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Late Jurassic igneous rocks in south-central Arizona and north-central Sonora: Magmatic accompaniment of crustal extension

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ABSTRACT

In Middle Jurassic time, the region of south-central Arizona and north-central Sonora was part of a continental magmatic arc. In early Late Jurassic time, this magmatic arc gradually gave way to a extensional regime. Late Jurassic rifting was accompanied by magmatism, typically small in volume relative to the preceding arc phase, and with mildly alkaline compositions. These igneous rocks, the 158- to 146-Ma Ko Vaya Suite, make up much or most of the Comobabi, Artesa, Quijotoa, and Brownell Mountains and Sierra del Cobre. The bimodal Ko Vaya Suite constitutes volcanic to shallow plutonic complexes comprising chiefly trachyandesite and volcanic wacke; monzodiorite; rhyolite porphyry; distinctive, compositionally and texturally heterogeneous, quartz-poor granite (the Ko Vaya Granite); A-type perthite granite and quartz syenite; aphyric intrusive rhyolite; and locally abundant hematite veins. Alteration, particularly potassic alteration, is widespread. Minimally altered samples of granite and quartz syenite

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have the composition of trachyte or trachydacite and alkali rhyolite. The Ko Vaya Suite is nonconformably overlain by the latest Jurassic Sand Wells Formation, approximately correlative with the Glance Conglomerate, the basal unit of the Bisbee Group. The Ko Vaya Suite is in some ways analogous to the coeval Independence dike swarm of eastern California, but less diffuse. We infer that the Ko Vaya Suite represents especially intense or focused Late Jurassic extensional magmatism.

MIDDLE JURASSIC ARC MAGMATISM: LATE JURASSIC CRUSTAL EXTENSION AND ASSOCIATED MAGMATISM

In Middle Jurassic time, the region of present-day southern Arizona and northern Sonora was part of a continental magmatic arc (Tosdal et al., 1989; Anderson et al., 2005; Haxel et al., 2008). This arc evidently was low-standing (Busby-Spera et al., 1990), presumably reflecting a moderately extensional tectonic setting. In early Late Jurassic time the magmatic arc gradually gave way to a more strongly or pervasively extensional regime (Anderson and Nourse, 2005). Late Jurassic rifting was accompanied by magmatism, small in volume relative to the preceding arc phase, and typically mildly alkaline. Late Jurassic rift basins and associated magmatism are well documented in several areas of southeast Arizona, southwest New Mexico, and northeast Sonora (e.g., Bilodeau et al., 1987; Krebs and Ruiz, 1987; Lawton and McMillan, 1999; Lawton, 2000; Bassett and Busby, 2005; McKee et al., 2005). Similar basins west of the longitude of Tucson, Nogales, and Magdalena de Kino are generally less well known. Our primary purpose in this paper is to elucidate the petrochemistry of a distinctive suite of synextensional Late Jurassic igneous rocks in south-central Arizona and north-central Sonora. As background for this discussion, we also present a speculative tectonic map of Late Jurassic faults and basins in this region (Fig. 1).

Pre-Late Jurassic geologic framework

Most of the area of south-central Arizona and north-central Sonora shown in Figure 1 lies within an anomalous region, the Papago domain, where no autochthonous Proterozoic or Paleozoic rocks are exposed beneath or among the dominant Middle and Late Jurassic supracrustal and plutonic rocks (Haxel et al., 1984, 1988; Riggs and Haxel, 1990; Tosdal et al., 1990; Nourse et al., 1994; Nourse, 1995; Anderson et al., 2005). Despite the absence of exposed Proterozoic rocks, Sr, Nd, and Pb isotopic data (Farmer and Depaolo, 1984; Lang and Titley, 1998; Asmerom et al., 1991; Bouse et al., 1999) show the Papago domain is underlain by the same Paleoproterozoic continental crust as surrounding regions of the southwest North American craton. Absence of facies changes in Paleozoic strata at the margins of the Papago domain further indicates that its pre-Mesozoic history does not differ from that of adjacent areas. The peculiarities of the Papago domain have been attributed to early Mesozoic rifting or crustal extension, prior to development of the Middle Jurassic magmatic arc (Stewart et al., 1986, 1990); or to foundering of the upper crust during Late Jurassic extension (Anderson and Nourse, 2005). Or, within the Papago domain older rocks may simply have been overwhelmed by successive floods of Jurassic magma. All three mechanisms could have contributed, cumulatively.

In most of southern Arizona and northern Sonora, the main phase of Jurassic arc magmatism commenced ≈ 180 or 175 Ma, preceded by scattered igneous activity as early as ~ 190 Ma along the northeast edge of the arc. In the northern two-thirds of the area considered in this paper (Fig. 1), two pulses of Middle Jurassic volcanism and plutonism can be distinguished. The first is represented by the Topawa Group (Haxel et al., 2005), the Cobre Ridge Tuff and related hypabyssal and plutonic rocks exposed in a tilted upper crustal section near Arivaca (Riggs and Haxel, 1990; Riggs and Busby-Spera, 1991; Riggs et al., 1993), and similar rocks in northern Sonora (Segerstrom, 1987; Anderson et al., 2005). These units are almost entirely rhyolitic or granitic, and have several U-Pb interpreted ages between 178 and 170 Ma (all ± 2–5 Ma) (Haxel et al., 2008, this volume, Table 1). The second magmatic pulse began with pipes and stocks of hornblende-rich mesodiorite, which intrude the Topawa Group. The main phase of the second pulse, at 165 Ma, produced extensive granodiorite plutons widespread in both Arizona and Sonora. This granodiorite was followed by leucogranitic plutons, also large but less widespread, circa 159 Ma. This final phase of the second pulse apparently was transitional to the succeeding episode of Late Jurassic magmatism related to post-arc extension.

Late Jurassic rift basins

Anderson and Nourse (2005) present evidence that Late Jurassic rift basins in southern Arizona and northern Sonora define a zone several hundred kilometers wide flanking, and related to, the sinistral Mojave-Sonora megashear. Other recent interpretations of Late Jurassic basins in this region include those of Bilodeau (1982), Drewes and Hayes (1983), Harding and Coney (1985), Dickinson et al. (1989), Fackler-Adams et al. (1997), Lawton and McMillan (1999), and Dickinson and Lawton (2001). Our discussion of the petrology of rift-related igneous rocks, the main focus of this paper, is independent of any particular tectonic model for rifting. On the other hand, our speculative map of Late Jurassic faults and basins in south-central Arizona and north-central Sonora is model-based. Figure 1 is an elaboration upon smaller-scale maps in Anderson and Nourse (2005), and incorporates the kinematic hypotheses of the earlier work.

Locations of faults and basins in Figure 1 are based largely on the distribution of six key regional lithostratigraphic units, described in the next section. Most of the faults are necessarily conjectural, for two reasons. First, more than one-half of the area is occupied by valley-fill alluvium. Second, many of the Late Jurassic faults have been reactivated as or modified by latest Cretaceous to early Paleogene ("Laramide") reverse or thrust faults.

Regional lithostratigraphic units

(1) Proterozoic and Paleozoic rocks. In Arizona scattered exposures of Proterozoic and Paleozoic rocks surround, on the east and north, the main area of Middle and Late Jurassic igneous rocks (units 2 and 3). Proterozoic rocks—Pinal Schist, orthogneiss, granite, Apache Group and associated diabase—are exposed only in the northernmost part of the map area. Paleozoic strata must have once covered the entire area, but exposures are now restricted to small remnants, some strongly metamorphosed. Most of these remnants occur along or within west- to northwest-trending fault or shear zones, notably in the Coyote, Sheridan, Santa Rosa, Silver Bell, and Waterman Mountains (Titley, 1976; Briskey et al., 1978; Bergquist, et al., 1978; Wright and Haxel, 1982; Richard et al., 2000a). Within the Papago domain, Proterozoic and Paleozoic rocks crop out in only one range, Sierra Blanca, where they constitute part of the upper plate of a thrust fault.

(2) Middle (to earliest Late) Jurassic plutonic, volcanic, and sedimentary rocks, representing the main phase of arc magmatism. Extensive, semicontinuous exposures of this unit in the Baboquivari, Las Guijas, San Luis, and Pajarito Mountains, Cobre Ridge, and Sierras Las Avispas, Cibuta, and La Joroba define the eastern margin of the Late Jurassic basins and their igneous and sedimentary fill. Middle Jurassic (meta)igneous and (meta)sedimentary rocks in Sierra Blanca, Kupk Hills, Sierras Cobota and del Cobre, Cerro del Plomo, Sierra La Gloria, and ranges farther west likewise form the western margin. Middle Jurassic rocks presumably also constitute a major part of the substrate of the Late Jurassic basins.

(3) Late Jurassic plutonic, hypabyssal, volcanic, and volcaniclastic rocks. This distinctive assemblage, herein called the Ko Vaya Suite, crops out mainly in the central part of the map area. Our hypothesis is that the Ko Vaya Suite, described in detail in subsequent sections, is uniquely associated with Late Jurassic rifting.

(4) Latest Jurassic (to earliest Cretaceous?) clastic sedimentary strata, with subordinate interlayered andesitic and rhyolitic volcanic and subvolcanic rocks. In Arizona, these nonconformably overlie the Ko Vaya Suite, so the two units are distinct. As explained in a subsequent section, these strata probably correlate with the latest Jurassic Glance Conglomerate (basal unit of the Bisbee Group), widespread in southern Arizona and northern Sonora (Bilodeau et al., 1987; Dickinson and Lawton, 2001; Nourse, 2001). Unit 4 crops out most extensively in the northern part of the map area, in the Combabi and Gu Achi basins (Fig. 1).

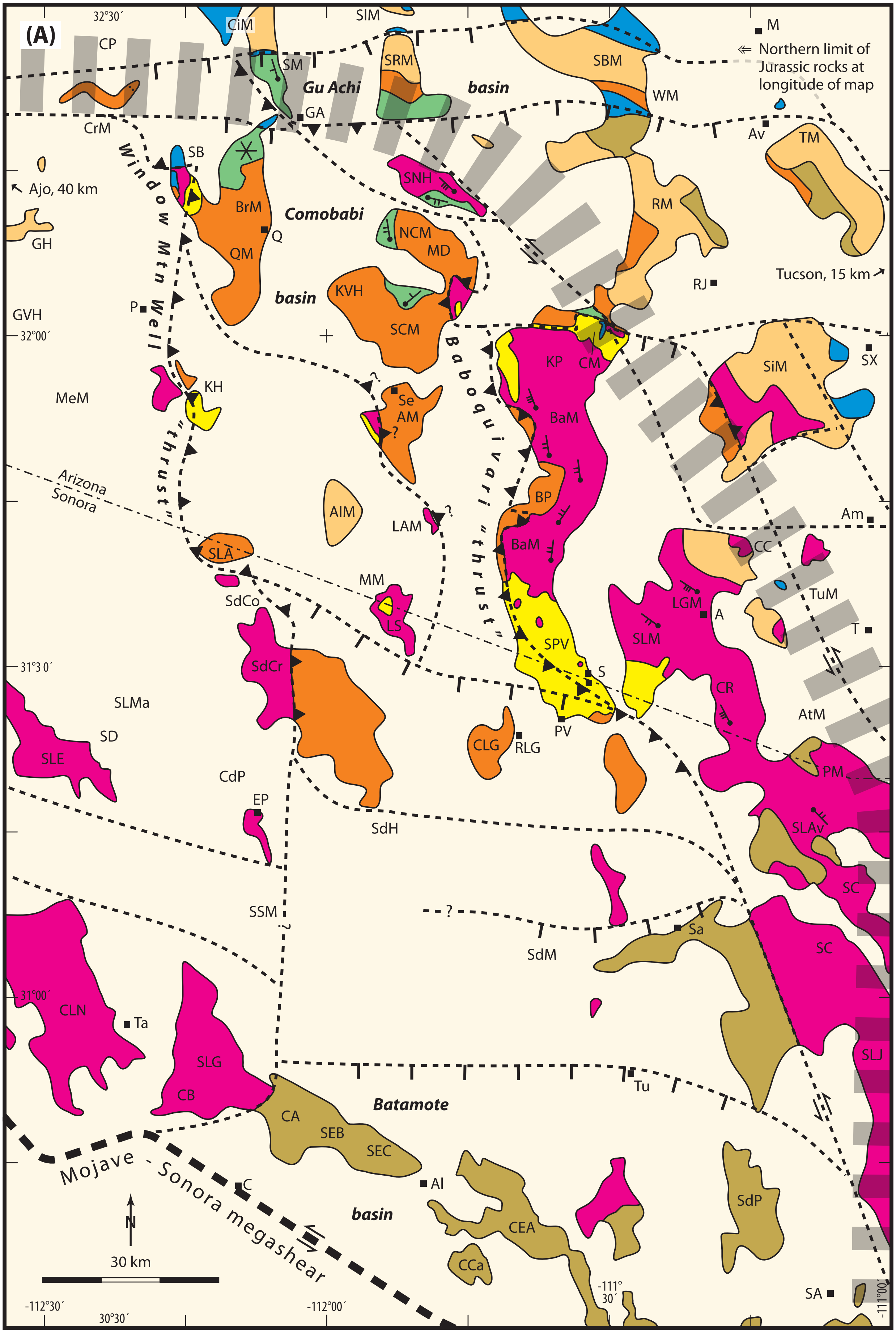
(5) Late Jurassic to Early Cretaceous sedimentary and volcanic rocks, undifferentiated. Older rocks of this unit correlate with units 3 and 4 (Fig. 2B); younger rocks include or correlate with the Early Cretaceous (post-Glance Conglomerate) part of the Bisbee Group. In Sonora, the nonconformity above the Ko Vaya Suite mapped in Arizona has not been recognized. Undated conglomerate and breccia units are widespread. Some may correlate with the latest Jurassic Glance Conglomerate, but others could be as old as latest Middle Jurassic. Several finer-grained sedimentary sequences, largely sandstone and siltstone, are assigned to the Bisbee Group.

(6) Early Paleogene (≈ 58 Ma) peraluminous leucogranites. Though some 40 to 100 m.y. younger than the Jurassic and Cretaceous units (2–5) that define most of the patterns shown in Figure 1, these leucogranites are important because of their close association with latest Cretaceous to early Paleogene thrust or reverse faults (Haxel et al., 1984) that we interpret as reactivated Late Jurassic strike-slip or normal faults. This connection is explained in a subsequent section.

LATE JURASSIC KO VAYA SUITE: DISTRIBUTION, LITHOLOGY, AGE

Four sizable ranges in south-central Arizona—Comobabi, Artesa, Quijotoa, and Brownell Mountains—are composed largely of interrelated Late Jurassic plutonic, hypabyssal, volcanic, and sedimentary rocks (Fig. 2). We refer to this distinctive lithologic assemblage as the *Ko Vaya Suite,* named for the Ko Vaya Hills, an outlier of the Comobabi Mountains. (Our Ko Vaya Suite includes both the plutonic Ko Vaya Superunit and supracrustal Artesa sequence of Tosdal et al., 1989.) Similar rocks crop out in at least nine additional ranges in south-central Arizona and north-central Sonora (Fig. 1). Ko Vaya Suite rocks in the Comobabi, Artesa, and Baboquivari Mountains have been mapped at 1:62,500 (Haxel et al., 1978, 1980, 1982; May and Haxel, 1980). More detailed petrologic

Figure 1 (next two pages). **(A)** Interpretive tectonic map of Late Jurassic faults and basins in south-central Arizona and north-central Sonora, based largely on the distribution of the six key tectonostratigraphic units described in text. Sources: Haxel et al. (1984), Beikman et al. (1995), Richard et al. (2000b), Nourse (2001), Anderson and Nourse (2005), Anderson et al. (2005), Secretaría de Programación y Presupuesto (no date). "Cerros La Garrapata" is an informal term referring to low hills, composed of Ko Vaya Suite supracrustal rocks, southwest of Rancho La Garrapata in northernmost Sonora. In Sonora the gradational eastern boundary of the Papago domain approximately coincides with the southeast edge of the map. The southern boundary of the Papago domain is the Mojave-Sonora megashear. **(B)** Correlation of map units, showing slight temporal overlap of units 3 and 4; and relation between units 3 and 4 (mapped in Arizona and northernmost Sonora) and unit 5 (mapped farther south in Sonora). Ages of period and epoch boundaries after International Commission on Stratigraphy (2008).


