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Mid-crustal Cretaceous roots of Cordilleran metamorphic core complexes

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ABSTRACT

Thermobarometry for Cretaceous to mid-Tertiary plutonism and deformation in the lower plate of Whipple and Santa Catalina metamorphic core complexes shows that both crystalline terranes originated in the middle crust. Moreover, they are characterized by a striking acceleration of tectonic decompression coincident with middle Tertiary, low-angle detachment faulting leading to erosional and tectonic unroofing by mid-Miocene time.

Depth estimates for emplacement of five intrusive suites within the Whipple complex include (1) 33 ±4 km for the peraluminous, 89 Ma Whipple Wash plutonic suite; (2) 29 ±1 km for the 73 Ma Axtel quartz diorite; (3) 16 ±5 km for mylonitization and synkinematic plutonism at 26 Ma; (4) 6.2 ±1.9 km for the postkinematic, 19 Ma War Eagle gabbro–quartz diorite complex; and (5) 5.2 ±2.3 km for a 17 Ma postkinematic granodiorite. Decompression initially occurred at a low rate of 0.3 mm/yr from 89 to 26 Ma and increased to approximately 2 mm/yr during the late Oligocene to middle Miocene. Estimated depths for four pluton emplacement or deformational events in the Santa Catalina Mountains include (1) 21 ±1 km for the magmatic epidote-bearing, 68 Ma Leatherwood quartz diorite; (2) 15 ±3 km for the garnet, two-mica, 47 Ma Wilderness granite; (3) 9.3 ±1.9 km for post-Wilderness mylonitization; and (4) 6.3 ±2.6 km for the 27 Ma Catalina monzogranite. Post-Laramide decompression, estimated at 0.3 mm/yr, accelerated to 1.3 mm/yr prior to the cessation of detachment faulting.

Whereas most batholithic terranes of the North American Cordillera are representative of an upper crustal setting, core complexes provide, as a consequence of their tectonic evolution, a petrological and structural view into middle crustal processes.

INTRODUCTION

The metamorphic core complexes of the Whipple Mountains of southern California and the Santa Catalina Mountains of southern Arizona are representative of several similar terranes exposed in the southwest United States (Fig. 1). Common structural features include (1) a shallow-dipping Miocene detachment fault or faults of extensional origin and (2) a lower plate or "core" of metamorphosed crystalline rocks, usually containing a regional, low-angle mylonitic foliation. The question addressed in this study is the depth of origin of the crystalline assemblages that compose the lower plates of these complexes.

MAGMATIC AND DEFORMATION HISTORY

The lower plate of the Whipple Mountains complex contains five Phanerozoic magmatic suites including (1) six or more plutons of 89 ±3 Ma, marginally peraluminous granodiorite to tonalite of the Whipple Wash suite; (2) the metaluminous, 73 ±3 Ma Axtel quartz diorite; (3) 26 ±5 Ma synkinematic (to mylonitization) biotite tonalite and trondhjemitic aplite; (4) the postkinematic, 19 ±2 Ma War Eagle gabbro–quartrz diorite complex; and (5) 17 ±2 Ma biotite, hornblende granodiorite. The first four ages originate from the U/Pb (zircon) study of Wright et al. (1986), and the last age is based on geologic constraints. A petrologic description of the first three plutonic suites is given in Anderson and Rowley (1981). Earliest unroofing of the complex to surface exposure and erosion is estimated at 16 to 19 Ma (G. A. Davis, 1987, personal commun.).

As summarized by Keith et al. (1980), the Santa Catalina complex contains three ages of Phanerozoic plutonism including (1) the metaluminous, 68 ±8 Ma Leatherwood quartz diorite; (2) the 47 ±3 Ma garnet, two-mica Wilderness granite; and (3) the 27 ±2 Ma postkinematic biotite-hornblende Catalina monzogranite. Keith et al. (1980) also used the terms "Leatherwood," "Wilderness," and "Catalina" to refer to several similar plutons within each plutonic event. In this study, we have restricted our investigation to the type plutons. Unroofing of the Santa Catalina complex is estimated to be younger than 17 to 21 Ma (S. Reynolds, 1985, personal commun.).

