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Tectonic underplating of trench sediments beneath magmatic arcs: the central California example

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We summarize the post Late Cretaceous regional tectonic evolution of the central California Coast Ranges, west of the San Andreas fault system. The Monterey terrane of North American origin was laterally transferred to the Pacific plate via the San Andreas fault. The Monterey terrane is an assembly of three tectonic units, Salinia, Nacimiento and Sierra de Salinas blocks, two of which have been previously identified as separate terranes. These blocks are separated by two regionally important thrust faults: the Sur fault as well as the Salinas shear zone. Based on thermobarometric and thermochronologic constraints and the existence of a common younger cover sequence, these blocks were juxtaposed together after the latest Cretaceous. The Salinian assemblage represents a crustal section through the continental interior side of the Mesozoic California arc and formed during the Late Cretaceous, primarily during a regionally significant magmatic flare-up between 95 and 80 Ma. In the Santa Lucia Range, parts of the arc are exposed to palaeo-depths in excess of 30 km. The Nacimiento and Sierra de Salinas assemblages comprise basement rocks representing Late Cretaceous variants of the Franciscan Complex and are interpreted to be correlative. They represent the lower plate of a regionally important thrust system; the upper plate is the Salinian assemblage, whereas the Sur and Salinas faults are local exposures of the structure. We concur with previous estimates of 150 to 180 km of shortening during a brief time span (<6 my), at a rate of >3 cm/yr. This fault system corresponds to the megathrust of the Farallon subduction beneath North America during the early stages of the regionally extensive episode of shallow subduction (Laramide orogeny). As a result, trench sediment was thrust under North America and tectonically underplated to the lower crust of North America. The Salinas shear zone, in particular, is a ductile expression of shallow subduction; thermobarometry in the upper plate, lower plate and the shear zone itself indicate that this is the fossil subduction megathrust originating at depths of $\sim$35 km. The entire system collapsed extensionally soon after the trench sediment was underthrust, possibly because of the lack of strength of the lower plate. Arc magmatism in the upper plate ceased at the onset of underplating. This regional example illustrates the significance of tectonic underplating in shallow subduction systems. Accretion-related trench sediment was shuffled from the trench to the sub-arc region of the upper plate, but not recycled into the mantle. This process requires that the subduction megathrust be located solely within the North American crust. This geometry requires a sudden migration of the

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subduction interface toward the arc and may apply to other regional examples, including the modern shallow subduction of the Cocos plate beneath southern Mexico. The tectonically underplated trench sediment undergoes regional, Barrovian metamorphism, after initially following a high-pressure/low-temperature path. Moreover, the shear zone marking the fossil intracrustal megathrust was subject to granulite-facies metamorphism and limited partial melting.

Keywords: tectonics; subduction; underplating; California

Introduction

Subduction of oceanic plates is a major plate tectonic process that has operated for much of the Earth's history. During subduction, dense oceanic lithosphere is returned to the mantle primarily owing to its negative buoyancy. In the process, sedimentary sequences that were either deposited on the oceanic plate or accumulated at the subduction zone trenches can be dragged into this downgoing motion. Modern trenches have been surveyed extensively (e.g. Plank and Langmuir 1998); it is well documented that more than half of them, some long lived, are sediment starved. Direct evidence exists that trench sediment is being transported downward with the oceanic plates, and that this process is volumetrically significant at modern margins. This process is broadly defined as sediment subduction (Von Huene and Scholl 1991). Addition of sediment or oceanic crust to the margins' upper plate is generally referred to as 'subduction accretion', whereas transfer from the upper plate to the lower plate is referred to as 'subduction erosion'.

Tectonic underplating is a combination of subduction accretion and erosion, whereby wedge sediment and/or related forearc segments are underthrust at shallow subduction zones and added to the base of the upper plate. The extent to which tectonic underplating is significant relative to that which is delivered to the mantle (Cliff and Vannucchi 2004) or recycled via arc magmatism (Plank 2005) is unclear. Very few worldwide examples of underplated sequences have been identified or studied (e.g. Jacobson 1997; Matzel *et al.* 2004).

In this paper, we review current geologic knowledge of the central California Coast Ranges, south of Monterey (Page 1981), a crustal section that provides solid documentation for tectonic underplating. We focus primarily on the latest Cretaceous tectonic disruption that was regionally significant for the segment of the Cordilleran margin located within the realm of present-day southern California (Figure 1). This area underwent shallow subduction during the Laramide orogeny, sensu Saleeby (2003). During the early stages of the Laramide, the slab penetrated landward at remarkably shallow crustal depths. The top of the subducting plate was at 35 km depth, some 150–180 km inland from the trench, and led to the underplating of trench sediment beneath Cordilleran arc-related rocks. This architecture has been documented in southern California (Burchfiel and Davis 1975; Gastil *et al.* 1992), but no better, more coherent exposures of the deep roots of the system exist than those in the central California Coast Range.

The Monterey terrane (defined below) is a part of the southwestern North American Cordillera in southern California that was displaced northward with the San Andreas (and possibly Cenozoic proto-San Andreas) fault system. More than just another piece to the southern California-Mojave puzzle, the Monterey terrane exposes some of the deepest crustal rocks of the southern California subduction system, and has the least amount of disruptive subsequent complexities (e.g. Cenozoic extension). Below we present the major tectonic elements of the Monterey

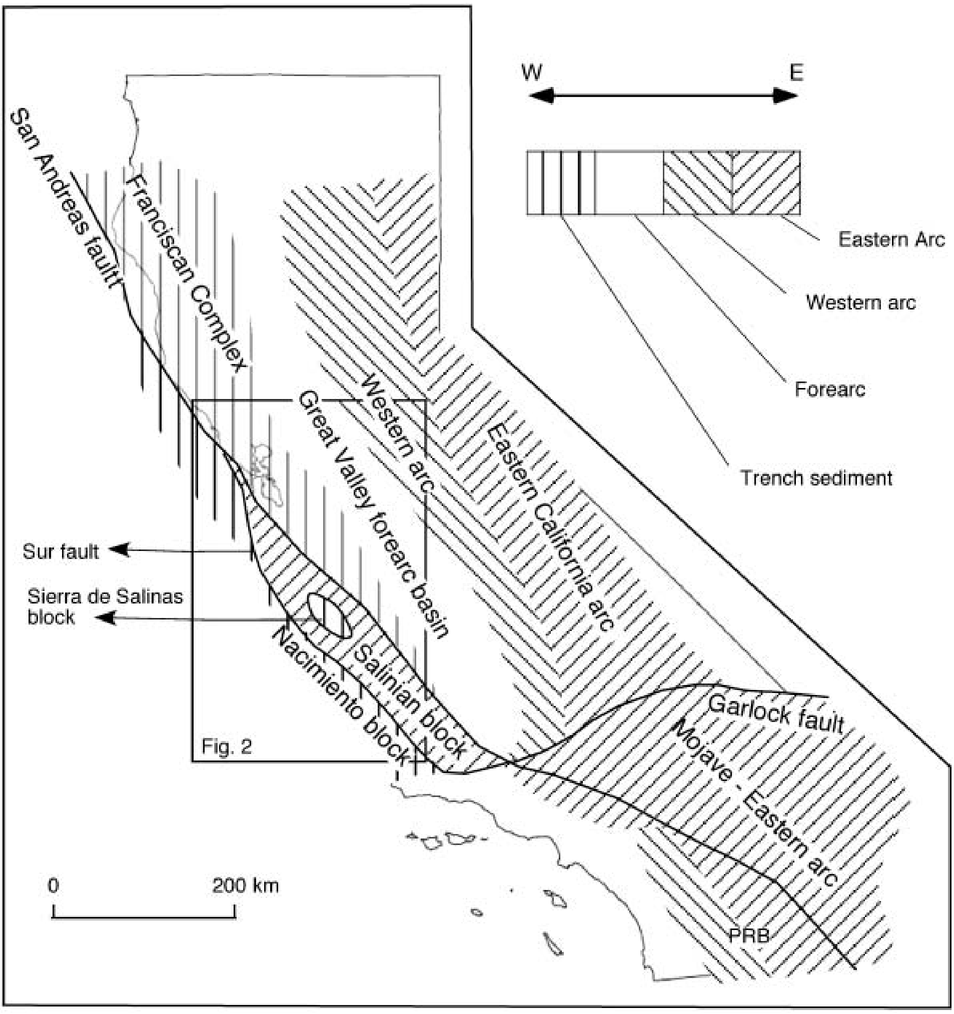

Figure 1. Simplified geologic map of California showing the major tectonic elements discussed in this study. The Franciscan Complex, Great Valley forearc basin, western and eastern facies of the California arc are preserved intact in central and northern California, as well as in the Peninsular Ranges Batholith (PRB) whose northernmost extension is in southern California. The Mojave region and its correlative units west of the San Andreas fault exhibit primarily the eastern arc facies, which was presumably thrust westward over much of the western structural domains.

terrane, the history of tectonic underplating, the significance for understanding subduction processes, and we conclude with a set of discriminating criteria for recognizing similar processes in the geologic record.

