Nonexplosive and explosive magma/wet-sediment interaction during emplacement of Eocene intrusions into Cretaceous to Eocene strata, Trans-Pecos igneous province, West Texas

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Abstract

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Eocene intrusion of alkaline basaltic to trachyandesitic magmas into un lithified, Upper Cretaceous (Maastrichtian) to Eocene fluvial strata in part of the Trans-Pecos igneous province in West Texas produced an array of features recording both nonexplosive and explosive magma/wet-sediment interaction. Intrusive complexes with 40Ar/39Ar dates of ~47–46 Ma consist of coherent basalt, peperite, and disrupted sediment. Two of the complexes cutting Cretaceous strata contain masses of conglomerate derived from Eocene fluvial deposits that, at the onset of intrusive activity, would have been >400–500 m above the present level of exposure. These intrusive complexes are inferred to be remnants of diatremes that fed maar volcanoes during an early stage of magmatism in this part of the Trans-Pecos province. Disrupted Cretaceous strata along diatreme margins record collapse of conduit walls during and after subsurface phreatomagmatic explosions. Eocene conglomerate slumped downward from higher levels during vent excavation. Coherent to pillowed basaltic intrusions emplaced at the close of explosive activity formed peperite within the conglomerate, within disrupted Cretaceous strata in the conduit walls, and within inferred remnants of the phreatomagmatic slurry that filled the vents during explosive volcanism. A younger series of intrusions with 40Ar/39Ar dates of ~42 Ma underwent nonexplosive interaction with Upper Cretaceous to Paleocene mud and sand. Dikes and sills show fluidal, billowed, quenched margins against the host strata, recording development of surface instabilities between magma and groundwater-rich sediment. Accentuation of billowed margins resulted in propagation of intrusive pillows into the adjacent sediment. More intense disruption and mingling of quenched magma with sediment locally produced fluidal and blocky peperite, but sufficient volumes of pore fluid were not heated rapidly enough to generate phreatomagmatic explosions. This work suggests that Trans-Pecos Texas may be an important locale for the study of subvolcanic phreatomagmatic processes and associated phenomena. Eocene intrusions in the study area underwent complex interactions with wet sediment at shallow levels beneath the surface in strata as old as Maastrichtian, which must have remained un lithified and rich in pore water for ~20–25 Ma.

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1. Introduction

Trans-Pecos Texas contains large volumes of Cenozoic igneous rock emplaced during arc magmatism and subsequent Basin-and-Range extension (Fig. 1; Henry et al., 1991; White et al., 2006). Widespread felsic extrusive units in the province have received most attention from volcanologists, but mafic to intermediate rocks are also common and include abundant hypabyssal intrusions (e.g., Maxwell et al., 1967; Henry and McDowell, 1986; Henry et al., 1989).

Little previous work has been carried out on physical interactions between these intrusions and their host sedimentary sequences. Here we describe mafic to intermediate Eocene intrusions that exhibit a spectrum of features formed when magma penetrated un lithified fluvial strata ranging in age from Cretaceous to Eocene. Nonexplosive interaction between magma and sediment rich in pore water led to formation of intrusive pillows and different types of peperite. Explosive interactions produced complex diatremes inferred to represent the conduits of small phreatomagmatic volcanoes now eroded away. Such features are of interest because they shed light on processes occurring in the subsurface prior to and during explosive hydrovolcanism, at levels not accessible by direct observation of active maars and tuff rings. Also, they may provide constraints on paleohydrological and paleoclimatic conditions.
during the evolution of sedimentary and volcanic sequences in non-marine depositional settings.

2. Geological framework

Initial stages of Cenozoic igneous activity in the Trans-Pecos province define the eastern edge of the Cordilleran magmatic arc (Barker, 1987; Price et al., 1987; Gilmer et al., 2003). A felsic stock in the western part of the province was emplaced in the Paleocene at ~64 Ma (Gilmer et al., 2003), but the oldest known Cenozoic igneous rocks elsewhere in the region are Eocene and have isotopic dates of ~48–46 Ma (Henry and McDowell, 1986; Henry et al., 1986, 1989; Miggins et al., 2006). These early phases of magmatism preceded emplacement of voluminous felsic rocks throughout the province beginning at ~38 Ma (Henry and McDowell, 1986). Henry et al. (1991) inferred that subduction-related magmatism within the province gave way to Basin-and-Range extensional magmatism at ~31 Ma. More recently, White et al. (2006) suggested that much of the Cenozoic magmatism prior to ~27 Ma in Trans-Pecos Texas was related to roll-back or break-off of the subducted slab, followed by lithosphere delamination during initial stages of continental rifting. Igneous rocks emplaced throughout the Cenozoic in the Trans-Pecos province,

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Fig. 1. Extent of Cenozoic igneous rocks in Trans-Pecos Texas, modified from Barker (1977). Study area indicated by star. Area of Big Bend National Park is indicated by dark grey shading (green in color version). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Geologic map of study area. General geology after Horton (2006). Thickness of dikes not to scale. Boundary of Big Bend National Park is indicated; rest of area lies within privately owned Pitcock Rosillos Ranch.
including those emplaced during early stages of arc-related magmatism, are characterized by alkaline, partly silica-undersaturated compositions (Barker, 1987; Price et al., 1987).

In this paper we focus on Eocene hypabyssal intrusions present on the southern flank of the Rosillos Mountains in the southeastern part of the Trans-Pecos province, adjacent to and partly within Big Bend National Park (Fig. 2). The study area is partly covered by Plio-Pleistocene alluvial fan deposits shed from the Oligocene Rosillos Mountains quartz syenite laccolith. Cretaceous and Paleogene fluvial strata exposed beneath the fan deposits are assigned to the Aguja, Javelina, and Black Peaks Formations (Fig. 3; Horton, 2006), following the terminology of Maxwell et al. (1967) and Lehman (1988, 1991). The Aguja Formation contains restricted outcrops of near-vent Cretaceous intraplate basaltic phreatomagmatic deposits (Breyer et al., 2007), but there is no other evidence for local volcanism until the Eocene. The Javelina Formation and succeeding units were deposited within the intermontane Tornillo basin, which was delimited by regions that underwent uplift during latest Cretaceous to Paleogene Laramide deformation (Lehman, 1991). Vertebrate fossils generally provide good age control on stratigraphic units within the Tornillo basin (Fig. 3; Lehman, 1985; Schiebout et al., 1987; Lehman, 1991; Lehman and Coulson, 2002).