(A)
Northern limit of Jurassic rocks at longitude of map
Ajo, 40 km
Tucson, 15 km
Gu Achi
basin
Comobabi
basin
Window Mtn Well "thrust"
Baboquivari "thrust"
Arizona
Sonora
Batamote
basin
Mojave - Sonora megashear
30 km
N
32°30′
32°00′
31°30′
31°00′
30°30′
-112°30′
-112°00′
-111° 30′
-111°00′
CiM
SlM
CP
SM
SRM
SBM
M
WM
CrM
GA
SB
SNH
Av
TM
GH
BrM
Q
QM
NCM
MD
RM
RJ
KVH
GVH
P
SCM
KP
CM
SiM
SX
MeM
KH
Se
AM
BaM
BP
AIM
LAM
Am
SLA
CC
MM
SdCo
LS
LGM
A
TuM
SLM
T
SdCr
SPV
S
CR
SLMa
SD
AtM
SLE
CLG
RLG
PV
PM
CdP
EP
SdH
SLAv
SC
SSM
SdM
Sa
CLN
Ta
SLG
CB
Tu
SLJ
CA
SEB
SEC
C
Al
CEA
SdP
CCa
SA

(A) EXPLANATION

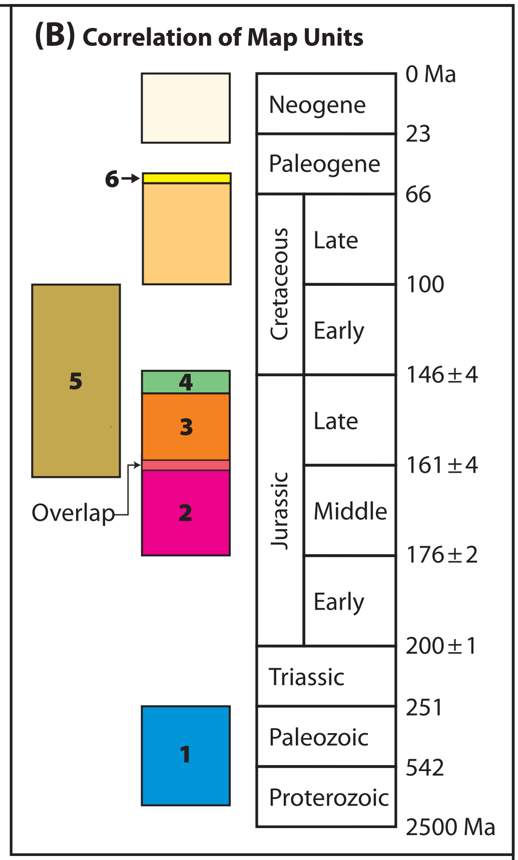
Description of Map Units and Symbols

- Sedimentary, volcanic, subvolcanic and minor plutonic rocks [late Paleogene to Neogene]
- **6** Peraluminous leucogranite [early Paleogene, ≈ 58 Ma]
- Plutonic, volcanic, and sedimentary rocks [Late Cretaceous to early Paleogene]
- **5** Late Jurassic to Early Cretaceous sedimentary and volcanic strata, undifferentiated; including Bisbee Group
- **4** Latest Jurassic (to earliest Cretaceous?) sedimentary and volcanic strata, chiefly Sand Wells Formation and "Gu Achi sequence"; correlative with Glance Conglomerate
- **3** *Ko Vaya Suite*—Late Jurassic synextensional plutonic, hypabyssal, volcanic, and sedimentary rocks [158 – 146 Ma]
- **2** Middle (to earliest Late) Jurassic magmatic arc rocks—plutonic, volcanic, and sedimentary [175 – 159 Ma]
- **1** Pre-Jurassic rocks [Proterozoic, Paleozoic]
- North, northeast, and east boundary of Papago domain; gradational
- Contact: depositional, intrusive, or post–early Paleogene fault

Late Jurassic faults

- Strike-slip fault
- Basin-bounding normal fault; hachures on basin side
- Undifferentiated fault

- Late Jurassic fault reactivated as latest Cretaceous to early Paleogene reverse or thrust fault; barbs point toward hanging wall
- Generalized strike, dip, and facing of sedimentary or volcanic strata: dip ≤ 30°, 30° < dip < 60°, dip ≥ 60°; strike and dip highly variable



Ranges, peaks, towns, villages, and ranches

A	Arivaca	CP	Cimarron Peak	Q	Quijotoa	SiM	Sierrita Mtns
Al	Altar	CrM	Crooked Mtns	QM	Quijotoa Mtns	SlM	Slate Mtns
AlM	Alvarez Mtns	CR	Cobre Ridge	RJ	Robles Junction	SLA	Sierra La Alesna
Am	Amado	EP	El Plomo	RLG	Rancho La Garrapata	SLAv	Sierra Las Avispas
AM	Artesa Mtns	GA	Gu Achi	RM	Roskruge Mtns	SLE	Sierra La Espuma
AtM	Atascosa Mtns	GH	Gunsight Hills	S	Sasabe (AZ and SO)	SLG	Sierra La Gloria
Av	Avra	GVH	Gu Vo Hills	Sa	Saríc	SLJ	Sierra La Joroba
BaM	Baboquivari Mtns	KH	Kupk Hills	SA	Santa Ana	SLM	San Luis Mtns
BP	Baboquivari Peak	KP	Kitt Peak	SB	Sierra Blanca	SLMa	Sierra La Manteca
BrM	Brownell Mtns	KVH	Ko Vaya Hills	SBM	Silver Bell Mtns	SM	Sheridan Mtns
C	Caborca	LAM	Las Animas Mtn	SC	Sierra Cibuta	SNH	Sil Nakya Hills
CA	Cerro Alamo	LGM	Las Guijas Mtns	SCM	South Comobabi Mtns	SPV	Sierra Pozo Verde
CB	Cerro Basura	LS	La Sierrita	SdCo	Sierra de Cobota	SRM	Santa Rosa Mtns
CC	Cerro Colorado	M	Marana	SdCr	Sierra del Cobre	SSM	Sierra San Manuel
CCa	Cerro Carnero	MD	Mt. Devine	SdH	Sierra del Humo	SX	San Xavier
CdP	Cerros del Plomo	MeM	Mesquite Mtns	SdM	Sierra del Mezquital	T	Tumacacori
CEA	Cerros El Amol	MM	Morena Mtn	SdP	Sierra del Picacho	Ta	Tajitos
CiM	Cimarron Mtns	NCM	North Comobabi Mtns	SD	Sierra Durazno	TM	Tucson Mtns
CLG	"Cerros La Garrapata"	P	Pisinimo	Se	Sells	Tu	Tubutama
CLN	Cerros Las Norias	PM	Pajarito Mtns	SEB	Sierra El Batamote	TuM	Tumacacori Mtns
CM	Coyote Mtns	PV	Pozo Verde	SEC	Sierra El Chanate	WM	Waterman Mtns

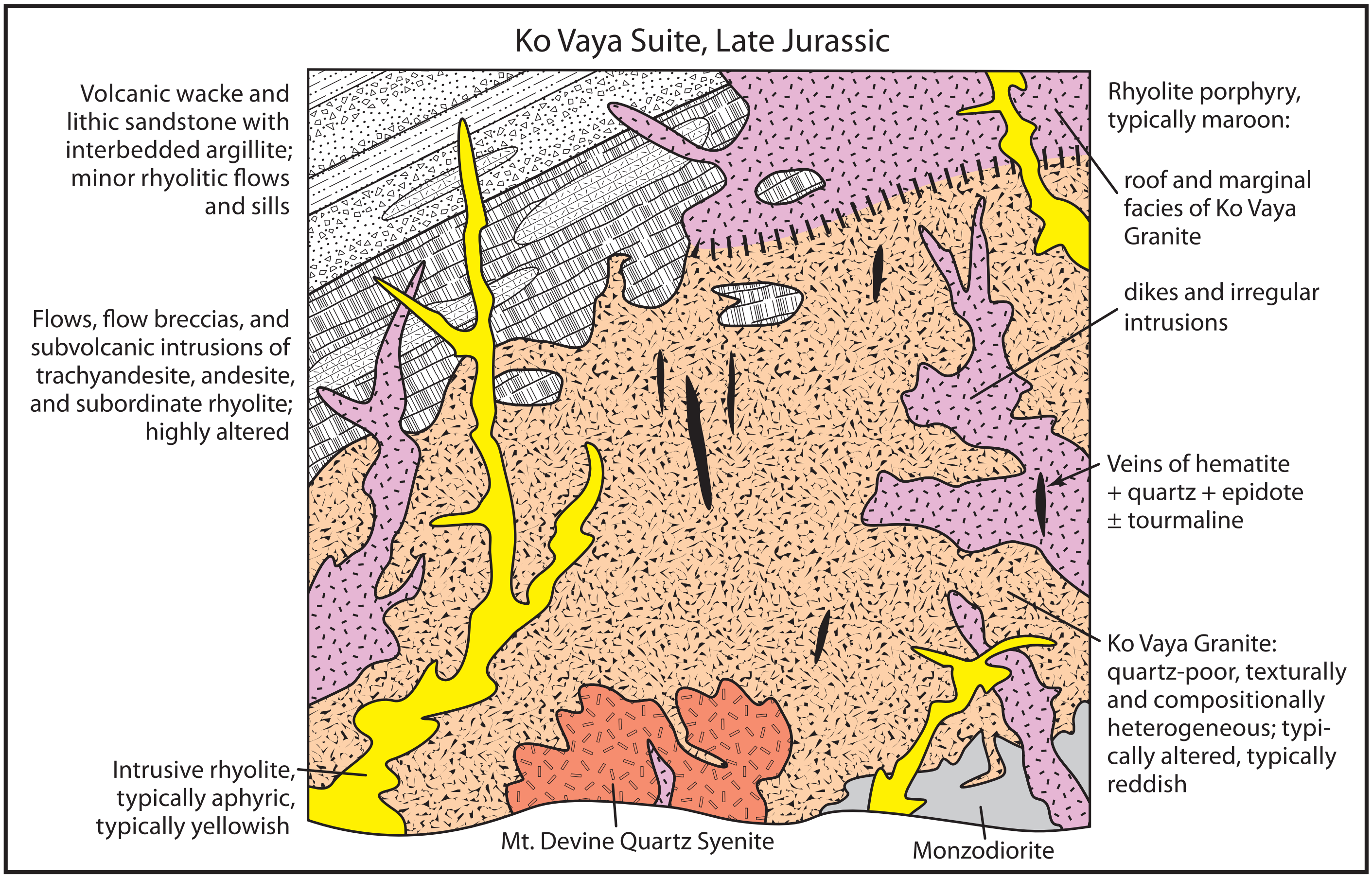


Figure 2. Characteristic lithologic units of the Late Jurassic Ko Vaya Suite and their interrelations (not to scale), based largely on the geology of the Ko Vaya Hills and Comobabi Mountains (Haxel et al., 1978). Hachured line represents gradational contacts between Ko Vaya Granite and rhyolite porphyry (see text). Baboquivari Peak Perthite Granite, not exposed in contact with other members of the Ko Vaya Suite, is not shown.

studies of the Ko Vaya Suite by Briskey and Tosdal have focused on the Ko Vaya Hills and Brownell Mountains, building upon earlier work by MacKallor (1957), Bryner (1959), Williams (1963), and Heindl (1965). In ranges beyond those mentioned, the Ko Vaya Suite has been identified with confidence, owing to its distinctive lithology, but has not been studied in detail (Haxel et al., 1984; Tosdal et al., 1989; Beikman et al., 1995). As the Ko Vaya Suite gradationally spans the entire range from plutonic to hypabyssal to subvolcanic to volcanic, volcaniclastic, and sedimentary, subdivision is somewhat arbitrary. We describe three facies: plutonic, hypabyssal, and supracrustal and subvolcanic, emphasizing those distinctive rock types that are key to recognition of the Ko Vaya Suite.

Plutonic rocks

Many plutonic and hypabyssal rocks of the Ko Vaya Suite are characterized by pronounced heterogeneity, on scales of meters to hundreds of meters. Among the attributes that change from place to place are grain size, quartz content, proportions of plagioclase and alkali feldspar, color index, and texture, which varies from equigranular to porphyritic to micrographic to aplitic. Some of the textural variety is that typical of shallow intrusive rocks, which commonly display gradations from equigranular to porphyritic. Additional compositional and possibly textural complexity have been imposed upon the Ko Vaya Suite by widespread alteration. Even after allowing for both of these factors, however, Ko Vaya Suite plutonic and hypabyssal rocks evidently have an unusual degree of intrinsic heterogeneity. Both MacKallor (1957) and Bryner (1959) before us noted this variability.

Amidst this diversity, one rock type stands out as the central, unifying member of the Ko Vaya Suite: the distinctive Ko Vaya granite. We use Ko Vaya *Granite* to refer to this plutonic rock in its type area, the Ko Vaya Hills and Comobabi Mountains, and Ko Vaya *granite* to refer to similar granitic rocks in other ranges or in all ranges collectively. Ko Vaya Granite is quartz-poor (locally grading to quartz syenite or quartz monzonite; Fig. 3); fine- to coarse-grained; equigranular to porphyritic; leucocratic (color index 0–11 %); and typically pale red, pink, orange, yellow, tan, or brown in outcrop. In some ranges Ko Vaya granite locally includes quartz-poor granodiorite. Abrupt and seemingly random variations in grain size are usual. Dikes or irregular patches of aplite or microgranite are locally abundant. Biotite is more abundant and widespread than hornblende, absent from some rocks.

Both minerals are generally altered to chlorite, iron oxides, and white mica. Plagioclase is generally altered to white mica, alkali feldspar, epidote, and carbonate. In many places alkali feldspar is partially altered to white mica. Quartz and epidote veins are widespread and locally abundant. Two textural variants of Ko Vaya Granite have been mapped separately in the Ko Vaya Hills, and occur in other areas as well: porphyritic granite aplite and granite porphyry. Each, especially aplite, contains areas of intrusion breccia or microbreccia.

Heterogeneous dioritic rocks, probably averaging monzodiorite in composition, are widespread in the South Comobabi and Artesa Mountains, where they are heavily intruded by Ko Vaya Granite and rhyolite porphyry. The dioritic rocks include medium- to coarse-grained diorite, tonalite, monzodiorite, quartz monzodiorite, monzonite, syenodiorite, and quartz monzonite, all with hornblende as the principal mafic mineral; and hornblendite. Most contain minor quartz; some, according to Bryner (1959), contain as much as 30 percent quartz or contain nepheline or cancrinite. Similar dioritic rocks crop out, but have not been mapped separately, in several other ranges.

The Ko Vaya Suite also includes a type of plutonic rock unusual in Arizona and Sonora: perthite granite and quartz syenite. Baboquivari Peak Perthite Granite (BPPG) makes up a stock about 10 km across centered on the eponymous peak (Haxel et al., 2005, 2008). Similar plutonic rock, of uncertain extent, crops out east of Sierra del Cobre. Mt. Devine Quartz Syenite (MDQS) forms a small stock in the North Comobabi Mountains. These perthite-rich rocks range from quartz perthite syenite to perthite granite or to quartz syenite, and in some places contain sodic amphibole — hastingsite or arfvedsonite. Both units are leucocratic, medium- to coarse-grained, and typically red to brown in outcrop. Each is fairly homogeneous, lacking the variability characteristic of Ko Vaya granite. Silicification and intense alteration of mafic minerals is common in BPPG, much less so in MDQS.

Hypabyssal rocks

The third most distinctive member of the Ko Vaya Suite, after the Ko Vaya granite and the perthite-rich granitoids, is the "maroon porphyry" (of Bryner, 1959). This rhyolite porphyry is characterized by conspicuous, abundant phenocrysts of alkali feldspar, plagioclase, or both, with smaller phenocrysts of partially resorbed bipyramidal quartz. Groundmass and overall rock color are typically some shade of maroon. In some areas, particularly the North Comobabi Mountains, this porphyry forms a gradational border or roof facies of the Ko Vaya Granite. In other places, dikes or irregular intrusions of porphyry invade Ko Vaya granite. A few mapped bodies of maroon porphyry in the Comobabi Mountains have complex partially gradational and partially intrusive relations with the granite.

The youngest member of the Ko Vaya Suite is aphyric to sparsely porphyritic rhyolite that intrudes all other members (Fig. 2). Compared to the maroon porphyry this rhyolite is much lighter colored, typically yellowish in outcrop; has fewer and smaller phenocrysts; and has consistent intrusive relations to Ko Vaya granite. In many areas the archaic term "felsite", first applied by MacKallor (1957), is apt. Rhyolite dikes are commonly flow banded, with fine-grained margins. In the Ko Vaya Hills the rhyolite contains possibly magmatic muscovite. In several ranges, the rhyolite contains sparse pyrite or other sulfides, and is typically the youngest rock in that range that does. Both the aphyric intrusive rhyolite and the maroon porphyry are pervasively altered, to mineral assemblages similar to those in Ko Vaya Granite.

Supracrustal and subvolcanic rocks.

Stratigraphic thicknesses of Ko Vaya Suite supracrustal sections are locally as much as about 2 km. These strata include the Nolia Volcanic and Roadside Formations of Heindl (1965). In several ranges, particularly the Comobabi Mountains and Ko Vaya Hills, volcanic rocks predominate, typically with sparse sedimentary lenses or interbeds, mostly volcaniclastic. In a few ranges, notably the Artesa Mountains and Cerros La Garrapata (Fig. 1, caption), supracrustal sections are largely sedimentary but include some interlayered volcanic rocks and subvolcanic sills, mostly rhyolitic, less commonly andesitic.