Geotectonic background and terminology

The Coast Ranges of central California (Page 1981) represent a tectonically displaced segment of the southernmost Sierra-Mojave block (Saleeby 2003) of southern California (Figures 1 and 2). The basement of the Coast Ranges is exposed in several distinct topographic highs (Ross 1976c), separated by lower relief areas in which the basement is covered by an extensive sequence of Cenozoic sedimentary rocks

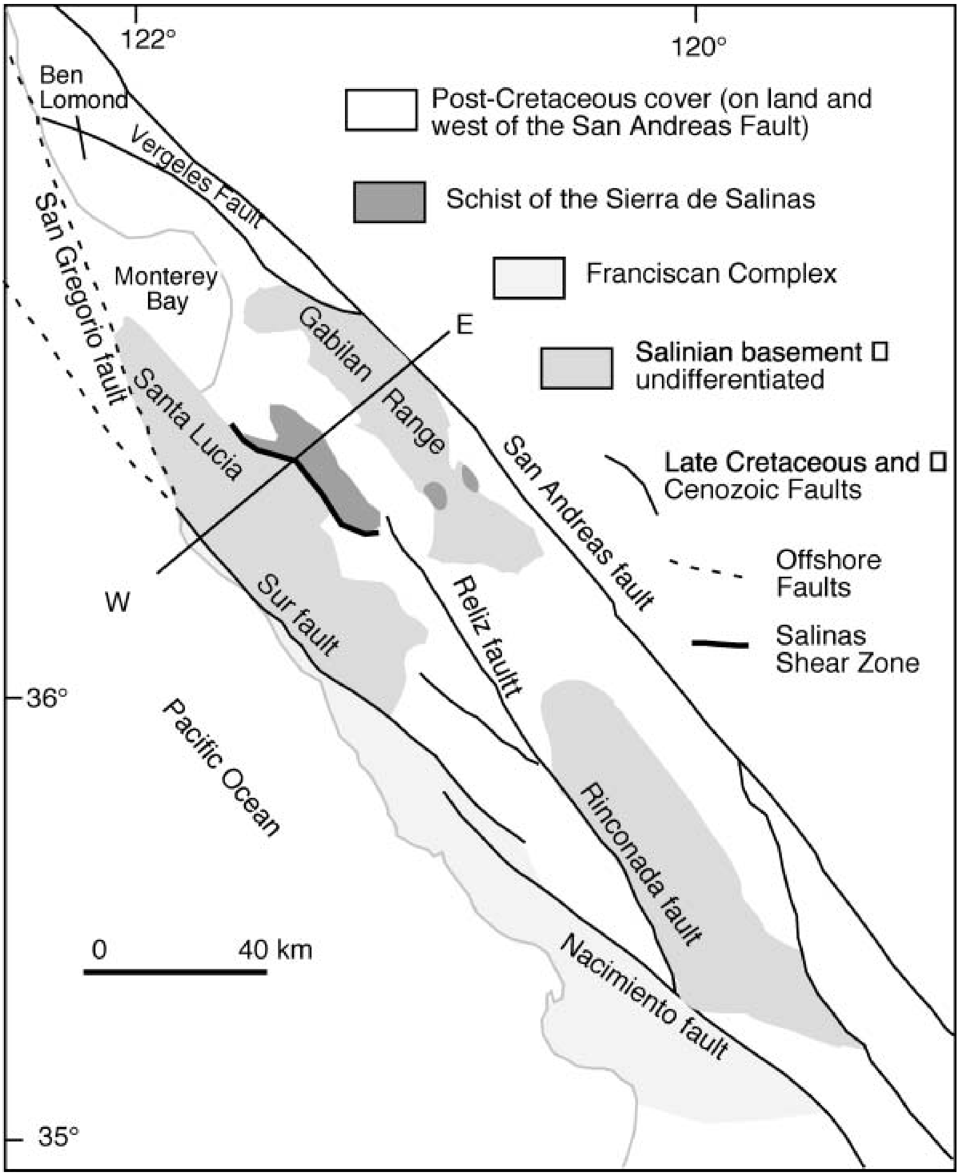

Figure 2. Simplified geologic map of the central Monterey terrane, showing the outcrop pattern of the three basement blocks discussed in the paper (Salinia, Sierra de Salinas and Nacimiento), as well as the location of major Late Cretaceous and Cenozoic faults, and the Salinas shear zone.

(Almgren and Reay 1977; Howell *et al.* 1977, 1978; Poore *et al.* 1977; Taliaferro 1944). The Coast Ranges are segmented by numerous Late Cenozoic strike-slip and high-angle reverse faults associated with the San Andreas system (Page *et al.* 1998). Formation of the modern Coast Ranges ended with an episode of latest Miocene-Quaternary transpressional uplift (Compton 1966; Ducea *et al.* 2003a).

In this paper, we will refer to the region bounded by the Pacific Ocean to the west and the San Andreas fault to the east between the Transverse Ranges to the south and Cape Mendocino to the north, as the Monterey terrane. The lateral displacement that defined its allochthonicity is Cenozoic, and is a consequence of the formation of the San Andreas fault system in southern and central California. All rock units east of the Pacific coast are included into this block. We are aware of the already complex and confusing terrane nomenclature of the California Coast Ranges, and thus the danger of introducing yet another set of names for tectonic blocks in this region. However, we believe that this tectonic classification is a simplifying one – it is based on the observation that most of the separate blocks of the Coast Ranges were locked together possibly by the latest Cretaceous or during the Early Cenozoic, and the 'out-of-place' nature of these rocks is fundamentally related to the San Andreas fault system (Graham *et al.* 1989), not cryptic and/or poorly defined pre-Cenozoic structures.

The Monterey terrane was translated 310–350 km to the north by the San Andreas fault with respect to its origin in southern California (Page *et al.* 1998). The San Andreas is unambiguously the eastern boundary of this block (Figure 2); however no obvious fault uniquely separates the block's large-scale fabric from outboard geologic domains to the west. The San Gregorio-Hosgri (Dickinson *et al.* 2005) is a well-documented significant right-lateral fault of Late Cenozoic age (~150 km displacement) and it parallels other, less significant faults in the area (Hall 1991). The offshore relationship of the Pacific plate to the terrane are largely unresolved (Greene *et al.* 2002). However, it appears that the continental fragment is attached to the offshore Monterey oceanic plate as no known major faults separate the two (Ewing and Talwani 1991; Londsdale 1991). Consequently, we suggest that the Monterey terrane is currently part of the Monterey plate, and that its western boundary should be taken as the transition from Franciscan rocks of the Nacimiento block to the younger Pacific oceanic crust, perhaps delineated by the Santa Lucia escarpment (Meltzer and Levander 1991).

