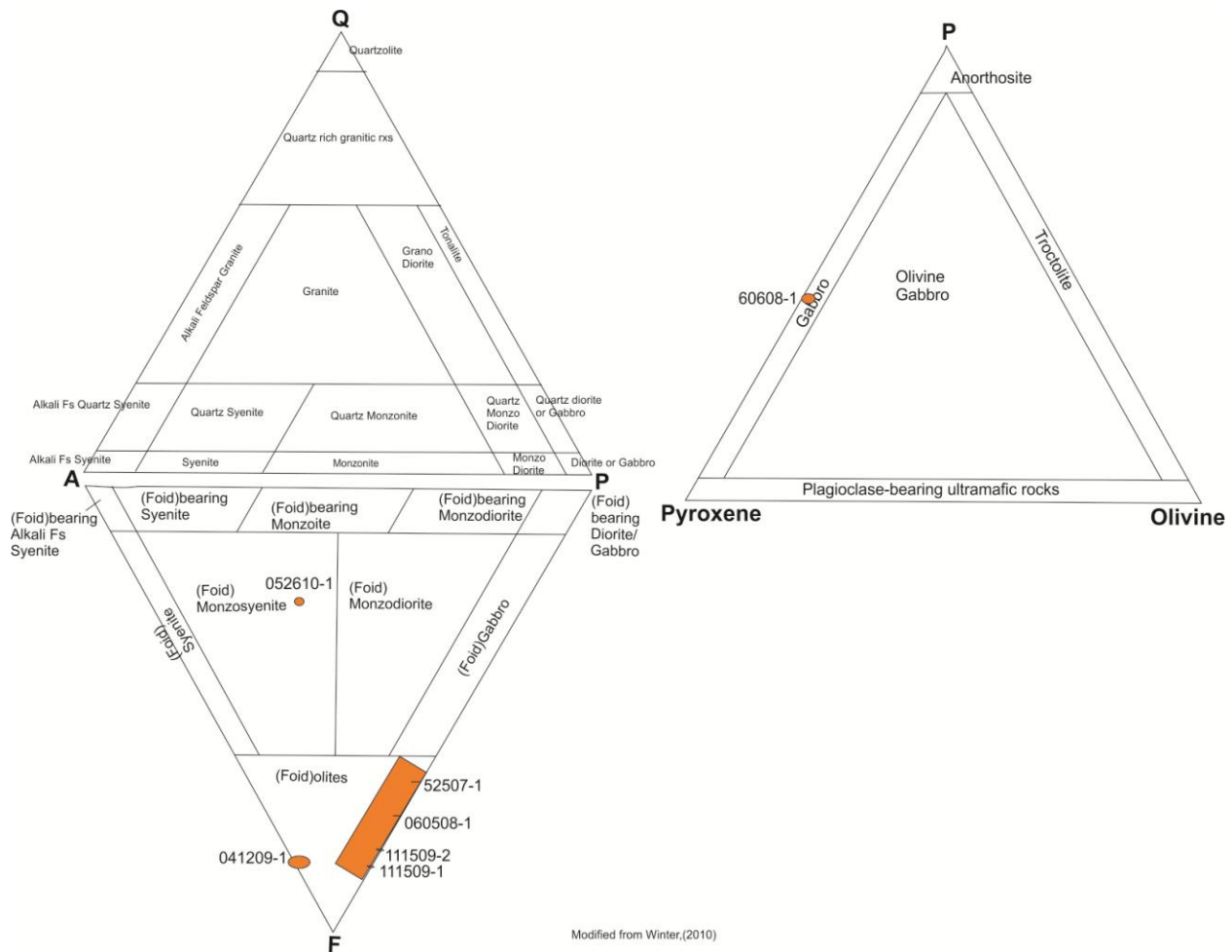
Dagger Mountain sills are tentatively assigned a Tertiary age because in nearby Dagger Flat a felsic segregation within a

mafic sill was dated at  $32.47 \pm 0.41$  Ma ( $^{40}\text{Ar}/^{39}\text{Ar}$  on fine-grained groundmass; Morgan and Shanks, 2008). Other intrusions in or near northern Sierra del Carmen are similar in age: Rosillos Mountains syenite has been dated at  $32.1 \pm 0.2$  Ma and the McKinney Hills laccolith is dated at  $32.2 \pm 0.3$  Ma (U-Pb on zircon; Turner *et al.*, 2011). Sills could possibly be as old as Cretaceous since they intrude Late Cretaceous rocks and Late Cretaceous mafic extrusive igneous rocks have been discovered in the Rosillos Mountains (Breyer *et al.*, 2007).



060508-1

**Figure 8.** Photo-micrograph of typical Dagger Mountain sill viewed under crossed polars. Major minerals visible are feldspathoid minerals nepheline or leucite (neph/leu), clinopyroxene (cpx), plagioclase feldspar (plag), and biotite (bt). Figure 9 shows composition of this sample (060508-1). Nepheline or leucite is showing characteristic dark gray, nearly isotropic maximum birefringence.