The most abundant volcanic and subvolcanic rocks are flows, flow breccias, dikes, sills, small irregular intrusions, and intrusion breccias of trachyandesite and andesite (or basalt). Flows, flow breccias, and shallow intrusions of rhyolite and trachyte also are common, but subordinate in volume to andesitic rocks. Rhyolitic welded tuff is locally abundant but uncommon overall. Dacitic rocks are rare. In most rocks both phenocrysts and groundmass are strongly altered, typically to various combinations of white mica, alkali feldspar, carbonate, iron oxides, chlorite, quartz, and epidote. Amygdules of some of these minerals also are widespread. Among the volcanic rocks of the Ko Vaya Suite, the "amygdaloidal andesite" (of Bryner, 1959) is the most distinctive, particularly where it contains abundant spheroidal epidote amygdules $\approx$ 0.5–3 cm in diameter. In the Artesa Mountains, andesite is largely converted to greenstone.

The thickest sedimentary sections known crop out in the Artesa Mountains and Cerros La Garrapata. The Artesa section is deformed and slightly metamorphosed, rendering its thicknesses uncertain, but it is at least several hundred meters thick. The apparently undeformed and homoclinal Garrapata section (which has not been mapped) probably is considerably thicker. Sedimentary rocks include several types of sandstone, siltstone or argillite, conglomerate, and minor limestone (Heindl, 1965; May and Haxel, 1980). Well-bedded, immature conglomerate to sedimentary breccia, volcanic wacke, and lithic sandstone are particularly characteristic and widespread. Reddish to purplish colors predominate; metamorphosed strata become grayish. Much of the coarser detritus is intraformational, derived from other Ko Vaya Suite

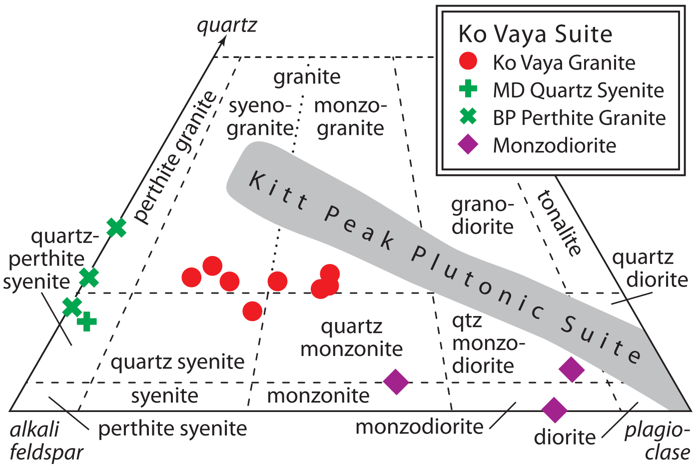


Figure 3. Modal compositions of plutonic rocks of the Late Jurassic Ko Vaya Suite. Samples, except BP Perthite Granite, are from the Ko Vaya Hills and Comobabi Mountains. Coarser-grained rocks were point counted using polished slabs and finer-grained rocks using thin sections, both stained for alkali feldspar. Data for Ko Vaya Granite includes porphyritic and aplitic facies (see text). The three data points for monzodioritic rocks do not represent the full range of composition of this unit (see text). MD, Mt. Devine; BP, Baboquivari Peak.

volcanic and sedimentary rocks. Clasts derived from nearby Proterozoic and Paleozoic rocks are locally abundant.

Interrelations of volcanic and intrusive rocks

In the Ko Vaya Hills, volcanic and intrusive rocks are linked by close spatial association and by mutually intrusive relations. At several localities, volcanic flows are intruded by granite porphyry (a facies of Ko Vaya Granite), which in turn is intruded by small dikes virtually identical to the flows. Furthermore, local breccia dikes within Ko Vaya Granite contain fragments of the host plutonic rock in a matrix closely resembling nearby volcanic rocks. These relations indicate magmas that erupted as volcanic rock and those that crystallized as plutonic rock were contemporaneous.

Several features common in the Ko Vaya Hills evince shallow emplacement of hypabyssal and plutonic rocks: porphyritic textures, micrographic (granophyric) textures, brecciation within intrusive bodies and along contacts, angular vugs within breccias, intrusions with sharp contacts and fine-grained margins, absence of appreciable contact metamorphic effects, bipyramidal quartz, and miarolitic cavities. In a few places masses of vesicular rock, about 3 m long, are found within granite porphyry. The vesicular rock has fine-grained margins and is apparently identical to surrounding lava flows. These masses evidently derive from small subvolcanic dikes that fed adjacent flows, again implying shallow emplacement of the granite porphyry.

Taken together, these field relations indicate that the igneous rocks of the Ko Vaya Hills are all broadly coeval and represent a volcanic pile and underlying, closely related subvolcanic to hypabyssal to shallow plutonic intrusions. Gradations between rhyolite porphyry and Ko Vaya Granite, observed several places in the main Comobabi Mountains, serve to further unite the hypabyssal and plutonic rocks. Similar though less detailed observations in other ranges show that this conclusion is generally applicable: Ko Vaya granite, rhyolite porphyry, and associated volcanic rocks constitute one or a few coherent plutonic-volcanic complexes.

Less common members of the Ko Vaya Suite are linked to the Ko Vaya Granite and rhyolite porphyry by association and composition. In the Artesa and South Comobabi Mountains, monzodiorite is intricately intermixed, on a map scale, with Ko Vaya Granite and rhyolite porphyry. In places heterogeneous rocks of the monzodiorite unit appear to grade into Ko Vaya Granite (Bryner, 1959). MDQS forms a single stock surrounded and intruded by Ko Vaya Granite and rhyolite porphyry. Only BPPG is not exposed in contact with other members of the Ko Vaya Suite. We include BPPG because of its obvious similarity to MDQS, and the regional uniqueness of these two unusual rocks. After mapping the Ko Vaya Hills and Comobabi Mountains, we were uncertain whether the young, aphyric to sparsely porphyritic intrusive rhyolite is a member of the Ko Vaya Suite or the association is coincidental. Over the next several years we repeatedly found similar rhyolite intruding rocks of the Ko Vaya Suite in other ranges, and so eventually concluded that the rhyolite must belong to the Suite. However this rhyolite may be less closely related to the other members of the Ko Vaya Suite than they are to one another.

Hematite veins

In the Quijotoa, Brownell, and Santa Rosa Mountains, altered plutonic and hypabyssal rocks of the Ko Vaya Suite host scattered to locally abundant hematite veins (Gebhardt, 1931; Williams, 1960; Harrer, 1964; Keith, 1974; Rytuba and others, 1978). Hematite, typically massive or specular, is accompanied by various combinations of magnetite (locally lodestone), epidote, quartz, and, less commonly, tourmaline. Several subvertical veins (or groups of closely spaced, subparallel veins) in the eastern Quijotoa Mountains are large, as much as 50–150 m thick and 2 km long. Veins in the Brownell Mountains are accompanied by hematite breccia pipes. In some ranges hematite veins are clearly related to Ko Vaya granite or rhyolite porphyry; in other ranges possibly to the aphyric rhyolite unit.

Age of the Ko Vaya Suite

Perthite granite east of Sierra del Cobre, petrographically similar to BPPG, has a concordant U-Pb interpreted age of 149 Ma (Anderson and Silver, 1978; Anderson et al., 2005). Wright determined U-Pb isotopic ages, by thermal-ionization mass spectrometry, of zircon from four Ko Vaya Suite plutons in Arizona (Table 1). Isotopic ratios of zircon from MDQS and BPPG are marginally normally discordant—for each unit the

Table 1. TIMS U-Pb isotopic ages of zircon from plutons of the Ko Vaya Suite, Comobabi, Baboquivari, and Santa Rosa Mountains, southern Arizona {1}.

Unit {2}	Sample	Size fraction {3}	Concentration (µg/g) {4}		Observed ratios {5}			Atomic ratios {6}			Apparent ages (Ma) {7, 8}		
			U	$^{206}Pb^*$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{235}U$	$^{207}Pb^*/^{206}Pb^*$	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{235}U$	$^{207}Pb^*/^{206}Pb^*$
MDQS	PUP 5	<200	195.2	4.31	602	0.07405	0.19490	0.02496	0.17016	0.04962	158.6	159.5	177.0
BPPG	PUP 19	<200	371.9	7.35	1316	0.060456	0.15894	0.02300	0.15634	0.04930	146.6	147.5	162.1
KVG	PUP 4	<200	506	11.77	575	0.07459	0.27906	0.02621	0.17723	0.049035	166.8	165.7	149.5
KVg	PUP 24	total	437	10.37	568.2	0.051645	0.14988	0.02762	0.18682	0.04906	175.6	173.9	150.8

{1} TIMS, thermal-ionization mass spectrometry. Pb* denotes radiogenic Pb. Analytical methods: Wright (1981).
{2} MDQS, Mt. Devine Quartz Syenite, North Comobabi Mountains (Haxel et al., 1978); BPPG, Baboquivari Peak Perthite Granite, Baboquivari Mountains (Haxel et al., 1980, 2005, 2008); KVG, Ko Vaya Granite, North Comobabi Mountains; KVg, Ko Vaya granite, Santa Rosa Mountains (Bergquist et al., 1978, unit Mz gd).
{3} Mesh. Analyzed zircon fractions 10–25 mg.
{4} Estimated precision 0.25 %.
{5} Precision: $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$, ≤0.10 %; $^{206}Pb/^{204}Pb$, ≤1.0 %.
{6} Total Pb blanks 0.2–0.5 ng. Common Pb corrections: $^{206}Pb/^{204}Pb$ = 18.6, $^{207}Pb/^{204}Pb$ = 15.6, $^{208}Pb/^{204}Pb$ = 38.0.
{7} Decay constants (Steiger and Jäger, 1977): ^{235}U, 0.98485•10^{-9} yr^{-1}; ^{238}U, 0.155125•10^{-9} yr^{-1}; $^{238}U/^{235}U$ = 137.88.
{8} Estimated errors: $^{206}Pb^*/^{238}U$ apparent age, ±0.3 % (~0.5 m.y.); $^{207}Pb^*/^{235}U$ apparent age, ±0.7 % (~1 m.y.).

$^{206}Pb^*/^{238}U$ apparent age is less than the $^{207}Pb^*/^{235}U$ apparent age by 0.9 m.y. The best estimate of the age of each pluton is its $^{206}Pb^*/^{238}U$ apparent age. If marginal discordance is attributed to slight inheritance of Proterozoic radiogenic lead (Anderson and Silver, 1977), the ages are decreased by about 1 or 2 m.y. We estimate MDQS is 158 ± 3 Ma and BPPG 146 ± 3 Ma.

Pb*/U isotopic ratios of zircon from two samples of Ko Vaya granite are reversely discordant ($^{206}Pb^*/^{238}U$ apparent age > $^{207}Pb^*/^{235}U$ apparent age) and probably meaningless, owing to analytical problems (caused by the Santa Barbara earthquake of August, 1978). The only available estimate of the age of Ko Vaya Granite is then the two essentially identical $^{207}Pb^*/^{206}Pb^*$ apparent ages, 150 and 151 Ma. Provisionally, we suggest the Ko Vaya granite is roughly 150 Ma.

Although these five single-fraction U-Pb zircon ages, determined circa 1970–1978, are imperfect by current standards, they are consistent with one another and with all geologic constraints. The two petrographically similar perthite granites, one in Sonora and one in Arizona, dated independently at different laboratories, have virtually identical interpreted U-Pb ages (149, 146 Ma). The provisional age of the Ko Vaya Granite (~150 Ma) is younger than the interpreted age of MDQS (158 Ma), as required by intrusive relations. Both units are no younger than an amphibole K-Ar date of 140 Ma (J.G. Smith, written communication, 1978), as expected. Plutonic rocks of the Ko Vaya Suite intrude the Middle Jurassic (170 Ma) Topawa Group in the Baboquivari Mountains (Haxel et al., 2005), and are intruded by Late Cretaceous plutons in the Santa Rosa Mountains (Bergquist et al., 1978; Briskey et al., 1978). As described in a subsequent section, Ko Vaya Granite is nonconformably overlain by conglomerate of very probable latest Jurassic age. Thus, all available isotopic and geologic data indicate the Ko Vaya Suite is Late Jurassic. Volcanic rocks in southeast and western Arizona in tectonic settings similar to that of the Ko Vaya Suite yield remarkably similar dates, 154–146 Ma, by Rb-Sr, K-Ar, and U-Pb methods (Marvin et al., 1978; Kluth et al., 1982; Krebs and Ruiz, 1987; Asmerom et al., 1990; Spencer et al., 2005).

PETROCHEMISTRY OF KO VAYA SUITE IGNEOUS ROCKS

Our reconnaissance study of the petrochemistry of the Ko Vaya Suite is based on analyses of 70 samples, apportioned among the several lithologic units as shown in Figure 4. About one-half of the samples are Ko Vaya granite, the single most extensive unit. Monzodiorite and mafic volcanic rocks (most highly altered) are underrepresented. About one-half of the samples are from the Ko Vaya Hills and Comobabi Mountains; and another one-quarter from the Artesa, Quijotoa, Brownell, and Baboquivari Mountains. The remainder come from nine other ranges in Arizona and one range in Sonora.

As shown by geologic maps of the Comobabi and Artesa Mountains and Ko Vaya Hills (Haxel et al., 1978; May and Haxel, 1980), the Ko Vaya Suite is dominated by mafic rocks—andesitic volcanics and monzodiorite—and by silicic rocks—granite and rhyolite porphyry. Intermediate rocks are sparse, limited to minor trachytic volcanic rocks and local granodioritic variants of Ko Vaya granite. Despite imperfect sampling and widespread alteration (considered in the next section), the bimodal character of the Ko Vaya Suite is apparent in histograms of SiO_2 (Fig. 5A, B). The histogram for the Ko Vaya Hills (Fig. 5A) most closely represents the true proportion of rock types (though mafic volcanic rocks were undersampled).

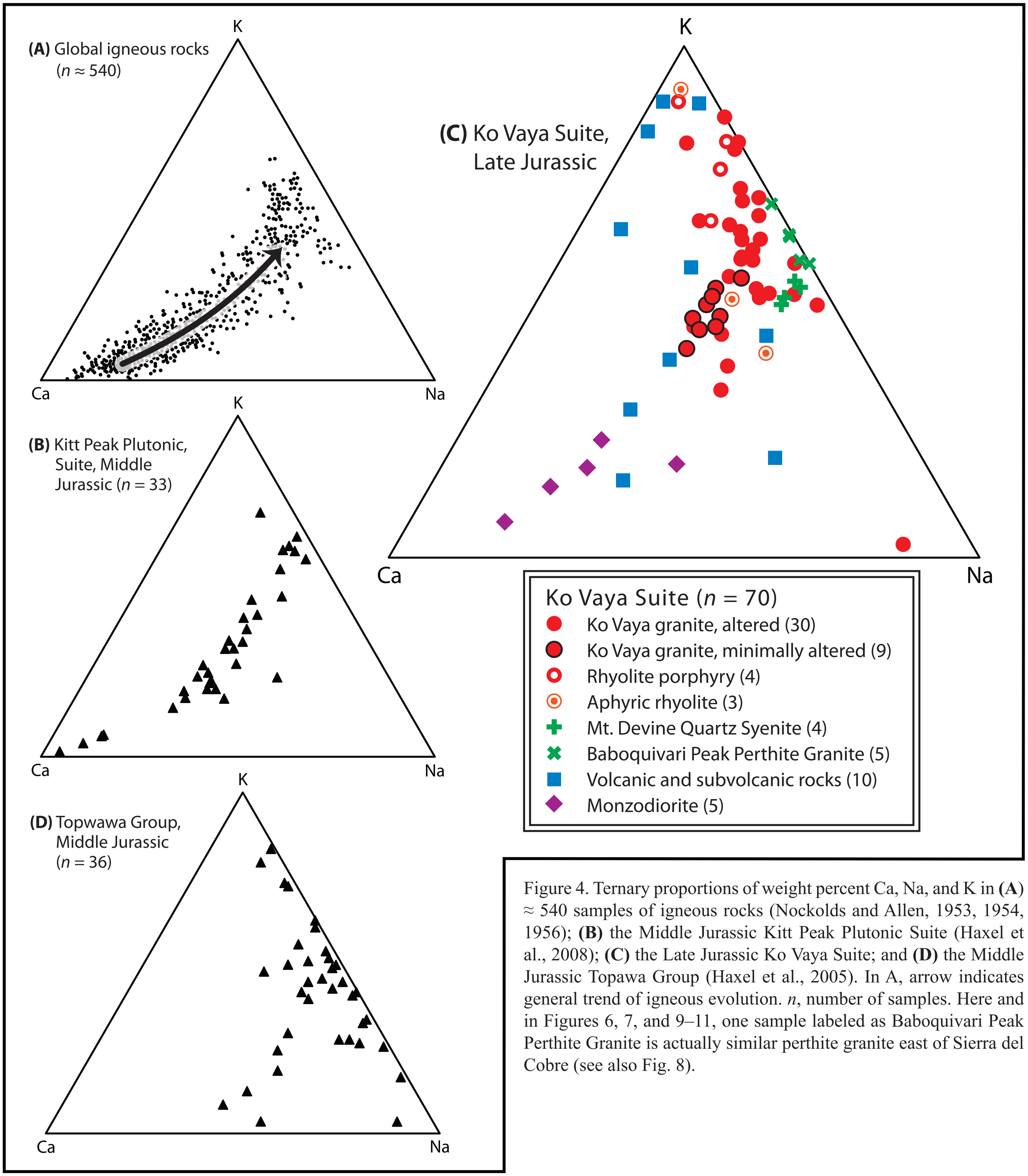
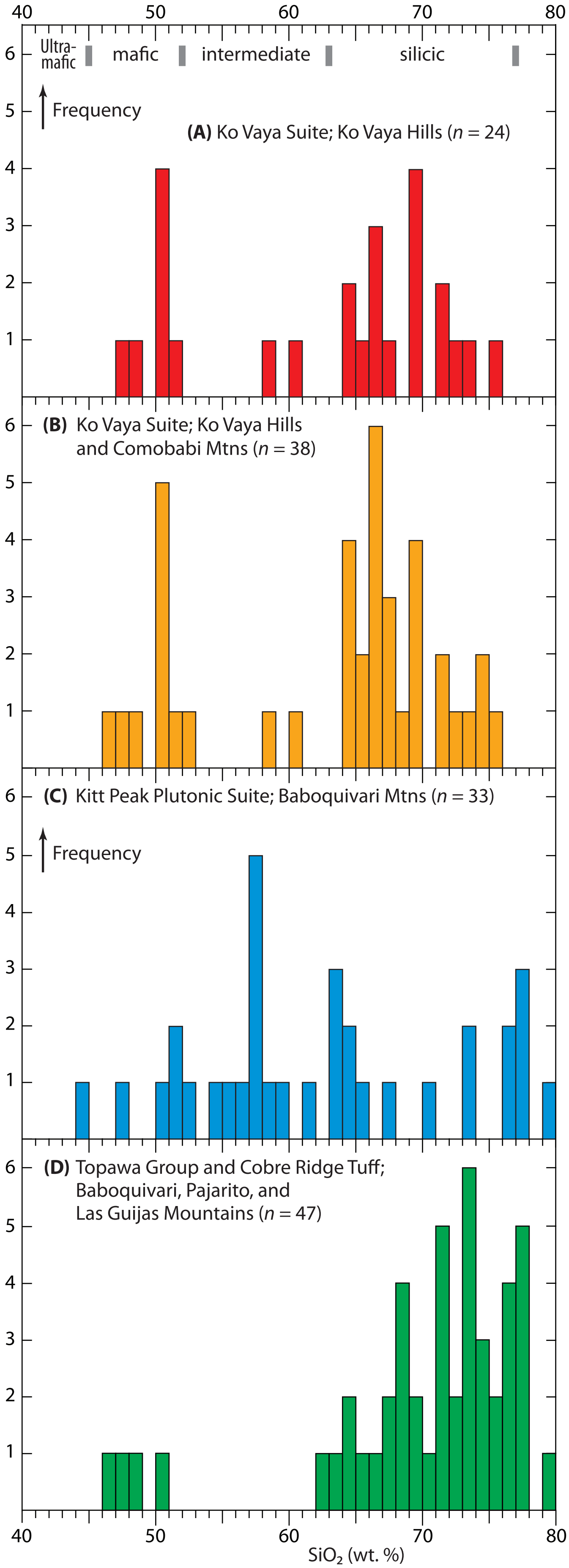


