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EARLY TRANS-PECOS MAGMATISM: PETROLOGY AND GEOCHEMISTRY OF EOCENE INTRUSIVE ROCKS IN THE EL PASO AREA

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Abstract—Hypabyssal dikes, sills and plugs that crop out in the vicinity of El Paso, Texas are one of the earliest manifestations of Trans-Pecos magmatism. These porphyritic rocks of trachyandesite composition intrude Lower Cretaceous rocks and have been dated at 47–48 my. They are a comagmatic series that possibly represent part of the roof zone of a caldera-sized pluton. The trachytic liquid component of these rocks evolved from a more basic parent magma by fractional crystallization involving amphibole and plagioclase at deeper levels in the crust. Ubiquitous enclaves of diorite, monzonite and quartz diorite appear to represent cognate xenoliths associated with this fractionation. Enclaves of deformed anorthosite may be xenoliths of lower crustal material. Similarities in the texture, mineralogy, enclaves and major and trace element compositions of these rocks indicate that they are co-magmatic. Though contamination by Cretaceous country rock material is minimal, phenocryst zoning patterns reflect changes in liquid composition by crustal assimilation or magma mixing. Distinctive incompatible trace element compositions are also indicative of an origin in an orogenic environment. The elements Rb, Ba, Cs, Sr and LREE are especially enriched in these rocks relative to MORB's, and suggest source material with a MORB-like composition enriched in these hygromagmatic components. These rocks locally intrude post-Laramide high-angle faults, indicating a coincidence between this early phase of Trans-Pecos magmatism and a change in the local stress regime.

INTRODUCTION

A series of small post-Cretaceous intrusive bodies crop out in the vicinity of the New Mexico, Texas and Mexican borders in and around the cities of El Paso, Texas and Juarez, Mexico. The intrusions are dikes, sills and plugs that intrude lower Cretaceous rocks over a distance of 40 km in a north-south direction. These intrusive bodies straddle the enigmatic Texas lineament (Muehlberger, 1980). Rocks comprising these bodies are all composed of texturally similar medium-grained porphyritic rocks that also have a similar appearance in the field. Owing to their megascopic similarities, Hoffer (1970) regarded most of these rocks as andesitic in composition based on his reconnaissance study of the largest of these bodies, the Campus Andesite. It has since been generally assumed by most workers in the region that all these rocks are similar in composition and age. However, unpublished major element analyses of samples from two of these bodies are the only data known apart from the reconnaissance work of Hoffer (1970) and Chavez (1986). The age of this magmatism has been based on a single K-Ar biotite age of 47.1 my from an altered sample of the Campus Andesite reported by Hoffer (1970). These rocks, therefore, appeared to represent the only manifestation of magmatism in the region at that time. Because the area is in a tectonically key region associated with the Rio Grande rift, the Basin and Range and the Trans-Pecos magmatic belt, the tectonic implications of this period of magmatism are unclear and require additional information on the geochemistry and age of these rocks.

In this paper, we present the results of preliminary work on the rocks from eight localities in the El Paso area. From north to south, these intrusion localities are: the Three Sisters intrusion (ATHERS), Colorado intrusion (ACORN) and Thunderbird intrusion (THA) in the northwestern part of El Paso; the University Plaza (UNIPA), Campus Andesite (CAMPA) and Cerro de Cristo Rey (CRIST) localities in the vicinity of the University of Texas at El Paso campus; and the Sierra de Juarez (SDJ, HD and TAB) and Sierra de Sapello (CR and SM) localities south of El Paso (Fig. 1).

The major trace element compositions of samples from these localities are presented together with compositions of constituent minerals from three of the plutons and a new K-Ar age for relatively fresh dike samples from the Sierra de Juarez locality. These data provide the first comprehensive report on the petrology, geochemistry and tectonic implications of these alkali-calcic igneous rocks. Throughout the text of this report, these rocks are often referred to as being "andesitic." None of these rocks are volcanic, and the use of this term is intended only to connote compositional affinities.

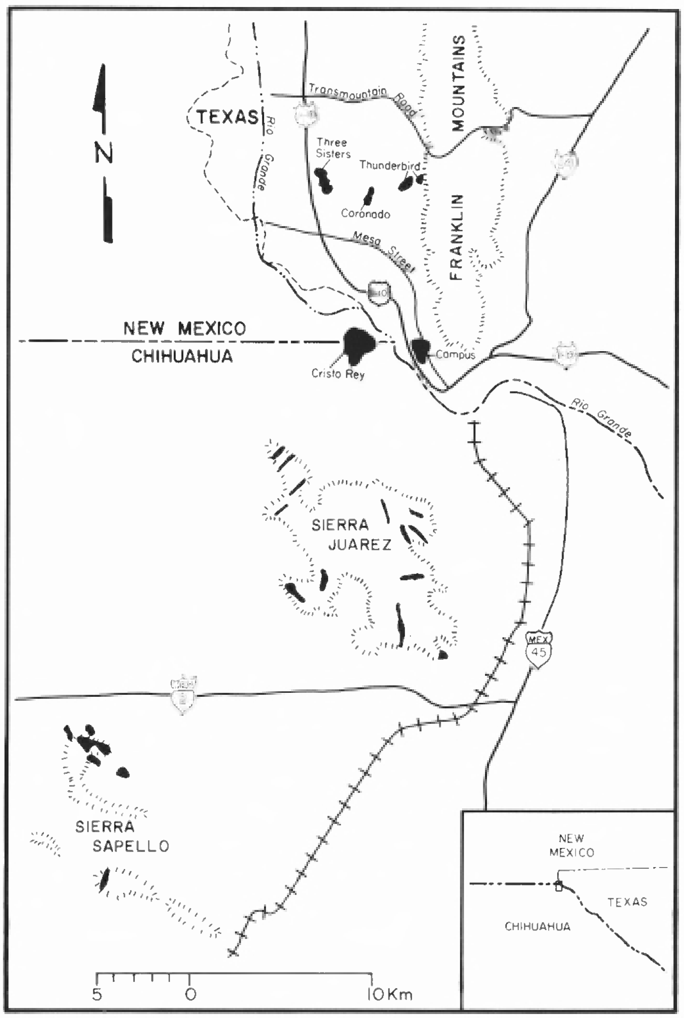

FIGURE 1. Sketch map of the El Paso area indicating outcrop localities of dikes, sills and plugs in black. The University Plaza site (not labeled) is located in the northeastern corner of the Campus Andesite body.

ANALYTICAL METHODS

Analytical data presented here were obtained using a combination of WDS electron microprobe methods and instrumental neutron activation methods. Bulk rock analyses were performed only on the freshest parts of samples free of weathered surfaces, hammer or crusher marks. Samples were prepared by breaking large pieces with a rock hammer and crushing selected parts to a size suitable for grinding to powder in a ceramic ball mill. About 500–800 mg of each powder was analyzed for trace elements by INAA. About 250 mg of each powder were rapidly fused in air at 1350°C for up to one hour and quenched in water. Samples fused completely to glass were analyzed for major elements with the electron microprobe at Southern Methodist University, as were minerals in polished thin sections of selected samples. Neutron activation analysis was performed using the INAA facility at the University of Texas at El Paso using a modified version of the TEABAGS data reduction method. Modal data represent point counts on a minimum of 1000 points.

K-Ar ages were determined by the staff of the United States Geological Survey, Isotope Geology Branch through the courtesy of Harold Drewes. Dated material consisted of biotite concentrate containing 8.73 wt% K_2O that yielded 6.139×10^{-10} moles/gm radiogenic Ar (81% Ar^{40}) and a Ar^{40}/K^{40} ratio of 2.84×10^{-3}.