**Figure 9.** IUGS classification of phaneritic igneous rocks (version in Winter, 2010) showing normalized mineral percentage estimates from six thin-sections of Dagger Mountain sills. Five of seven samples plot as feldspathoid-rich leucitoliths or nephelinites.

## STRUCTURAL GEOLOGY

The Dagger Mountain area contains two phases of Laramide structures and one phase of younger Basin and Range structures. The largest structures are first-phase ( $D_1$ ) and second-phase ( $D_2$ ) Laramide folds. Dagger Mountain exposes a map-scale NNW-trending  $D_1$  anticline consisting of Santa Elena Limestone in its core refolded by a map-scale, NE-trending  $D_2$  anticline (Dagger Mountain anticline; figs.

3, 5, 6). To the southeast, a map-scale, NNW-trending  $D_1$  syncline containing a Tertiary(?) sill in its core is refolded by a map scale, NE-trending  $D_2$  syncline (figs. 3, 5, 6).

The Dagger Mountain anticline consists of a steep southwest limb that dips up to  $84^\circ$  SW and a gentle northeast limb dipping at most  $18^\circ$  NE. Its half-wavelength is at least 0.5 km. Moustafa (1988) described the Dagger Mountain anticline as two NNW-oriented monoclines forming a

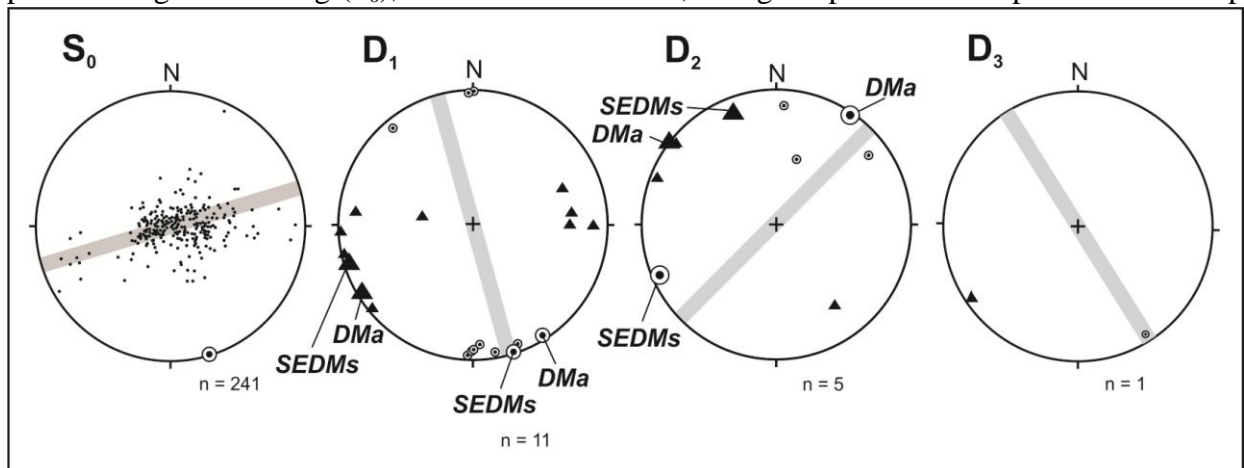
box fold. More-detailed mapping shows that the anticline is a single asymmetric fold containing a uniformly gently dipping northeast limb.

D<sub>1</sub> map- and outcrop-scale folds contain subvertical axial planes striking ~342 and fold axes at ~162 02 (Fig. 10). D<sub>1</sub> interlimb angles average 108° and range from 34 - 166°. Thrust faults coeval with D<sub>1</sub> folding crop out northeast of Dagger Mountain (Figs. 2, 3; Satterfield and Dyess, 2007). D<sub>2</sub> map- and outcrop-scale folds display subvertical axial planes striking ~038 and fold axes at ~038 02 (fig. 10). D<sub>2</sub> interlimb angles average 124° and range from 41 - 166°. Figure 10 shows that the

Dagger Mountain anticline (DMa) and the large syncline SE of Dagger Mountain (SEDMs) have similar D<sub>1</sub> and D<sub>2</sub> axial plane and fold axis orientations. Figure 10 also shows that outcrop-scale D<sub>1</sub> and D<sub>2</sub> fold orientations are similar to orientations of map-scale D<sub>1</sub> and D<sub>2</sub> folds.

Third-phase (D<sub>3</sub>) high-angle faults in the Dagger Mountain area strike ~348 and ~320. They cross-cut D<sub>1</sub> folds, D<sub>2</sub> folds, and Tertiary(?) sills (figs. 3, 4, 5). Sparse drag folds adjacent to D<sub>3</sub> faults indicate normal offset; one is shown on cross-section B-B' (fig. 6). D<sub>3</sub> faults and folds do not significantly reorient D<sub>1</sub> or D<sub>2</sub> folds (fig. 10).