Figure 4. Ternary proportions of weight percent Ca, Na, and K in **(A)** ≈ 540 samples of igneous rocks (Nockolds and Allen, 1953, 1954, 1956); **(B)** the Middle Jurassic Kitt Peak Plutonic Suite (Haxel et al., 2008); **(C)** the Late Jurassic Ko Vaya Suite; and **(D)** the Middle Jurassic Topawa Group (Haxel et al., 2005). In A, arrow indicates general trend of igneous evolution. *n*, number of samples. Here and in Figures 6, 7, and 9–11, one sample labeled as Baboquivari Peak Perthite Granite is actually similar perthite granite east of Sierra del Cobre (see also Fig. 8).



Alteration

At the time of our earlier synthesis (Tosdal et al., 1989), we had not fully appreciated the alteration of the igneous rocks of the Ko Vaya Suite. Recognition of the extent of this alteration was in part prompted by the work of Fox (1989; Fox and Miller, 1990) on similar Jurassic rocks in California.

Alteration of the Ko Vaya Suite is highlighted by comparison with the minimally altered Middle Jurassic Kitt Peak Plutonic Suite (KPPS), of the Baboquivari Mountains (Haxel et al., 2008). Effects of alteration of igneous rocks are evident in Ca-Na-K systematics, as indicated by ternary proportions of these three elements (Fig. 4). Minimally altered igneous suites in general, including tholeiitic, calcalkaline, and alkaline types,

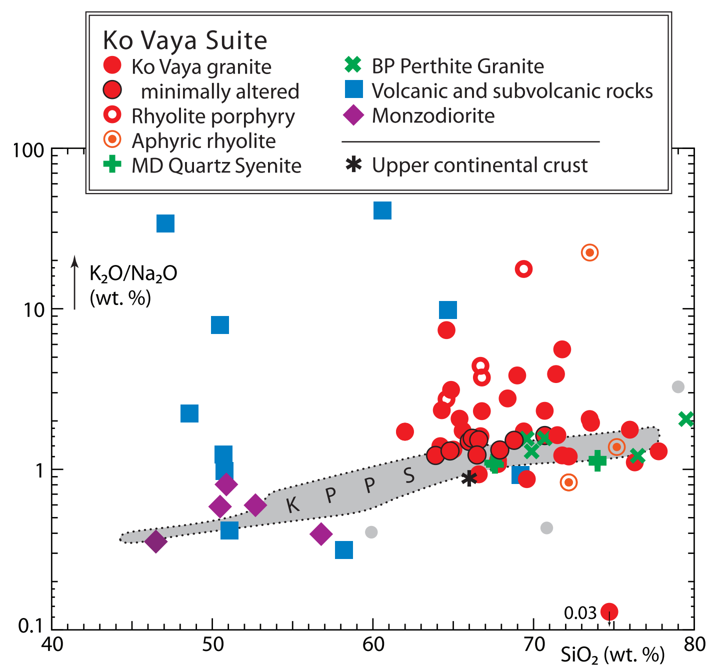


Figure 6. Variation of SiO_2 and K_2O/Na_2O in the Late Jurassic Ko Vaya Suite, compared with that in the Middle Jurassic Kitt Peak Plutonic Suite (KPPS; gray field and three outlying points). One data point for Ko Vaya granite plots below this graph, at $K_2O/Na_2O \approx 0.03$. MD, Mt. Devine; BP, Baboquivari Peak. Composition of upper continental crust from McLennan (2001).

Figure 5 (left). Histograms of SiO_2 for samples from **(A, B)** the two best documented areas of the Late Jurassic Ko Vaya Suite, the Ko Vaya Hills and Comobabi Mountains (Haxel et al., 1978; May and Haxel, 1980); and from **(C)** Middle Jurassic Kitt Peak Plutonic Suite (KPPS) (Haxel et al., 2008) and **(D)** Middle Jurassic Topawa Group, Cobre Ridge Tuff, and related granite (Kerr, 1946, p. 24; Riggs, 1987; Haxel et al., 2005). One-half the KPPS samples have $53 < SiO_2 < 66$ percent. Among Ko Vaya Suite samples, mafic rocks—trachyandesitic volcanics and monzodiorite—are underrepresented. For the KPPS, mafic and ultramafic rocks ($45 \leq SiO_2 \leq 52$ %) are overrepresented, relative to their small outcrop area (Haxel et al., 2008, Fig. 2). Boundaries of ultramafic, mafic, intermediate, and silicic compositions after Le Maitre (2002).

follow slightly arcuate paths extending from the Ca corner toward the Na-K side. With the exception of a couple of aberrant samples, the rocks of the KPPS follow such a trend. Correspondingly, the KPPS shows a restricted range of K_2O/Na_2O and a smooth progression of gently increasing K_2O/Na_2O with increasing SiO_2 (Fig. 6). This regular chemical trend (and many others not shown) accord with petrographic evidence of minimal alteration in most KPPS samples.

In contrast, the Ca-Na-K plot for the Ko Vaya Suite displays much more scatter, with a distinct turn toward potassic compositions along the Na-K side (Fig. 4C). Values of K_2O/Na_2O do not correlate with SiO_2, and span the thousandfold range from 0.03 to 40 (Fig. 6). Even if a few extreme values are excluded, K_2O/Na_2O varies from 0.3 to 10, with most samples in the range 0.6–6. These ranges are far too wide to represent primary (magmatic) values within one or a few suites of related igneous rocks (Le Maitre, 1976; Cox et al., 1979; Bergman, 1987). Furthermore, very few unaltered igneous rocks have $K_2O/Na_2O > 2$. Uncommon to rare potassic to ultrapotassic rocks have greater K_2O/Na_2O, but none of the members of the Ko Vaya Suite possess any of the unusual mineralogic features of such rocks (Bergman, 1987; Mitchell and Bergman, 1991; Rock, 1991). So, we infer that the present highly potassic character of many Ko Vaya Suite igneous rocks is not primary.

Further evidence for the altered condition of the Ko Vaya Suite comes from oxidation ratios—the ratio of ferric to total iron, Fe_2O_3/Fe_2O_3*. Figure 7 shows oxidation ratios of four sets of plutonic rocks: Mesozoic and Cenozoic plutons (mostly granitic) in the western United States, Phanerozoic granitoids in Australia and Japan, KPPS, and the Ko Vaya Suite. None of the Australian and Japanese granitoids, only 10 percent of western U.S. samples, and only 9 percent of KPPS samples have oxidation ratios > 0.65. Highly oxidized rocks can be considered those with $Fe_2O_3/Fe_2O_3* > 0.65$. By this criterion 59 percent of the Ko Vaya Suite samples are highly oxidized. In fact, one-third of the Ko Vaya Suite samples are extremely (fully) oxidized, with $Fe_2O_3/Fe_2O_3* = 0.95–1.0$. Confirmation that these high oxidation ratios are not primary comes from the rare earth element spectra of BPPG (the only Ko Vaya Suite unit for which we have REE data). Four of five samples of BPPG are now extremely oxidized, but REE spectra of all samples show pronounced negative Eu anomalies (Fig. 8), signifying original crystallization under reduced conditions (such that Eu was partially divalent). Finally, we note that Fe_2O_3/Fe_2O_3* correlates with K_2O/Na_2O (Fig. 9), supporting our inference that abnormally high values of K_2O/Na_2O owe to alteration.

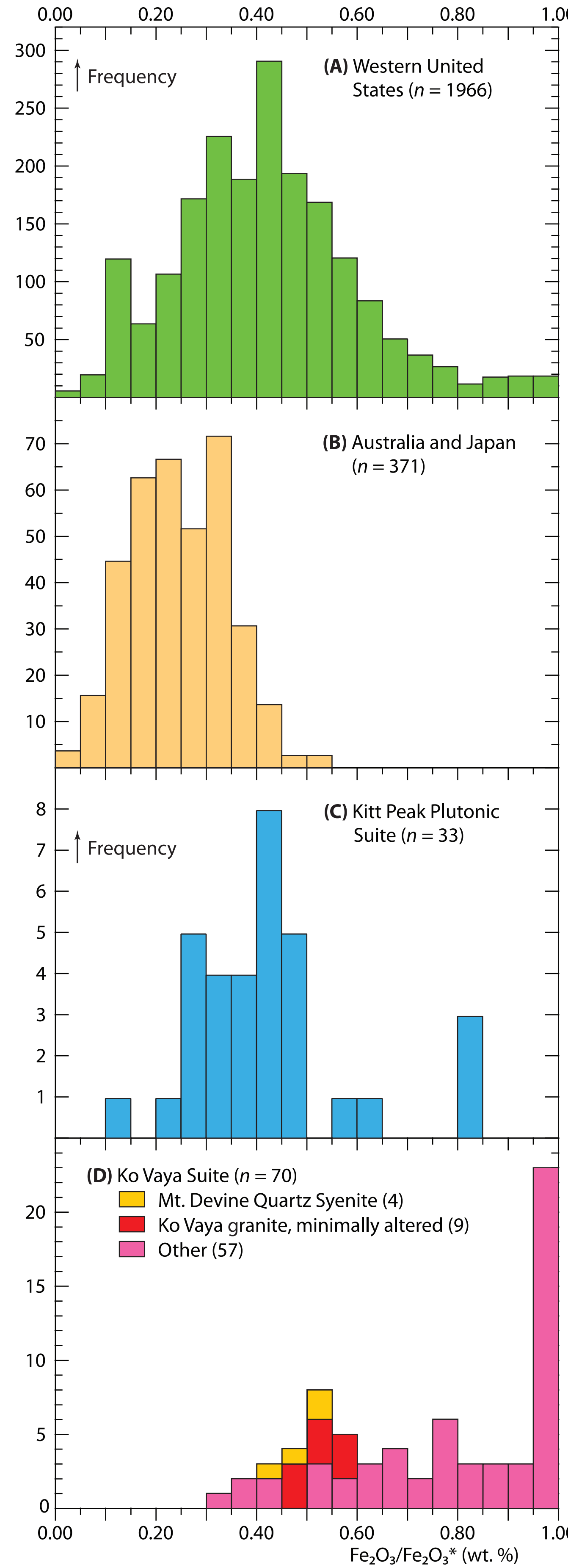


Figure 7. Distribution of oxidation ratios, Fe_2O_3/Fe_2O_3*, in Mesozoic and Cenozoic (0–200 Ma) plutonic rocks, mostly granitic, in the western United States (NAVDAT; see acknowledgements); Phanerozoic granitoids in Australia and Japan (Takahashi and others, 1980); Middle to Late Jurassic Kitt Peak Plutonic Suite (Haxel et al., 2008); and Late Jurassic Ko Vaya Suite. Fe_2O_3* denotes total iron as Fe_2O_3.

On a graph of Na_2O versus K_2O, most ordinary intermediate to silicic plutonic rocks plot within a subvertical array that spans a wider range of K_2O than Na_2O (probably because K is more incompatible than Na) (Fig. 10A). KPPS plots within this array, as expected. The Ko Vaya Suite data cluster in the upper part of the "normal array", but about one-third of the samples have significantly higher K_2O and lower Na_2O (Fig. 10B). A few samples plot below the main cluster. Figure 10C shows that nearly all Ko Vaya Suite rocks conform to a simple pattern—they plot within or near a diagonal band representing semiconstant molar K_2O+Na_2O. This pattern suggests that alteration of the Ko Vaya Suite involved alkali exchange (Johnson, 2000). Such alteration is common in Jurassic igneous terranes in the Great Basin and southern California (Johnson and Barton, 1997; Johnson, 2000; Barton et al., 2000), and has been observed several places in Early or Middle Jurassic volcanic and hypabyssal rocks in southern Arizona (Drewes, 1971; Riggs, 1987; Haxel et al., 2005). In Jurassic hydrothermal systems potassic alteration takes place at shallower levels, and sodic alteration at deeper levels, of the upper crust (Battles and Barton, 1995; Barton and Johnson, 1996). Such zonation would explain the preponderance of potassic alteration in the Ko Vaya Suite, generally exposed at high crustal levels.

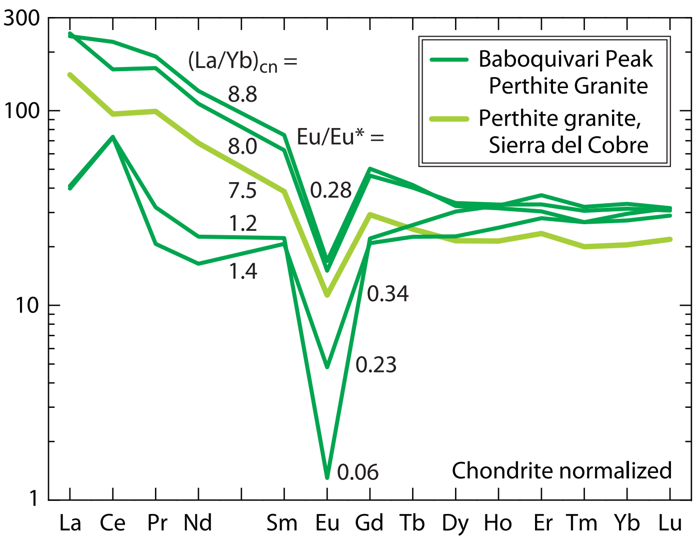


Figure 8. Chondrite-normalized (Nakamura, 1974) rare earth element spectra of Baboquivari Peak Perthite Granite and similar perthite granite east of Sierra del Cobre. Slight to moderate positive or negative Ce anomalies suggest oxidation of cerium to Ce^{4+} during alteration, so that Ce behaved differently from trivalent La and Pr. Eu* designates Eu interpolated between Sm and Gd: $Eu^* = 0.325\sqrt{(Sm \times Gd)}$, for concentration of Sm and Gd in µg/g. The two upper spectra both have Eu/Eu* = 0.28. All 14 stable lanthanides were determined, by inductively-coupled-plasma–mass spectrometry (Haxel et al., 2008, Appendix).