FIELD RELATIONS

The intrusive rocks in the El Paso area intrude Lower Cretaceous sedimentary rock of the Cristo Rey Group and are only seen where these sedimentary rocks are exposed above Quaternary lacustrine and alluvial deposits on pediment surfaces and in topographically high ranges. These igneous rocks crop out as isolated dikes, sills and plugs that collectively form a narrow zone less than 10 km wide that extends from the western flank of the Franklin Mountains to the Sierra de Sapello 30–40 km to the south and southwest (Fig. 1). In the northern part of this zone the bodies occur as sills or split sills less than 0.16 km^2 in areal extent and range in thickness from 35 m to over 100 m. The Campus Andesite and Cerro de Cristo Rey intrusions are the largest of the exposed bodies. The Campus Andesite is a lobate body with an areal extent of about 5.2 km^2 (Hoffer, 1970) and a minimum thickness of 100 m, although its form is difficult to discern. The Cerro de Cristo Rey body, located west of the Campus Andesite astride the Texas-New Mexico-Mexico borders, has an outcrop area of about two km^2 and an exposed thickness of at least 225 m. Lovejoy (1976) presumed its shape to be laccolithic in form; however, more recent investigations (Ensenat et al., 1987) find that it is a plug-like body. In the Cerro de Cristo Rey body, crystals oriented roughly parallel to the intrusive contact in places impart an igneous lamination to the rock in outcrop. Quaternary lake deposits and eolian sand veneer most of the area for about 10 km south to the Sierra de Juarez, where northeast-trending sills and northeast-trending dikes up to 30 m thick intrude thrusted blocks of structurally higher Cretaceous sediments. The largest sill in the southeastern part of the Sierra de Juarez is cut by a north-northeast-trending normal fault. Dikes are continuous across thrust surfaces at all structural levels. Dikes in the northwest part of Sierra de Juarez commonly intrude along northeast-trending normal faults which cut and displace thrust surfaces. No brecciation or slickensided surfaces have been noted in these northeast-trending intrusives, suggesting that dike emplacement postdates an early Tertiary episode of northwest-southeast extension. In the Sierra de Sapello, 10–15 km southwest of the Sierra de Juarez, the intrusive rocks occur as sill-like bodies and dikes which intrude them, that range up to 30–50 m in thickness.

The intrusive rocks are typically exposed as topographically high features that stand out above the Quaternary sediments except where they occur as dikes in Cretaceous carbonates. There they tend to weather more readily than carbonates, and form topographic low areas and gullies. In general, the larger bodies are the most extensively altered. Few, if any, samples from the Campus Andesite or Cerro de Cristo Rey bodies are completely free of alteration; conversely, the dike rocks tend to be the least altered. In outcrop, these rocks appear light gray to yellow-brown on weathered or altered surfaces, and gray to black on fresh surfaces of some dikes. At least part of this color difference may also be attributed to variation in the modal proportions of phenocrysts, as well as to extent of alteration.

Samples from all eight localities are medium-grained porphyritic rocks with essentially the same mineralogy. Plagioclase, amphibole and biotite phenocrysts are ubiquitous to all specimens, though most of the felsic groundmass components cannot be distinguished with the naked eye. One of the main megascopic differences between these rocks, apart from those related to alteration, is in the proportions of the phenocrysts. The total fraction of phenocrysts and the relative proportions of the individual phenocryst constituents vary within individual bodies (cf. Hoffer, 1970) and also among the various intrusive bodies.

Each of the intrusions examined contains one or more types of enclave. We use the term enclave here to refer to rock types texturally or mineralogically distinct from, and clearly surrounded by, the host, without genetic implications. The enclave types include fine-grained monzodiorite, porphyritic trachyandesite, diorite and a suite of distinctive coarse-grained anorthositic to gabbroic samples. This material ranges in size from individual crystals to subrounded blocks less than a meter in diameter. Xenoliths of host Cretaceous sedimentary rocks are also present but are rare and largely restricted to intrusion margins. The results of a detailed mineralogical and geochemical study of the enclaves will be presented elsewhere (Ensenat and Barnes, in progress). The dominant enclave types, however, are briefly described in a later section.

GEOCHRONOLOGY

The only radiometric age previously determined for these post-Cretaceous intrusive rocks was that made by F. E. Kottlowski and reported by Hoffer (1970). Biotite in a single sample from the center of the Campus Andesite pluton was analyzed, and the resulting K-Ar biotite age was 47.1 ± 2.3 my. As with chemical composition, this age has been used as a reference for the El Paso area "andesites" in general. The validity of this age determination was questioned, however, because essentially all samples of Campus Andesite exhibit evidence of hydrothermal alteration and, therefore, potential radiogenic argon loss. Although the alteration appears to have affected the groundmass preferentially, a confirming age had not been obtained for these rocks. It was also determined that biotite in the Campus Andesite, Cerro de Cristo Rey and in the Coronado Andesite bodies was not stoichiometric with respect to potassium.

Through the courtesy of Harold Drewes and the Isotope Geology Branch of the United States Geological Survey, we report a new K-Ar biotite age on material from a dike in the Sierra de Juarez. The age of this analyzed dike is 48.2 ± 1.7 my (2σ), and within analytical uncertainty, is consistent with the biotite age reported by Hoffer (1970). It is indicated from these two ages that if the biotite ages are representative, the magmas that gave rise to the dikes in the Sierra de Juarez were contemporaneous with those that formed the Campus Andesite. Additional dates will be required to confirm these ages.

Fission-track ages on apatites separated from a sill of biotite andesite porphyry and from a cross-cutting dike from the Sierra de Sapello were reported by Chavez (1986) to be 64 ± 2–3 my and 62 ± 2 my, respectively. These ages have not been confirmed radiometrically, however, and their reliability is not known at this time. It is also probable that some or most of the apatite in these rocks could be xenocrystic owing to the abundance of apatite in anorthositic enclaves. Although the fission track blocking temperature for apatite is relatively low, the thermal history of apatite in the enclaves is unknown. More credence is, therefore, given to the radiometric ages at this time. Whether the age of one or more of these bodies can be assumed to be representative of other bodies in the group depends on whether they can be demonstrated to be genetically related. This possibility is addressed in the following sections.

PETROGRAPHY

Host rock

The alkalic-calcic intrusive rocks in the El Paso area generally contain similar types of phenocrysts and groundmass minerals. However, the size and proportions of minerals vary between and within localities.

TABLE 1. Modal proportions (volume %) of constituent minerals in El Paso area intrusive rocks.

	PHENOCRYSTS						GROUNDMASS	SECONDARY MINERALS (qtz, calcite, zeolite)
	PLAGIOCLASE	AMPHIBOLE	BIOTITE	FE-TI OXIDE	APATITE	QUARTZ		
LOCALITY								
Coronado	21.8	14.5	1.6	0.9	0.2	0.0	59.9	1.1
Three Sisters	27.7	9.0	2.5	0.9	0.1	0.0	60.0	tr
Sierra de Sapello	28.0	13.0	2.5	0.1	0.2	0.0	54.6	1.6
Sierra de Cristo Rey	33.7	11.9	3.4	1.5	0.3	0.8	48.5	0.0

Modal determinations are reported in Table 1, and some representative phenocryst compositions are given in Table 2. All of the analyzed samples are porphyritic-glomeroporphyritic and contain phenocrysts set in a fine-grained groundmass that is intergranular to microgranular or subtrachytic. The ubiquitous phenocryst phases are plagioclase, calcic amphibole and biotite. Quartz, magnetite, ilmenite and apatite occur as microphenocrysts and also as phenocrysts in some samples. Plagioclase also forms glomeroporphyritic clusters containing grains as large as five mm in diameter. In hand specimen, the proportions of phenocrysts are estimated to range from 30–60%, and the measured modes on six specimens (Table 1) largely support this estimate. Where it is not altered to an indiscernible mass, presumably of clay minerals, the groundmass consists of plagioclase, alkali feldspar, quartz, biotite, oxide minerals and apatite, with subordinate amounts of zircon and sphene. In the Three Sisters intrusion, amphibole is also a groundmass mineral, though rod-shaped clinopyroxene locally occurs in place of amphibole. Plagioclase phenocrysts enclose euhedral amphibole and biotite phenocrysts in all these rocks. In samples from the Three Sisters locality, plagioclase also encloses magnetite, ilmenite and short acicular apatite, and in University Plaza and Sierra de Juarez samples it also includes rare zircon. Biotite phenocrysts in samples from Cerro de Cristo Rey are also seen to include magnetite and apatite. Amphibole phenocrysts in the Coronado Intrusion contain abundant inclusions of apatite, ilmenite and magnetite.

Plagioclase phenocrysts are typically strongly zoned euhedral to subhedral grains ranging up to five mm in length. Most display oscillatory zoning and at least one prominent compositional reversal. The reversal is typically near the core of grains, and the cores are typically rounded. The cores are unzoned with compositions that range from An_{45} in the Coronado Intrusion, An_{39-41} in the northern end of the Campus Andesite (University Plaza locality) and to An_{30} in the Three Sisters, Sierra de Juarez dikes and Sierra de Sapello intrusives. In the Coronado Intrusion, the large plagioclase phenocrysts have a resorbed mantle ($\approx An_{54}$) surrounding the unzoned cores and a wide, oscillatory-normally zoned rim ($\approx An_{36}$). The rims in samples from other localities (e.g., Cerro de Cristo Rey, University Plaza) range to compositions as sodic as An_{10-15}.