Mid-Tertiary deformation involved mylonitization and, at higher structural levels, detachment faulting. Whereas the latest detachment faulting in both ranges is as young as 14 to 15 Ma, the age of exposed mylonitic sections is less well constrained. In the Whipple complex, the more than 3.9-km-thick section of mylonitic gneisses formed synchronously with intrusions at 26 ±5 Ma and is largely, if not exclusively, postdated by intrusions dated at 19 ±2 Ma (Wright et al., 1986; DeWitt et al., 1986). Mylonitization in the Santa Catalina complex is considered to have occurred between 27 and 47 Ma (Keith et al., 1980).

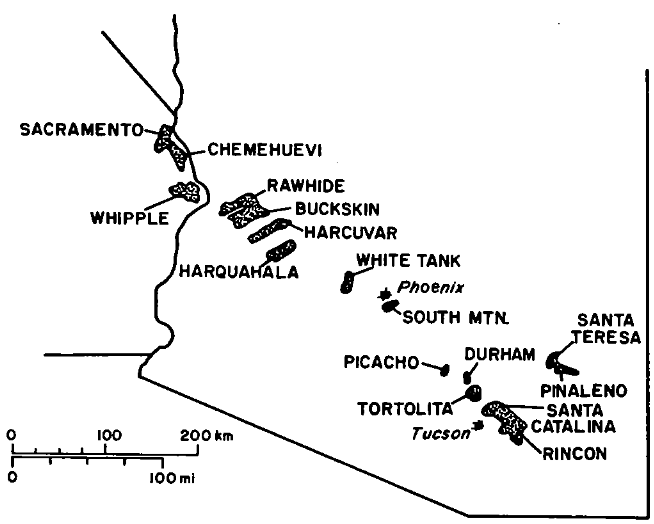

Figure 1. Location of Whipple, Santa Catalina, and other metamorphic core complexes of southwest United States.

THERMOBAROMETRY OF PLUTON EMPLACEMENT

Recent advances in our ability to solve the pressure-temperature-time (*P-T-t*) paths of orogenic terranes (Spear et al., 1984) have reemphasized the relation between petrology and tectonics. The approach used here is to determine the conditions of emplacement for plutons in multiply intruded terranes with the goal to constrain *P-T-t* conditions during descent and/

or ascent of deformed crust during orogenic tectonism.

Although contact metamorphic rocks may contain mineral assemblages appropriate for emplacement barometry, application is difficult in pervasively intruded terranes because of extensive overprinting. In contrast, refractory igneous phases are commonly less affected by younger thermal events. Even where severely mylonitized, such as in some plutons important to this study, mylonitically deformed porphyroclasts in many cases retain compositions related to igneous crystallization (Anderson and Rowley, 1981; Anderson, 1988).

Many igneous rocks lack pressure-sensitive phase assemblages, yet a prominent example in peraluminous granites is based on the assemblage garnet, muscovite, plagioclase, and biotite (Ghent and Stout, 1981; Hodges and Royden, 1984). The equilibria (hereafter referred to as the GMPB barometer) is fluid-independent and involves an increase in grossular component in garnet at the expense of anorthite component in plagioclase with increasing pressure and/or decreasing temperature. Although originally developed for pelitic schists, the barometer appears to work well for these granitic rocks and can be used in concert with the garnet-biotite thermometer of Ferry and Spear (1978) or, for more manganiferous garnets, with a modified formulation suggested by Ganguly and Saxena (1984). Two other possible barometers are based on the pressure-sensitive Si-content of muscovite in equilibrium with biotite, alkali feldspar, quartz, and a hydrous fluid, hereafter referred to as the MBAQ (calibration of Powell and Evans, 1983) and the phengite (calibration of Massonne and Schreyer, 1987) barometers.