Identification and character of minimally altered granitic rocks

Although many samples of Ko Vaya granite have abnormal K_2O/Na_2O, clearly attributable to alteration (Figs. 8, 9), about one-half of the granite samples cluster in the upper (high-K_2O) part of the field of "normal" intermediate to silicic plutonic rocks (Fig. 10B). Among the samples that plot in this cluster, nine are special in that they appear to be minimally altered, meeting all five of these criteria: (1) $4.0 < K_2O < 6.0$, (2) $3.0 < Na_2O < 4.0$, (3) $1.0 < K_2O/Na_2O < 2.0$, (4) $Fe_2O_3/Fe_2O_3^* < 0.60$, and (5) molar $Al_2O_3/(CaO+Na_2O+K_2O) < 1.05$. These samples all have similar compositions, even for highly mobile trace elements susceptible to redistribution by alteration, such as Sr and Ba (Fig. 11). We infer that these nine minimally altered rocks (identified separately on our geochemical diagrams) most closely approximate the original, pre-alteration composition of Ko Vaya granite. Most are from the Comobabi, Brownell, or Santa Rosa Mountains.

Petrographically, MDQS is unusual in that it is less altered than most Ko Vaya granite, and much less altered than BPPG. Four of five samples of BPPG are extremely oxidized,

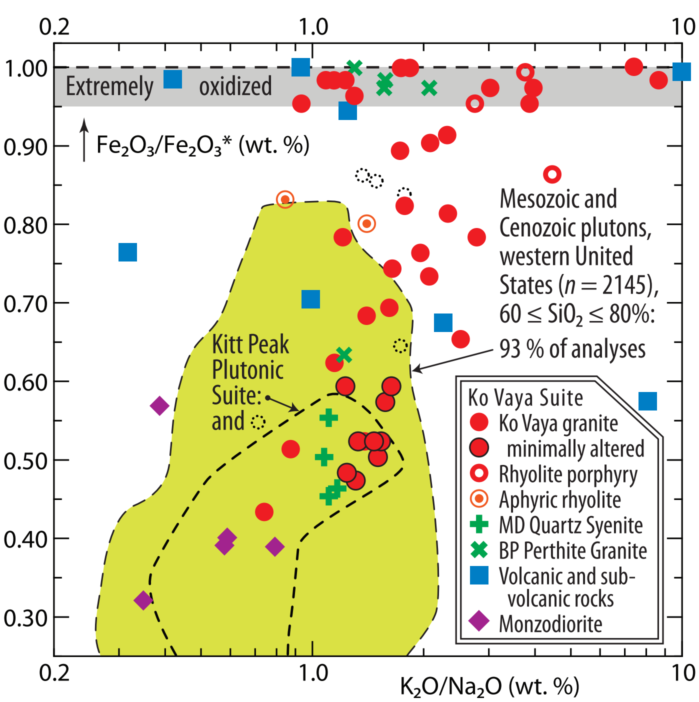


Figure 9. Covariation of K_2O/Na_2O and $Fe_2O_3/Fe_2O_3^*$ in the Late Jurassic Ko Vaya Suite. Yellowish-green field includes 93 percent of analyses of Mesozoic and Cenozoic (0–200 Ma) plutonic rocks with $60 \le SiO_2 \le 80$ weight percent in the western United States (NAVDAT; see acknowledgements) (2145 samples). The Kitt Peak Plutonic Suite is represented by the heavy dashed outline and four outlying data points with dotted outlines. One data point for Ko Vaya granite plots to the left of this graph, at $K_2O/Na_2O \approx 0.03$. Four data points—two volcanic-subvolcanic rocks, one rhyolite porphyry, and one aphyric rhyolite—plot to the right of this graph, at $K_2O/Na_2O \sim 20–30$ and $Fe_2O_3/Fe_2O_3^* \approx 0.80–0.95$. MD, Mt. Devine; BP, Baboquivari Peak.

whereas all four samples of MDQS have normal oxidation ratios, < 0.55 (Fig. 7D). We believe that these four samples reasonably represent the primary composition of MDQS.

Identification of these 13 minimally altered rocks (Ko Vaya granite, 9; MDQS, 4) allows us to ascertain the magmatic composition of the silicic plutonic rocks of the Ko Vaya Suite (Table 2). In the standard silica-"total alkalis" (Na_2O+K_2O) diagram for the classification of volcanic rocks (Le Maitre, 2002), the Ko Vaya plutons have the composition of trachyte

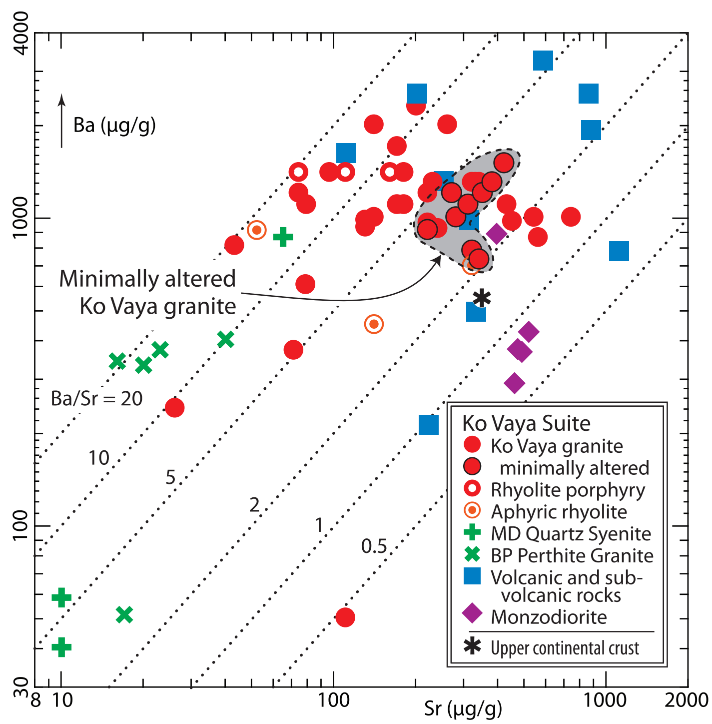


Figure 11. Variation of Sr and Ba in the Ko Vaya Suite, demonstrating limited range of values in minimally altered samples of Ko Vaya granite (dotted outline). For all samples of Ko Vaya granite, Ba/Sr ranges from 0.5 to 19, but the nine minimally altered samples have 2.2 < Ba/Sr < 4.4. MD, Mt. Devine; BP, Baboquivari Peak. Concentration of Sr and Ba in upper continental crust from McLennan (2001).

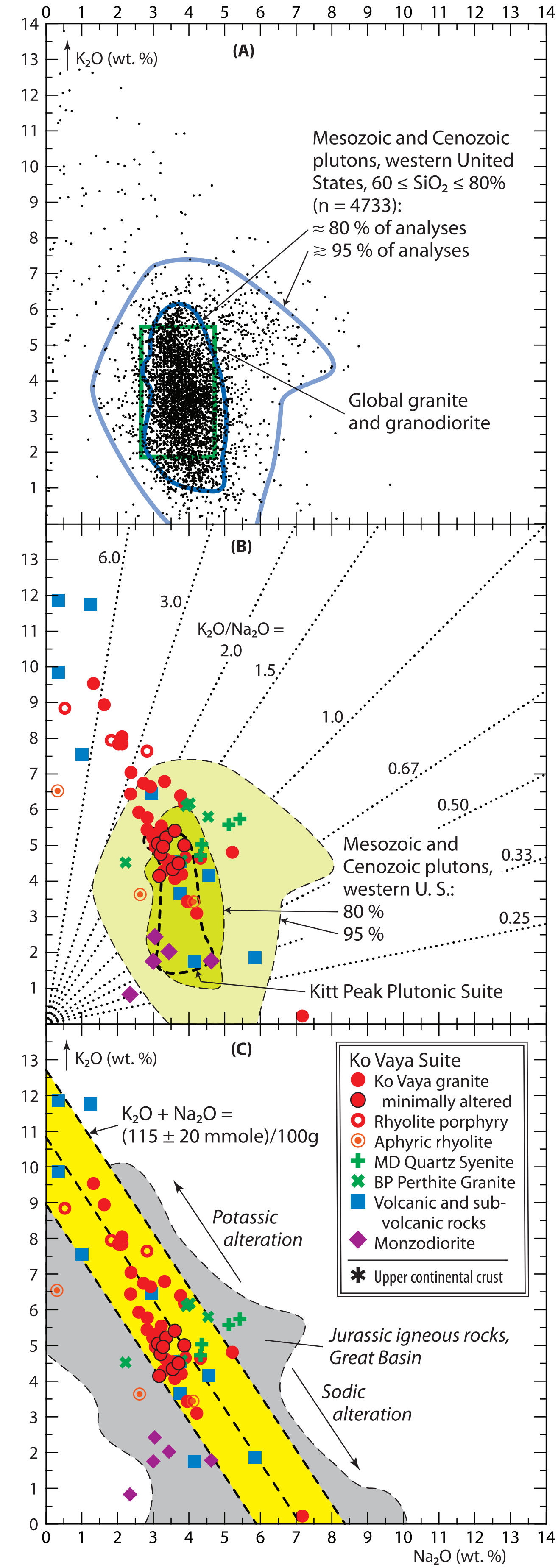


Figure 10. Sodium and potassium in intermediate to silicic plutonic rocks. **(A)** Mesozoic and Cenozoic (0–200 Ma) plutonic rocks, 60 ≤ SiO_2 ≤ 80 weight percent, in the western United States (NAVDAT; see acknowledgements) (4733 samples). Dark and light blue lines respectively enclose approximately 80 and 95 percent of the data points. Green rectangle represents the global range of compositions (arithmetic mean ± one standard deviation) of granite, "adamellite", and granodiorite, presumably most minimally altered (3505 samples; Le Maitre, 1976). **(B)** Ko Vaya Suite, compared with plutons of the western U.S. (from A) and with the Kitt Peak Plutonic Suite (KPPS; field excludes three mesodiorites with Na_2O < 2 and K_2O < 1) (Haxel et al., 2008). **(C)** Ko Vaya Suite, with diagonal band of semiconstant molar K_2O+Na_2O. Gray field represents potassic and sodic alteration in Jurassic igneous terranes of the Great Basin (Barton and Johnson, 1997; Johnson and Barton, 1997; Johnson, 2000). MD, Mt. Devine; BP, Baboquivari Peak.

or trachydacite and alkali rhyolite (Fig. 12). The alkaline chemical composition of these rocks is consistent with their quartz-poor, alkali feldspar-rich modal composition (Fig. 3).

MDQS and BPPG belong to a special class of granite, A-type granite (where *A* stands for anhydrous, "anorogenic", alkaline, or alkali-feldspar), intruded at high temperature and low water pressure (Whalen et al., 1987; Eby, 1990; Pitcher, 1993, chapter 15; Kemp and Hawkesworth, 2005). A-type granite suites are alkali feldspar-rich and quartz-poor; and commonly include hypersolvus (one-feldspar) granites, like MDQS and BPPG. A-type granite suites may encompass metaluminous, peraluminous, or peralkaline rocks, but the latter are most characteristic. Three of four samples of MDQS are slightly peralkaline. A-type granites are also characterized by high values of Na+K, Fe/Mg, F, Ga, Ga/Al, Zn, Zr, Nb, and REE, relative to ordinary granites. High F and Ga/Al are particularly important. Figure 13 and Table 2 show that MDQS has the major and trace element characteristics of A-type granite, including high Ga/Al. Although concentrations of F in MDQS are moderate, F and F/H_2O exceed those in the representative samples of A-type granite tabulated by Whalen et al. (1987) (and in Ko Vaya granite and KPPS):

	F	H_2O	F/H_2O
Mt. Devine Quartz Syenite (*n* = 3)	0.12	0.44	0.28
Representative A-type granite (22)	0.08	0.50	0.18
Ko Vaya granite, minimally altered (9)	0.06	0.96	0.07
Kitt Peak Plutonic Suite (33)	0.07	0.92	0.09
	(arithmetic means)		

Pronounced negative Eu anomalies in the REE spectra of BPPG (Fig. 8) indicate relatively reduced magma, common for A-type granite. Compared to minimally altered Ko Vaya granite, MDQS is slightly more sodic and has appreciably higher Be, La, Ce, Y, Zr, Zn, Ga, and Ga/Al (Table 2; Figs. 6, 9, 10, 12, 13, 15).

Composition of volcanic rocks

The volcanic and subvolcanic rocks of the Ko Vaya Suite, petrographically mostly trachyandesite and andesite, are so strongly altered that their original compositions can not be inferred from their present major element chemistry alone (e.g., Fig. 6). Instead, we have turned to several geochemical diagrams specifically designed for the classification of altered rocks, using supposedly more-or-less immobile elements (Winchester and Floyd, 1977; Floyd and Winchester, 1978). For example, on a graph of Zr/TiO_2 versus SiO_2 (one of the most frequently used of such diagrams), most Ko Vaya Suite volcanic rocks plot in or near the fields of trachybasalt (or similar rocks), alkali basalt, trachyandesite, and phonolite (Fig. 14). A Ga–Zr/TiO_2 graph (not shown) indicates that trachyandesite and phonolite are most common. How much of this apparent variety is primary and how much owes to alteration remains uncertain. Evidently the Ko Vaya Suite includes several types of alkaline volcanic rocks, mostly mafic, of approximately trachybasaltic or trachyandesitic average or overall composition.

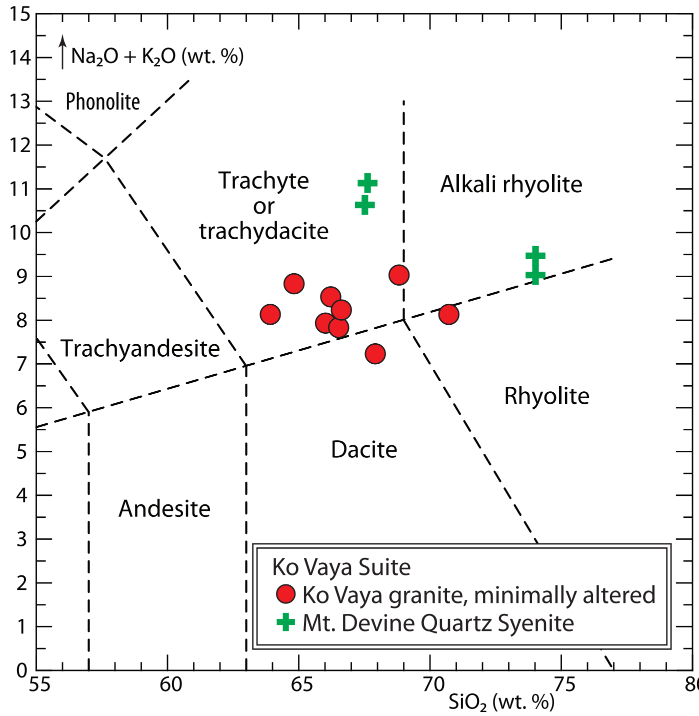


Figure 12. Volcanic rock classification in terms of silica and Na_2O+K_2O ("total alkalis") (after Le Maitre et al., 2002), showing composition of minimally altered samples (see text) of Ko Vaya granite and Mt. Devine Quartz Syenite. By definition trachyte has < 20 percent normative quartz and trachydacite > 20 percent. The Ko Vaya Suite granites and syenites have 13–29 percent normative quartz (c.f. Fig. 3).

Tectonic environment, inferred from petrology of igneous rocks

All of the major igneous rock types of the Ko Vaya Suite are moderately alkaline. The volcanic rocks evidently are dominantly trachybasalt and trachyandesite. The monzodiorite unit is generally quartz-poor, and at least locally feldspathoidal. Ko Vaya granite and MDQS are alkali feldspar-rich and quartz-poor, and have the composition of trachyte or trachydacite and alkali rhyolite. Given the well-known association of igneous alkaline rocks and bimodal suites with extensional tectonic settings (e.g., Wilson, 1989, chapter 11; Christiansen, 2001), the bimodal and moderately alkaline character of the Ko Vaya Suite supports the hypothesis that it formed in a rift environment. This point is emphasized by the presence within the Ko Vaya Suite of two A-type granites, MDQS and BPPG. Phanerozoic A-type granite suites characteristically occur in intracontinental rift zones. Finally, the hematite veins the Ko Vaya Suite have affinities to the Fe-oxide metallization associated with Jurassic igneous rocks in the Great Basin and Mojave Desert (Barton et al., 2000). This style of metallization commonly occurs in extensional settings (Barton and Johnson, 1996).

The modest alkalinity characteristic of the Late Jurassic Ko Vaya Suite as a whole stands in contrast to the composition

Table 2. Ko Vaya Suite plutonic rocks—representative analyses of minimally altered samples, Comobabi Mountains, Arizona {1}.