A standard palinspastic restoration to the pre-San Andreas configuration shows that the Monterey terrane can be correlated with southern California geology (Barbeau *et al.* 2005; James 1992; Kidder *et al.* 2003; Kistler and Champion 2001; Page *et al.* 1998). Some have argued that a robust tie to southern California geology requires an additional 200–300 km of right lateral displacement along an Early Cenozoic, proto-San Andreas fault (e.g. Armstrong and Suppe 1973). However, slivering of the block along internal faults (Dibblee 1976; Dickinson *et al.* 2005) can easily account for 300 km right-lateral slip. In either case, the genetic linkage between the Monterey terrane and southern California is not violated.

In contrast, arguments based on palaeomagnetic data have been used to suggest that the Monterey terrane and equivalents in central coastal California have travelled some 2100 km northward (from southern Mexico), since the Late Cretaceous (Champion *et al.* 1984). These conclusions have sparked an intense debate regarding the origin of 'orphan' fragments in the Coast Ranges (e.g. Whidden *et al.* 1998). However recent geologic information does not support a southern Mexico origin of the block prior to the latest Cretaceous. For example, detrital zircons in metamorphosed framework rocks from the Santa Lucia basement, contain several Precambrian age peaks that are standard for southwestern North America, but incompatible with a southern Mexico origin (Barbeau *et al.* 2005). Thus, it is unlikely that the rocks of the Monterey terrane are far travelled since the latest Cretaceous, and the old debate on the orphan Salinia (and equivalents) is no longer an issue of contention. One possible reconciliation of the discrepancy between geologic and palaeomagnetic data is that the palaeomagnetic data reflect tilting rather than latitudinal transport (Butler *et al.* 1991; Dickinson and Butler 1998).

In this paper, we will review existing data and present some new observations from the central part of the Monterey terrane, from the Santa Lucia, Sierra de Salinas and Gabilan Ranges (Figure 2). The focus will be primarily on the latest Cretaceous tectonics, and thus we will not detail the post-Cretaceous cover of the area, for which there is an extensive available literature (Hall 1991). Three tectonically distinct blocks crop out in the area of interest for this study: the Salinian, the Sierra de Salinas and the Nacimiento blocks. The Salinian block, previously referred to as the Salinian composite terrane (Page 1981) is a displaced fragment of the great Sierra Nevada–Peninsular Ranges magmatic arc (Mattinson 1978; Ross 1983). The Sierra de Salinas block (Ross 1976b) comprises a sequence of accretion wedge micaschists (metagraywackes) whose sedimentary precursors are Maastrichtian in age (Barbeau *et al.* 2005; Barth *et al.* 2003) and were underplated beneath Salinia (Kidder and Ducea 2006). These rocks are correlative with the Pelona, Orocopia and Rand schists in southern California (Jacobson *et al.* 1988). The Nacimiento block (Gilbert 1973a), is also known as the Sur-Obispo terrane (Vedder 1983), and is composed primarily of Cretaceous accretion wedge (Franciscan) sediments with mafic and ultramafic blocks and is correlative with the Sur Obispo block to the south (Page 1981).

Salinian block

The Salinian block (Reed and Hollister 1936) consists of Cretaceous calc-alkaline intrusions, their metamorphosed equivalents (Mattinson 1978, 1990; Ross 1978, 1983; Wiebe 1970a), and a series of highly metamorphosed framework rocks referred to as the Sur Series (Trask 1925). The Salinian block makes up much of the basement in the Santa Lucia and Gabilan ranges (Ross 1983), among the ranges covered by this study. In addition, correlative Salinian block basement rocks are also present in the Santa Cruz Mountains, and in more isolated exposures in other areas throughout coastal California (James 1992; James and Mattinson 1988; Kistler and Champion 2001; Mattinson 1978, 1990; Ross 1983), and are covered by latest Cretaceous and Cenozoic unmetamorphosed sedimentary rocks (Grove 1993; Hall 1991; Vedder 1983). The Sur Series term encompasses all deformed and metamorphosed rocks in the Salinian block and the term has no stratigraphic significance. The Series comprise pelitic micaschists, marbles, subordinate quartzite representing metamorphosed equivalents of the southwestern United States Cordilleran miogeocline, and their Mesozoic cover rocks (Barbeau *et al.* 2005). Upper amphibolite to granulite facies regional metamorphism of the Sur Series is Late Cretaceous, and synchronous with arc magmatism (Ducea *et al.* 2003b). The classic interpretation of the Sur Series is that it represents almost exclusively a metamorphosed equivalent of a passive margin sequence (Ross 1978). More recently, it was shown that Sur Series rocks metasedimentary rocks are in fact interlayered with Late Cretaceous orthogneiss – arc-related rocks metamorphosed in the middle crust soon after their emplacement (Kidder *et al.* 2003). The ratio of metaigneous to metasedimentary rocks varies from zero to four in the Series, with only the quartzitic, pelitic and marble-rich layers being unambiguously metasedimentary.

Magmatic activity in the Salinian block began between 100 and 110 Ma (James and Mattinson 1988), and continued until 79 Ma (Kidder *et al.* 2003). This timing is coincident with the major pulse of magmatism that generated the main segments of the California arc, the Sierra Nevada and Peninsular Range batholiths (Coleman and Glazner 1998; Ducea 2001). The average composition of the Salinian arc is granodiorite, where emplaced at shallow (6–15 km) crustal levels (Ross 1975, 1976d), whereas tonalitie, quartz-diorite and mafic lithologies dominate greater palaeo-depths (Ducea *et al.* 2003c). Much of the Salinian block in the central Santa Lucia Range is exposed at palaeo-depths of 25–33 km and has been metamorphosed in the amphibolite and granulite facies during arc magmatism (Hansen and Stuk 1993; Kidder *et al.* 2003; Wiebe 1970b). In contrast, exposures in the northern Santa Lucia and Gabilan ranges are plutons of larger area and shallower crystallization depths (<15 km). The timing of magmatism in the shallow and deeper emplacements is coincident, and the chemical and isotopic characteristics are of similar nature (Ducea *et al.* 2003c; Kistler and Champion 2001).

Overall, the Salinian block provides an excellent view of the California arc, as it was shaped during Cordilleran magmatism, especially by a major, regionally significant Late Cretaceous event comprised of plutonic rocks and smaller areas of metamorphosed framework rocks that were converted to amphibolite facies metamorphic screens during arc magmatism. Large, oval shaped composite plutons of upper crustal exposures, such as the Monterey Granodiorite and the Soberanes Point Tonalite in the Santa Lucia Mountains (Ross 1976d) are similar in map view, composition and fabrics to plutons exposed in the Sierra Nevada batholith. Metamorphic pendants separating these plutons appear to be steep and deformed as a result of magmatic emplacement (Ducea *et al.* 2003c). In contrast, at deeper crustal levels, plutonic rocks are commonly garnet- and pyroxene-rich (Compton 1960), have sill-like geometries and were emplaced during the formation of a regionally coherent palaeo-horizontal foliation (Kidder *et al.* 2003). Volumetrically minor, late-stage alaskite and pegmatite dikes and a few mafic-ultramafic plutons (Ross 1976a) are the only post-kinematic, undeformed intrusive rocks in the deeply exposed rocks in the Santa Lucia Mountains.

Thermochronologic data (Naeser and Ross 1976; Mattinson 1978) indicate that the Salinian block underwent rapid exhumation from peak pressure–temperatures (Ducea *et al.* 2003b) during the late Campanian-Maastrichtian, where unmetamorphosed marine Maastrichtian turbiditic sediment uncomformably overlie the basement (Barbeau *et al.* 2005; Grove 1993). The Salinian block was further covered by as much as 4 km of sedimentary deposits during the Cenozoic (Compton 1966); most of these rocks are shallow marine. The shift from predominantly marine to subaerial deposition took place at about 4 Ma, and is a result of the uplift of the modern Coast Ranges (Ducea *et al.* 2003a).