For metaluminous granitoids, barometric determinations are possible when the pressure-dependent solubility of total aluminum in hornblende (Hammarstrom and Zen, 1986; Hollister et al., 1987) and the P-T-fO_2 stability of magmatic epidote (Zen and Hammarstrom, 1984) are used. To estimate crystallization temperatures, we have used the Al^{IV} hornblende thermometer (Nabelek and Lindsley, 1985) and two-feldspar thermometry (Hazelton et al., 1982; Whitney and Stormer, 1977) which, in this study, have yielded comparable results.

The assumption that the phase compositions represent near-emplacement conditions is critical to this approach, necessitating a restriction to near-rim or rim compositions.

TABLE 1. SUMMARY OF PRESSURE ESTIMATES

		GMPB* (kbar)	MBAQ (kbar)	Mu-Si (kbar)	Hb-Al (kbar)
Whipple Mountains:	Whipple Wash Suite	9.2 ±0.9	9.9 ±0.9	7.6 ±1.2	
	Axtel quartz diorite				7.9 ±0.3
	Mylonitization		4.5 ±1.1	4.7 ±1.4	
	War Eagle quartz diorite				1.7 ±0.5
	Younger granodiorite				1.4 ±0.6
Santa Catalina Mountains:	Leatherwood qtz diorite				5.6 ±0.3
	Wilderness granite	3.8 ±0.9	(7.8 ±0.7)	4.3 ±0.5	
	Mylonitization		(5.3 ±0.2)	2.5 ±0.5	
	Catalina granite				1.7 ±0.7

*GMPB = garnet-biotite-muscovite-plagioclase barometer of Ghent and Stout (1981); MBAQ = muscovite-biotite-alkali feldspar-quartz barometer of Powell and Evans (1983); Mu-Si = phengitic muscovite barometer of Massonne and Schreyer (1987); Hb-Al = hornblende barometer of Hollister et al. (1987).