Mafic to intermediate intrusions in the study area include a series of east–northeast-trending, generally subvertical dikes (Fig. 2), as well as less common sills and inclined sheets. Two discordant intrusive masses with complex internal makeup occur in the southwestern part of the study area (“western intrusive complexes” in Fig. 2). Farther east, several irregular intrusions in close proximity (“eastern intrusive complex”) underlie a prominent small peak. Another discordant intrusion with a less complicated internal structure forms an isolated body exposed in Cottonwood Wash (Fig. 2). The long dike in the southwestern part of the study area was interpreted by Henry et al. (1989, 1991) to belong to a dike swarm that radiates from the ~42 Ma Christmas Mountains igneous center located ~10 km to the west. Most of the other mafic to intermediate intrusions in the study area are not shown on previously published maps.

The intrusions cut both the Javelina and Black Peaks Formations (Fig. 2). Conglomerate derived from the younger Hannold Hill Formation also occurs within the western intrusive complexes, although that unit presently does not crop out in the study area. Mudstones deposited in overbank settings are the dominant lithofacies in all three formations; sandstones and channel-lag conglomerates are less common and accumulated in meandering rivers on low-relief floodplains (Schiebout et al., 1987; Lehman, 1991). The overbank mudstones exhibit prominent color banding in shades of black, gray, purple, and red that is subparallel to bedding and is the result of ancient pedogenic processes (Schiebout et al., 1987; Lehman, 1989, 1990; White and Schiebout, 2003). The lowermost part of the Canoe Formation (Fig. 3) represents a change to braided river environments. Abundant volcaniclastic deposits and intercalated lavas are present in the lowermost parts of the Eocene–Lower Oligocene Chisos Group and laterally equivalent parts of the Canoe Formation, and record the onset of Cenozoic volcanism in this part of the Trans-Pecos province (Runkel, 1990; Henry and Davis, 1996).

3. Petrography and chemistry

Most of the dikes and sills, as well as the Cottonwood Wash intrusion, are basaltic rocks containing olivine and plagioclase phenocrysts ≤5 mm in length set within an aphanitic, pilotaxitic to intergranular groundmass, in which olivine and clinopyroxene grains occupy interstices between plagioclase microlites. The long dike in the southwestern part of the study area is lighter in color and contains phenocrysts of olivine, plagioclase, and titanomagnetite within a plagioclase-rich, intergranular groundmass that is aphanitic along dike

![Fig. 3. Stratigraphy of Upper Cretaceous and Paleogene rocks in Big Bend region, modified from Lehman (1991), with additions from Runkel (1990), Lehman and Coulson (2002), and Miggin et al. (2006). Time scale from Gradstein et al. (2004). Thicknesses (not to scale) are from the following sources: Chisos Group and lower Canoe Formation – Maxwell et al. (1967); Hannold Hill Formation – Beatty (1992); Black Peaks Formation – Straight (1996); Javelina Formation – Lehman and Coulson (2002). Where thicknesses of units are variable, values considered most appropriate for study area are used when possible.](image-url)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Chemical analyses and CIPW norms of dikes (A9b, A10a, D10), Cottonwood Wash intrusion (C15), and other discordant intrusions (A2, B6, C8)</th>
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Major elements in wt.% (normalized to 100% on volatile-free basis), trace elements in ppm. Major elements analyzed by XRF on fused glass beads with lithium tetraborate flux. Trace elements analyzed by ICP-MS. Analyses were carried out at Washington State University GeoAnalytical Laboratory, Pullman, Washington.

* Total before normalization.
margins and becomes barely phaneritic in the dike interior. The two western intrusive complexes and the eastern intrusive complex are petrographically very similar to each other and consist of basalt that grades locally into diabase and contains plagioclase phenocrysts to 1 cm in length. The groundmass in the finer grained parts of these intrusions show intergranular texture defined by plagioclase, olivine, and titanaugite, but where the rocks become diabasic, the titanaugite develops subophitic to ophitic texture.

Olivine in most of the rocks is partly to completely replaced by carbonate or green brown smectitic (?) clay minerals. In the more altered samples, plagioclase and pyroxene are also partly replaced by the same secondary phases. Elongate, carbonate-filled amygdules are intergrown with igneous minerals in the groundmass of some samples and does not show replacement relations with the igneous phases, suggesting it is of late-magmatic origin. Similar, possibly primary analcite is common in a wide variety of mafic to intermediate rocks in the Trans-Pecos province (e.g., Lonsdale, 1940; Henry et al., 1989).

Chemical analyses are shown in Table 1, with sample locations indicated in Fig. 2; see Befus (2006) for a more complete discussion of the geochemistry. The samples fall in trachyandesite to trachybasalt and basalt fields on the total alkalis versus silica diagram (Fig. 4A).

![Fig. 4. Analyses of intrusions plotted on (A) total alkalis vs. silica diagram (Le Bas et al., 1986) and on (B) Zr/TiO2 vs. Nb/Y discrimination diagram (Winchester and Floyd, 1977; revised by Pearce, 1996). Bta = basaltic trachyandesite; TA = trachyandesite; TB = tephrite and basanite; AB = alkali basalt; Trb = trachybasalt.](image)

<table>
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<th>Table 2</th>
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</table>

Abundance of 40Ar/K and 39Ar/K (K/Ar) is measured in volts and calculated to five decimal places. Voltage may be converted to moles using 1.160 × 10^-12 moles argon per volt signal. 40Ar/39ArK is calculated to three decimal places. All three are rounded to significant figures using analytical precision.

b Corrected for mass discrimination. Mass discrimination was determined by calculating the 40Ar/39Ar ratio of aliquots of atmospheric argon pipetted from a fixed pipette on the extraction line; the ratio during these experiments was between 298.5 and 299.1, which was corrected to 295.5 to account for mass discrimination.

c Corrected for radioactive decay. Abundances of interfering isotopes from K and Ca were calculated from reactor production ratios determined by irradiating K-feldspar and analyzing pure CaF2 and K2SO4; the K2SO4 was degassed in a vacuum furnace prior to irradiation to release argon. Corrections for Cl-derived 39Ar were also calculated for all interfering isotopes of argon including atmospheric argon.

d Apparent ages and associated errors were calculated using the method of Roddick (1987). Production ratios for this experiment were determined for 40Ar/K, 40Ar/39ArK, 39Ar/K, 37Ar/39ArK, and 36Ar/37ArK; measured values are available upon request.

e To calculate apparent K/Ca ratios, divide the 40Ar/K by 2. The accuracy of apparent K/Ca ratios is dependent upon fast to thermal neutron ratios in the particular reactor. In the U.S. Geological Survey TRIGA reactor the correction factor has not been determined since Dalrymple et al. (1981). Because reactor fuel in the USGS TRIGA has been changed since 1981, this ratio must be viewed as approximate but is internally consistent for each sample and reveals within-sample variability.