The calcic amphibole phenocrysts are euhedral to subhedral tschermakite to tschermakitic hornblende ($Mg/(Mg+Fe^{2+})=0.52–0.82$) that range from 1–5 mm in length. The amphibole locally displays slightly resorbed cores, as in University Plaza samples and as many as four distinct zones that range from tan-brown cores, to olive-green rims in samples from the Three Sisters. Some of these crystals are rimmed with a fine-grained, magnetite-rich corona. In one dike sample from Sierra de Juarez, the amphibole has been largely replaced by a fine-grained aggregate of iron oxide, plagioclase, quartz, calcite and hydroxide minerals. Biotite phenocrysts occur as euhedral to slightly ragged grains measuring up to two mm across. They vary in color from brown to reddish brown to yellow and have brown to tan pleochroism.

Enclaves

Monzodiorite

These enclaves are composed primarily of fine- to medium-grained calcic amphibole together with plagioclase, alkali feldspar, ± biotite. Accessory minerals include magnetite, rare zircon and equant to elongate apatite. Most of the amphiboles are zoned and have resorbed cores. These enclaves have spheroidal outlines in cross section and are commonly rimmed by a thin biotite-rich zone. The spheroidal form of these enclaves suggests that they are the result of magma mixing or mingling, although these possibilities require further study. Enclaves of this type are especially abundant in the Cerro de Cristo Rey intrusion.

Diorite

This enclave type is less common and consists of fine- to coarse-grained diorite composed of plagioclase, calcic amphibole and biotite with accessory amounts of magnetite, ilmenite and apatite. Most of the amphibole crystals have partially resorbed cores and contain inclusions of biotite and apatite.

TABLE 2. Major element compositions of constituent minerals in El Paso area intrusive rocks.

	PLAGIOCLASE PHENOCRYSTS			GROUNDMASS PLAGIOCLASE			BIOTITE		AMPHIBOLE			MAGNETITE	SPHENE
SAMPLE: (wt% Oxide)	UNIPA	CRIST-3	CRIST-1	UNIPA	CRIST-3	CRIST-1	CRIST-1	CRIST-3	CRIST-3 (low Fe)	CRIST-3	UNIPA n pl pheno)	CRIST-3	CRIST-3
SiO2	56.45	59.31	60.49	63.04	64.84	67.45	35.35	34.80	44.16	43.51	39.55	0.04	30.04
TiO2	0.03	0.00	0.00	0.01	0.01	0.00	3.78	3.83	1.67	1.82	1.72	1.32	32.31
Al2O3	26.23	24.91	23.77	21.22	20.09	19.66	14.99	15.55	11.03	11.08	14.16	0.55	3.70
FeO	0.20	0.17	0.12	0.20	0.27	0.15	13.78	11.53	6.84	11.12	16.08	90.38	2.38
MnO	0.05	0.01	0.04	0.00	0.02	0.00	0.29	0.16	0.09	0.29	0.41	0.38	0.04
MgO	0.04	0.00	0.01	0.02	0.02	0.05	15.16	17.83	17.50	13.90	9.86	0.13	0.02
CaO	7.72	6.54	5.19	2.84	1.71	1.69	0.58	0.36	10.96	10.15	9.50	0.02	25.50
Na2O	6.14	7.05	7.82	9.09	9.94	9.15	0.47	0.42	2.50	2.32	2.68	0.01	0.04
K2O	0.19	0.38	0.60	0.59	0.71	1.09	6.98	6.83	0.79	0.75	0.71	0.00	0.06
P2O5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BaO	0.05	0.12	0.16	0.20	0.10	0.17	1.33	1.11	0.08	0.09	0.07	0.08	0.20
Total	97.10	98.49	98.20	97.21	97.71	99.41	92.68	92.42	95.62	95.03	94.74	92.91	94.29
Mg/(Mg+Fe)							66	73	82	69	52		
mole% An	41	34	27	15	9	9							

Quartz diorite

Enclaves of this type occur as a subordinate variety in the Coronado intrusion. They consist of a hypidiomorphic granular arrangement of plagioclase, calcic amphibole, biotite and quartz. Accessory minerals include apatite, sphene, ilmenite, magnetite and zircon. In outline, these enclaves have a knobby appearance owing to protrusion of plagioclase crystals into the host. Plagioclase crystals are undeformed subhedral grains with oscillatory-normal zoning (An_{37}–An_{20}) and a single reversal in the outer core. Dark green amphibole is largely replaced by biotite ± chlorite. Anhedral quartz occurs in interstitial pools and is partially resorbed. The lack of deformation, the presence of fine-grained interstitial material and the shape of the enclave-host contact suggest that this enclave type is the result of an earlier period of crystal accumulation.

Anorthosite

Anorthositic material comprises the bulk of the enclaves in the Three Sisters intrusion and is a common member of enclave suites in the Cerro de Cristo Rey and Coronado bodies. These enclaves have sharp, angular contacts with their host and range in size from single crystals up to 20 cm in diameter. They are generally coarse grained and have xenomorphic granular textures. Most are composed of weakly normally zoned plagioclase (cores $\approx An_{50}$), calcic amphibole, ± biotite, ± interstitial pale-green clinopyroxene. The accessory minerals include apatite, interstitial pools of ilmenite and, in samples from the Coronado locality, sphene with inclusions of ilmenite. The plagioclase in these rocks typically has sutured contacts with adjacent plagioclase crystals. This feature together with the commonly bent twin lamellae and intricate albite and pericline twin sets suggest that these enclaves underwent protoclastic deformation. This type of high-temperature deformation is especially pronounced in clinopyroxene-bearing enclaves in which trails of granular anhedral clinopyroxene mark healed fractures in the crystals. Many of the amphiboles have cores charged with minute inclusions of opaque minerals, suggestive of moderate- to low-temperature oxidation. The sharp, angular contacts between enclaves and host and textural features indicative of high-temperature deformation indicate that the anorthositic enclaves are xenoliths unrelated to differentiation of the host magmas. Moreover, ilmenite is the only Fe-Ti oxide mineral in these enclaves, whereas the hosts contain magnetite and ilmenite; a feature possibly indicative of a relatively reducing environment for crystallization of the anorthositic material (Ensenat and Barnes, work in progress).

BULK-ROCK COMPOSITION

Major elements

Major element compositions of samples from each of the eight localities (Table 3) are broadly similar. Compositional distinctions within the group can be related to crystal fractionation and/or crystal accumulation. The bulk-rock compositions of these rocks range from high-silica andesite to trachyandesite. This terminology is a more accurate classification than "andesite." Representative samples of the El Paso area intrusive rocks all have quartz-normative compositions and contain 55–66 wt.% SiO_2, 1.3–5 wt% K_2O and 2.3–5.2 wt% Na_2O.

The composition of these rocks displays largely continuous major element trends in plots of SiO_2 versus other oxides (Fig. 2), as well as systematic variations among these trends. The contents of TiO_2, FeO, MgO and CaO correlate negatively with increasing SiO_2, but ratios of the Na/Ca and mg# (i.e. $Mg/[Mg+Fe^{2+}]$) remain relatively constant over the range of SiO_2 contents. Compared to many andesites, the concentration of TiO_2 (<1.0 wt%) in these rocks is relatively low and the mg# is relatively high for compositions containing <2.5–6.0 wt% ferrous iron.

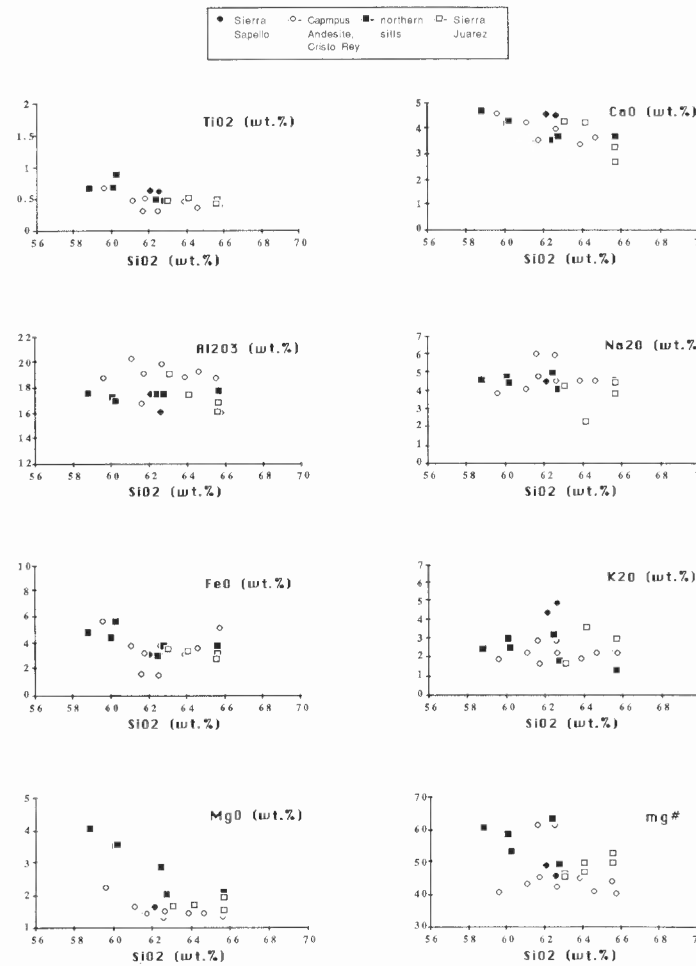

FIGURE 2. Major element variation diagrams for the El Paso area intrusive rocks. The data are plotted in four groupings: the compositions of samples from the northernmost sills (Three Sisters, Coronado and Thunderbird intrusions) are plotted as filled squares; those from the Campus Andesite and Cerro de Cristo Rey bodies are plotted as open diamonds; analyses of dikes from the Sierra de Juarez are plotted as open squares; and the compositions of rocks from Sierra de Sapello appear as filled diamonds.