**Figure 10.** Stereographic projections of outcrop- and map-scale folds. Key to symbols: dots-poles to original bedding (S<sub>0</sub>), circle-dots- fold axes, triangles- poles to axial planes. Two map-



scale folds are identified: *DMa*- Dagger Mountain anticline, *SEDMs*- SE Dagger Mountain syncline cored by Tertiary sill. Stereonets show fold axis and axial plane orientations can clearly distinguish D<sub>1</sub> folds from D<sub>2</sub> folds.

## DISCUSSION

Dagger Mountain folds, faults, and sills are significant for four reasons. First, recent detailed mapping has distinguished three generations of folds. D<sub>1</sub> and D<sub>2</sub> folds

are Laramide structures, while D<sub>3</sub> folds are drag folds associated with Basin and Range faults. Polyphase, orthogonal Laramide fold phases have been described in other Laramide basement uplifts although their



origin remains poorly understood (e.g. Oldow *et al.*, 1989).

Second, the shapes and vergence of the Dagger Mountain anticline and other  $D_1$  folds are characteristic of fault-propagation folds above blind reverse faults. A reverse fault characteristically produces a broad asymmetric anticline and tight syncline above the fault termination. The broad anticline verges in the direction of tectonic transport of the reverse fault below (e.g. Mitra and Mount, 1998). The Dagger Mountain anticline verges southwestward (figs. 3, 6), consistent with SW-tectonic transport of northeast-dipping reverse faults exposed nearby to the northeast (figs. 2, 3) and similar to other map-scale folds in SW Sierra del Carmen displaying steep SW limbs (fig. 2). Fault-propagation folds and southwest tectonic transport on reverse faults are expected on the southwest margin of a Laramide basement uplift (Lehman, 1991). The northeastern margin of the Marathon-El Burro-Peyotes uplift, the southernmost US Laramide uplift, includes the northeast margin of the Marathon uplift (fig. 2). A further implication of this little-recognized basement uplift is that Laramide structures could extend into the southern and eastern Permian basin.

Third, Dagger Mountain sills provide timing constraints on regional deformation events in the Big Bend region. Along the southern flanks of Dagger Mountain two Basin and Range faults cross-cut undated sills correlated with a 32.5 Ma Dagger Flat sill. Thus these Basin and Range faults moved after 32.5 Ma. Sills are apparently folded in map-scale  $D_1$  folds (figs. 5, 6). The simplest interpretation is that Laramide

deformation in this part of Sierra del Carmen occurred after 32.5 Ma, much younger than published pre-47 Ma Laramide deformation constraints, and possibly overlapping with post-31 Ma Basin and Range extension.

A second interpretation is that undated folded Dagger Mountain sills are much older than the 32.5 Ma Dagger Flat sill. If sills are Late Cretaceous then Laramide deformation in Dagger Mountain area occurred no earlier than Late Cretaceous.

A third interpretation is that Dagger Mountain sills intruded perfectly parallel to bedding within the hinges of existing  $D_1$  folds and thus postdate Laramide deformation. Mafic sills in the hinge and limbs of the Mariscal Mountain anticline (fig. 2) first interpreted to predate folding (Maxwell *et al.*, 1967) were later inferred to have intruded after folding on the basis of consistent, untilted paleomagnetic poles of sill samples from both limbs of the fold (Harlan *et al.*, 1995). Mariscal Mountain sill samples have been dated at 46.0 Ma ( $^{40}\text{Ar}/^{39}\text{Ar}$  on pyroxene; Miggins *et al.*, 2009),  $46.5 \pm 0.3$  Ma (U-Pb on zircon; Turner *et al.*, 2011), and  $36.11 \pm 0.19$  ( $^{40}\text{Ar}/^{39}\text{Ar}$  on Potassium feldspar; Turner *et al.*, 2011).

Dagger Mountain exposures are also significant because well-exposed sills show evidence of both passive and forceful emplacement. The absence of deformation zones and magmatic foliations supports passive emplacement. Although folds are common adjacent to sills, fold styles and consistent axial plane and fold axis orientations correlate to regional Laramide

D<sub>1</sub> folds (fig. 10) and folds are not restricted to sill margins. Evidence for forceful emplacement includes concordant margins, boudins indicating ductile stretching in adjacent Boquillas Formation, and the rarity of xenoliths within sills. Work to date cannot establish whether sill emplacement was primarily forceful or passive.

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**View to north of west-dipping feldspathoid-rich sill on the west flank of the Dagger Mountain anticline. This Tertiary(?) sill intrudes thin limestone and calcareous shale beds of the Cretaceous Boquillas Formation. Wind gap in ridge on horizon is Persimmon Gap, the northern entrance to Big Bend National Park in West Texas. Photo by Joseph I. Satterfield.**