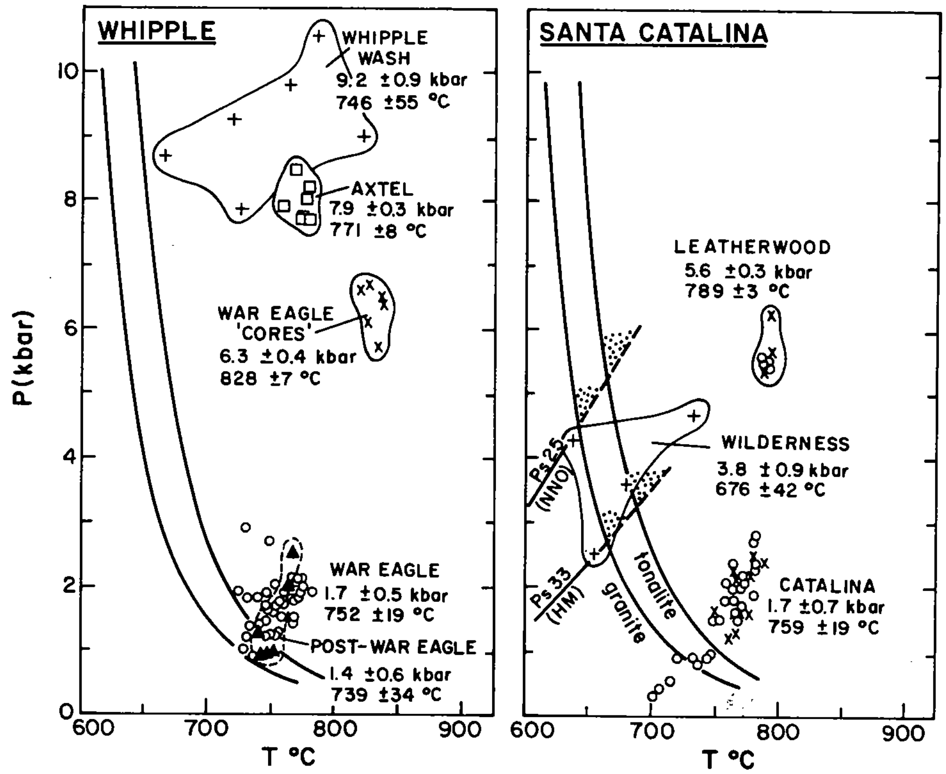

Figure 2. Summary of *P-T* conditions of pluton emplacement for Whipple Mountains and Santa Catalina complexes. Open or solid symbols indicate interior and rim hornblende compositions; x indicates hornblende cores. Plus symbols (+) are *P-T* solutions for garnet-muscovite-plagioclase-biotite equilibria. Epidote stability contours (Liou, 1973), shown as function of pistacite mole fraction and buffered oxygen fugacity, are presented for comparison to estimated emplacement of Leatherwood quartz diorite.

CONDITIONS OF MYLONITIZATION

Pressure estimates for Tertiary mylonitization of the Cretaceous Whipple Wash two-mica plutons include 4.7 ±1.4 kbar and 4.5 ±1.1 kbar (Table 1). In the Santa Catalina complex, results for mylonitization of the two-mica Wilderness granite are more diverse, averaging 2.5 ±0.5 and 5.3 ±0.2 kbar (Table 1). The latter value (from the MBAQ barometer) we view as unreasonably high. Two-feldspar mylonitization thermometry for the Santa Catalina Mountains yields an average temperature of 494 ±10 °C. Similar results have been calculated for the Whipple Mountains, which record an average of 458 ±35 °C at higher structural levels, increasing with depth to 535 ±44 °C. From mylonitic mineral assemblages, the depth-dependent metamorphic grade change is from upper greenschist to lower amphibolite.

EMPLACEMENT CONDITIONS OF GARNET, TWO-MICA GRANITES

Prekinematic, peraluminous granites volumetrically make up much of the Whipple and Santa Catalina complexes. All plutons of the Whipple Wash suite contain garnets that are unusually calcic (XCa = 0.17–0.28). On the basis of the GMPB barometer (and by using the Ghent and Stout calibration), the calculated pressures and temperatures of crystallization averaged 9.2 ±0.9 kbar at 746 ±55 °C (Fig. 2).

We have questioned the validity of this seemingly high pressure, yet even higher pressures are attained with the alternative formulation of Hodges and Royden (1984). Similar estimates are provided by the MBAQ and phengite barometers (Table 1).

Garnets in the Wilderness granite are less calcic (XCa = 0.04–0.05) and consequently yielded lower pressures by the GMPB barometer. The results average 3.8 ±0.9 kbar at 676 ±42 °C. The pressure is consistent with that inferred from contact mineral assemblages by Palais and Peacock (1987). Other barometric estimates include 4.3 ±0.5 and 7.8 ±0.7 kbar (Table 1). The latter value is derived from the MBAQ barometer, a calibration that here, as well as for mylonitization conditions of this pluton, yields high estimates.

Figure 3. Photomicrograph of magmatic epidote enclosed in biotite from Leatherwood quartz diorite.