f Apparent ages and associated errors were calculated from raw analytical data and then rounded using associated analytical errors. Apparent ages of each fraction include the error in J value (0.01%), which was calculated from the reproducibility of splits of the argon from several standards. Apparent ages were calculated using decay constants of Steiger and Jäger (1977). All apparent age errors are cited at 1σ.
and most are nepheline-normative (Table 1). Samples from the long dike in the southwestern part of the study area (D10), the Cottonwood Wash intrusion (C15), the eastern intrusive complex (B6), and one of the western intrusive complexes (A2) exhibit only minor alteration in thin section. However, the other three dike samples (A9b, A10a, and A10b) and sample C8 from the other western intrusive complex are heavily altered, as reflected in their higher LOI values, and contain abundant secondary carbonate and clay minerals. The major-element contents have probably been significantly perturbed in these altered samples, and Fig. 4A is unlikely to provide a reliable indication of their original magmatic affinities. All but one of the samples plot within the alkali basalt field in the discrimination diagram in Fig. 4B, which uses ratios of trace elements less susceptible to secondary alteration (Winchester and Floyd, 1977). Sample D10 from the long dike plots on the boundary between alkali basalt and trachyandesite fields in that diagram, in agreement with the result from Fig. 4A. The other three dike samples and the Cottonwood Wash intrusion are tightly clustered in Fig. 4B, implying that they are closely related petrogenetically, whereas the three samples from the western and eastern intrusive complexes form a separate cluster.

4. 40Ar/39Ar geochronology and temporal relations of the intrusions

Samples of four intrusions showing the least alteration in thin section were selected for 40Ar/39Ar dating. Sample locations are shown in Fig. 2, and chemical analyses of the dated rocks are given in Table 1. All four samples were collected well away from zones of magmasediment interaction. Groundmass concentrates from the samples were used in this study and were prepared as described in Miggins et al. (2002, 2004). Common sources of inaccuracy in groundmass dating of basaltic rocks are xenoliths and phenocrysts, and special care was taken to remove any such impurities from the concentrates using a magnetic separator and/or hand picking. Argon isotopic compositions were measured at the U.S. Geological Survey laboratory in Denver, Colorado. Analytical techniques are given in Table 2 and in general followed procedures given in Miggins et al. (2002, 2004). Standard methods were employed to produce 40Ar/36Ar age spectra and isochron diagrams (Snee, 2002).

Incremental heating results are given in Table 2, and age spectra are shown in Fig. 5. As used herein, the term “plateau” refers to two or
more contiguous temperature steps with apparent dates that are indistinguishable at the 95% confidence interval and represent ≥50% of the total $^{39}$Ar released (Fleck et al., 1977); $^{39}$Ar is defined in Table 2. An “average date” represents what we infer to be the best estimate of the apparent age for a sample that contains no plateau. Generally we restrict this term to a portion of the age spectrum that shows near concordancy but comprises <50% of the released argon, or the included argon fractions have dates that overlap within three standard deviations of the weighted mean. Isochron analysis (York, 1969) was used to assess if extraneous radiogenic argon components were trapped in any samples. A total gas date, analogous to a conventional K–Ar date, is calculated for each sample by taking the weighted mean of the dates for all gas fractions of the sample.

All four samples show the effects of $^{39}$Ar recoil (Hess and Lippolt, 1986), with gas fractions at lower temperatures yielding older ages and gas fractions at higher temperatures yielding younger ages (Fig. 5). Initial $^{40}$Ar/$^{36}$Ar ratios calculated from the isochrons for the four samples are close to or within error of the atmospheric value of 295.5, suggesting that extraneous radiogenic argon is not present in significant amounts.

Sample B6, which comes from basalt within the eastern intrusive complex, yielded a plateau date of 46.78 ± 0.14 Ma for heating steps 4 and 5, representing 53.4% of the total $^{39}$Ar released. This result is within error of an isochron date of 46.75 ± 0.48 Ma for steps 3–8 (Fig. 5A) and is taken as the crystallization age of the basalt. Sample A2, which comes from similar basalt in one of the western intrusive complexes, has a more discordant age spectrum. Steps 4–7 yielded an average date of 46.12 ± 0.36 Ma, representing 63.1% of the total $^{39}$Ar released, whereas an isochron for all eight steps yielded an older date of 47.89 ± 0.97 Ma (Fig. 5B). We interpret the data from both samples to indicate that the eastern and western intrusive complexes were emplaced in a similar time frame at 47–46 Ma. Their emplacement coincides with an early pulse of Eocene magmatism elsewhere in the Trans-Pecos province, which is partly recorded by widely scattered mafic to intermediate hypabyssal intrusions that have isotopic dates of ~48–47 Ma (Henry and McDowell, 1986; Henry et al., 1986; Miggins et al., 2006). Compositionally variable basaltic lavas at or near the base of the Chisos Group were also extruded over wide areas to the south and west of our study area in the same time frame (Henry et al., 1989; Carman et al., 2003). These lavas (Alamo Creek Basalt and correlative units) have yielded $^{40}$Ar/$^{39}$Ar and conventional K–Ar dates of 47–46 Ma (Schucker and Nelson, 1988; Henry et al., 1989; Miggins et al., 2006). Our new age data extend the known distribution of hypabyssal intrusions related to this early, 48–46 Ma episode of Trans-Pecos magmatism.

Neither of the other two samples yielded a plateau. Sample D10 from the long trachyandesitic dike yielded an isochron date of 42.64 ± 0.91 Ma for all eight heating steps. This result is within error of the average date of 42.17 ± 0.16 Ma for steps 4 and 5 (Fig. 5C), which contain 60.5% of the total $^{39}$Ar released from the sample. We take the average date as the best estimate of the crystallization age of the rock. This result supports the interpretation of Henry et al. (1989, 1991) that the dike belongs to the Christmas Mountains dike swarm; dikes within the swarm farther west have yielded conventional K–Ar dates of ~44–40 Ma (Henry et al., 1989). We infer that the other east–northeast-trending dikes in the study area are also part of the Christmas Mountains swarm. Sample C15, from the Cottonwood Wash intrusion, has a somewhat more disturbed spectrum (Fig. 5D), but the data are consistent with emplacement of this intrusion at ~42.5–42 Ma. The similarity of this result to the date for sample D10 suggests that the Cottonwood Wash intrusion represents part of the same magma plumbing system as the east–northeast-trending dikes in the study area, although its geometric relations to those dikes are unclear because of the extensive Plio–Pleistocene cover in the area.