TABLE 3. Major element compositions of early Tertiary intrusive rocks from the El Paso area.

	CORONADO INTRUSION			THREE SISTERS INTRUSION	THUDERBIRD INTRUSION	CAMPUS ANDESITE (Hoffer, 1970)		CAMPUS ANDESITE-UNIVERSITY PLAZA LOCALITY (NE MARGIN)			SIERRA DE CRISTO REY INTRUSION		SIERRA DE JUAREZ DIKES				SIERRA DE SAPELLO DIKES AND SILLS	
SAMPLE	ACORN-1	ACORN-2A	ACDRN-2B	ATHERS	THA	SW MARGIN	CENTER	UNIPA-1A	UNIPA-1B	UNIPA-2	CRIST-3	CRIST-2	TAB-HI	SDJ-66	SDJ-1	HD8640	36-B	38-D
(wt% Oxide)																		
SiO2	62.41	58.82	60.05	65.65	60.22	61.63	62.52	59.60	65.76	64.61	63.85	65.56	64.11	65.61	63.04	65.61	62.07	62.57
TiO2	0.49	0.68	0.69	0.39	0.90	0.3	0.3	0.67	0.39	0.36	0.46	0.38	0.50	0.43	0.48	0.43	0.64	0.63
Al2O3	17.48	17.67	17.20	17.84	16.93	16.71	17.42	18.72	15.96	19.27	18.81	18.70	17.41	16.01	19.14	16.01	17.49	16.14
FeO	2.94	4.69	4.42	3.74	5.52	1.57	1.45	5.67	5.17	3.61	3.05	2.91	3.31	2.78	3.57	2.78	3.03	3.13
MnO	0.09	0.11	0.05	0.09	0.05	0.23	0.29	0.13	0.12	0.07	0.90	0.07	0.05	0.02	0.09	0.02	0.60	0.50
MgO	2.85	4.04	3.57	2.11	3.58	1.41	1.29	2.21	1.97	1.42	1.40	1.30	1.67	1.55	1.65	1.55	1.63	1.46
CaO	3.54	4.70	4.21	3.71	4.32	3.49	3.55	4.59	3.69	3.64	3.37	3.24	4.20	2.63	4.23	2.63	4.54	4.47
Na2O	5.04	4.66	4.77	3.73	4.47	6.03	5.96	3.80	4.16	4.61	4.57	4.63	2.27	3.84	4.24	3.84	4.78	4.28
K2O	3.16	2.49	3.00	1.30	2.54	2.81	2.9	1.92	2.16	2.19	1.94	2.31	3.58	3.02	1.63	3.02	4.36	4.85
P2O5	0.12	0.26	0.21	0.27	0.26	0.44	0.41	0.37	0.12	0.09	0.26	0.18	0.28	0.05	0.51	0.05	0.00	0.00
LOI	nd	nd	nd	nd	nd	3.25	2.42	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
TOTAL	98.12	98.12	98.17	98.83	98.79	97.87	98.51	97.68	99.5	99.87	98.61	99.28	97.38	95.94	98.58	95.94	99.14	98.03
FeO/MgO	1.03	1.16	1.24	1.77	1.54	1.11	1.12	2.57	2.62	2.54	2.18	2.24	1.98	1.79	2.06	1.79	1.86	2.14
mg#	63.3	60.6	59.0	50.1	53.6	61.6	61.3	41.0	40.4	41.2	45.0	44.3	47.4	49.8	46.4	49.8	49.0	45.4

TABLE 4. INAA trace element compositions of early Tertiary intrusive rocks from the El Paso area.

	NORTHERN SILLS (CORONADO)		NORTHERN SILLS THREE SISTERS	NORTHERN SILLS THUNDERBIRD	CAMPUS ANDESITE		SIERRA DE CRISTO REY		SIERRA DE JUAREZ DIKES				SIERRA DE SAPELLO DIKES AND SILLS		
SAMPLE	ACORN-2A	ACDRN-2B	ATHERS	THA	CAMPA	UNIPA-1B	CRIST-3	CRIST-2	TAB-HI	SDJ-66	SDJ-1	HD8640	36-B	38-D	SM-3
(wt%)															
K2O	nd	1.8	nd	nd	3.0	nd	2.2	nd	nd	nd	nd	nd	5.2	6.0	3.6
Na2O	nd	4.66	nd	nd	4.84	nd	5.16	nd	nd	nd	nd	nd	5.21	4.98	3.43
CaO	5.34	4.4	3.86	3.7	2.9	3.79	2.4	3.46	4.05	3.63	3.95	4.68	4.4	5.7	3.39
FeO	5.66	5.13	4.14	4.99	2.661	3.61	3.095	3.51	3.625	3.66	3.83	3.37	3.79	3.82	2.65
(ppm)															
Sc	12.57	10.83	6.38	10.27	2.592	3.78	3.7	4.18	5.39	5.45	3.95	6.29	7.49	6.5	4.15
Cr	148	128.6	34	107.8	5.96	8.27	16.3	11.83	29.1	37.2	5.13	25.66	39.2	53.6	37.5
Co	37.0	51	50.8	32.1	17.45	27.2	71.5	29.17	29.08	26.8	18.34	26.16	65.8	98.5	52.7
Ni	65	66	19.6	45	6.9	9.8	12.6	12.7	12.8	31.2	15	14.8	16	24	22
Rb	56.2	49.3	66.5	58.7	45	52.6	52.3	58.2	84.7	71.1	27.3	81.1	84	116	56.6
Sr	931	690	920	851	810	1400	1030	1370	876	1282	771	1002	980	1100	1020
Zr	163	145	168	175	123	151	142	145	142	170	163	173	207	190	nd
Nb	14.9	7.7	12.6	10.8	5.8	10.6	6.2	10.3	11.2	12.3	10.1	12	12.7	13.6	nd
Ba	1216	1300	1458	1202	1285	1535	1770	1710	2475	1492	2685	1767	1420	1460	1100
Cs	1.61	1.26	1.14	0.82	1.883	1.89	2.67	2.5	4.01	1.379	0.617	2.77	3.17	2.38	1.41
La	29.7	25.85	28.9	30.6	20.08	35.2	25.99	30.7	27.6	29.4	30.7	34.9	35.02	39.38	21.37
Ce	62.9	54.3	61.1	64.7	40.9	71.7	52.4	61.7	53.7	61	65.1	70.5	66.8	73.9	40.5
Nd	27.6	24.5	27.1	28.1	18	26.3	24	24.1	22	26.2	26.1	29.4	32	33	19.3
Sm	5.76	5.07	5.45	5.82	2.97	5.05	3.97	4.5	4.68	5.58	4.8	5.81	5.53	5.33	3.64
Eu	1.819	1.589	1.715	1.785	0.977	1.534	1.162	1.423	1.26	1.528	1.587	1.467	1.85	1.67	1.23
Tb	0.578	0.56	0.604	0.544	0.251	0.363	0.31	0.402	0.364	0.494	0.39	0.49	0.65	0.56	0.41
Yb	1.35	1.41	1.34	1.31	0.64	1	0.95	1.03	1.12	1	1	1.42	1.2	0.7	0.526
Lu	0.199	0.184	0.178	0.184	0.094	0.145	0.14	0.14	0.161	0.133	0.142	0.198	0.159	0.09	0.062
U	nd	0.96	nd	nd	0.91	2.13	1.35	1.92	2.68	1.73	1.72	1.72	1.38	1.17	1.09
Th	4.28	4.1	5.17	4.75	3.158	4.27	3.97	4.04	4.78	5.08	4.41	6.26	5.59	7.53	3.58
Hf	4.76	4.21	5.13	5.11	3.36	4.64	3.74	4.41	4.5	5.49	4.44	5.78	6.18	6.11	nd
Ta	0.782	0.925	1.39	0.768	0.628	0.932	1.38	0.955	0.813	0.819	0.666	0.773	0.893	0.99	1.00
Sb	0	0.288	0.31	0.71	0.144	0.23	0.217	0.39	0.5	0.28	0.52	1.24	0.314	0.187	0.133
As	nd	nd	nd	nd	1.95	1.00	2.8	nd	nd	nd	nd	nd	nd	1.9	1.1
W	64	70	195	72	29.6	99	119	99	88	72	79	92	307	400	272
Zn	47.5	54.5	66.5	84.4	47.9	73.6	59.8	57	53.2	98.6	60.5	52.6	55	48	nd

Trace elements

The trace element contents of samples from the eight intrusion localities are listed in Table 4, and some of these data are plotted in Figures 3, 4 and 5. Notable features of the trace element compositions of these rocks are: (1) the general continuity of trace element abundances among samples from the intrusive bodies, especially for the magmaphile elements, (2) the lack of systematic correlation with major elements such as SiO_2, (3) strong correlations among transition metal contents and also with FeO*, MgO and mg# and (4) distinctive trace element compositions that are common to all samples.