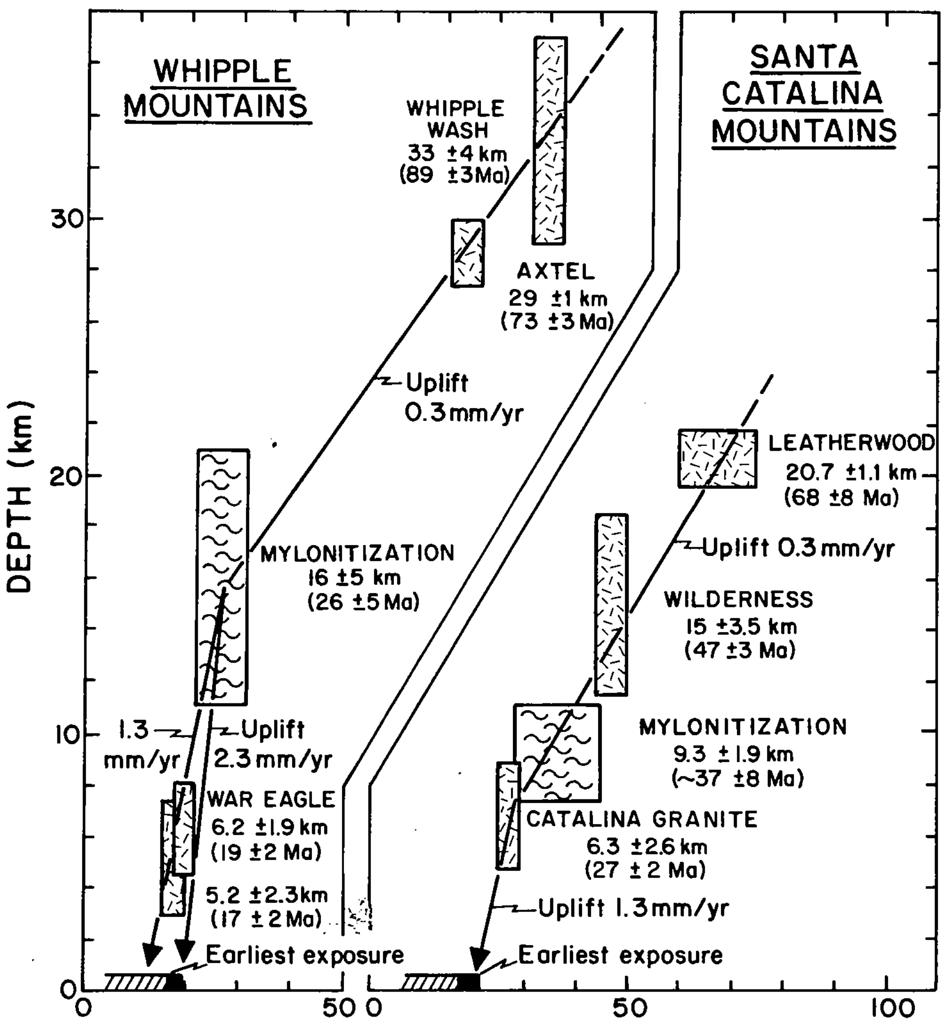

Figure 4. Upward transport of Whipple and Santa Catalina crustal sections as function of age.

EMPLACEMENT CONDITIONS OF METALUMINOUS SUITES

Prekinematic Plutons

Prekinematic (to mylonitization) metaluminous plutons include the Axtel quartz diorite of the Whipple Mountains and the Leatherwood quartz diorite of the Santa Catalina Mountains. Both contain aluminous hornblende, potentially indicative of high-pressure crystallization, in addition to a range of subsolidus amphiboles (low-Al hornblende and actinolite) resulting from subsequent deformation and/or thermal overprinting. When the inferred primary compositions were used, hornblende barometry yielded 7.9 ±0.3 kbar and 5.6 ±0.3 kbar for the two plutons, respectively.

Consistent with this high pressure of crystallization, the Leatherwood contains an early generation of epidote that we interpret to be of magmatic origin. The epidote has a pistacite composition ($Fe^{3+}/[Fe^{3+} + Al^{VI}]$) of 0.29 ±0.01 and occurs as large euhedral crystals partly or totally enclosed in biotite (Fig. 3). Secondary epidote is ubiquitous and often abundant but is texturally distinct from the inferred magmatic epidote. Although Zen and Hammarstrom (1984) inferred that magmatic epidote may be indicative of pressures in excess of 6 to 8 kbar, inspection of epidote stability contours (Liou, 1973) relative to a water-saturated, tonalite solidus (Fig. 2b), suggests that the epidote in the Leatherwood requires a minimum 4.0 to 4.5 kbar, which is consistent with our estimate. Andalusite occurs near this intrusion (Bykerk-Kauffman, 1987, personal commun.); however, we attribute its existence to the contact effects of the regionally extensive intrusions of the Wilderness and related plutons.