5. Field relations and styles of magma/sediment interaction

Hypabyssal intrusions in the study area are generally in contact with mudstone, although they also truncate sandstone interbeds in places. Dikes and sills have irregular contacts marked by fluidal, billowed margins and intrusive pillows (Fig. 6). Similar features have been described by other authors where magma has come in contact with wet, unconsolidated sediment (e.g., Kokelaar, 1982; Leat and Thompson, 1988; Kano, 1991; Walker, 1992; Kano, 2002; Lavine and Aalto, 2002; Németh and Martin, 2007). In the present study, billows are defined as smooth, ovoid or elongate, centimeter- to meter-scale undulations that curve outward from intrusive margins and are separated by cuspat e, sediment-filled invaginations (up to 50 cm deep in the largest billows). Intrusive pillows have bulbous or tubular forms with roughly elliptical cross-sections 0.2–3 m across and protrude from or occur near the parent intrusive body; pillows that appear
detached from the main body on two-dimensional outcrop surfaces may connect with it in three dimensions. We use the term peperite in the sense of White et al. (2000) and Skilling et al. (2002) to refer to a rock composed of intermixed igneous and sedimentary components that forms when magma is disrupted during interaction with unconsolidated, typically wet sediment. Terminology of different peperite types in general follows Busby-Spera and White (1987). In blocky peperite, the igneous component consists of angular clasts generated by brittle processes; jigsaw-fit texture between clasts is common and results from nonexplosive fragmentation of quenched magma (Skilling et al., 2002). Fluidal or globular peperite is used in cases where the magma forms centimeter- to decimeter-scale amoeboid, tongue-like, or globular bodies surrounded by sediment. In microglobular peperite, fine-scale fluidal bodies (≤1–2 cm across in this study) are more intimately intermixed with sediment. Igneous bodies in fluidal peperite may form by ductile tearing apart of magma or may be at least partly interconnected (e.g., Hanson and Hargrove, 1999); in the latter case, it may be inappropriate to refer to them as clasts. Along some intrusive contacts described in this paper, mudstone has been hardened by baking in zones ≤50 cm wide. The baking presumably occurred due to continued conduction of heat into the adjacent sediment, after features recording magma/wet-sediment interaction had formed.

5.1. Western intrusive complexes

The two intrusive complexes in the western part of the study area cut typical fluvial strata in the middle part of the Javelina Formation along subvertical contacts (Figs. 7 and 8). The host strata consist predominantly of color-banded mudstones, with less abundant, laterally discontinuous, lenticular sandstone interbeds from a few cm to ≤5 m thick. Pillowed basaltic intrusions are aligned along a

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**Fig. 8.** View looking southwest at main intrusive complex cutting mudstone and sandstone in Javelina Formation in western part of study area. Inclined pillowed sheet near intrusive complex is also indicated.

**Fig. 9.** Tape-and-compass map of main intrusive complex in southwestern part of study area. Location is shown in Fig. 7; view of complex is shown in Fig. 8.
northeast trend between the two complexes (Fig. 7) and presumably follow an underlying zone of structural weakness or a feeder dike.

5.1.1. Main intrusive complex

The most complex intrusive mass, which is shown in Fig. 8, is ~70 m across and consists of coherent to disrupted basalt (locally coarsening into diabase) and various clastic components (Fig. 9). Sample A2, which yielded an \(^{40}\text{Ar}/^{39}\text{Ar}\) average date of ~46 Ma, comes from typical coherent basalt. The basalt intrudes sandstone along sharp contacts lacking peperite, but intrusive pillows and peperite are well developed in areas up to several meters wide along basalt–mudstone contacts (Fig. 9). These areas contain ellipsoidal pillows ≤2 m across set within a matrix of microglobular peperite, in which basalt is thoroughly commingled with homogenized mudstone in a fluidal manner (Fig. 10). Numerous tendrils of mudstone ≤15 cm wide also penetrate well into the intrusion along irregular cooling fractures.

Along the northwestern edge of the complex, peperite or coherent basalt is in contact with a zone of strongly disrupted mudstone that contains discontinuous bodies of sandstone showing soft-sediment deformation, only the largest of which are depicted in Fig. 9. Basalt pillows are widely dispersed within this zone, but fine-scale peperite is lacking. Meter-scale patches rich in well-rounded pebbles and cobbles of sandstone, limestone, and chert ≤10 cm in diameter also occur within this zone. The same clast types are present over a larger area within disrupted mudstone near the southwestern edge of the complex (only partly shown in Fig. 9).

Three discrete masses of conglomerate within the intrusive complex (Fig. 9) contain identical sizes and types of pebbles and cobbles to those present in clast-rich areas in the marginal zones of disrupted mudstone. Bedding is absent in the conglomerate masses, and a structureless mudstone or sandstone matrix fills interstices between the pebbles and cobbles. Basalt forms closely packed to dispersed globular bodies 10–40 cm across intruding the conglomerate (Fig. 11), as well as larger, irregular tongues and centimeter-scale, angular to irregular fragments that locally show jigsaw-fit texture and are dispersed within the finer matrix between cobbles. The result is an unusual type of conglomerate-hosted peperite (cf., Squire and McPhie, 2002). In places, thin, interconnected basalt tendrils partly surround pebbles and cobbles, and the basalt incorporates some detrital clasts as xenoliths.

These conglomerate masses and the clast-rich areas within disrupted mudstone along the margins of the intrusive complex have strikingly similar clast populations to channel-lag conglomerate within the Eocene Hannold Hill Formation. This formation is exposed just beyond the eastern edge of the area shown in Fig. 2, but the present western limits of the unit are erosional, suggesting that it extended farther west. The combination of limestone and chert cobbles (without coarse volcanic detritus) is a particularly distinctive feature of Hannold Hill conglomerate (Beatty, 1992) and is not found lower in the stratigraphic section within the Tornillo basin (Lehman, 1988, 1991). Clast counts carried out on outcrops of the conglomerate masses within the intrusive complex and on typical Hannold Hill conglomerate outside the study area demonstrate the close similarity in clast types and proportions (Befus, 2006). Based on stratigraphic thicknesses given in Straight (1996) and Lehman and Coulson (2002) and uncorrected for compaction, the Hannold Hill Formation would have been ~400–500 m above the present level of exposure of the intrusive complex. Detailed mapping has revealed no evidence for

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**Fig. 10.** Microglobular peperite present along margin of main intrusive complex. Basalt is dark, host Javelina mudstone is white.

**Fig. 11.** Conglomerate-hosted peperite within main intrusive complex (b=intrusive amygdaloidal basalt bodies and clasts; c=pebbles and cobbles within conglomerate; Cc=calcite vein). Basalt bodies are outlined, as are some clasts in conglomerate.

**Fig. 12.** Inner peperite developed within main intrusive complex. Peperite is composed of basalt (dark) commingled with sediment-rich host (light grey), which also contains small, angular fragments of basalt. C=pocket of Hannold Hill conglomerate.
tectonic faults that could have juxtaposed parts of the Hannold Hill Formation against Javelina strata in this area. As discussed in more detail in Section 6, we infer that Hannold Hill conglomerate slumped downward from higher levels to become incorporated within the growing intrusive complex.

