integrated with crustal structure constraints further pose viable alternative mechanisms.

***(Daven the grayed out below is deleted, and the incorporated into ext modules below, in order to mover through the myriad of topics that we have with more focus)***

The presence of underplated material beneath the Salinian block is in line with the results of seismic surveys [*Tréhu*, [1991](#ref-Trehu1991)which have demonstrated the presence of high V material at 20-30 km beneath the Coast Ranges near Crystal Knob, and that this material is bounded above by, and contains internally low-dipping-to-horizontal reflection events. This gently low-dipping layer extends as far east as the San Andreas fault, and has been widely interpreted to be underplated oceanic lithosphere[**???**;*Tréhu*, 1[991](#ref-Trehu1991); *Wilson et al.*, [2005](#ref-Wilson2005)]. due to its apparently mafic nature.***))***

Both the seismic observation of a sharp truncation of the lower crust by material, and the isotopically-depleted nature of the Crystal Knob xenoliths can be explained either by subduction and underplating of suboceanic mantle lithosphere, or by mantle convective upwelling beneath the crust following Franciscan subduction. Both underplating of subducted material and asthenospheric upwelling are documented for the southern to central California margin in Neogene time (*Atwater and Stock*, [1998](#ref-Atwater1998); *Luffi et al.*, [2009](#ref-Luffi2009)]. Stalled slab, upper mantle duplex formation, and slab window models for underplating have been proposed in more detail for these mechanisms [*Erkan and Blackwell*, [2008](#ref-Erkan2008); *Groome and Thorkelson*, [2009](#ref-Groome2009); Luffi et al., 2009]. To illuminate how the Crystal Knob samples may fit into this conceptual framework, we must examine the tectonic processes that have affected the sub-Salinia mantle lithosphere over the history of the crustal block.

lithosphere nappe(s) that lie in structural sequence with the upper mantle duplex resolved beneath the Dish Hill xenolith location (Luffi et al., 2009).

***(Daven, the material that I have grayed out below, to be deleted, is all very good for a relatively complete, and scholarly treatment of the geology, but for the purposes of our paper it is too detailed and thus it will take a way from our focus. If we keep it in it will very likely draw criticism from our reviewers, most likely of which will be petrology-geodynamics types with little aptitude, nor patience for geologic details.)***

South of this evolving Mendocino slab window, the Farallon slab was broken into a series of microplates which rotated clockwise before stalling during the early Miocene. These features of the Neogene tectonic setting of Salinia inform two models for the composition of its mantle lithosphere.ion form its southern California

The total and blockwise offset along the North American--Pacific plate boundary is well-constrained by paleomagnetic and geodynamic data augmented with the coupling of the locations of Neogene volcanic centers to slab windows [*Wilson et al.*, [2005](#ref-Wilson2005)]. Reconstruction of slip on outboard members of the San Andreas system (particularly the San Gregorio--Hosgri Fault) using geologic markers [*Dickinson et al.*, [2005](#ref-Dickinson2005)] gives matching results to within ~5 km. Crystal Knob can be restored for Neogene offset to a location ~350 km SE of its current location, with ~310 km displacement of Salinia on the modern San Andreas Fault and ~40 km on the Rinconada fault within the Salinian block .

A 100 km discrepancy between positions of batholithic features in the southern Sierra Nevada and Salinian block still exists after accounting for these offsets, requiring pre-Neogene offset of or within Salinia [*Dickinson et al.*, [2005](#ref-Dickinson2005); *Wilson et al.*, [2005](#ref-Wilson2005)]. We believe that the early Miocene restoration of Salinia represents its configuration since the late Cretaceous--Paleocene. In this framework, the mismatch between Salinia and the southern Sierras is related to the late-Cretaceous disaggregation of the southern California arc and northward extrusion of batholithic rocks [*Chapman and Saleeby*, [2012](#ref-Chapman2012)] and that the apparent rotation of the Sierra Nevada-Tehachapi extension is a recent feature of thrust shortening [*Hall and Saleeby*, [2013](#ref-Hall2013)]. Therefore, unlike *Dickinson et al.* [[2005](#ref-Dickinson2005)], we do not attempt to unrotate the Sierra Nevada-Tehachapi "tail" to correct this discrepancy.

The Nacimiento fault is not given special treatment in this reconstruction despite pre-Neogene sinistral slip of up to 500 km that has been proposed by some workers [*Dickinson et al.*, [2005](#ref-Dickinson2005); *Jacobson et al.*, [2010](#ref-Jacobson2010)]. An origin as a subduction megathrust in a low-angle subduction system is more representative of the geologic data [*Hall and Saleeby*, [2013](#ref-Hall2013)]. In either case, the Nacimiento block has been tectonially coupled to the Salinian block since the late Cretaceous [**???**]. Moreover, recent detrital zircon constraints on the source locale of the metaclastic rocks in the Nacimiento block point to its formation off of southern California, precluding sinistral strike-slip [*Chapman et al.*, [2016](#ref-Chapman2016)].