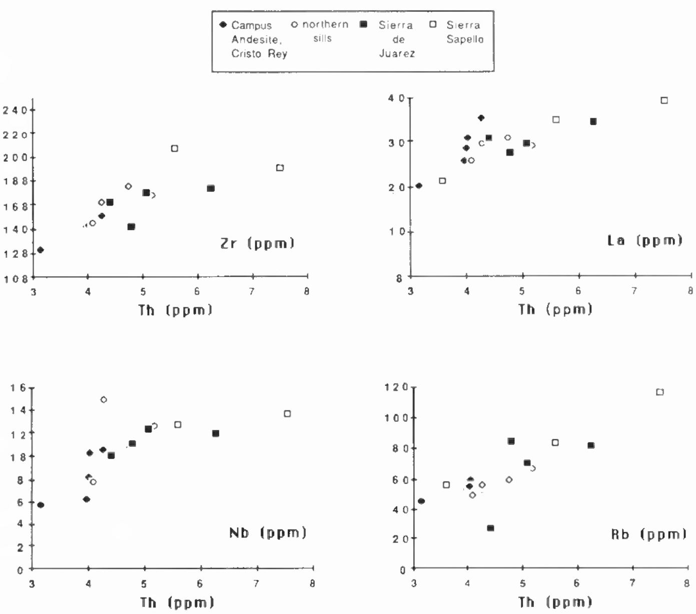

FIGURE 3. Plots of incompatible trace-element contents of the El Paso area intrusive rocks. Data are plotted in four groups: Sierra de Sapello samples as open squares; samples of Campus Andesite and Cerro de Cristo Rey as filled diamonds; the northern sills as open diamonds and Sierra de Juarez as filled squares. Note the continuity and positive correlations for incompatible trace elements between sample groupings.

Strong positive correlations exist among the contents of the high-field strength elements Zr, Th, Ta, Hf and also between these and most other magmaphile element contents (e.g. Rb, Nb and the REE's; Fig. 3). The abundances of these elements show no systematic correlation with SiO_2. Moreover, samples richest in SiO_2 do not have the largest concentrations of magmaphile elements (Fig. 4).

Transition element contents are typically low. Concentrations of Sc, Cr and Ni are typically less than eight, 54 and 31 ppm, respectively,

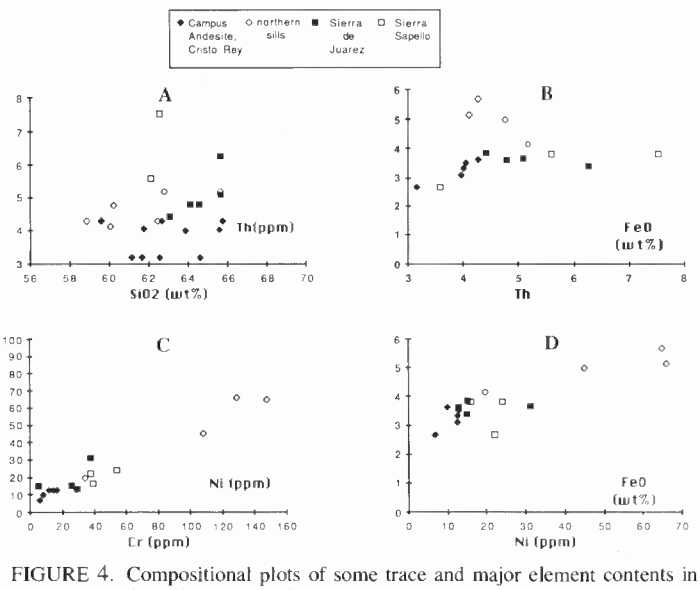

FIGURE 4. Compositional plots of some trace and major element contents in El Paso area intrusive rocks. These plots illustrate the problem of interpreting compositional data for rocks containing abundant phenocrysts. Parts A and B illustrate the general lack of correlation between SiO_2, FeO and incompatible elements. Part C shows the strong positive correlation between Cr and Ni, due to the compositions of mafic phenocrysts. Part D shows that FeO behaves in a similar way to the transition metals. Symbol designations are given at the top of the figure: filled diamonds = Campus Andesite and Cerro de Cristo Rey; open diamonds = northern sills (Three Sisters, Coronado and Thunderbird intrusions); filled square = Sierra de Juarez dikes; open squares = Sierra de Sapello intrusions.

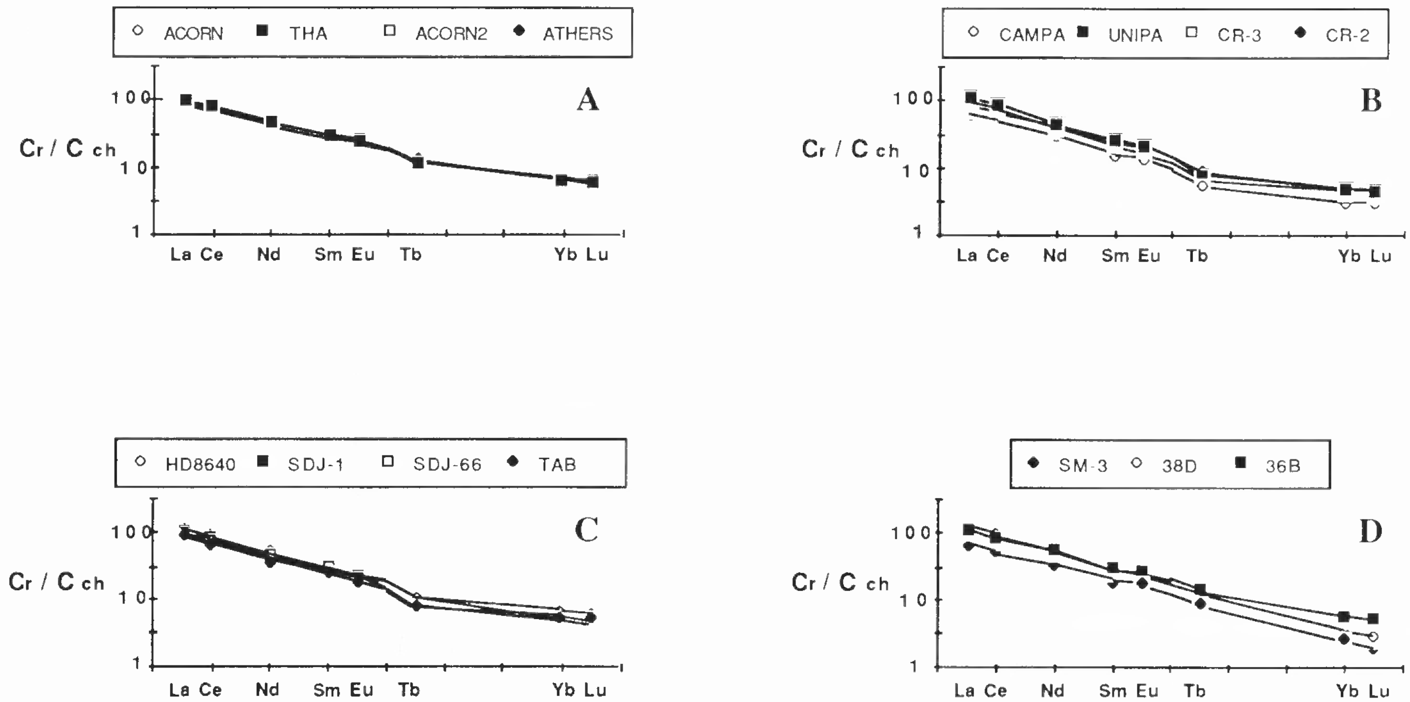

FIGURE 5. Chondrite normalized REE plots for El Paso area intrusive rocks. C_r/C_{ch} denotes bulk rock concentration divided by chondrite abundances. The patterns for four groups are plotted separately. A—northern sills, B—Campus Andesite and Cerro de Cristo Rey bodies; C—Sierra de Juarez; D—Sierra de Sapello.

but are somewhat higher (13, 148 and 66 ppm, respectively) in three samples from the northern sills. The concentrations of these elements correlate positively with each other and with FeO and MgO, though the concentrations of these elements in the three samples from the northern sills form a distinct population rich in FeO, Ni and Cr (Fig. 4).