Postkinematic Plutons

Younger intrusions in both complexes include the Catalina granite in the Santa Catalina Mountains and the War Eagle gabbro–quartz diorite and a crosscutting granodiorite in the Whipple Mountains. Thermobarometric results for the Catalina pluton average 1.7 ±0.7 kbar at 759 ±22 °C. The temperature estimates, from the Al^{IV} hornblende thermometer of Nabelek and Lindsley (1985), are comparable to those obtained from feldspar thermometry (726 ±63 °C).

Estimates of crystallization conditions for the quartz diorite of the War Eagle intrusion average 1.7 ±0.5 kbar. This result is derived from rim and near-rim hornblende compositions and excludes dark brown, aluminous cores that yield 6.3 ±0.4 kbar, a possible indication that the mafic magma pooled during its ascent, allowing some early crystallization to proceed. The amphiboles of the younger granodiorite yielded pressure estimates of 1.4 ±0.6 kbar (Fig. 2).

DISCUSSION

The data presented above demonstrate a provocative, age-dependent variation in the crustal dept]h for rocks now exposed at the surface. For older plutons, calcic garnet, siliceous muscovite, aluminous hornblende, and occurrence of magmatic epidote all require a middle crust residence at approximately 21 km for the Santa Catalina complex and in excess of 25 km for the Whipple complex during the middle to Late Cretaceous. Middle Tertiary pluton emplacement and mylonitization occurred at shallower levels, but still exceeded 11 km. Emplacement of postkinematic plutons was upper crustal (5 to 7 km) en route to the near-surface conditions (<5 km) of detachment faulting at 14 to 18 Ma, when parts of these terranes were being exposed at the surface.

The decompression trajectory of the complexes is shown in Figure 4; depth is calculated from a crustal geobarometric gradient of 3.7 km/kbar. Sequential decompression is constrained by five plutonic or deformational events in the Whipple complex and four in the Santa Catalina complex, plus an additional tie point provided by earliest unroofing to subaerial exposure and erosion. A similar style of uplift is evident in both terranes, characterized by moderate decompression from Late Cretaceous to middle Tertiary, followed by accelerated uplift coincident with core complex mylonitization and detachment faulting. The same conclusion has been independently derived from rapid closure of various isotopic systems for the Whipple complex (Davis et al., 1987).

For comparison, Anderson (1985) documented that moderate decompression must also characterize the Sacramento core complex, and John (1986) has recognized that early plutonic members of the Chemehuevi core complex contain magmatic epidote, which would have required major uplift of that complex after the Late Cretaceous. Both terranes are near the Whipple Mountains (Fig. 1). Similar findings were reported by Rhodes (1986) for the Priest River complex (Spokane dome) of northeastern Washington. Most batholithic terranes of the Cordillera represent upper crustal conditions, yet our conclusion is that core complexes, because of their unusual petrotectonic evolution, can provide a unique exposure of the magmatic and deformational processes within the middle crust.

An explanation for the mechanics of the uplift bears on any model of core complex evolution. We assume the initial, moderate rate to reflect static decompression, a probable uplift and erosional response to earlier crustal thickening during the Mesozoic. The late acceleration of decompression signals a major change in tectonic setting and should relate to their extensional evolution, which involved broadly coeval mylonitization and detachment faulting. Mechanisms of accelerated tectonic decompression include lower plate upward transport along a variably dipping zone of crustal shear and localized arching or doming.

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