Another type of peperite (termed the "inner peperite" in Fig. 9) forms a domain surrounded by coherent basalt inside the intrusive complex. Basalt within this peperite domain occurs as meter-scale elongate tongues and intrusive pillows (Fig. 12), as well as coarse, angular to irregular clasts that show jigsaw-fit texture and are clearly derived from the larger basalt bodies. Areas of fluidal peperite exhibiting complex, small-scale intrusive relations occur in places between the larger tongues and pillows (Fig. 13). The basalt bodies are set within a light-colored, massive, sediment-rich host containing quartz, chert, and feldspar sand grains; small, subrounded clasts of mudstone; and less common, angular to fluidal, nonvesicular basalt clasts ≤ 1 mm to 5 cm across consisting of altered sideromelane and tachylite. All of these grains are chaotically dispersed in a structureless matrix of terrigenous mud and silt. Irregular pockets of Hannold–Hill-type conglomerate ≤ 1 m across are also present (Fig. 12). This sediment-rich host is texturally and compositionally unlike adjacent Javelina mudstones and sandstones and records thorough intermixing of finely fragmented basalt and terrigenous detritus prior to intrusion of basaltic magma to form the peperite. Clastic tendrils extending into coherent basalt from the peperite domain are filled with the same sediment-rich material that hosts the peperite. Similar material also forms larger clastic dikes cutting coherent basalt and the inner peperite (Fig. 9).

5.1.2. Associated pillowed intrusions

A pillowed sheet transgresses across Javelina strata to the southwest of the main intrusive complex, as shown in Figs. 7, 8, and 14. The map pattern in Fig. 14, in which three separate masses of basalt appear to be present, results from erosional breaching of a single sheet that has variable dips but is inclined toward the main complex. The sheet does not connect to the complex at the current exposure level but is lithologically identical to basalt in that complex. Intrusive pillows ≤ 3 m in diameter within the sheet are in direct contact or are separated by tendrils of mudstone, within which microglobular peperite is locally developed. Where exposure permits, some pillows can be seen to have tubular shapes with visible connections. Isolated pillows occur within disrupted mudstone near the margins of the sheet. Discontinuous, ellipsoidal pods of sandstone showing soft-sediment deformation are also present near the intrusive contacts (Fig. 14), as are areas of disrupted mudstone containing abundant pebbles and cobbles similar to those present in the conglomeratic domains within and around the main intrusive complex.

A smaller basaltic intrusion ~15 m long (labeled "P" in Fig. 7) cuts Javelina mudstone southwest of the inclined pillowed sheet. The intrusion has a highly irregular form, with tongues several meters long extending into the adjacent mudstone, and with intrusive pillows ~1 m in diameter present along the margins. The host mudstones are

Fig. 13. Small, irregular tongues of amygdaloidal basalt within sediment-rich host in inner peperite.

Fig. 14. Tape-and-compass map of inclined pillowed sheet extending from main intrusive complex (location shown in Fig. 7). Intrusive pillows are shown to scale.
disrupted and contain thin sandstone layers showing soft-sediment deformation, but no Hannold–Hill-type conglomerate is present in the zones of sediment disruption.

5.1.3. Second intrusive complex
Farther to the southwest, a zone of intensely disrupted Javelina Formation ~60 m wide is located along the same trend as the pillowed intrusions (Figs. 7 and 15). Three masses of basalt intruding mudstone in the northeastern part of this disrupted zone are composed of pillows 1–3 m across. Intrusive pillows are also dispersed in mudstone separating the larger basalt masses. Irregular masses of conglomerate inferred to be derived from the Hannold Hill Formation are in contact with the basalt and have clast proportions identical to the conglomerate associated with the other intrusive complex to the northeast. As in that complex, the basalt shows complicated intrusive relations with the conglomerate and forms ovoid, globular to amoeboid bodies or tongues down to 3 cm across penetrating between pebbles and cobbles (Fig. 16). Angular, centimeter-scale basalt clasts showing jigsaw-fit texture and derived by quench frag-

mentation of the larger bodies occur within the silty matrix of the conglomerate. The conglomerate has subvertical contacts with adjacent disrupted Javelina mudstone.

The zone of disrupted sediment around the intrusive basalt consists predominantly of mudstones that lack the bedding-parallel color banding typical of the Javelina Formation and instead show irregular, randomly arranged patches of variable color a few meters across, indicating that the original stratification has been destroyed. Sandstone interbeds within the disrupted zone typically form dispersed, detached masses ≤4 m across with variable dips, rounded to irregular margins, and internal convolute lamination. In the southern part of the disrupted zone, a more continuous sandstone layer partly wraps around the area of intrusive basalt (Fig. 15). Other sandstone masses, most of which are too small to show at the scale of Fig. 15, are also aligned in a roughly concentric pattern around the area of basalt intrusions and appear to be derived from originally continuous beds. Poorly exposed, discontinuous, elongate areas up to 10 m long that are rich in limestone and chert cobbles are dispersed within the disrupted zone and help to define its margin.

5.2. Eastern intrusive complex
Several irregular, closely spaced basaltic to diabasic intrusions with subvertical contacts occur within a roughly semicircular area ~250 m across in the Black Peaks Formation in the eastern part of the study area, where they hold up a small peak (Figs. 2, 17, and 18). Given their close proximity, the intrusions are almost certainly connected in three dimensions. Outside this intrusive complex, the host Black Peaks mudstones show a regular, bedding-parallel color banding that is truncated against the margins of the complex. In contrast, mudstone separating individual intrusive bodies inside the complex shows irregular color variations over distances of several meters, indicating thorough disturbance of this part of the sequence during basalt intrusion.

Maxwell et al. (1967) mapped the intrusions as two curved, dike-like masses, but our work reveals the more complicated map pattern shown in Fig. 17. The largest intrusive body contains a 5-m-thick tilted raft of cross-bedded, internally undeformed sandstone (Figs. 17 and 18). We infer that the raft is derived from parts of the Black Peaks Formation that were slightly above the present level of exposure; similar sandstone occurs in higher parts of the formation nearby. Intrusive contacts between the raft and adjacent basalt are covered by scree. A mass of Black Peaks mudstone also occurs within the.
Fig. 17. Tape-and-compass map of eastern intrusive complex. Location shown in Fig. 2. Contours in feet.

Fig. 18. View looking east at eastern intrusive complex cutting Black Peaks Formation. Tilted sandstone raft within intrusive complex is indicated; other high points within complex consist of basalt and diabase.
same intrusion to the east of the sandstone raft (Fig. 17). Near this mudstone mass, and in many other places within the intrusions, tendrils of mud up to 20 cm thick penetrate into the basalt along roughly hexagonal contraction cracks (Fig. 19). The sediment filling these tendrils is similar to that making up nearby Black Peaks strata. Some tendrils contain small pockets of blocky peperite derived from quench fragmentation of the adjacent basalt.