Among the most distinctive features of these rocks are the unusually large contents of Sr (770–1400 ppm) and Ba (1100–2700 ppm) and the REE contents and patterns. Chondrite normalized REE patterns for these rocks are characterized by steep LREE to MREE slopes ($La_n/Sm_n \approx 3.5$–4.5), relatively flat MREE to HREE slopes ($Tb_n/Lu_n \leq 2$) and slightly positive Eu anomalies (Fig. 5). Systematic differences are also seen in the abundances of HREE and other magmaphile trace elements among the four groups of intrusive bodies. Samples from the northern sills, Campus Andesite and Cerro de Cristo Rey localities generally have the lowest magmaphile trace-element contents (Fig. 4). Yet, the northernmost sills have the largest HREE concentrations and the smallest LREE/HREE ratios; Sierra de Juarez dike rocks have comparable to slightly lower HREE contents; Campus Andesite and Cerro de Cristo Rey samples have somewhat lower REE contents and the largest LREE/HREE ratios. The contents of magmaphile trace elements in rocks from Sierra de Sapello span most of the range of the other three groups and also have the least flattened HREE patterns.

DISCUSSION

Genetic relations

The igneous rocks that intrude Cretaceous sediments in the El Paso area of west Texas, southern New Mexico and northern Chihuahua, Mexico have been presumed to be of similar age and origin by most workers in the region, owing to the general similarities in textures and in the style and stratigraphic level of intrusions. The type and form of the bodies, the sharp contact relations, the age of the host rocks and the fine to medium grain size are features indicative of relatively shallow hypabyssal intrusions. Although the volume represented by exposed intrusive rocks is small, the manner in which these bodies are collectively exposed is strikingly similar to the pattern seen in exhumed dike-sill swarms overlying and connected to the core of large unroofed plutons (Fiske et al., 1963). In such cases, the lateral extent of the exposed dikes and sills are roughly comparable to the diameter of the underlying pluton. For the dikes and sills in the El Paso area, the extent of the Tertiary intrusive suite (10–40 km) is comparable to the dimensions of major igneous centers of the Trans-Pecos that underlie calderas (4–30 km; Henry and Price, 1984). Moreover, if these bodies are cogenetic, then they must certainly be connected to a larger body at depth. The present data set allows us to evaluate this hypothesis on the basis of textural, mineralogical and geochemical evidence. It is not known whether these intrusions were associated with volcanism; however, volcanic products have not been identified.

Phenocryst assemblages and elemental abundances in host rocks and enclaves suggest that the magmas parental to the El Paso area intrusive rocks experienced fractionation of at least amphibole and plagioclase prior to emplacement at the present level in the crust. The apparent sequence of crystallization was plagioclase and amphibole, followed by biotite and subordinate amounts of Fe-Ti oxides and apatite. Quartz, sphene and zircon also crystallized in some rocks. The concentrations of Ba preclude significant amounts of biotite fractionation prior to emplacement. The lack of negative Eu anomalies may be indicative of relatively oxidizing conditions during fractionation; an interpretation supported by the presence of magnetite, and locally by sphene, as microphenocryst phases (Wones, 1981) and by the relatively high mg# of the mafic phases (Barnes, 1987). Although the effect of plagioclase accumulation could feasibly offset the negative Eu anomaly in its host liquid component, the lack of Eu anomaly in plagioclase-rich enclaves thought to represent cognate cumulates also indicates high fO_2 conditions. Oxide-rich reaction rims on some of the mafic minerals are presumably due to the decrease in water pressure associated with shallow intrusion or eruption rather than to high fO_2 alone.

Phenocryst zoning patterns, particularly in amphibole and plagioclase, reflect abrupt changes in the intensive variables (P, T, or fugitive components) in the magma, or contamination due to magma mixing. Reversals in plagioclase zoning, for example, could be attributable to a largely isothermal increase in the H_2O content of the magma, or to an increase in the Ca content of the magma due to magma mixing or assimilation of calcareous wall rock. We interpret the zoning features to reflect an increase in water content or magma mixing judging from the absence of calc-silicate xenoliths in these intrusions.

Contrary to the interpretations of Hoffer (1970), amphibole, biotite and quartz phenocrysts in these rocks did not form by assimilation and reaction with the Cretaceous country rock, nor were the country rocks related to formation of the mafic enclaves. The overall effect of contamination by Cretaceous country rock appears to have been negligible. The mineralogy, texture and composition of most enclaves indicate that they are cognate xenoliths derived by accumulation of crystals from fractionation from magma in an underlying chamber. However, the textures and compositions of the anorthositic enclaves suggest that they are not directly related to differentiation of the host magma and are xenoliths of deformed lower crustal material possibly Precambrian in age.

The striking similarities in mineralogy, texture, mode, and enclave type likely reflect similarities in the composition of the parental magma and in the crystallization paths that produced these rocks. These features, together with the identical radiometric ages for two of the bodies, suggest that the intrusions could be genetically related or comagmatic. However, geochemical data provide one of the strongest arguments for their genetic relationship.

The general continuity of major and trace element abundances among the analyzed samples is typical of a magma series related by fractional crystallization and/or crystal accumulation. Yet, some of the major and/or trace element systematics are equivocal, such as the lack of systematic correlations between the abundances of SiO_2 and magmaphile elements (Fig. 4A). It might be argued that such relationships represent evidence against cogenetic relationships because they cannot be explained by fractional crystallization. However, because these rocks are highly porphyritic, their major element compositions do not represent those of liquids. The abundances of major and trace elements should be expected to vary significantly as a function of the relative proportions of phenocrysts and groundmass. Similarities or lack of similarities to other magmatic suites of comparable composition (i.e., andesites) can, therefore, be misleading or fortuitous. The magmaphile element contents of the El Paso intrusive rocks primarily reflect the composition of the liquid fraction in the rocks. Covariation among these elements is positive (Fig. 3). Conversely, the abundances of the transition metal elements and many major elements reflect weighted mean values of mafic phenocrysts. Thus, the abundances of these elements can show an apparent lack of correlation or reversed correlations between magmaphile elements and elements such as SiO_2 or Ni (Fig. 4A) even if the compositions of the liquid component (i.e., groundmass) are identical. The implications of this relationship on elemental abundances in porphyritic bulk rocks are illustrated in Figure 6A, where *rock* concentrations of elements having bulk solid/liquid partition coefficients (bulk D values) of five, one, 0.2 and zero, are plotted against the liquid fraction present in a rock. Compared to the composition of the liquid alone, magmas containing phenocrysts have lower contents of magmaphile elements and greater contents of elements preferentially partitioned into the phenocrysts. Thus, rocks solidified from the same magma, but containing 30% and 60% phenocrysts, can have magmaphile element abundances (i.e., bulk D = 0) that differ from each other by a factor of 1.75, and compatible element contents (e.g., bulk D = 5) that can differ by a factor of over 1.5. These factors are larger than many of the observed ranges of elements with the smallest or largest bulk D values (e.g., Th, REE's and Ni respectively).