Unit	Ko Vaya Granite		Mt. Devine Quartz Syenite {2}	
Sample	CB28B	CB53 {3}	NCB3H {4}	{5}
Lithology	granite		quartz-perthite syenite	quartz syenite
SiO_2	66.0	66.6	67.5	74.0
Al_2O_3	15.2	15.2	15.2	12.0
Fe_2O_3	1.98	1.96	1.84	1.80
FeO	1.80	1.66	2.06	1.63
MgO	1.51	1.31	0.37	0.14
CaO	2.97	2.50	0.98	0.44
Na_2O	3.18	3.25	5.09	4.32
K_2O	4.72	4.92	5.54	4.84
TiO_2	0.55	0.63	0.61	0.30
P_2O_5	0.17	0.18	0.10	0.03
MnO	0.08	0.14	0.16	0.12
H_2O	1.18	0.95	0.52	0.40
F	0.04	0.05	0.08	0.14
Cl	0.03	0.04	0.04	0.025
CO_2	0.17	0.02	0.20	0.13
Total	99.9	99.7	100.6	100.4
$Fe_2O_3/Fe_2O_3^*$ {6}	0.50	0.52	0.45	0.50
FeO*/MgO {6}	2.4	2.6	***10.0***	***23***
Na_2O+K_2O	7.9	8.2	***10.6***	***9.2***
K_2O/Na_2O	1.48	1.51	1.09	1.12
K_2O/MgO	3.1	3.8	***15***	***35***
Alkali SI {7}	0.68	0.70	***0.95***	***1.03***
Alumina SI {8}	0.97	1.00	0.94	0.91
F/H_2O	0.03	0.05	***0.15***	***0.35***
Rb	131	180	103	166
Be	1.7	2.2	***7.0***	***11***
Sr	350	310	65	<15
Ba	1200	1100	860	49
La	52	54	***88***	***140***
Ce	100	<100	***210***	***285***
Y	24	27	***66***	***82***
$(La/Y)_{cn}$ {9}	13.2	12.0	8.1	10.4
Zr	190	300	***950***	***1100***
V	72	62	12	<10
Co	8.7	6.3	3.8	3.0
Ni	7.6	8.6	10	9.8
Cu	22	17	3.9	2.0
Zn	<50	67	***100***	***175***
Ga	10	10	***27***	***26***
$(Ga/Al)\times10^4$	1.2	1.2	***3.4***	***4.2***
Pb	14	26	22	26

{1} Major and minor element oxides, F, Cl—weight percent; trace elements—µg/g. Total includes all Fe as Fe_2O_3, SrO, BaO, –O≙F, and –O≙Cl. Major elements determined by wavelength-dispersive x-ray fluorescence and other methods; trace elements by direct-current-arc quantitative-emission spectrometry (Haxel et al., 2005).

{2} Special characteristics of this A-type granite are highlighted in ***bold italic*** type.

{3} Modal composition: plagioclase, 30.2 volume percent; alkali feldspar, 36.0%; quartz, 20.4%; hornblende+biotite, 10.6%; magnetite, 2.8%.

{4} Modal composition: plagioclase, 3.0%; akali feldspar (perthite), 74.2%; quartz, 13.8%; hornblende+biotite, 7.2%; magnetite, 1.8%.

{5} Arithmetic mean of two similar samples: NCB183, NCB184.

Table 2 continued.

{6} $Fe_2O_3^*$, FeO*: total Fe as Fe_2O_3, FeO.

{7} Alkali saturation index, molar $(Na_2O+K_2O)/Al_2O_3$. Peralkaline: alkali SI > 1.0.

{8} Alumina saturation index, molar $Al_2O_3/(CaO+Na_2O+K_2O)$.

{9} cn, chondrite-normalized (Nakamura, 1974).

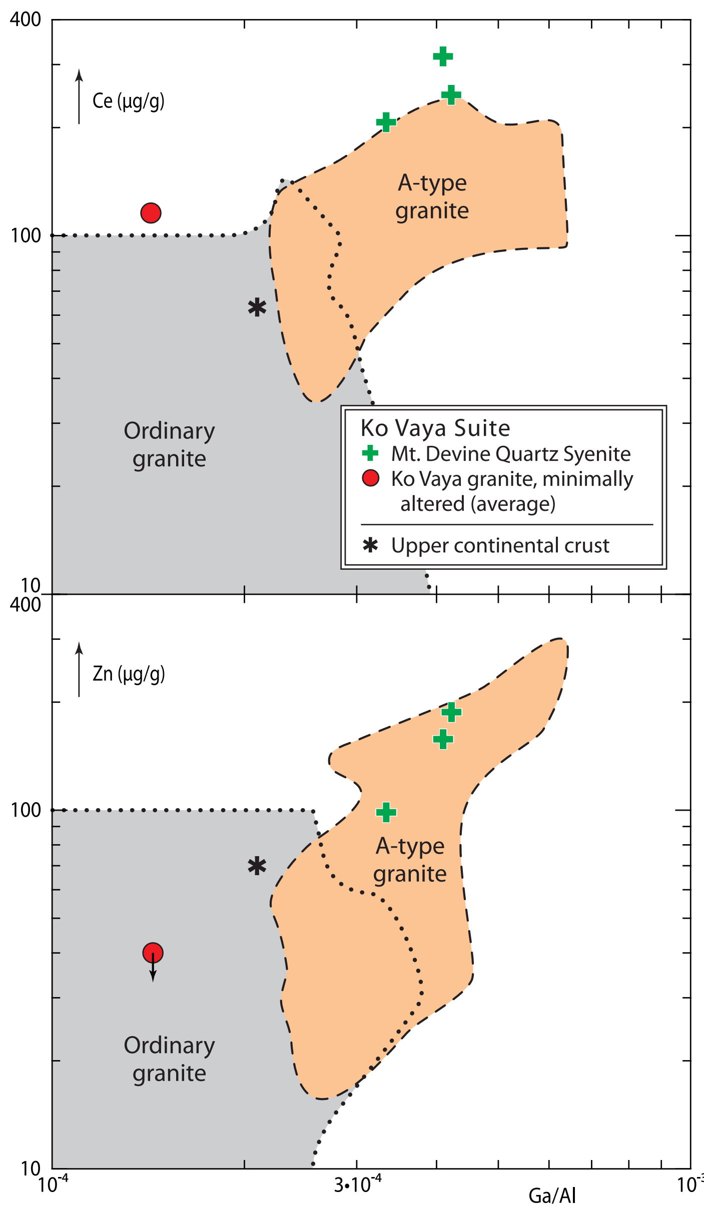


Figure 13. Comparison of Ga/Al and concentration of Ce and Zn in Mt. Devine Quartz Syenite, minimally altered Ko Vaya granite, global A-type granite, and global ordinary (non–A-type) granite (after Whalen et al., 1987). In this graph and Figure 15, one of four samples of MDQS (e.g., Fig. 12) is not plotted because trace elements were not analyzed. Data points for minimally altered Ko Vaya granite represent the arithmetic mean of nine similar samples (Figs. 4, 6, 7, 9–12). Plotted value of Zn in Ko Vaya granite is an estimated maximum, as for most samples Zn is reported < 50 µg/g. Composition of upper continental crust from McLennan (2001).

of the igneous rocks of the Middle Jurassic magmatic arc in south-central Arizona and north-central Sonora. Nearly all the Middle Jurassic igneous rocks are "calcalkaline"; alkaline rocks are uncommon (known only from the upper part of the Topawa Group), quite small in volume, and overwhelmed by ordinary rhyolite, granite, granodiorite, and dacite. This contrast is readily apparent in modal compositions: Ko Vaya Granite contains significantly less quartz than do Middle Jurassic granites (Fig. 3). Although differences in major element composition between the Ko Vaya Suite and Middle Jurassic arc rocks are subtle, the Ko Vaya Suite has appreciably higher concentration of incompatible trace elements generally enriched in alkaline igneous rocks, particularly REE and Zr (Fig. 15; Tosdal et al., 1989).

The bimodality of the Ko Vaya Suite (Fig. 5A, B) also sets it apart from Middle Jurassic magmatic arc suites in our region. In the Middle Jurassic KPPS, intermediate rocks prevail (Fig. 5C). The Middle Jurassic Topawa Group and Cobre Ridge Tuff are strongly dominated by silicic and highly silicic rocks, with few intermediate rocks and only very small volumes of mafic rock (Fig. 5D) (Haxel et al., 2005).

LATEST JURASSIC TO EARLY CRETACEOUS SEDIMENTATION AND MAGMATISM

Where relations between the Ko Vaya Suite and younger supracrustal rocks are best exposed and best known, in the Comobabi Mountains, these two lithostratigraphic units are separated by a nonconformity. In latest Jurassic time volcanic, hypabyssal, and shallow plutonic rocks of the Ko Vaya Suite were uplifted and eroded, then quickly covered by conglomerate and sedimentary breccia that contain readily recognizable clasts of Ko Vaya Granite and maroon porphyry, as well as clasts probably derived from other units of the Ko Vaya Suite. In one area this conglomerate rests directly on Ko Vaya Granite. In another area conglomerate interfingers with and overlies andesite flows that in turn rest on the Ko Vaya Suite. The conglomerate is overlain by a finer-grained sequence comprising sandstone, siltstone, and pebble conglomerate, with minor tuffaceous sandstone and sandy limestone and minor flows of andesite and trachyandesite. The thickest exposed section comprises several hundred meters of andesite flows overlain by >≈ 1900 m of interbedded sedimentary and subordinate volcanic strata (Bryner, 1959; Haxel et al., 1978).

Sedimentary and volcanic rocks overlying the Ko Vaya Suite have yielded neither fossils nor isotopic ages and could be latest Jurassic, Early Cretaceous, or both. They were named Sand Wells Formation by Heindl (1965), and have previously been correlated with the latest Jurassic to Early Cretaceous Bisbee Group, including its basal unit, the latest Jurassic Glance Conglomerate, of southeast Arizona and northeast Sonora (Dickinson et al., 1989; Tosdal et al., 1989). However, the Sand Wells Formation includes more

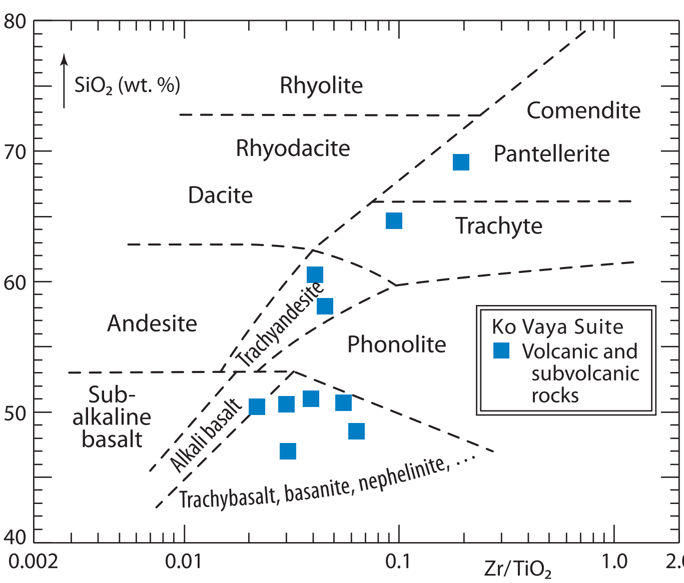


Figure 14. Example of a variation diagram for geochemical classification of altered and metamorphosed rocks (after Winchester and Floyd, 1977; Floyd and Winchester, 1978), showing compositions of volcanic and subvolcanic rocks of the Ko Vaya Suite.

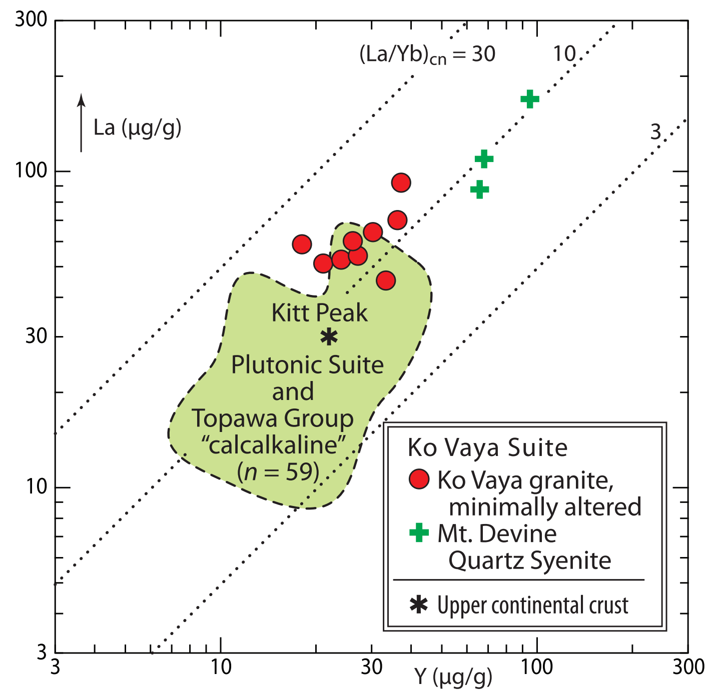


Figure 15. Comparison of concentrations of La and Y (representing the light and heavy REE, respectively) in minimally altered Late Jurassic Ko Vaya granite and Mt. Devine Quartz Syenite, and in the Middle Jurassic Kitt Peak Plutonic Suite (Haxel et al., 2008) and rhyolite and silicic dacite of the Middle Jurassic Topawa Group (Haxel et al., 2005). Field for the latter two units encompasses 59 samples. For consistency, concentrations determined by quantitative emission spectroscopy are plotted for all three units. Dotted diagonal lines are loci of constant La/Y, chondrite-normalized (Nakamura, 1974). Concentration of La and Y in upper continental crust from McLennan (2001).

volcanic rocks than typical Bisbee sections. Possibly magmatism continued slightly longer in south-central Arizona and north-central Sonora, even into earliest Cretaceous time, than in areas to the east. More likely, most or all of the Sand Wells Formation correlates not with the entire Bisbee Group but only with the Glance Conglomerate. Bassett and Busby (2005) describe a Late Jurassic unit in the Santa Rita Mountains (≈ 20 km east of the area shown in Fig. 1) that they call the "Santa Rita Glance Conglomerate", comprising numerous heterogeneous, complexly interfingering lithofacies of rhyolite, andesite, conglomerate, and breccia. This volcanic and sedimentary complex is probably a reasonable analog for the Sand Wells Formation. Following Anderson and Nourse (2005), we designate the area of the Sand Wells Formation as the Comobabi basin.

The other major latest Jurassic supracrustal sequence in south-central Arizona crops out in the Sheridan and southern Santa Rosa Mountains, near the village of Gu Achi (Briskey et al., 1978; Bergquist et al., 1978). This "Gu Achi sequence" (partially metamorphosed) is largely sandstone and conglomerate, with subordinate hypabyssal intrusions and flows of trachyandesite and minor volcanic to hypabyssal rhyolite. Much of the sandstone and conglomerate are distinctly arkosic. The trachyandesite contains large, prominent hornblende phenocrysts; in this attribute and in appearance it differs from any volcanic and hypabyssal rocks of the Ko Vaya Suite or Sand Wells Formation. Sedimentary and igneous rocks of the Gu Achi sequence are sufficiently different from the Sand Wells Formation as to suggest deposition in a separate basin, the Gu Achi basin (Fig. 1). Alternatively, the Gu Achi sequence may be a northern or basin-margin facies of the Sand Wells Formation.

In Sonora, stratigraphic and structural relationships of Late Jurassic to Early Cretaceous rocks are best documented in Sierra El Batamote, northwest of Altar (Jacques-Ayala, 1995; Nourse, 1995, 2001). Although these rocks are folded, metamorphosed, and cut by thrust faults, original stratigraphic relations have been determined. The Late Jurassic to Early Cretaceous Altar Formation — polymict conglomerate, sandstone, mudstone, andesite, and rhyolitic tuff — rests depositionally upon Jurassic, probably Middle Jurassic, volcanic rocks; and is gradationally overlain by the Early Cretaceous (Neocomian and Aptian) Morita Formation, the Bisbee Group unit immediately above the Glance Conglomerate. Thus, the Altar Formation is broadly correlated with the Glance Conglomerate. Conglomerate sections, locally more than a kilometer thick, in the Altar Formation contain boulders and cobbles eroded from highlands composed of local Middle Jurassic magmatic arc rocks and Neoproterozoic to Paleozoic miogeoclinal strata of the Caborca block, southwest of the Mojave-Sonora megashear. Accordingly, Anderson and Nourse (2005) infer that the Altar Formation was deposited in the Late Jurassic Batamote basin, bounded on its southwest side by the megashear.

POST-JURASSIC DEFORMATION AND PLUTONISM

Reactivation of Late Jurassic faults as Laramide reverse faults

In southeast Arizona and southwest New Mexico pre-Laramide faults, many of them demonstrably or arguably Late Jurassic, were reactivated during Laramide northeast-southwest contraction (Titley, 1976; Davis, 1979; Drewes, 1981, 1991, Fig. 13; Jensen and Titley, 1998; Anderson and Nourse, 2005). Laramide displacement on these reactivated faults accommodated inversion of Late Jurassic basins (e.g., Lawton, 1996, 2000; Hodgson, 2000). We suggest a similar scenario for south-central Arizona and north-central Sonora.