Nacimiento block

The Nacimiento block (Gilbert 1973a; Hall 1991; Raymond 1974), also referred to Sur-Obispo terrane (Vedder 1983) comprises on land rocks in the central California Coast Ranges west of the Sur fault, south of Monterey Bay and north of Ventura Basin (Figure 2). The western, offshore, boundary of the Nacimiento block is not explicitly defined in the literature, although fundamentally, a structural break must exist that separates the Nacimiento block from the younger oceanic rocks of the Monterey plate. The basement of the block consists of Franciscan Complex rocks (Gilbert 1973b; Hall 1991) and limited exposures of the Coast Range Ophiolite (Vedder 1983) are overlain by an uppermost Cretaceous-Cenozoic sedimentary cover, possibly correlative to the Salinian block (Hall 1991). In addition to the continuous exposures west of the Sur fault, Franciscan Complex rocks crop out in a structural window below the Salinian block in the vicinity of Big Sur – this key location underscores the important structural interpretation that the Salinian block was thrust over the Nacimiento block along the Sur fault.

The Coast Range Ophiolite (Shervais *et al.* 2004) crops out as dismembered structural klippe in the Santa Lucia and San Rafael mountains, and west of the town of Santa Maria. The Coast Range Ophiolite comprises the bulk of a nappe sitting structurally above the Franciscan units in the Nacimiento block. The sedimentary cover is similar to the Salinian cover and is discussed in detail here. Most authors agree that the Nacimiento and Salinian blocks were locked together by the latest Cretaceous (see discussion in Hall, 1991), an interpretation that we also endorse.

Franciscan rocks of the Nacimiento block (Ernst 1980) are divided into a pervasively sheared unit and a lesser-deformed bedded unit (Ernst 1980; Gilbert 1973a; Hall 1991). The first is also referred to as a mélange and contains locally exotic blocks of greenschist and blueschist facies rocks. The second unit was either not subducted or was subducted to minimal depths, based on its relative lack of deformation and metamorphism. Overall, the abundance of mafic, ultramafic and of metamorphosed rocks is lower in the Nacimiento block compared to other exposure of Franciscan rock sequences in California.

The Franciscan rocks of the Nacimiento block have latest Cretaceous depositional ages (Gilbert 1973b; Hall 1991; Suppe and Armstrong 1975). A detrital zircon study of turbiditic sandstone from the Nacimiento block along the coastal Highway 1 (Alvarado-Patricia *et al.* 2003) places some important constraints on the origin of the Franciscan Complex in this area. Specifically, the youngest age peak of zircons grains at 79–83 Ma is coincident with a major pulse of magmatism in the Salinian block and elsewhere in the California arc; this peak constrains the depositional age of the Franciscan here to be younger than $\sim$79 Ma. Older detrital age peaks in the analysed rocks are Late Cretaceous (90–110 Ma), latest Jurassic (150–160 Ma), Triassic ($\sim$200 Ma and 220 Ma), Late Permian (260–270 Ma), and a few Proterozoic grains (1.1 Ga, 1.4 Ga, 1.7 Ga). All of these ages are fully consistent with a 'southern California' origin of this segment of the Franciscan Complex. Metamorphic ages are as young as 70 ± 5 Ma in the Nacimiento block (Suppe and Armstrong 1975), which is consistent with less precise palaeontological ages for this area. Detrital U-Pb zircon ages in graywacke have distributions that are virtually identical to those in the schist of the Sierra de Salinas (Barth *et al.* 2003), and in agreement with a Campanian depositional age. The similarities between compositional and detrital age patterns in the Nacimiento block and the schist of the Sierra de Salinas will be further interpreted below.

Sierra de Salinas block

The schist of Sierra de Salinas (Figure 2) is a homogeneous metagraywacke cropping out in two structural windows within the Salinian block (Barth *et al.* 2003; Kidder and Ducea 2006; Ross 1976b). The schist is linked to the Pelona, Orocopia, and Rand schists of southern California, which represent Cretaceous and Tertiary accretion wedge or forearc sediment underthrust beneath the California continental arc during Laramide flat slab subduction (Jacobson *et al.* 2000; Jacobson and Dawson 1995; Jacobson *et al.* 1996; Saleeby 2003; Grove *et al.* 2003).

The main exposure of the schist underlies the Sierra de Salinas, a northwest trending range southwest of the Salinas Valley (Figure 2). The schist is bounded on the northeast by the Rinconada-Reliz fault, on which ~44km dextral slip occurred in the Late Tertiary (Dibblee 1976). Barth *et al.* (2003) found that the Cretaceous granitic rocks to the southwest and northwest of the schist are older than the schist and could not have intruded it as proposed (Ross 1976b). The schist has a southwest-dipping monoclinal form in most of the range. Both the schist and adjacent granite bodies are overlain by Miocene sedimentary rocks, which dip gently to the southwest and northwest away from schist. These orientations are similar to those in the schist, indicating that prior to post-Miocene tilting, foliation in the schist approached horizontal. The schist is homogeneous in appearance, with the exception of dikes and veins composed predominantly of quartz, plagioclase and potassium feldspar and quartz veins. Quartzofeldspathic veins are most common at higher structural levels, but are found throughout the schist and presumably indicate syndeformational partial melting of the schist near the wet solidus. Mineral assemblages in the schist correlate with structural depth. For example, the northwest and southwest edges of the schist are marked by an absence of primary muscovite, increased abundance of biotite, and the appearance of magnesiohornblende, actinolite and myrmekite.

Together, these observations indicate higher metamorphic grade at structurally higher levels, an observation supported by thermobarometry (Kidder and Ducea 2006). Geologic reconstruction suggests that the graywacke was deposited, subducted to depths of ~10 kbar, and exhumed quickly. This interval occurred between 79 and 68 Ma, respectively, the youngest age of detrital zircons and oldest muscovite Ar/Ar cooling age in the schist (Barth *et al.* 2003; Grove *et al.* 2003). This interval in the Sierra de Salinas corresponds to a timing gap in the Salinian block between the cessation of arc related magmatism after 79 Ma and the appearance of deep arc related rocks at the surface at about 68–69 Ma (Kidder *et al.* 2003).

Salinas shear zone

The Salinas shear zone (Ducea *et al.* 2007; Kidder and Ducea 2006) is a ductile fault along the western flank of the Sierra de Salinas range that separates the Salinian block from the Sierra de Salinas block (Figure 2). The ductile shear zone itself is preserved only locally and in several places is overprinted by minor normal faulting. The Salinas shear zone is marked by the development of mylonitic foliation in upper plate hornblende–quartz diorite. Over a distance of ~100 m, the coarse-grained hornblende–quartz diorite grades downward towards the schist into a foliated, finer-grained mylonite. Clinopyroxene becomes the major, and sometimes only, mafic phase with increasing degree of mylonitization. The absence of clinopyroxene elsewhere in upper plate rocks within a few km of the shear zone, and patchy remains of formerly continuous hornblende grains in clinopyroxene indicate growth of clinopyroxene at the expense of hornblende. The association of deformation with the appearance of clinopyroxene is further highlighted by small-scale layering, in which hornblende and clinopyroxene alternate as the predominant mafic phase. Both smaller grain size and higher quartz content contribute to weakening the clinopyroxene-bearing layers, which appear microstructurally to have experienced more ductile shearing. Small-scale variations in fluid composition may also have played a role in stabilizing hornblende, as evidenced by mm–cm scale hornblende-bearing quartzofeldspathic veinlets, which cut across the foliation. These veins probably represent the frozen plumbing system through which H_2O ($\pm CO_2$?)-rich fluids or melt escaped during deformation. The breakdown of hornblende to form clinopyroxene marks a transitional state between the amphibolite and granulite facies. Foliations in the upper and lower plates are consistent across the contact. Stretching lineations formed mainly by elongate quartz grains are ubiquitous in the schist near the shear zone and occur as far as 2 km from the contact.