Sample B6, which yielded an $^{40}$Ar/$^{39}$Ar plateau date of ~47 Ma, comes from coherent basalt within a second large intrusive body (Fig. 17). A distinct peperite domain 20 m across near the margin of this second intrusive body is similar to the inner peperite within the main intrusive complex in the southwestern part of the study area (cf. Fig. 9). As in that example, intrusive pillows and coarse, angular basalt clasts are set within a sediment-rich host (Fig. 20) that is unlike the strata outside the intrusion. This host material has a muddy to silty matrix supporting quartz, feldspar, and chert sand grains and pebbles, as well as abundant, angular to fluidal, holocrystalline to originally glassy basalt particles ≤1 cm across. Most of the basalt particles are nonvesicular, but sparse clasts of highly vesicular tachylite are also present. Clastic tendrils up to 50 cm thick and filled with the same mixture of terrigenous sediment and finely fragmented basalt extend from the peperite into adjacent parts of the intrusion (Fig. 20).

Fig. 19. Mud-filled contraction cracks (outlined) in basalt near margin of discordant intrusion within eastern intrusive complex. Cracks are filled with brownish red mudstone (see color photograph in online version).

Fig. 20. Part of peperite domain in interior of discordant intrusion within eastern intrusive complex.

matrix supporting quartz, feldspar, and chert sand grains and pebbles, as well as abundant, angular to fluidal, holocrystalline to originally glassy basalt particles ≤1 cm across. Most of the basalt particles are nonvesicular, but sparse clasts of highly vesicular tachylite are also present. Clastic tendrils up to 50 cm thick and filled with the same mixture of terrigenous sediment and finely fragmented basalt extend from the peperite into adjacent parts of the intrusion (Fig. 20).

Fig. 21. View perpendicular to billowed margin of long, subvertical dike in southwestern part of study area. Billows are exposed where host mudstone has been eroded away. Hammer rests on remnants of baked mudstone not yet removed by erosion (labeled “B” and outlined by dashed line). Arrows point to invaginations filled with baked mudstone between billows.

Fig. 22. Geologic map of vertical to inclined dikes cutting Black Peaks Formation and exposed in steep valley in eastern part of study area. Thickness of dikes not to scale. Location shown in Fig. 2. Westernmost exposed dike changes into a sill to the east, as indicated.
5.3. Other dikes and sills

The long trachyandesitic dike cutting the Javelina Formation in the southwestern part of the study area, which yielded an $^{40}$Ar/$^{39}$Ar date of ~42 Ma, is 5–10 m thick and continues for another 6 km west of the boundary of Fig. 2. A sill several meters thick extends into the adjacent strata from one part of the dike (Fig. 2) but is heavily weathered. The dike is mostly in contact with baked mudstone but also cuts interbeds of fine- to medium-grained sandstone; features along intrusive contacts are similar in either case. Erosion of the weaker sedimentary rocks has left the dike standing as a prominent wall, resulting in excellent exposures of its margins. These margins exhibit well-defined billows that average ~1 m across (Fig. 21) and tend to be elongate parallel to the trend of the dike, with long axes up to 5 m. An altered, originally glassy chilled rind defines the outer surfaces of the billows. The glass has been replaced by extremely fine-grained zeolites and smectitic clays but retains the characteristic light-brown, transparent appearance of sideromelane in thin section. Cuspate invaginations filled with sediment between billows locally contain centimeter-scale pockets of blockly peperite. In places, intrusive pillows ≤1 m across extend for up to 6 m from the dike. Some pillows show tubular shapes in three dimensions, but connections with the dike are not exposed. Where billows and pillows rest against sandstone, bedding is homogenized within ~50 cm of the contact. A similar zone is not obvious in the mudstones because of their typically massive, poorly bedded nature.

Six vertical to inclined basaltic dikes intruding mudstone of the Black Peaks Formation are well exposed in a steep valley in the eastern part of the study area (Figs. 2 and 22) and, as discussed earlier, are assumed to belong to the same dike swarm as the dated trachyan- desitic dike to the southwest. Dike margins are again well exposed where the host sedimentary rocks have been stripped away by erosion. The dikes are 0.5–4.0 m thick, and sills extend from some dikes for several meters into the adjacent strata. Billows are present along vertical dike margins and along lower and upper margins of inclined parts of dikes and horizontal sills (Fig. 23). Some of the dikes have complex, irregular forms, as shown in Fig. 24, where a crook-shaped, sill-like apophysis can be seen to extend from the margin of a dike. Intrusive pillows occur near the apophysis. One margin of the

Fig. 23. Billowed margins on inclined basaltic dike intruding Black Peaks mudstone. Pencil rests on baked mudstone and points to lower margin of dike; upper margin is arrowed. Note baked mudstone (B) preserved between some billows.

Fig. 24. Irregular basaltic dike intruded into Black Peaks mudstone. Dike margin and intrusive pillows are outlined. Sill-like apophysis extends to left from main dike, which continues into cliff face beneath cover. Width of view is ~14 m. B=baked mudstone adjacent to dike. Location of Fig. 25 is indicated.

Fig. 25. A. Billowed margin of dike shown in Fig. 24. Third-order billows are superimposed on second-order billows. Invaginations between some second-order billows are dashed. B. Closer view of third-order billows in central part of area shown in panel A. B=baked mudstone in invagination between second-order billows.
The dike is well exposed (Fig. 24) and shows three orders of billows developed against adjacent baked mudstone, with smaller billows superimposed on larger billows. First-order billows are ~1 m across and are separated by cuspate invaginations up to 15 cm deep. Second-order billows are 10–30 cm across, and third-order billows are 5–10 cm across (Fig. 25A and B). A few bulbous to tubular basalt pillows ~30 cm across penetrate a short distance into the adjacent mudstone.

Another dike up to 4 m thick exposed in the same drainage shows a gradual decrease in dip until it changes into a sill before disappearing under cover. Billows similar to those described above are developed along the margins of the dike. Chilled, originally glassy margins on the billows are relatively well preserved in places and show millimeter-scale, fluidal “microbillows” (Fig. 26). In the outer part of the chilled margin, plagioclase microlites are set within slightly altered, yellow-orange palagonite (after sideromelane), which passes inward to nearly opaque tachylite (Fig. 26). Some of the plagioclase microlites have swallow-tail quench morphologies (Bryan, 1972). Farther in (not visible in the figure), the glass (altered to smectitic clays) becomes transparent again and decreases in amount until the rock becomes holocrystalline. The textural zonation is analogous to that present in the quenched rims of extrusive basalt pillows (e.g., Melson and Thompson, 1973; Kawachi and Pringle, 1988).