The best-exposed example of a Laramide fault that we regard as a reactivated Late Jurassic fault is the Baboquivari "thrust". This fault extends from the eastern Comobabi Mountains 60 km southward through the western foothills of the Baboquivari Mountains to Sierra Pozo Verde (Fig. 1; Haxel et al., 1984, Figs. 3, 11). The hanging wall comprises the Late Jurassic Ko Vaya Suite rocks of the Comobabi and Artesa Mountains, western foothills of the Baboquivari Mountains, Cerros La Garrapata, and hills south-southeast of Sasabe. The footwall is the Middle Jurassic magmatic arc rocks of the main Baboquivari Mountains and San Luis Mountains. We previously interpreted this structure as a regionally extensive thrust fault. Consequently, we envisioned the Comobabi and Artesa Mountains as part of a large allochthon, underlain by this subhorizontal thrust. However, this interpretation conflicts with present understanding of the tectonic style of adjacent southeast Arizona. For that region, Drewes (e.g., 1976, 1980, 1981, 1991) postulated a vast system of subhorizontal Laramide thrust sheets, extending over an area $\sim 10^4$ km². Subsequent research (e.g., Dickinson, 1984, 1991; Krantz, 1989) has shown that some Laramide faults are indeed low-angle but such faults are of local or mountain-range scale rather than of regional extent. These observations support the concepts of Davis (1979), who emphasized the importance of basement-cored uplifts with steep marginal reverse faults.

We can now reinterpret the Baboquivari "thrust" as a steeply to moderately dipping reverse fault, and infer that the Comobabi and Artesa Mountains are essentially autochthonous, displaced by predominantly vertical movements with subordinate horizontal components. The area of these ranges subsided in Late Jurassic time, to form the floor of the Comobabi basin, which was then flooded by Late Jurassic volcanic and shallow intrusive rocks of the Ko Vaya Suite, upon which latest Jurassic sedimentary and volcanic rocks then accumulated. During Laramide contraction the basin was inverted and its igneous and sedimentary basin fill overrode its eastern flank, the Baboquivari Mountains, along the Baboquivari reverse fault. We postulate an analogous sequence of events for the less-well-exposed fault or faults bounding the west side of the Comobabi basin, from the Window Mountain

Well "thrust" mapped in Sierra Blanca southward through the Kupk Hills to a thrust or reverse fault we have observed in Sierra del Cobre (Haxel et al., 1984, Figs. 4, 11).

Early Paleogene peraluminous leucogranite plutonism

In eight ranges in south-central Arizona and north-central Sonora, boundaries between Middle Jurassic arc rocks and the Late Jurassic Ko Vaya Suite are closely associated with early Paleogene (≈ 58 Ma) peraluminous leucogranite (Fig. 1). In the Coyote and southern Baboquivari Mountains and Sierras Blanca and Pozo Verde, the two regional Jurassic terranes are in part separated by leucogranite. In the northern Baboquivari Mountains, Comobabi, Artesa, and San Luis Mountains, and Kupk Hills, leucogranite crops out near or subparallel to the boundary between the two Jurassic units. Haxel et al. (1984; see also Wright and Haxel, 1982; Farmer and DePaolo, 1984) documented close spatial, temporal, and genetic relations between Laramide thrust faulting and intrusion of early Paleogene crustal-anatectic leucogranite, and attributed these relations to crustal melting beneath thrust sheets. We can now view the observed association between reverse ("thrust") faults and peraluminous leucogranite somewhat differently: Active reverse faults acted as passageways that facilitated and guided the ascent of lower crustal melt into the upper crust. As the granitic magmas were emplaced into and crystallized in the upper crust, they were subject to the same deformation field as metamorphic rocks and tectonites adjacent to the reverse faults, accounting for the synkinematic or syntectonic character of the leucogranite plutons.

Late Paleogene crustal extension

In several ranges, faults with complex Late Jurassic and Laramide histories have been further reactivated as late Paleogene (to early Neogene?) low-angle extensional faults ("detachment" faults). Overprinting of Laramide structures, fabrics, and plutons by late Paleogene structures and fabrics is documented in the southern Baboquivari, easternmost Comobabi, and northern Coyote Mountains, and in Sierras Blanca and Pozo Verde (Wright and Haxel, 1982; Haxel et al., 1982, 1984; Goodwin and Haxel, 1990). Furthermore, some Late Jurassic and Laramide faults may have been significantly rotated during late Paleogene extension.

REGIONAL CORRELATION

Igneous rocks of the Middle Jurassic, arc phase of magmatism are widely distributed across southern and western Arizona and northern Sonora. Igneous rocks of the Late Jurassic Ko Vaya Suite are much more restricted in extent and much smaller in volume. Despite their relatively small scope and volume, the rocks of the Ko Vaya Suite are the local manifestation of a tectonic episode that affected much of the southern Cordillera in Late Jurassic time. We have already mentioned igneous and sedimentary rocks in southeast Arizona and northeast Sonora and in western Arizona similar in tectonic setting to the Ko Vaya Suite; that is, associated with Late Jurassic rifting. Farther west, in the Mojave Desert of California (as in southern Arizona and northern Sonora), most Jurassic plutons and volcanic accumulations belong to the Middle Jurassic, arc phase (e.g., Mayo et al., 1998; Walker et al., 2002). Nonetheless, Late Jurassic plutons and volcanic rocks broadly comparable to the Ko Vaya Suite have been identified a several places (e.g., Karish et al., 1987; Fox and Miller, 1990; Schermer et al., 2002; Walker et al., 2002). These localities are significant because they suggest or establish a tie with the well-known latest Jurassic Independence dike swarm.

The Independence dike swarm (summarized by Carl and Glazner, 2002) extends some 600 km from east-central California to the western and central Mojave Desert, and possibly into the northwest Sonoran Desert. Nearly all of numerous U-Pb ages for dikes of the swarm are between 146 and 152 Ma; 148 Ma is the modal and preferred age. Widely varying chemical compositions seem to reflect local factors, rather than some overall tectonic control. Though dominantly mafic, the swarm includes intermediate and silicic dikes as well. Subalkaline compositions predominate, but in some ranges dikes are alkaline. Most who have commented on the tectonic significance of the Independence dike swarm agree that it records a wide-ranging change of tectonic regime or plate motion in the southern Cordillera in latest Jurassic time, involving crustal extension, sinistral shear (Glazner et al., 1999), or both.

Although the Ko Vaya Suite is not as well dated as the Independence dike swarm, available data indicate the two are approximately coeval. We infer that the Ko Vaya Suite, like the Independence dike swarm, is a manifestation of Late Jurassic regional extension. The most significant difference between these two Late Jurassic igneous phenomena is spatial density. The Independence dike swarm comprises innumerable thin dikes in swarms sparsely spread over a region $\sim 10^5$ km². In contrast, the Ko Vaya Suite is largely restricted to several mountain ranges (an area 1½–2 orders of magnitude smaller) in south-central Arizona and north-central Sonora, but makes up most of those ranges. The Comobabi, Artesa, Quijotoa, and Brownell Mountains and Sierra del Cobre were, for reasons not yet clear to us, a locus of especially intense or focused Late Jurassic extensional magmatism.

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REFERENCES CITED

Anderson T.H., Rodrîguez-Castañeda, J.L., and Silver, L.T., 2005, Jurassic rocks in Sonora, Mexico: relations to Mojave-Sonora megashear and its inferred northwestward extension, *in* Anderson, T.H., Nourse, J.A., McKee, J.W., and Steiner, M.B., editors, The Mojave-Sonora megashear hypothesis: Development, assessment, and alternatives: Geological Society of America Special Paper 393, p. 51–95.

Anderson, T.H., and Nourse, J.A., 2005, Pull-apart basins at releasing bends of the sinistral Late Jurassic Mojave-Sonora fault system, *in* Anderson, T.H., Nourse, J.A., McKee, J.W., and Steiner, M.B., editors, The Mojave-Sonora megashear hypothesis: Development, assessment, and alternatives: Geological Society of America Special Paper 393, p. 97–122.

Anderson, T.H., and Silver, L.T., 1977, U-Pb isotope ages of granitic plutons near Cananea, Sonora: Economic Geology, v. 72, p. 827–836.

Anderson, T.H., and Silver, L.T., 1978, Jurassic magmatism in Sonora, Mexico: Geological Society of America Abstracts with Programs, v. 10, no. 7, p. 359.

Asmerom, Y., Zartman, R.E., Damon, P.E., and Shafiqullah, M., 1990, Zircon U-Th-Pb and whole-rock Rb-Sr age patterns of lower Mesozoic igneous rocks in the Santa Rita Mountains, southeast Arizona: Implications for Mesozoic magmatism and tectonics *in* the southern Cordillera: Geological Society of America Bulletin, v. 102, p. 961–968.

Asmerom, Y., Patchett, P.J., and Damon, P.E., 1991, Crust-mantle interaction in continental arcs: inferences from the Mesozoic arc in the southwestern United States: Contributions to Mineralogy and Petrology, v. 107, p. 124–134.

Barton, M.D., and Johnson, D.A., 1996, Evaporitic-source model for igneous-related Fe oxide-(REE-Cu-Au-U) mineralization: Geology, v. 24, p. 259–262.

Barton, M.D., and Johnson, D.A., 1997, A comparison of Fe-oxide (-Cu-Au-REE-U-Co-Ag) mineralization: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. 51.

Barton, M. D., Johnson, D. A., and Zürcher, L., 2000, Phanerozoic iron-oxide (-REE-Cu-Au-U) systems in southwestern North America and their origins: *in* Roberts, M.D. and Fairclough, M.C., editors, Fe-oxide-Cu-Au Deposits: A discussion of critical issues and current developments: James Cook University, Economic Geology Research Unit Contribution 58, p. 5–11.

Bassett, K.N., and Busby, C.J., 2005, Tectonic setting of the Glance Conglomerate along the Sawmill Canyon fault zone, southern Arizona: A sequence analysis of an intra-arc strike-slip basin, *in* Anderson, T.H., Nourse, J.A., McKee, J.W., and Steiner, M.B., editors, The Mojave-Sonora megashear hypothesis: Development, assessment, and alternatives: Geological Society of America Special Paper 393, p. 377–400.

Battles, D.A., and Barton, M.D., 1995, Arc-related sodic hydrothermal alteration in the western United States: Geology, v. 23, p. 913–916.

Beikman, H.M., Haxel, G.B., and Miller, R.J., 1995, Geologic map of the Tohono O'Odham Indian Nation, southern Arizona: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-2017, scale 1:125,000.

Bergman, S.C., 1987, Lamproites and other potassium-rich igneous rocks: a review of their occurrence, mineralogy and geochemistry, *in* Fitton, J.G., and Upton, B.G.J., editors, Alkaline igneous rocks: Geological Society Special Publication 30, p. 103–190.

Bergquist, J.R., Blacet, P.M., and Miller, S.T., 1978, Reconnaissance geologic map of the Santa Rosa Mountains quadrangle, Pima County, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-935, scale 1:62,500.

Bilodeau, W.L., 1982, Tectonic models for early Cretaceous rifting in southeastern Arizona: Geology, v. 10, p. 466–470.

Bilodeau, W.L., Kluth, C.F., and Vedder, L.K., 1987, Regional stratigraphic, sedimentologic, and tectonic relationships of the Glance conglomerate in southeastern Arizona, *in* Dickinson, W.R., and Klute, M.A., editors, Mesozoic rocks of southern Arizona and adjacent areas: Arizona Geological Society Digest 18, p. 229–256.

Bouse, R.M., Ruiz, J., Titley, S.R., Tosdal, R.M., and Wooden, J.L., 1999, Lead isotope compositions of Late Cretaceous and early Tertiary igneous rocks and sulfide minerals in Arizona; implications for the sources of plutons and metals in porphyry copper deposits: Economic Geology, v. 94, p. 211–244.

Briskey, J.A., Haxel, G.B., Peterson, J.A., and Theodore, T.G., 1978, Reconnaissance geologic map of the Gu Achi 15′ quadrangle, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-965, scale 1:62,500.

Bryner, L., 1959, Geology of the South Comobabi Mountains and Ko Vaya Hills, Pima County, Arizona: University of Arizona, Ph.D. dissertation, 156 p.

Busby-Spera, C.J., Mattinson, J.M., Riggs, N.R., and Schermer, E.R., 1990, The Triassic-Jurassic magmatic arc in the Mojave-Sonoran deserts and the Sierran-Klamath region; similarities and differences in paleographic evolution, *in* Harwood, D.S., and Miller, M.M., editors, Paleozoic and early Mesozoic paleogeographic relations; Sierra Nevada, Klamath Mountains, and related terranes: Geological Society of America Special Paper 255, p. 325–337.

Carl, B.S., and Glazner, A.F., 2002, Extent and significance of the Independence dike swarm, eastern California, *in* Glazner, A.F., Walker, J.D., and Bartley, J.M., editors, Geologic evolution of the Mojave Desert and southwestern Basin and Range: Geological Society of America Memoir 195, p. 117–130.

Christiansen, R.L., 2001, Geology of Yellowstone National Park — The Quaternary and Pliocene Yellowstone Plateau volcanic field: U. S. Geological Survey Professional Paper 729–G, 145 p.

Cox, K.G., Bell, J.D., and Pankhurst, R.J., 1979, The interpretation of igneous rocks: Allen and Unwin, 450 p.

Davis, G.H., 1979, Laramide folding and faulting in southeastern Arizona: American Journal of Science, v. 279, p. 543–569.

Dickinson, W.R., 1984, Reinterpretation of the Lime Peak thrust as a low-angle normal fault; Implications for the tectonics of southeastern Arizona: Geology, v. 12, p. 610–613.

Dickinson, W.R., 1991, Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona: Geological Society of America Special Paper 264, 106 p.

Dickinson, W.R., and Lawton, T.F., 2001, Tectonic setting and sandstone petrofacies of the Bisbee Basin (USA-Mexico): Journal of South American Earth Sciences, v. 14, p. 475–504.

Dickinson, W.R., Fiorillo, A.R., Hall, D.L., Monreal, R., Potochnik, A.R., and Swift, P.N., 1989, Cretaceous strata of southern Arizona, *in* Jenny, J.P., and Reynolds, S.J., editors, Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 447–461.

Drewes, H., 1971, Mesozoic stratigraphy of the Santa Rita Mountains, southeast of Tucson, Arizona: U.S. Geological Survey Professional

Paper 658-C, 81 p.

Drewes, H., 1976, Laramide tectonics from Paradise to Hells Gate, southeastern Arizona, *in* Wilt, J.C. and Jenney, J.P., editors, Tectonic digest: Arizona Geological Society Digest 10, p. 151–167.

Drewes, H., 1980, Tectonic map of southeast Arizona: U. S. Geological Survey Miscellaneous Investigations Map I-1109, scale 1:125,000.

Drewes, H., 1981, Tectonics of southeastern Arizona: U. S. Geological Survey Professional Paper 1144, 96 p.

Drewes, H., 1991, Description and development of the Cordilleran orogenic belt in the Southwestern United States and northern Mexico: U. S. Geological Survey Professional Paper 1512, 92 p.

Drewes, H., and Hayes, P.T., 1983, Comment on "Tectonic models for early Cretaceous rifting in southeastern Arizona": Geology, v. 11, p. 364–365.

Eby, G.N., 1990, The A-type granitoids; a review of their occurrence and chemical characteristics and speculations on their petrogenesis: Lithos, v. 26, p. 115–134.

Fackler-Adams, B.N., Busby, C.J., and Mattinson, J.M., 1997, Jurassic magmatism and sedimentation in the Palen Mountains, southeastern California: Implications for regional tectonic controls on the Mesozoic arc: Geological Society of America Bulletin, v. 109, p. 1464–1484.

Farmer, G.L. and DePaolo, D.J., 1984, Origin of Mesozoic and Tertiary granite in the western United States and implications of pre-Mesozoic crustal structure. 2. Nd and Sr isotopic studies of unmineralized and Cu- and Mo-mineralized granite in the Precambrian craton: Journal of Geophysical Research, v. 89, no. B12, p. 10,141–10,160.

Floyd, P.A., and Winchester, J.A., 1978, Identification and discrimination of altered and metamorphosed volcanic rocks using immobile elements: Chemical Geology, v. 21, p. 291–306.

Fox, L.K., 1989, Albitization of Jurassic plutons in the southern Bristol Mountains, east-central Mojave Desert, southeastern California: Ph.D. dissertation, University of California, Santa Barbara, 324 p.

Fox, L.K., and Miller, D.M., 1990, Jurassic granitoids and related rocks of the southern Bristol Mountains, southern Providence Mountains, and Colton Hills, Mojave Desert, California, *in* Anderson, J.L. editor, The nature and origin of Cordilleran magmatism: Geological Society of America Memoir 174, p. 111–132.

Gebhardt, R.C., 1931, Geology and mineral resources of the Quijotoa Mountains: University of Arizona, M.S. thesis, 63 p.

Glazner, A.F., Bartley, J.M., and Carl, B.S., 1999, Oblique opening and non-coaxial emplacement of the Jurassic Independence dike swarm: Journal of Structural Geology, v. 21, p. 1275–1283.

Goodwin, L.B., and Haxel, G.B., 1990, Structural evolution of the southern Baboquivari Mountains, south-central Arizona and north-central Sonora: Tectonics, v. 9, p. 1077–1095.

Harding, L.E., and Coney, P.J., 1985, The geology of the McCoy Mountains Formation, southeastern California and southwestern Arizona: Geological Society of America Bulletin, v. 96, p. 755–769.

Harrer, C.M., 1964, Reconnaissance of iron resources in Arizona: U.S. Bureau of Mines Circular 8236, 204 p.

Haxel, G.B., Briskey, J.A., Rytuba, J.J., Bergquist, J.R., Blacet, P.M., and Miller, S.T., 1978, Reconnaissance geologic map of the Comobabi Mountains 15′ quadrangle, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-964, scale 1:62,500.