The schist is characterized by a negative thermal gradient ranging from measured values of 400°C away from the shear zone to 714°C closer to the shear zone (Kidder and Ducea 2006). The inverted thermal gradient occurs over a structural thickness of 2.5 km, at an average value of 47°C/km. The gradient increases near the contact to at least 74°C/km. Grove *et al.* (2007) described a similar inverted gradient in the Catalina Schist in southern California.

A variety of 1D and 2D thermal models, which neglect shear heating, do not satisfactorily explain the steep inverted thermal gradients found in the shear zone, given the temperature constraints from the upper plate away from the shear zone. The observed inverted metamorphic gradient can only be produced by excess heat that corresponds to a minimum increase of some 200°C along the shear zone. In addition, the most direct evidence for shear heating is the association of granulite facies recrystallization with focused ductile deformation in the upper plate. Thus the initially hot upper plate appears to have increased in temperature, rather than cooled, when placed against the cool lower plate. It is possible that dehydration partial melting of the hottest part of the shear zone accompanied the development of granulite facies rocks (Ducea *et al.* 2007).

The late Cretaceous Sur fault

The Sur fault (Trask 1925) is a steep, near-vertical brittle fault (Figure 2) that has an inferred Late Cretaceous history (Hall 1991), and has been reactivated during the Late Cenozoic as a dextral strike-slip fault, possibly with a reverse slip component (Page 1970). There are numerous contradictory definitions of the Sur fault (see a review in Hall, 1991). Here we adopt Hall's definition, that the Sur fault is fundamentally the boundary between the Nacimiento block and the Salinian block. The recent history of the fault is linked to the development of the San Andreas system and the fault is spatially related to the Nacimiento fault, in the coastal Santa Lucia Mountains (Reed and Hollister 1936; Trask 1925). In places the two faults are mapped as a single fault, the 'Sur-Nacimiento fault' (Page 1970, 1981; Page *et al.* 1979a, b, 1998). Locally, the Sur fault also overlaps with another fault that is exclusively Cenozoic in origin, the San Gregorio-Hosgri fault (Dickinson *et al.* 2005). Poor outcrop patterns prevent detailed structural analysis of the fault, and there are no good piercing points to estimate the Late Cenozoic lateral offset. However, the magnitude of young lateral displacement is limited to a few tens of kilometres at most, based on local constraints (Hall 1991).

The original position of the Nacimiento and Salinian blocks during the latest Cretaceous are some 150–180 km apart, based on the well-established structural anatomy of California's Cretaceous continental margin. The Nacimiento block basement rocks are 'Franciscan' trench sediment, whereas the Salinian block represents a part of the easternmost California arc. The juxtaposition of these two, assuming that it is not a result of Late Cenozoic tectonics, implies that the proto (Late Cretaceous?) Sur fault is a significant tectonic boundary. Dickinson's (1983) interpretation was that the fault is a significant Late Cretaceous sinstral fault

(>500 km, note that to Dickinson, the Nacimiento fault is the block-bounding structure), whereas Hall (1991) interpreted it (the Sur fault) to be a major latest Cretaceous thrust fault that brought the 'allocthonous' Salinian block outboard (>150 km) over the accretionary wedge, similar to the Vincent thrust in the San Gabriel Mountains (Jacobson 1997). The forearc and western part of the arc were presumably underthrust in the process. The subsequent reactivation of the Sur-Nacimiento fault system as a near-vertical structure makes any interpretations on the earlier history difficult.

We concur with Hall's interpretation that the Sur fault is fundamentally a thrust fault of latest Cretaceous age that was subsequently reactivated as a strike slip and/or high-angle reverse-slip fault. If the original block-bounding fault had been strike slip (Nacimiento fault, in the view of Dickinson (1983)), the western arc and forearc of the subduction system should be present elsewhere along the margin, and they had not been identified. We notice striking compositional and detrital zircon age pattern similarities between the Nacimiento block and the schist of the Sierra de Salinas. Thus, we view the Sur fault as the leading edge of the shallow subduction system of the latest Cretaceous in the Monterey terrane, and a shallower, brittle equivalent to the Salinas shear zone. The proposed correlations between blocks and faults are further discussed below.

History of block commonality

Geobarometric constraints from the Salinian block 'upper plate' (Hansen and Stuk 1993; Kidder *et al.* 2003), the Sierra de Salinas 'lower plate' and the shear zone itself (Kidder and Ducea 2006), all yield pressures as high as 8–10 kbar, indicating depths in excess of 30 km, with no major breaks in section between the Salinian and Sierra de Salinas blocks (Figure 3). The timing of high-pressure metamorphism is well constrained to be syn- to immediately post-magmatic; the youngest determined age is 76–77 Ma by Sm-Nd garnet-whole rock ages from the upper plate (Ducea *et al.* 2003b). The timing of underplating of the schist is constrained by the youngest age of detrital zircon (<80 Ma) and post-peak metamorphic cooling ages of the schist (Barth *et al.* 2003; Grove *et al.* 2003).

The emplacement of the Sierra de Salinas block under the Salinian block, started ~76 Ma, and continued for only a few million years (Figure 3). By 74 Ma, the entire section (Salinia and Sierra de Salinas) was undergoing exhumation at relatively high rates (Mattinson 1978; Naeser and Ross 1976) and by about 70–68 Ma was exposed at the surface and covered by marine sediments (Barbeau *et al.* 2005; Kidder *et al.* 2003). In addition, the latest Cretaceous sedimentary cover of the Nacimiento block is possibly correlative to the Salinian block cover, although in detail the cover sequences are not identical (Hall 1991). We conclude that all the three blocks were locked together by the latest Cretaceous, with some uncertainty arising from the incomplete cover of the Nacimiento block.

Correlations between blocks

We propose that the basement of the Nacimiento and Sierra de Salinas blocks are correlative. They both represent Franciscan assemblages, with the schist of the Sierra de Salinas being a higher grade equivalent. The Nacimiento block exposes more structural complexity than the schist. In particular, the thin nappe sheet of Coast Range Ophiolite, (mapped locally in the upper part of the Nacimiento block