The billows become more pronounced and grade into intrusive pillows as the dip of the dike decreases. The associated sill consists predominantly of ellipsoidal pillows that are in direct contact, with cuspatate margins, or are separated by tongues of mudstone up to 20 cm across (Fig. 27). Highly irregular, fluidal contacts between basalt and mudstone are developed in places (Fig. 27). The pillows decrease in size toward the margin of the sill, and some smaller pillows are visibly connected to larger parent bodies (Fig. 28). Chilled margins on the pillows are defined by decrease in groundmass grain size and in size and abundance of amygdules. The margins likely consisted originally of sideromelane, although intense alteration to clay minerals obscures primary textures. Pockets of blocky peperite up to 0.5 m across occur between and adjacent to the pillows and contain altered, angular, consequent to irregular hyaloclastite shards set within disrupted mudstone (Fig. 29). The shards show jigsaw-fit texture, and some can be matched with broken parts of adjacent pillow rims.

5.4. Cottonwood Wash intrusion

The Cottonwood Wash intrusion forms a discordant basaltic mass exposed over an area of 60 m×15 m in the western wall of the wash (Fig. 2). The western margin of the intrusion is in contact with Javelina mudstone, but the other margins are covered by Recent alluvium, making the overall shape and dimensions of the intrusion unclear. Tongues of the host sediment ≤3 m long penetrate into the intrusion,
and microglobular peperite forms a zone up to 3 m across along the western intrusive contact. The peperite contains fluidal basalt particles ≤2 cm in size that are thoroughly intermixed with mudstone (Fig. 30) and consist of light-brown, altered sideromelane. The central part of the intrusion consists of holocrystalline basalt that in places exhibits only minor alteration; sample C15 (Figs. 4 and 5D) comes from this part of the intrusion.

6. Discussion

6.1. Formation of ~47–46 Ma intrusive complexes

As shown in Fig. 31, intrusive complexes cutting the Javelina Formation in the southwestern part of the study area are interpreted to represent diatreme feeders to small, maar-type Eocene phreatomagmatic volcanoes now eroded away (cf., Leat and Thompson, 1988; White, 1991). We infer that explosive interactions between rising basalt magma and groundwater-rich sediment excavated craters that initiated at shallow levels and migrated downward, based on standard models of maar formation (Lorenz, 1973, 1986). Detached masses of sediment, including Hannold Hill conglomerate, slumped progressively downward into the conduits as explosive activity continued (Fig. 31). The inferred vertical extents of the feeder conduits (Fig. 31) are well within range of those documented from known examples of maar/diatreme systems (e.g., Lorenz, 1973, 1975; Lorenz and Hanek, 2004).

Following Kokelaar (1983) and Leat and Thompson (1988), we envision the diatreme conduits to have been filled with a slurry of disrupted sediment, shattered basalt, steam, and condensed water during explosive phreatomagmatic activity (see also McClintock and White, 2006; Ross and White, 2006). Remnants of this phreatomagmatic slurry are probably represented by the finely intermixed sedimentary and basaltic debris that hosts intrusive basalt bodies in the inner peperite within the complex shown in Fig. 9. Strata along conduit margins were intensely disrupted, as is particularly well displayed in the second intrusive complex (Fig. 15). Disrupted strata from adjacent parts of the Javelina Formation contain pockets and stringers of Hannold Hill conglomerate, indicating intermixture between poorly consolidated strata forming the conduit walls and sediment that had slumped downward from higher levels. Sediment disruption and mixing are inferred to be the result of repeated shock waves affecting heated, partly liquefied or fluidized mud, sand, and gravel, coupled with failure of unstable conduit walls as material was explosively excavated from lower levels (e.g., Lorenz and Kurszlaukis, 2007). Cobbles derived from Hannold Hill conglomerate are also intermixed with mudstone along the margins of the inclined pillowed basaltic sheet extending to the southwest from the main intrusive complex. We interpret the disrupted sediment in this area to represent a blind apophysis injected laterally into the host Javelina strata from the zone of sediment disruption and intermixing within and along the margins of the main conduit.

Coherent to pillowed basalt was emplaced as magma continued to rise within the conduits at the close of explosive activity, when much of the groundwater driving the eruptions had been consumed. Peperite formed as the magma interacted with the phreatomagmatic slurry remaining within the conduits and with adjacent, still wet Javelina strata. Magma also intruded along the apophysis of disrupted sediment extending southwest from the main intrusive complex to

Fig. 30. Photomicrograph of microglobular peperite developed along western margin of Cottonwood Wash intrusion. Altered sideromelane (dark) contains plagioclase micro-lites and carbonate-filled amygdules and shows fluidal contacts against Javelina mudstone (labeled S). Plane light; width of view is ~5 mm.

Fig. 31. Model for formation of diatreme root zones exposed in southwestern part of study area. Generalized thicknesses of strata from Beatty (1992), Straight (1996), and Lehman and Coulson (2002). Present erosional level is indicated.
form the tabular pillowed sheet in that area. A comparable sequence of events has been documented from other exposed feeders to phreatomagmatic volcanoes, which in some cases exhibit similar types of peperite and/or pillowd intrusions that formed during closing stages of activity (e.g., Hanson and Elliot, 1996; White and McClintock, 2001; Martin and Németh, 2007; Németh et al., 2007).

McClintock and White (2006) have suggested that peperitic textures may form within volcanic vents where magma intrudes rock that has been disaggregated by explosive shocks or other processes. In the present case, complex, fine-scale intrusive relations between chilled magma and sediment (e.g., Fig. 10), as well as development of typical intrusive pillows, are more consistent with injection of magma into sediment that still retained sufficient pore water to quench the magma. Thin tendrils filled with mudstone or phreatomagmatic slurry and extending for several meters along contraction cracks into coherent basalt adjacent to peperite domains (Figs. 9, 17, 19, and 20) are also consistent with fluidization of wet sediment during peperite formation (e.g., Kokelaar, 1982; Hanson and Wilson, 1993). Discrete clastic dikes cutting coherent basalt (Fig. 9) appear to record injection of fluidized slurry from deeper levels, during final stages of explosive magma–sediment interaction.

Diatremes beneath subaerial phreatomagmatic volcanoes typically comprise three zones (Lorenz, 1986; White, 1991; Lorenz and Kurszlaukus, 2007; and references therein). The upper diatreme consists of bedded tephra that was deposited within the associated crater or has subsided into the diatreme from higher levels. This zone passes into the lower diatreme, which is characterized by the presence of massive or chaotic tuff breccia recording repeated explosions and recycling of clasts back into the conduit. The diatreme root zone represents the transition between coherent hypabyssal intrusive rock and brecciated material generated by subsurface explosions; large fragments of material derived from higher levels may occur both in the lower diatreme and the root zone (e.g., White, 1991). According to this standard model, the two intrusive complexes cutting the Javelina Formation in the southwestern part of the study area appear to expose parts of the lower diatreme and underlying root zone (Fig. 31), although evidence for explosive stages in diatreme development has been obscured by late-stage emplacement of basaltic magma into the conduits.