Differences in the concentrations of the trace elements due to fractional crystallization can be even larger. Relative enrichment and depletion factors attributable to Rayleigh-type crystal fractionation are plotted in Figure 6B. For 50% crystal fractionation, residual liquid concentration can be enriched by as much as a factor of two for magmaphile elements, and compatible trace elements (i.e., D = 5) can become depleted by a factor of over 16. Note that the effects of fractional crystallization versus differing proportions of accumulated phenocrysts are additive, so that, for example, differences in *liquid* concentrations of magmaphile elements could be reduced or enhanced in the bulk rock, depending on the number and type of accumulated phases. Therefore,

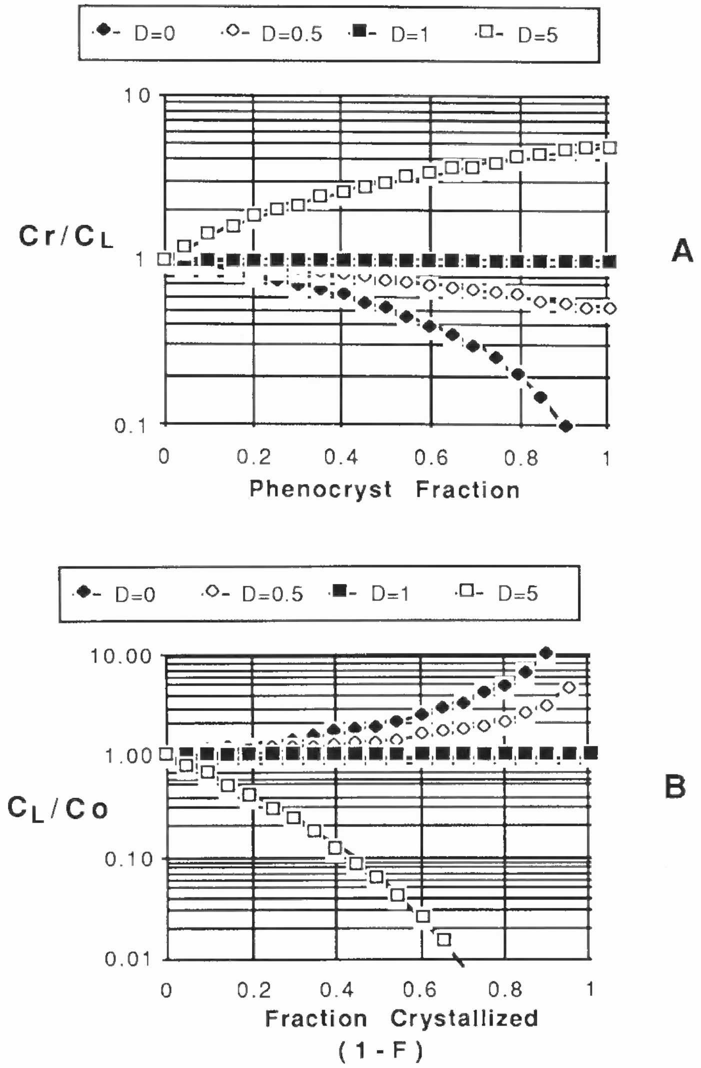

FIGURE 6. A, Graphical representation of the variation in the elemental contents of a rock containing phenocrysts. For elements having bulk distribution coefficients of D = 0, 0.5, 1.0 and 5.0 respectively, and reference concentration of 1.0 in the liquid (Cl = 1.0), the concentration of these elements in the rock (Cr/C_L) is shown as a function of phenocryst fraction. Compositions of phenocrysts are assumed to be in equilibrium with liquid. B, Graphical representation of liquid concentrations resulting from fractional crystallization of solids having the same bulk D values used in Part A. These concentrations are plotted aginst the fraction crystallized (1-F) where F is the fraction of liquid remaining. C_L/C_o denotes the concentration of an element in the liquid divided by the initial unfractionated liquid. Note how the magnitude of enrichment and depletion factors contrast with apparent enrichment or depletion due to crystal accumulation in Part A.

many element-element correlations (Fig. 4) are not capable of correctly indicating the genetic affinities of such rocks. It is impossible to evaluate the extent of fractionation in this suite of rocks without detailed modal and compositional data for each sample. However, mathematical "removal" of observed phenocryst phases from the bulk rock compositions can be used to calculate the liquid component in these rocks. This liquid component is calculated to contain 66–75% SiO_2, to be 1.4–2.5 times richer in magmaphile elements than the bulk rocks, to contain nearly half the concentration of transition elements and to be trachytic to rhyolitic rather than andesitic.

Together the geochemical and mineralogical data indicate that the rocks comprising the El Paso intrusive suite rocks are comagmatic. The striking similarities in incompatible element enrichment and covariation of magmaphile elements are especially compelling evidence. The similarities in REE patterns and abundances, for example, cannot logically be interpreted in any other way. Similarities in enclave populations and in the phenocryst mineralogy and composition in these rocks also argue strongly for cogenetic and comagmatic relationships. Together these data leave little doubt of such relationships.

Tectonic environment

Many of the geochemical and mineralogical features of the El Paso intrusive suite are also typical of magma generated in orogenic tectonic environments. Distinctively large contents of Ba and Sr are features of all samples. The abundances of these and other hygromagmatic trace elements (Rb, Cs and LREE) are typically enriched in arc-related magmas and serve as indicators of the tectonic affinities in these rocks. REE patterns for the intrusive rocks (Fig. 5) differ from those of orogenic andesites, but are similar to high-K varieties such as those from Indonesia (Whitford et al., 1979), the Eolian arc (Villari and Nathan, 1978), Chile (Thorpe et al., 1976), and also the high-K cross-arc dacites from Chihuahua that contain 66–70% of SiO_2 (Cameron et al., 1980, 1983). These REE patterns bear no resemblance to those of anorogenic andesites associated with Rio Grande rift magmatism (Zimmerman and Kudo, 1979; Gill, 1980).

The trace-element compositions of the El Paso intrusives are also indicative of high-K orogenic magmas related by fractional crystallization and/or crystal accumulation. The ratios of La/Nb, La/Ba, La/Th and La/Ta in these rocks, for example, exceed bulk earth values (Fig. 7), as do magmas generated in orogenic settings (Anders, 1977; Pearce and Norry, 1979). The values and range of ratios of Ni/Rb and Ni/Cr (Fig. 7D) are also indicative of a strongly fractionated magma suite.

The composition and age of the El Paso area intrusive rocks (47–48 my) indicate a relationship to magmatism in the Trans-Pecos belt. It is generally believed that igneous activity in the Trans-Pecos is the easternmost extension of magmatism that began near the western margin of North America over 100 my (Coney and Reynolds, 1977) and migrated eastward with time. Clark et al. (1982) proposed that the systematic spatial and temporal distribution of volcanic and intrusive rocks in the U.S. and Mexico reflect the genetic relationship between magmatism and subduction. This eastward migrating front of igneous activity is estimated to have reached central Chihuahua about 45 my, and the Trans-Pecos about 44–48 my and lasted until about 17 my (McDowell, 1979; Henry et al., 1983; Nelson et al., 1987).

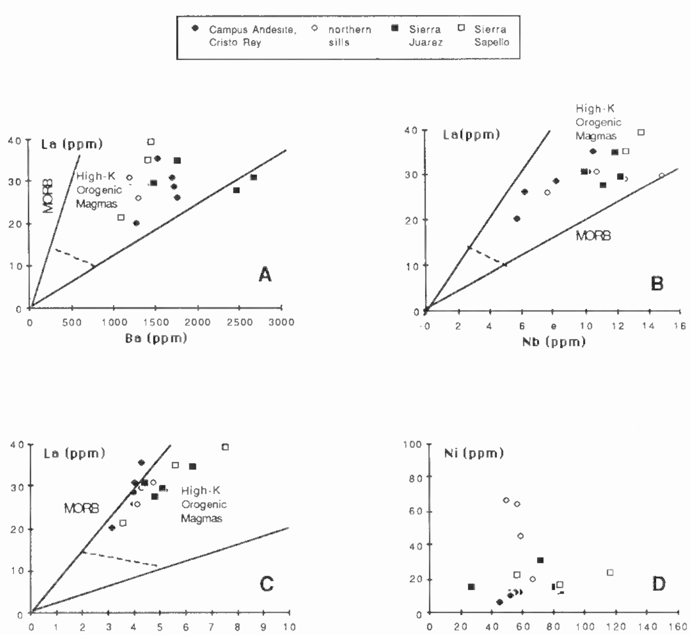

FIGURE 7. A, B, C, Plots of incompatible trace element ratios of intrusive rocks from the El Paso area compared to those of high-K orogenic magmas and MORB's summarized by Gill (1981). Nearly all samples plot in the high-concentration regions of high-K orogenic magmas (separated from medium-K orogenic magmas by the dashed line). D, Plot of Ni vs Rb concentration illustrating that the El Paso area intrusive rocks plot in regions of strongly fractionated compositions. Ni contents in the liquid component of these rocks are significantly lower than those plotted due to the effect of accumulated mafic minerals in the bulk rock composition. Symbols are the same as in Figures 3 and 4.

Most of this region experienced east-northeast-directed compression during Late Cretaceous and early Tertiary time. Sills in the Sierra de Juarez are clearly cut by north-northeast-trending normal faults, while northeast-trending dikes intruded along and post-date normal faults. These latter faults also cut folded and thrusted blocks of Early Cretaceous rocks.