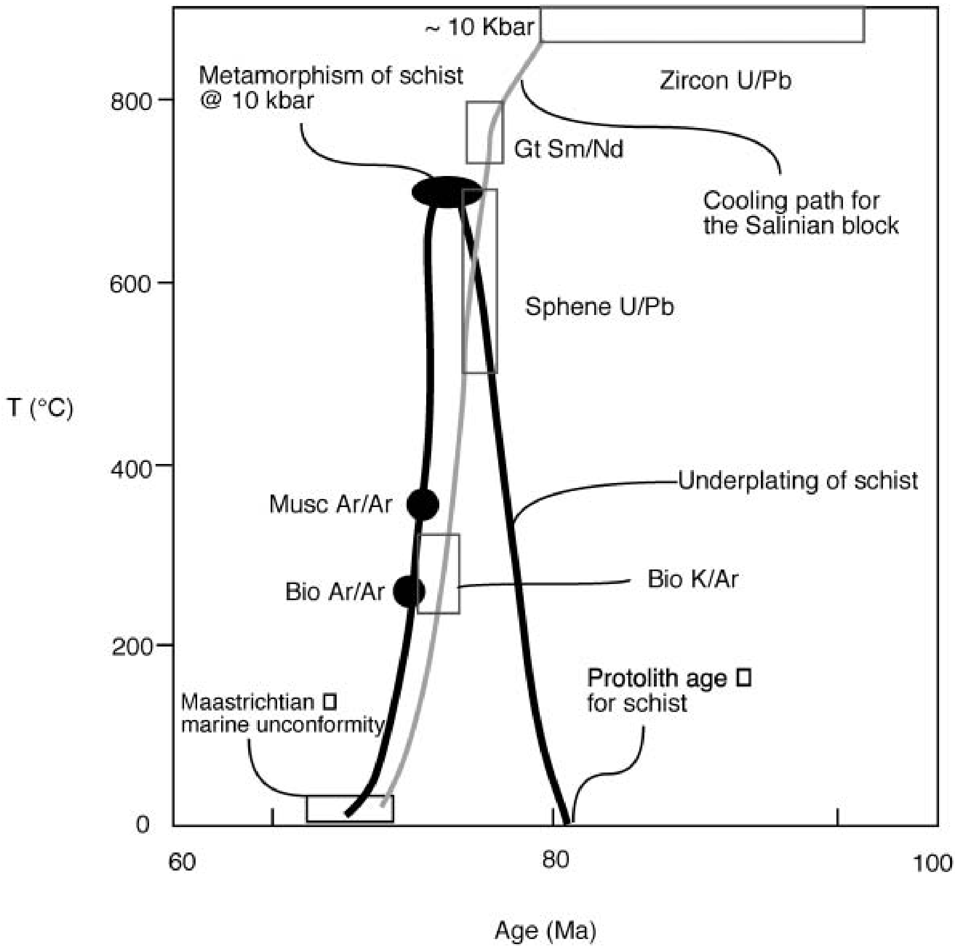

Figure 3. Time–temperature plot for the Monterey terrane, based on published data from the Santa Lucia and Sierra de Salinas regions. Protolith age constraints for the schist detrital zircon U–Pb ages and schist cooling Ar–Ar ages) are from Barth *et al.* (2003) and Grove *et al.* (2003). Salinian block thermochronologic constraints are from Mattinson (1978), Kistler and Champion (2001), Ducea *et al.* (2003b), Kidder *et al.* (2003) and Kidder and Ducea (2006). The inferred ages of marine clastic overlap strata are from a variety of sources summarized in Barbeau *et al.* (2005).

basement) does not have an equivalent in the Sierra de Salinas block, but we interpret that to be a result of limited exposures in the latter. The composition and detrital age patterns in the two blocks are remarkably similar. What differentiates the schist of the Sierra de Salinas from typical Franciscan metamorphic rocks is the higher temperature 'Barrovian' metamorphic conditions it exhibits. Indeed, the Sierra de Salinas basement rocks are mica schists (as in their name) with minor inclusions of amphibolite-facies meta-mafic rocks (Ross 1976b), not blueschist-facies rocks. A high pressure/medium temperature path is demonstrated by the schist, with peak temperatures in excess of 700°C close to the Salinas shear zone. High temperatures are not thought to be typical of subduction metamorphism (Davies 1999; Peacock 2003). However, they may be quite common, and commonly overlooked in ultra-shallow subducting systems lacking intervening mantle lithosphere. The schists in southern California (Pelona, Orocopia, Rand), equivalent to the Sierra de Salinas, exhibit similar metamorphic patterns (Dawson and Jacobson 1989; Jacobson 1995, 1997; Jacobson and Dawson 1995; Jacobson *et al.* 1988), and so does the early Cenozoic Swakane Gneiss in the Pacific Northwest, which is thought to have a similarly tectonically underplated origin (Matzel *et al.* 2004).

Possible reasons for heating of subduction related schists have been discussed previously for the Coast Range (Kidder and Ducea 2006) southern California (e.g. (Jacobson *et al.* 1988) and elsewhere (England and Molnar 1993; Graham and England 1976), and are beyond the scope of this paper. The compositional and provenance (detrital age patterns) similarities between Franciscan rocks in the Nacimiento block and the schist of the Sierra de Salinas represent the basis for interpreting them to be correlative. Furthermore, we interpret the Sur fault and the Salinas shear zone to represent the same structure within the Monterey terrane.

Latest Cretaceous extensional collapse

In the Monterey terrane, the upper plate was quickly exhumed in the latest Cretaceous (Maastrichtian), bringing the deep arc rocks of the Salinian block, the shear zone and the schist to the surface. Both the Salinian and the Nacimiento blocks are uncomformably covered by un-named Maastrichtian marine sedimentary sequences (Grove 1993; Barbeau *et al.* 2005), although they may or may not be correlative. The time succession from normal subduction to shallow subduction (and tectonic underplating) and rapid unroofing is based on a fairly comprehensive set of available geochronologic and thermochronologic data (see Figure 3). It took the Salinian block only 5–6 my to be exhumed from peak metamorphism (10 kbar) to the surface. The unroofing immediately postdated the thrusting of the Salinian block over Franciscan rocks along the Sur-Salinas fault system. The crustal thickness of the Salinian block was well in excess of 35 km, based on the geochemical composition of its Late Cretaceous arc-related rocks (Kidder *et al.* 2003). Although we do not have direct evidence for the topographic evolution of the arc's surface, clearly, it must have been an elevated area at least until the time of peak metamorphism (~76 Ma) recorded by Sm–Nd garnet geochronology in the gneisses of the Salinian block's Coast Ridge Belt (Ducea *et al.* 2003). The marine Maastrichtian cover of both the Salinian and Sierra de Salinas blocks (Grove 1993; Hall 1991) suggests a major topographic change over a short period of time, perhaps an episode of extensional collapse (Schott and Johnson 1998; Schott *et al.* 2004). Field evidence for normal faults bounding the uppermost Cretaceous sedimentary cover exists (Grove 1993; Hall 1991), but these faults are either poorly exposed or not as significant as expected from such a major event.

The conundrum is that in typical compressional settings, shortening events like the underthrusting of accretionary wedge units under the California arc, are not usually accompanied by extensional collapse. Modern forearcs in regions thought to undergo tectonic underplating today, such as parts of the Andean margin, only show evidence for limited extension (McNulty and Farber 2002; von Huene *et al.* 1999). A full understanding of the shallow subduction/tectonic underplating in the Monterey terrane needs a better model to explain the accompanying topographic collapse.

Tectonic reconstruction

The Monterey terrane is structurally a collapsed subduction margin – the original lateral subduction margin architecture (accretion wedge, forearc, arc) has been transposed into a vertical package of nappes, with the inner part of the arc being structurally the highest unit (Figure 4). The Salinas shear zone and the Sur fault delineate juxtaposition of two rock types that were originally some 150–180 km apart. Tectonic underplating requires that these sediments were transferred to the lower plate, the subducting Farallon plate in this case, and transported downward before being re-attached to the upper plate, North America. During that process, the upper boundary of the sediment became the subduction megathrust, which is currently exposed as the Salinas shear zone. Subsequently, the megathrust migrated downward, leaving the fossil shear zone and the newly underplated sediments on the upper plate.

The schist of the Sierra de Salinas could either represent the top of the subduction channel (Cloos and Schreve 1988a, b) that marked underflow beneath southern California during the earliest stages of 'Laramide' shallow subduction, or the Salinas shear zone is the manifestation of a landward step back in the subduction system (Ring and Brandon 1993) via out-of-sequence thrust faults. We do not favour the subduction channel hypothesis for three principal reasons:

(1) it requires a relatively narrow (1 km) pathway for sediment to move in and out of the subduction surface, whereas the thickness of the Sierra de Salinas sediment is >5 km,
(2) it predicts a high-pressure, low-temperature metamorphic path for the products found in the channel, in contrast to the medium pressure and temperatures recorded in the schist,
(3) it does not account for missing parts of the forearc and arc.