The intrusive complex cutting the Black Peaks Formation in the eastern part of the study area may represent part of a diatreme feeder to a third maar-type volcano. In this interpretation, the steeply dipping sandstone raft possibly was derived by downward slumping from higher parts of the diatreme. Intermixed sediment and finely fragmented basalt forming the host to the peperite domain within one of the intrusive bodies within the complex may represent remnants of phreatomagmatic slurry generated during explosive activity. Intrusion of coherent basalt would have occurred following explosive phreatomagmatism, representing a similar sequence of events to that inferred for the western intrusive complexes. An alternate interpretation is that the sandstone raft is derived by stoping of part of the roof of an intrusion that did not connect to a surface vent. In this scenario, remnants of phreatomagmatic slurry within the intrusive system would record localized, subterranean explosive magma/wet-sediment interaction that never vented to the surface (cf., Ross and White, 2006).

6.2. Nonexplosive magma/wet-sediment interaction associated with ~42 Ma intrusions

Other intrusions in the study area, two of which yielded 40Ar/39Ar dates of ~42 Ma, also show abundant evidence of interaction with poorly consolidated sediment containing significant amounts of pore water. In contrast to the earlier episode of intrusive activity, there are no indications that explosive phreatomagmatic processes played a significant role in mingling of magma and sediment.

All dikes associated with this intrusive episode show billowed margins against the adjacent sediment. Some dikes have typical tabular forms, but others exhibit pronounced irregularities in morphology that appear to record foundering of magma into weak, low-density sediment (Fig. 24). Billows on vertical dike surfaces or on the upper surfaces of inclined sheets or sills cannot be caused by gravitational loading. They must instead result from other types of surface instabilities that develop along interfaces between fluids with different material properties, such as Rayleigh–Taylor or Kelvin–Helmholtz instabilities (Pollard et al., 1975; Wohletz, 1986; Zimanowski, 1998; Lavine and Aalto, 2002). Quenched glassy margins on billows have similar textures to those shown by rims of extrusive pillow lavas, indicating rapid cooling in contact with water-rich sediment.

Billows appear to be a precursory stage to the development of intrusive pillows. We infer that outward-directed magma pressure caused accentuation of some surface instabilities, leading to propagation of pillows into adjacent sediment (e.g., Kano, 1991). Initial stages of magma/wet-sediment interaction at shallow levels in the subsurface are generally thought to involve formation of a film of vaporized pore water in the sediment adjacent to intrusive contacts (Kokelaar, 1982; Wohletz, 2002). The insulating effects of this vapor film are likely to be important in the formation of billows and intrusive pillows and allow the magma to develop complex fluidal contacts against sediment without undergoing significant quench fragmentation or explosive disruption. Propagation of pillows away from intrusive margins was probably facilitated by loss of cohesion and yield strength in host sediment fluidized by rapid migration of heated pore fluids along intrusive contacts (Kokelaar, 1982). Homogenization of bedding in sandstone in narrow zones against billows and intrusive pillows at the margins of the long trachyandesite dike provides evidence for this process (cf., Kokelaar, 1982; Busby-Spera and White, 1987; Hanson and Hargrove, 1999). However, because of the typically poorly bedded nature of the mudstone in the study area, we have been unable to recognize similar destruction of bedding along most of the studied intrusive contacts.

Peperite may have developed along intrusive margins when the insulating vapor film became unstable during rapid heating of pore fluids, as described by Wohletz (2002), or when the chilled margins were disrupted by dynamic stressing due to surges in magma supply (e.g., Goto and McPhie, 1996). Factors controlling the development of fluidal versus blocky peperite in the present case are unclear. There is no obvious relation between different peperite types and either magma composition (e.g., Dadd and Van Wagoner, 2002) or physical properties of the host sediment (Busby-Spera and White, 1987; Martin and Németh, 2007).

7. Conclusions

Detailed study of mafic to intermediate Eocene intrusions within a restricted part of the Trans-Pecos igneous province has revealed a range of features associated with magma/wet-sediment interaction. Basaltic intrusive complexes emplaced at ~47–46 Ma are inferred to represent diatreme feeders to maar volcanoes, recording explosive phreatomagmatic eruptions during initial stages of Cenozoic volcanism in this part of the Trans-Pecos province. Small, monogenetic volcanoes of this type commonly occur in clusters, making it likely that more such diatremes remain to be discovered in the region.

Slightly younger intrusions with 40Ar/39Ar dates of ~42 Ma developed billowed margins, intrusive pillows, and peperite against wet, un lithified sediment. These features provide insight into nonexplosive processes occurring during injection of magma into unconsolidated strata in the shallow subsurface. The intrusions preserve stages of coarse mixing that may culminate in explosive fuel-coolant interactions (e.g., White, 1996; Wohletz, 2002), although the lack of evidence for explosive activity associated with these intrusions suggests that sufficient volumes of finely disrupted magma
and wet sediment were not brought together in appropriate time frames to generate subsurface phreatomagmatic explosions. Barker (2007) noted the presence of peperite developed between Cenozoic basalt and benmoreite dikes and strata in the Chisos Group and parts of the underlying Upper Cretaceous succession to the south of our study area. Associated peralkaline rhyolite dikes developed fluidal contacts against unconsolidated sediment, forming features somewhat similar to those described along dike and sill margins in the present paper. Further study of hypabyssal intrusions in other parts of the province is likely to reveal additional examples of similar phenomena. The Trans-Pecos province thus could become an important locale for the study of nonexplosive to explosive processes of magma/sediment interaction.

Evidence presented in this paper requires that Upper Cretaceous to Paleocene strata in the Javelina and Black Peaks Formations remained unconsolidated into the Eocene. Neither formation was deeply buried, which would have played a role in delaying their lithification (note that much of the Chisos Group and Canoe Formation shown in Fig. 3 had not yet accumulated when the Eocene intrusions were emplaced). Moreover, this part of Texas during much of the Eocene was characterized by an equable, temperate climate with significant annual rainfall (e.g., Roth, 1984; Collinson and Rohr, 1986; Westgate and Gee, 1990). Thus, shallow levels beneath the surface are likely to have been rich in groundwater during Eocene magmatism, allowing formation of a range of features recording different styles of magma/wet-sediment interaction.

Intrusive pillows and blocky and fluidic peperite occur along contacts between Eocene intrusions and strata ranging in age from Maastrichtian (Javelina Formation) to Eocene (Hannold Hill Formation). Based on age ranges for the host strata shown in Fig. 3 and the 40Ar/39Ar dates reported herein for the Eocene intrusions, Javelina strata must have remained unconsolidated and rich in pore water for ~20–25 Ma prior to Eocene intrusive activity. This finding conflicts with a typical assumption in the literature that formation of peperite requires broadly contemporaneous sedimentation and magmatism. In cases where clastic and tectonic controls allow sequences of sediment to remain un lithified for long periods, the time span between sedimentation and peperite formation must be resolved by independent age constraints.

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