Igneous activity in the Sierra de Juarez must post-date Laramide compressive deformation since dikes cross-cut thrust planes at all structural levels. It is difficult to reconcile the field observations of both sills and northeast-trending dikes and associated faults with either a single, simple state of stress in the region, or with conventionally accepted ideas on the timing of transition from compressive to extensional deformation in the region.

Price and Henry (1984) found that the late Laramide stress field of the Trans-Pecos region was characterized by σ_1 oriented east-northeast and σ_3 oriented north-northwest. This stress state apparently persisted into the Oligocene, as reflected in the trends of dikes of this age. No normal faulting suggestive of north-northwest extension has been documented in early Tertiary rocks of the Trans-Pecos. It is generally accepted that early Basin and Range extension in the Trans-Pecos region and adjacent Chihuahua commenced between 31 my and 28 my, and was characterized by σ_3 oriented east-northeast (Henry and Price, 1986).

The presence of both sills and dikes and northeast-trending dikes in the Sierra de Juarez indicates that the orientation of σ_3 varied during magma emplacement, possibly as a function of depth. The association of undeformed dike rocks with northeast-trending normal faults which cut and displace thrust surfaces can be interpreted in several ways. Two competing hypotheses are: (1) that these faults are evidence for a previously unrecognized regional episode of early Tertiary northwest-southeast extension which postdated Laramide compression and predated dike emplacement (47–48 my), or (2) local faulting and near-synchronous dike emplacement was associated with arching and inflation of the overlying sedimentary cover during emplacement of the large body of the El Paso area intrusives. Since we know of no data to substantiate a regional episode of early Tertiary northwest-southeast extension, we currently favor the second interpretation. The present outcrop pattern of the El Paso area intrusives also rule out the possibility of significant post-47 my lateral movement along the west-northwest-trending Texas lineament.

Petrogenesis

The composition of the liquid component in the El Paso area intrusive rocks is also consistent with the compositions of volcanic material erupted elsewhere in the Trans-Pecos. Trace element compositions of the El Paso intrusives are distinct from those of trachytic volcanic rocks in the eastern Trans-Pecos magmatic province (TPMP) and resemble more closely the compositions of the alkaline basaltic rocks in the region (Nelson et al., 1987). However, liquid compositions adjusted for phenocryst proportions are similar to those of quartz trachyte elsewhere in the TPMP.

Many calderas in the Trans-Pecos had eruptive patterns that typically began with rhyolite, followed by trachyte and more mafic magma. Henry and Price (1984) suggested that this cycle was commonly repeated in a single caldera, a pattern that has been interpreted to reflect tapping of vertically zoned magma chambers (cf. McBirney, 1980). Other workers suggest that Trans-Pecos magmatic events were associated with as many as four main stages of magmatism and that magmas of different stages were produced throughout the evolution of the province (Nelson et al., 1987). In this model, various combinations of open and closed system crystal fractionation ± crustal assimilation and magma mixing were proposed for generation of the four stages: alkalic basalt to trachyte (I), trachyte to quartz trachyte (II), quartz trachyte to rhyolite/comendite (III) and rhyolite/comendite to high-silica rhyolite (IV).

The magma that gave rise to the El Paso area intrusive rocks evolved primarily from crystal fractionation and from magma that also contained sufficient H_2O for amphibole stability. However, the parental magma composition has not been constrained at this time. Amphibole and plagioclase fractionation dominated the stage of fractionation associated with formation of most enclaves. In comparison, the models of McDonough and Nelson (1984) and Nelson et al. (1987) require quartz trachyte formation by extensive (>90%) fractionation of plagioclase and K-feldspar and subordinate amounts of Ca-rich pyroxene, magnetite and apatite from alkali basalt ± minor amounts of magma replenishment. On the basis of the current data we see little evidence for fractionation of this type and extent in the El Paso quartz trachyte rocks. It is possible that rhyolitic sills associated with the Cerro de Cristo Rey pluton were derived from a silicic roof zone, but further study will be required to confirm or reject this hypothesis.

Most of the igneous activity in the Trans-Pecos has been thought to be related to changes in the angle of subduction, and/or foundering of the slab accompanied by upwelling of the asthenosphere to induce partial melting of the lower crust (Henry et al., 1983). However, magmas of the same age and tectonic enviroment in neighboring Chihuahua have been interpreted as having a relatively homogeneous mantle source rather than heterogeneous crustal sources (Cameron et al., 1983). It is premature to postulate on the specific roles of the mantle, slab and crustal material in generation of magma parental to the El Paso intrusions. However, incompatible trace element contents in these rocks (i.e., the liquid component) have MORB normalized patterns (Fig. 8) essentially identical to those of Mt. St. Helens dacites (Smith and Leeman, 1987). Both groups of rocks display similar patterns of enrichment in the hygromagmatic elements of Rb, Ba, Cs, Sr and the LREE's that are characteristic of arc basalts. Smith and Leeman (1987) concluded that patterns such as these can form by partial melting of a crustal source characterized by MORB-like relative abundances of most magmaphile elements, but enriched in slab-derived hygromagmatic elements. It was also suggested that such sources could be amphibolite facies crustal rocks representing subducted material, or material (mantle or crust) metasomatically enriched in hygromagmatic elements. The various roles of fractional crystallization, contamination, magma mixing and source rock composition in the origin of the El Paso intrusive rocks, however, require further study.

CONCLUSIONS

This study provides new information on the petrology and geochemistry of the post-Cretaceous intrusive bodies that straddle the U.S. and Mexican borders in the vicinity of El Paso, Texas. These 47–48-my-old rocks occur as hypabyssal dikes, sills and plugs of high-K trachyandesite composition. The intrusions are composed of 30–60% phenocrysts, primarily plagioclase, amphibole and biotite, hosted by a groundmass that is trachytic in composition. Enclaves of monzodiorite, diorite and quartz diorite occur as cognate xenoliths resulting from crystal fractionation and accumulation of plagioclase and amphibole at deeper levels in the crust rather than from country rock contamination. Enclaves of deformed anorthosite may represent lower crustal xenoliths. Phenocryst zoning reflects changes in intensive variables in the magma or contamination due to magma mixing. Similarities in mineralogy, texture, age, enclave types, phenocryst and bulk compositions of these intrusive rocks indicate that they are comagmatic. The extent to which these rocks are enriched in incompatible and hygromagmatic trace elements (Rb, Cs and especially Sr, Ba and LREE) is indicative of their cogenetic relationship and also of their affinities with orogenic arc magmas. Fractionation from a more basic parent magma is indicated by the range of cognate enclave types, and by features of their trace element compositions such as low transition metal contents and large Rb/Ni ratios. These intrusive bodies are believed to be interconnected at depth and to comprise the roof zone or the tops of larger cupolas of an underlying body having dimensions comparable to calderas elsewhere in the Trans-Pecos. Local differences in the phenocryst assemblages and compositions may reflect local fractionation within the roof zone or magmas of slightly different composition tapped from slightly different levels in a zoned chamber. Based on their age (47–48 my), these rocks appear to be the earliest manifestation of Trans-Pecos magmatism. The association of these rocks with post-Laramide high-angle faulting may indicate arching of the overlying sedimentary rocks during emplacement of the large igneous body. Significant post-47 my lateral movement on the west-northwest-trending Texas lineament can be ruled out. The similarity between MORB-normalized patterns of incompatible trace elements in these rocks and those of Mount St. Helens dacites is consistent with source material having MORB-like relative abundances of magmaphile elements, enriched in slab-derived hygromagmatic constituents.

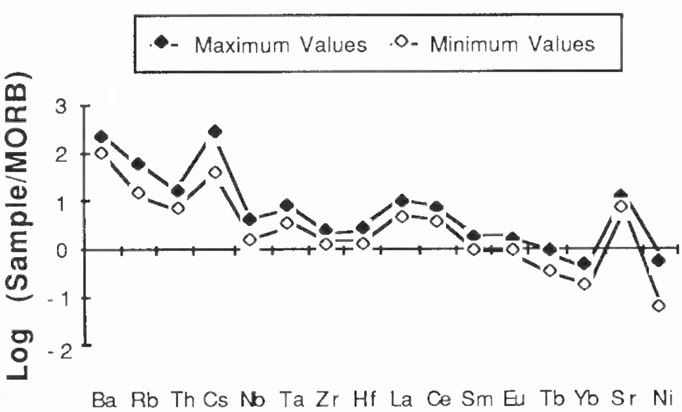

FIGURE 8. MORB-normalized trace element pattern for the El Paso area intrusive rocks. Enrichment factors of the incompatible elements indicated in this plot are minimum values since the liquid component comprised only 40–70% of the rocks. The samples are enriched in the hygromagmatic Ba, Rb, Cs, Sr and LREE's, as well as in Th, and to a lesser degree, Nb and Hf.

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