The Mesozoic and later regional tectonic evolution of the Monterey terrane can be summarized in four stages. The first stage (95–80 Ma) has the margin under normal subduction parameters, during the major magmatic flare-up that generated

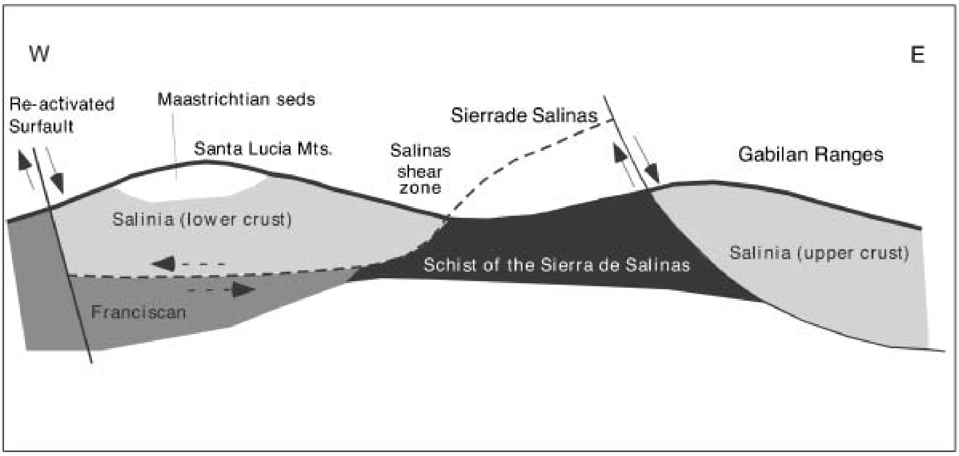

Figure 4. Interpretative cross-section (not to scale) of the modern crustal-scale configuration of the Monterey terrane (see Figure 2 map for cross section location).

much of the California arc. The second stage (~76–73 Ma) coincides with the inception of shallow subduction, cessation of magmatism (or migration inland of the area studied here) and tectonic underplating of the Sierra de Salinas schist. The Sur-Salinas structure was probably a hanging wall/flat-footwall ramp thust structure, as field observations suggest. The third stage (74–68 Ma) corresponds to the extensional collapse of the section, perhaps in response to the lack of strength of the newly underplated lower crust. Finally, the modern configuration of the blocks discussed in this paper is the result of continued sedimentation and brittle faulting – shown in cartoon form in Figure 4. The post-Late Oligocene birth of the Monterey terrane (as defined in this paper) requires northward lateral translation from the original location in southern California. This translation episode includes, in addition to the San Andreas fault, numerous right-lateral and high-angle reverse faults within the Monterey terrane, some with displacements as large as 150 km (i.e. San Gregorio-Hosgri, Dickinson *et al.* 2005). In addition, several episodes of sedimentation, deformation and minor magmatism occurred; they affected the area throughout the Cenozoic. Whereas these are regionally extensive, we do not think they significantly altered the fundamental large-scale geometric relationships of the terrane basement.

Regional significance

If we assume that the original geometry of the subduction margin of the Monterey terrane is preserved relatively intact in central California and across the Sierra Nevada (Saleeby *et al.* 2003), the amount of shortening corresponding to tectonic underplating along the Sur-Salinas structure can be estimated to be about 150–180 km (as first noted by Hall, 1991). Based on the magnitude of shortening alone, this is clearly one of the more significant structures in the southwestern United States Cordillera. The Pelona, Orocopia, Rand and other schists in southern California and western Arizona are direct equivalents to the schist of the Sierra de Salinas, although, peak temperatures of the schist of the Sierra de Salinas are higher than their equivalents in southern California (Jacobson 1997). Most of them have been exhumed during the Cenozoic with intervening breaks between the original upper and lower plates (Jacobson and Dawson 1995; Jacobson *et al.* 2007, 1996; Yin 2002). One exception is the well-studied Vincent thrust in the San Gabriel Mountains that separates the Rand Schist in the lower plate from the autochthonous granitic upper plate (Jacobson 1997).

A number of significant questions remain. How much sedimentary material has been underplated in the California Coast Ranges? What is the areal extent of shallow subduction and tectonic underplating? What is the extent of delamination along the North American margin? What percentage of material is recycled into the mantle relative to that which is underplated onto the overlying North American plate? What is the cause of the regionally significant extensional collapse and exhumation in the Monterey terrane, which appears to have no other modern analogues?

No solid constraints exist for the thickness of the schist of Sierra de Salinas, although limited geophysical data from the Coast Ranges suggest a minimum of about 5–6 km beneath the present surface is similar to the exposed rocks (McIntosh *et al.*, 1991). Deeper rocks are unlikely to represent parts of Salinia or the schist of Sierra de Salinas, but instead, as confirmed by seismic results (Clark *et al.* 1994;

Ewing and Talwani 1991) are mafic rocks representing either Farallon plate crust and/or the younger Monterey plate crust (Miller *et al.* 1992). The average modern crustal thickness in the central California Coast Ranges is about 25 km (Hauksson 2000), but the knowledge of mid- to deep-crustal composition is poor.

In contrast to southern California, much of the integrity of the Cretaceous margin to the north has been preserved. No shallowly subducting slab existed at the end of the Cretaceous beneath the great Sierra Nevada batholith to the north. The batholith is not deeply unroofed, and certainly no exposures of equivalent schists have been recognized. The areal distribution of the southern California schists is consistent with the hypothesis of plate segmentation during early stages of the Laramide orogeny, as proposed by Saleeby (2003). In his model, Saleeby proposed that only the southern California area (the Mojave-Salinia corridor) was subject to the shallow subduction that led to inland migration of magmatism and deformation in the latest Cretaceous–Eocene.

The subduction-accretion of Franciscan-like equivalents and presumably an underlying oceanic lithosphere at depths greater than 30–35 km beneath much of southern California requires that the original North American lower crust and mantle in this area were removed by a process that resembles ‘delamination’ sensu stricto (Bird 1979). The shallow subduction and underplating model, if correct, requires that the modern shallow mantle lithosphere under the Salinia-Mojave corridor be abyssal (depleted) peridotite of the Farallon or related plates. Most available geophysical (Fuis 2001; Malin *et al.* 1995) and xenolith data (Menzies *et al.* 1987; Mukasa and Wilshire 1997; Wilshire *et al.* 1988) are consistent with this hypothesis. One notable exception to the evolutionary tectonic scenario presented here (and in numerous other papers) is the presence of a few peridotite xenoliths from the Cima Volcanic Field in southeastern California (Lee *et al.* 2001) which based on re-depletion ages were interpreted by the authors to represent lithospheric mantle fragments of Late Archean – Early Proterozoic ages.

In addition to the original upper plate lower crust and mantle, much of the forearc and western arc regions resulting from extended Mesozoic subduction are missing in the Monterey terrane and correlative southern California areas. A small fraction of the forearc, the Coast Range ophiolite is exposed in the Nacimiento block and locally forms a thin sheet under the Salinian block. However, we do not know whether the bulk of the forearc and parts of the arc have been recycled into the mantle or are displaced laterally into the modern lower crust of the continental interior. Regardless, this is a world-class example for tectonic reorganization of the continental crust through lateral shuffling involving subducting oceanic plates.

The extensional collapse discussed above is another regional tectonic consequence. Rocks of eastern arc affinities were likely part of a high elevation, Andean-like mountain range while the arc was active throughout California (House *et al.* 2001). Much of the Sierra Nevada remained above sea level throughout the Cenozoic, although the details of the landscape evolution of that range remains controversial (Jones *et al.* 2004). In contrast, the Monterey terrane was quickly submerged below sea level, and indeed marine sediment of Early Cenozoic age is also found throughout the Mojave region (Malin *et al.* 1995). It appears that the high standing Andean-style range was breached along the segment that underwent shallow subduction, a scenario that does not have an obvious analogue in modern subduction margins involving a continental upper plate.

Implications for the process of subduction

Subduction margins represent ‘cold anomalies’, because of the introduction of materials that were at or close to the Earth’s surface into the Earth’s interior. The range of pressure–temperature paths taken by slabs (Hacker *et al.* 2003; Kincaid and Sacks 1997; Peacock 1992, 2003) is distinct from other environments because of the known kinematic parameters of subduction: slabs descend into the mantle at (geologically) high speeds of tens to over one hundred kilometres per million years. Experiments and models predict that at least along the shallow parts of the subduction paths, oceanic crustal and sedimentary rocks should experience high-pressure/low-temperature metamorphism. The geologic record confirms this prediction; rocks that travelled along the subduction path are commonly blueschist and eclogite facies (Miyashiro 1972).