Haxel, G.B., May, D.J., Wright, J.E., and Tosdal, R.M., 1980, Reconnaissance geologic map of the Baboquivari Peak 15′ quadrangle, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-1251, scale 1:62,500.

Haxel, G.B., May, D.J., and Tosdal, R.M., 1982, Reconnaissance geologic map of the Presumido Peak 15′ quadrangle, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-1378, scale 1:62,500.

Haxel, G.B., Tosdal, R.M., May, D.J., and Wright, J.E., 1984, Late Cretaceous and early Tertiary orogenesis in south-central Arizona: Thrust faulting, regional metamorphism, and granitic plutonism: Geological Society of America Bulletin, v. 95, p. 631–653.

Haxel, G.B., Anderson, T.H., Riggs, N.R., and Goodwin, L.G., 1988, The Papago terrane: A crustal anomaly in south-central Arizona and north-central Sonora: Geological Society of America with Programs, v. 20, no. 3, p. 168.

Haxel, G.B., Wright, J.E., Riggs, N.R., Tosdal, R.M., and May, D.J., 2005, Middle Jurassic Topawa Group, Baboquivari Mountains, south-central Arizona: volcanic and sedimentary record of deep basins within the Jurassic magmatic arc, *in* Anderson, T.H., Nourse, J.A., McKee, J.W., and Steiner, M.B., editors, The Mojave-Sonora megashear hypothesis: Development, assessment, and alternatives: Geological Society of America Special Paper 393, p. 329–357.

Haxel, G.B., May, D.J., Anderson, T.H., Tosdal, R.M., and Wright, J.E., 2008, Geology and geochemistry of Jurassic plutonic rocks, Baboquivari Mountains, south-central Arizona, *in* Spencer, J.E., and Titley, S.R., eds., Ores and orogenesis: Circum-Pacific tectonics, geologic evolution, and ore deposits: Arizona Geological Society Digest 22, p. 497–515.

Heindl, L.A., 1965, Mesozoic formations in the Comobabi and Roskruge Mountains, Papago Indian Reservation, Arizona: U.S. Geological Survey Bulletin 1194-H, 15 p.

Hodgson, S.A., 2000, Structural geology and Laramide tectonics of the Little Hatchet Mountains, southwestern New Mexico, *in* Lawton, T.F., McMillan, N.J., and McLemore, V.T., editors, Southwest passage—A trip through the Phanerozoic: New Mexico Geological Society Fifty-First Annual Field Conference, p. 109–116.

International Commission on Stratigraphy, 2008, International stratigraphic chart: http://www.stratigraphy.org/cheu.pdf.

Jacques-Ayala, C., 1995, Paleogeography and provenance of the Lower Cretaceous Bisbee Group in the Caborca-Santa Ana area, northwestern Sonora, *in* Jacques-Ayala, C., Gonzalez-Leon, C.M., and Roldan-Quintana, J., editors, Studies on the Mesozoic of Sonora and adjacent areas: Geological Society of America Special Paper 301, p. 79–98.

Jensen, P.W., and Titley, S.R., 1998, Wrench fault control of porphyry emplacement at the Sierrita porphyry copper deposit, Arizona: Geological Society of America Abstracts with Programs, v. 30, no. 7, p. 367.

Johnson, D.A., 2000, Comparative studies of iron-oxide mineralization, Great Basin: University of Arizona, Ph.D. dissertation, 450 p.

Johnson, D.A., and Barton, M.D., 1997, Comparison of Fe-oxide-(Cu-Au-REE) system mass-balance relationships with emphasis on examples from the Great Basin: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. 208.

Karish, C.R., Miller, E.L., and Sutter, J.F., 1987, Mesozoic tectonic and magmatic history of the central Mojave Desert, *in* Dickinson, W.R., and Klute, M.A., editors, Mesozoic rocks of southern Arizona and adjacent areas: Arizona Geological Society Digest 18, p. 15–32.

Keith, S.B., 1974, Index of mining properties in Pima County, Arizona: Arizona Bureau of Mines Bulletin 189, 156 p.

Kemp, A.I.S., and Hawkesworth, C.J., 2005, Granitic perspectives on the generation and secular evolution of the continental crust, *in* Holland, H.D., and Turekian, K.K., editors, Treatise on geochemistry, v. 3, chapter 3.01: Elsevier, p. 349–410.

Kerr, P.F., 1946, Tungsten mineralization in the United: Geological Society of America Memoir 15, 241 p.

Kluth, C.F, Butler, R.F., Harding, L.E., Shafiqullah, M., and Damon, P.E., 1982, Paleomagnetism of Late Jurassic rocks in the northern Canelo Hills, southeastern Arizona: Journal of Geophysical Research, v. 87, no. B8, p. 7079–7086.

Krantz, R.W., 1989, Laramide structures of Arizona, *in* Jenny, J.P., and Reynolds, S.J., editors, Geologic evolution of Arizona: Arizona

Geological Society Digest 17, p. 463–483.

Krebs, C.K., and Ruiz, J., 1987, Geochemistry of the Canelo Hills Volcanics and implications for the Jurassic tectonic setting of southeastern Arizona, *in* Dickinson, W.R., and Klute, M.A., editors, Mesozoic rocks of southern Arizona and adjacent areas: Arizona Geological Society Digest 18, p. 139–151.

Lang, J.R., and Titley, S.R., 1998, Isotopic and geochemical characteristics of Laramide magmatic systems in Arizona and implications for the genesis of porphyry copper deposits: Economic Geology, v. 93, p. 138–170.

Lawton, T.F., 1996, Laramide inversion of Late Jurassic-Early Cretaceous extensional faults, SE Arizona and SW New Mexico: Geological Society of America Abstracts with Programs, v. 28, no. 7, p. 509–510.

Lawton, T.F., 2000, Inversion of Late Jurassic–Early Cretaceous extensional faults, SE Arizona and SW New Mexico, *in* Lawton, T.F., McMillan, N.J., and McLemore, V.T., editors, Southwest passage—A trip through the Phanerozoic: New Mexico Geological Society Fifty-First Annual Field Conference, p. 95–102.

Lawton, T.F., and McMillan, N.J., 1999, Arc abandonment as a cause for passive continental rifting: Comparison of the Jurassic Borderland rift and Cenozoic Rio Grande rift: Geology, v. 27, p. 779–782.

Le Maitre, R.W., 1976, The chemical variability of some common igneous rocks: Journal of Petrology, v. 17, p. 589–637.

Le Maitre, R.W., 2002, editor, Igneous rocks; A classification and glossary of terms. Recommendations of the International Union of Geological Sciences subcommission on the systematics of igneous rocks: Cambridge, 236 p.

MacKallor, J.A., 1957, Geology of the western part of the Cobabi mining district, Pima County, Arizona: University of Arizona, M.S. thesis, 108 p.

Marvin, R.F., Naeser, C.W., and Mehnert, H.H., 1978, Tabulation of radiometric ages—including unpublished K-Ar and fission-track ages—for rocks in southeastern Arizona and southwestern New Mexico, *in* Callender, J.F., Wilt, J.C., Clemons, R.E., and James, H.L., editors, Land of Cochise; Southeastern Arizona: New Mexico Geological Society (with Arizona Geological Society) Twenty-ninth Field Conference, Arizona, p. 243–252.

May, D.J., and Haxel, G.B., 1980, Reconnaissance bedrock geologic map of the Sells 15′ quadrangle, Pima County, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-1166, scale 1:62,500.

Mayo, D.P., Anderson, J.L., and Wooden, J.L., 1998, Isotopic constraints on the petrogenesis of Jurassic plutons, southeastern California, *in* Ernst, W.G., and Nelson, C.A., editors, Integrated Earth and environmental evolution of the southwestern United States: Geological Society of America, p. 421–442.

McKee, J.W., McKee, M.B., and Anderson, T.H., 2005, Mesozoic basin formation, mass-gravity sedimentation, and inversion in northeastern Sonora and southeastern Arizona, *in* Anderson, T.H., Nourse, J.A., McKee, J.W., and Steiner, M.B., editors, The Mojave-Sonora megashear hypothesis: Development, assessment, and alternatives: Geological Society of America Special Paper 393, p. 481–507.

McLennan, S.M., 2001, Relationships between the trace element composition of sedimentary rocks and upper continental crust: Geochemistry, Geophysics, Geosystems, v. 2, paper number 2000GC000109.

Mitchell, R.H., and Bergman, S.C., 1991, Petrology of lamproites: Plenum, 447 p.

Nakamura, N., 1974, Determination of REE, Ba, Mg, Na, and K in carbonaceous and ordinary chondrites: Geochemica et Cosmochimica Acta, v. 38, p. 757–775.

Nockolds, S.R., and Allen, R., 1953, The geochemistry of some igneous rock series: Geochimica et Cosmochimica Acta, v. 4, p. 105–142.

Nockolds, S.R., and Allen, R., 1954, The geochemistry of some igneous rock series: Part II: Geochimica et Cosmochimica Acta, v. 5, p. 245–285.

Nockolds, S.R., and Allen, R., 1956, The geochemistry of some igneous rock series—III: Geochimica et Cosmochimica Acta, v. 9, p. 34–77.

Nourse, J.A., 1995, Jurassic-Cretaceous paleogeography of the Magdalena region, northern Sonora, and its influence on the positioning of Tertiary metamorphic core complexes, *in* Jacques-Ayala, C., Gonalez-Leon, C.M., and Roldan-Quintana, J., editors, Studies on the Mesozoic of Sonora and adjacent areas: Geological Society of America Special Paper 301, p. 59–78.

Nourse, J.A., 2001, Tectonic insights from an Upper Jurassic–Lower Cretaceous stretched-clast conglomerate, Caborca-Altar region, Sonora, Mexico: Journal of South American Earth Sciences, v. 14, p. 453–474.

Nourse, J.A., Anderson, T.H., and Silver, L.T., 1994, Tertiary metamorphic core complexes in Sonora, northwestern Mexico: Tectonics, v. 13, p. 1161–1182.

Pitcher, W.S., 1993, The nature and origin of granite: Blackie, 321 p.

Richard, S.M., Ferguson, C.A., Spencer, J.E., Youberg, A., and Orr, T.R., 2000a, Geologic map of the Waterman Peak 7.5′ quadrangle and northern La Tortuga Butte 7.5′ quadrangle, Pima County, Arizona: Arizona Geological Survey Digital Geologic Map DGM-02, v. 1.0, scale 1:24,000.

Richard, S.M., Reynolds, S.J., Spencer, J.E., and Pearthree, P.A., compilers, 2000b, Geologic map of Arizona: Arizona Geological Survey Map 35, scale 1:1,000,000.

Riggs, N. R., 1987, Stratigraphy, structure, and geochemistry of Mesozoic rocks in the Pajarito Mountains, Santa Cruz County, Arizona, *in* Dickinson, W.R., and Klute, M.A., editors, Mesozoic rocks of southern Arizona and adjacent areas: Arizona Geological Society Digest 18, p. 165–175.

Riggs, N.R., and Busby-Spera, C.J., 1991, Facies analysis of an ancient, dismembered, large caldera complex and implications for intra-arc subsidence: Middle Jurassic strata of Cobre Ridge, southern Arizona, USA: Sedimentary Geology, v. 74, p. 39–68.

Riggs, N.R., and Haxel, G.B., 1990, The Early to Middle Jurassic magmatic arc in southern Arizona: plutons to sand dunes, *in* Gehrels, G.E., and Spencer, J.E., editors, Geologic excursions through the Sonoran Desert region, Arizona and Sonora: Arizona Geological Survey Special Paper 7, p. 90–103.

Riggs, N.R., Mattinson, J.M., and Busby, C.J., 1993, Correlation of Jurassic eolian strata between the magmatic arc and the Colorado Plateau: New U-Pb geochronologic data from southern Arizona: Geological Society of America Bulletin, v. 105, p. 1231–1246.

Rock, N.M.S., 1991, Lamprophyres: Van Nostrand Reinhold, 285 p.

Rytuba, J.J., Till, A.B., Blair, W.N., and Haxel, Gordon, 1978, Reconnaissance geologic map of the Quijotoa Mountains 15′ quadrangle, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-937, scale 1:62,500.

Schermer, E.R., Busby, C.J., and Mattinson, J.M., 2002, Paleogeographic and tectonic implications of Jurassic sedimentary and volcanic sequences in the central Mojave block, *in* Glazner, A.F., Walker, J.D., and Bartley, J.M., editors, Geologic evolution of the Mojave Desert and southwestern Basin and Range: Geological Society of America Memoir 195, p. 93–115.

Secretaría de Programación y Presupuesto, no date, Carta geologica, Tijuana: Dirección General de Geographia del Territorio Nacional, escala 1:1,000,000, 1 sheet.

Segerstrom, L., 1987, Geology of the Planchas de Plata area, northern Sonora, Mexico, *in* Dickinson, W.R., and Klute, M.A., editors, Mesozoic rocks of southern Arizona and adjacent areas: Arizona Geological Society Digest Volume 18, p. 153–164.

Spencer, J.E., Richard, S.M., Gehrels, G.E., Gleason, J.D., and Dickinson, W.R., 2005, Geochronologic and geochemical evidence for extension of the Bisbee Trough to the lower part of the McCoy Mountains Formation in southwestern Arizona: Geological Society of America with Programs, v. 37, no. 7, p. 482.

Steiger, R.H., and Jäger, E., 1977, Subcommission on geochronology: Conventions on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–371.

Stewart, J.H., Anderson, T.H., Haxel, G.B., Silver, L.T., and Wright, J.E., 1986, Late Triassic paleogeography of the southern Cordillera: The problem of a source for voluminous volcanic detritus in the Chinle Formation of the Colorado Plateau region: Geology, v. 14, p. 567–570.

Stewart, J.H., Poole, F.G., Ketner, K.B., Madrid, R.J., Roldan-Quintana, J., and Amaya-Martinez, R., 1990, Tectonics and stratigraphy of the Paleozoic and Triassic southern margin of North America, Sonora, Mexico, *in* Gehrels, G.E., and Spencer, J.E., editors, Geologic excursions through the Sonoran Desert region, Arizona and Sonora: Arizona Geological Survey Special Paper 7, p. 183–202.

Takahashi, M., Aramaki, S., and Ishihara, S., 1980, Magnetite series/ilmenite series vs. I-type/S-type granitoids, *in* Ishihara, S., and Takenouchi, S., editors, Granitic magmatism and related mineralization: Mining Geology Special Issue, no. 8, p. 13–28.

Titley, S.R., 1976, Evidence for a linear tectonic pattern in southeastern Arizona, *in* Wilt, J.C. and Jenney, J.P., editors, Tectonic digest: Arizona Geological Society Digest 10, p. 151–167.

Tosdal, R.M., Haxel, G.B., and Wright, J.E., 1989, Jurassic geology of the Sonoran Desert region, southern Arizona, southeastern California, and northernmost Sonora: construction of a continental-margin magmatic arc, *in* Jenny, J.P., and Reynolds, S.J., editors, Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 397–434.

Tosdal, R.M., Haxel, G.B., Anderson, T.H., Connors, C.D., May, D.J., and Wright, J.E., 1990, Highlights of Jurassic, Late Cretaceous to early Tertiary, and middle Tertiary tectonics, south-central Arizona and north-central Sonora, *in* Gehrels, G.E., and Spencer, J.E., editors, Geologic excursions through the Sonoran Desert region, Arizona and Sonora: Arizona Geological Survey Special Paper 7, p. 76–88.

Walker, J.D., Martin, M.W., and Glazner, A.F., 2002, Late Paleozoic to Mesozoic development of the Mojave Desert and environs, California, *in* Glazner, A.F., Walker, J.D., and Bartley, J.M., editors, Geologic evolution of the Mojave Desert and southwestern Basin and Range: Geological Society of America Memoir 195, p. 1–18.

Whalen, J.B., Currie, K.L., and Chappell, B.W., 1987, A-type granites; geochemical characteristics, discrimination and petrogenesis: Contributions to Mineralogy and Petrology, v. 95, p. 407–419.

Williams, S.A., 1960, A new occurrence of allanite in the Quijotoa Mountains, Pima County, Arizona: Arizona Geological Society Digest 3, p. 46–51.

Williams, S.A., 1963, Oxidation of sulfide ores in the Mildren and Steppe mining districts, Pima County, Arizona: Economic Geology, v. 58, p. 1119–1125.

Wilson, M., 1989, Igneous petrogenesis: Unwin Hyman, 466 p.

Winchester, J.A., and Floyd, P.A., 1977, Geochemical discrimination of different magma series and their differentiation products using immobile elements: Chemical Geology, v. 20, p. 325–343.

Wright, J.E., 1981, Geology and U-Pb geochronology of the western Paleozoic and Triassic subprovince, Klamath Mountains, northern California: University of California, Santa Barbara, Ph.D. dissertation, 300 p.

Wright, J.E., and Haxel, Gordon, 1982, A garnet-two-mica granite, Coyote Mountains, southern Arizona: Geologic setting, uranium-lead isotopic systematics of zircon, and nature of the granite source region: Geological Society of America Bulletin, v. 93, p. 1176–1188.