In the example of tectonic underplating revealed by rocks from the Monterey terrane, the pressure–temperature trajectory is hotter than ‘typical’ subduction paths, although the Sierra de Salinas block is at the lower temperature range required for ‘Barrovian’ metamorphism. We interpret that the Salinas shear zone was the subduction megathrust at some point between 76 and 70 Ma, given the ‘plate-tectonic’ rate of shortening (>30 km/my) along this structure, and the obvious association of trench sediments with the fault. In contrast to subducted sediment that is carried into the mantle, the proto-sediment of the Sierra de Salinas schist was abandoned at the base of the upper plate, as the subduction megathrust migrated downward. This metasediment was either heated by the upper plate (Kidder and Ducea 2006) or by excess heat developed in the shear zone itself (Ducea *et al.* 2007) – the mechanism is unresolved. Regardless, the result is that tectonically underplated sediments from the Monterey plate ‘look’ like typical regionally metamorphosed rocks. The Swakane gneiss in the Pacific Northwest is an equivalent example (Matzel *et al.* 2004) in which underplated rocks followed a Barrovian metamorphic trajectory.

The local development of granulite facies metamorphism and partial melting in the Salinas shear zone is also significant in that it documents a subduction megathrust that was dry during shearing/heating. If the fault surface or shear zone acted as a sealant for fluids, granulite-facies metamorphism would not develop at 30–35 km depths, as in the case of the Salinas shear zone. Recently, episodic tremor and slip along shallow subduction zones worldwide, have been recognized at depths similar to the palaeo-exposure of the Salinas shear zone (Melbourne and Web 2003). Episodic tremors are common during ‘slow earthquake’ events and are interpreted by some to represent fluid bursts in or out of the fault zone. Tremors occurring today beneath the Cascadia subduction zone may represent dewatering during ductile slip along the megathrust at depths of some 30–50 km, and thus may signal the local formation of granulite facies rocks (Ducea *et al.* 2007)

An important aspect of shallow subduction during tectonic underplating is that it requires the subduction fault to pass entirely through continental crustal assemblages, without the presence of intervening upper plate mantle lithosphere. Presumably, over large enough distances away from the trench, these systems will also project the subducting materials (oceanic lithosphere and overlying sedimentary cover) into the upper plate’s mantle. However, at least in the example documented here, no intervening mantle lithosphere existed over the 150 to 180 km distance from the trench to the arc. A possible modern analogue would be the shallow subducting system of the Cocos plate under southern Mexico, along the Middle America

(Acapulco) trench. Subduction erosion (Moran-Zenteno *et al.* 1996) and tectonic underplating in particular (Ducea *et al.* 2004) have been documented in that region for much of the Miocene-Present time. The modern subduction geometry determined from a recent receiver function seismic experiment (Pérez-Campos and Clayton 2003) is similar to the Monterey terrane.

Implications for tectonic underplating

The process of recycling sediments at subduction zone margins is globally significant (Albarede 1998; Cloos and Shreve 1988a, b; Plank and Langmuir 1998). In fact, more than half of the modern trenches are sediment starved (Von Huene and Scholl 1991), clearly indicating that large volumes of sedimentary material are being dragged down with the subducting plate, a process commonly referred to as subduction erosion (Ranero and von Huene 2000; von Huene *et al.* 2004). There are three destinations for sedimentary rocks affected by subduction:

(1) recycling into the mantle,
(2) return to the upper plate by tectonic underplating,
(3) return to the upper plate by arc magmatism (Clift and Vannucchi 2004).

Of these, the third is by far the least significant by mass, yet it has received disproportional attention from the petrology community (Plank 2005; Stern 1991). Rarely does a subducting-sediment component contribute more than a few percentage of arc volcanism by mass. Of the first two mechanisms, it is difficult to resolve which one is more significant. However, most geologic models assume that 'subducted' sediment returns to the mantle (Clift and Vannucchi 2004).

The Monterey terrane and equivalents in southern California (Grove *et al.* 2003) are among the first documented examples in the geologic record for which a high degree of confidence exists that tectonic underplating was significant (Saleeby *et al.* 2003). Sediments derived from the upper plate (primarily from the high-standing arc region) were delivered to the trench and later accreted at the bottom of the overlying arc section. Essentially upper crustal rocks of 80–95 Ma ended up under the lower crustal section of the same age – like cutting a deck of cards. This process of 'crustal inversion', if common in the geologic record, must have significant consequences on the thermal and mechanical evolution of the crust. For example, the relatively hot schist of the Sierra de Salinas, had probably no strength at >500–600°C (Kidder and Ducea 2006) and thus contributed to the extensional collapse of the section soon after underplating. Another consequence is that upper plate, silicic, metasedimentary units like the Sierra de Salinas schist, are prone to partial melting and can likely produce aluminous granitoids such as many Laramide calc-alkaline plutonic rocks from the Cordilleran interior (Miller *et al.* 1996).

Several important pieces of geologic information can be learned from the deep crustal exposures of the Monterey terrane:

(1) tectonic underplating can occur along thrust faults without intervening mantle sections – i.e. underthrusting of accretion wedge/forearc beneath the arc can take place exclusively within the continental crust;
(2) underplating takes place along a short-lived subduction megathrust at plate tectonic rates;

(3) the upper plate of a subduction system undergoing shallow subduction can undergo ‘crustal inversion’, where upper crustal rocks can be recycled under the original lower crust of the upper plate.

Criteria for identifying subducted-accreted sediment

We use the example of the Monterey terrane documented above to set a few potentially relevant criteria for identifying tectonically underplated rocks in the geologic record, in exposed roots of subduction margins. We are not focusing on small scale shortening that may affect forearc domains and could in principle represent a smaller scale version of underplating. Instead, we are concerned only with identification of large-scale transport, at least tens of kilometres to more than 100 km, from the trench toward the Complex if swept under a continental arc somewhere in the North American Cordillera, or in an equivalent orogen? These rocks may be available via exposures of deep crustal rocks or as lower crustal xenoliths in mafic volcanic rocks. As exemplified by the Monterey terrane example, such rocks will not be characterized by ‘typical high-pressure/low-temperature subduction metamorphism (Davies 1999), although they may have started on such a P–T path, but instead look like typical regionally metamorphosed schists or gneisses.

In the example of exposed deep crustal sections, the critical observations for recognizing subduction accretion are:

(1) the existence of distinct former elements of the lower and upper plates, in which the remnant lower plate is composed of metagraywacke and mafic/ultramafic oceanic rocks and the upper plate is a part of the continental interior of a subduction system (e.g. the arc region);
(2) the existence of a shallowly dipping structure (a ductile structure, most likely), that puts the two plates in contact;
(3) the lower plate is cooler than the upper plate and may have an inverted thermal gradient;
(4) the lower plate was thrust under the upper plate at plate tectonic rates; the time difference between depositional age, constrained by the youngest detrital zircon ages, and metamorphic age (garnet Sm–Nd or Lu–Hf ages, U–Pb and Ar/Ar ages of dikes cross-cutting foliation, etc.) is on the order of only a few million years.

The Monterey terrane is a particularly favourable example where tectonic underplating can be identified in that the terrane exposes a ‘rootless’ arc. When viewed structurally downward, the Salinian block is dominated by Late Cretaceous arc related rocks, but none are found beneath the Salinas shear zone. It is unlikely that the California batholith and its roots did not have an expression at $>$30–35 km deep, especially because it is underlain by fairly melt-fertile wet metapelitic material – these lithologies were more likely introduced into the lower crust after the arc ceased to form. A similar example is the Swakane gneiss in the Cascade Mountains (Matzel *et al.* 2004), which is the structurally lowest plate in the region, contains no arc-related rocks, and is overlain by a continental arc, similar to the Monterey plate example.

If the underplated rock is a lower crustal xenolith, the second criterion above evidently cannot be used; however, one can recognize a metagraywacke rock that resided in the lower crust, can determine the temperature of the lower crust (was it unusually low compared to basement rocks exposed at the surface?), under favourable circumstances, can also determine elements of criterion, concerning the rate of tectonic burial (Ducea *et al.* 2003d).

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