Outboard elements of the subduction system can also be restored: *Wilson et al.* [[2005](#ref-Wilson2005)] shows that the Monterey microplate was originally located ~250 km south of Crystal Knob and Salinia, and was translated to its current position offshore of these features by ~155 km of slip on the San Gregorio--Hosgri fault during the late Miocene [*Dickinson et al.*, [2005](#ref-Dickinson2005)], plus ~100 km of earlier offshore dextral offset, dominantly channeled along the paleo-subduction interface [*Wilson et al.*, [2005](#ref-Wilson2005)].

Reconstruction of this Neogene tectonic history shows that the Salinian block was a marginal extension of the Mojave province prior to being offset along the San Andreas system. Salinia, along with Crystal Knob, restores to a location above the center of the Mendocino slab window which evolved during the early Neogene , and the current juxtaposition of the province with the Monterey microplate arose in the middle Miocene (~16-12 Ma). The "slab window" and "stalled slab" hypotheses fit into this framework as two potential mechanisms for the origin of the mafic lithosphere underplated beneath Salinia. Both scenarios have been developed at length in the literature.

### Slab window

During the late stages of subduction from 30-10 Ma, Crystal Knob resided in the center of the expanding slab window to the southwest of the Mendocino Fracture Zone [*Atwater and Stock*, [1998](#ref-Atwater1998)]. Within this zone, upwelling asthenospheric mantle came into contact with the cool forearc lithosphere. This event broadly drove a large pulse of non-arc volcanism in coastal California [*Cole and Basu*, [1995](#ref-Cole1995); *Wilson et al.*, [2005](#ref-Wilson2005)]. This volcanism is prominent in the Salinia/Nacimiento tectonic unit near Crystal Knob: Oligocene to mid-Miocene volcanic centers such as the Morro Rock/Islay Hills complex [*Stanley et al.*, [2000](#ref-Stanley2000)] and the Cambria Felsite [*Ernst and Hall*, [1974](#ref-Ernst1974)] are thought to be products of ridge subduction and slab window formation. It is possible that the ascent of asthenosphere into the slab window drove large-scale replacement of the sub-Salinia mantle lithosphere [*Groome and Thorkelson*, [2009](#ref-Groome2009)].

### Stalled slab

Another option proposed for the underplated sub-Salinian mantle lithosphere is that it represents a partially subducted "stalled slab". Relict slabs are observed as high-density anomalies in seismic imagery elsewhere in the Cordillera [*Schmandt and Humphreys*, [2011](#ref-Schmandt2011); *Wang et al.*, [2013](#ref-Wang2013)] and are generally associated with deep slab breakoff during the final stages of a subducting margin. The position of the offshore Monterey microplate remnant outboard of Salinia provides the context for this theory. However, older generations of stalled slabs underplated early in subduction are potentially more likely.

#### Monterey plate: a young stalled slab?

The canonical case of stalled-slab underplating is underplating by a partially-subducted extension of the Monterey microplate. When the East Pacific Rise first reached the North American plate at 28.5 Ma, the Monterey microplate broke from the Farallon slab and subducted independently until 19.5 Ma, while rotating clockwise with respect to the Pacific plate [*Wilson et al.*, [2005](#ref-Wilson2005)]. The remnant slab has been integrated into the Pacific plate and still forms part of the abyssal seafloor . Some workers have invoked a stalled slab attached to the Pacific Plate and extending as far eastward as the Central Valley to correspond with the Isabella seismic anomaly [*Brink et al.*, [1999](#ref-tenBrink1999); *Pikser et al.*, [2012](#ref-Pikser2012); *Wang et al.*, [2013](#ref-Wang2013)]. This geometry implies a shallowly dipping transform system beneath Salinia and, inland, the lateral translation of a steeply-dipping slab through the lithosphere and asthenosphere beneath the North American plate to match the motion of the San Andreas fault zone. If this slab extends eastward as described, it would form the bulk of the mantle lithosphere beneath Salinia and Crystal Knob.

The Monterey Plate hypothesis relies tenuously on the assertions that (1) the mafic mantle lithosphere beneath Salinia is continuous with the observed plate remnant and (2) that the Isabella seismic anomaly is a signature of a stalled slab. There are problems with both of these assertions.

First, the depth at which the Monterey plate slab broke after the cessation of subduction is unknown. There is significant ambiguity in seismic reflection data as to whether the high-density layer underlying Salinia is continuous with the outboard Monterey plate. The partially subducted slab is clearly visible in offshore seismic surveys [Nicholson et al., [1992](#ref-Nicholson1992); Tréhu, [1991](#ref-Trehu1991)]. Workers differ on how to interpret an apparent dislocation near the current coastline, with oceanic material dipping eastward at 16º offshore and abruptly flattening to 2º beneath the coast (Figure gives the rough configuration). Some interpret this data to show a single continuous slab [Brink et al., [1999](#ref-tenBrink1999); Brocher et al., [1999](#ref-Brocher1999); Pikser et al., [2012](#ref-Pikser2012); Van Wijk et al., [2001](#ref-Wijk2001); Wang et al., [2013](#ref-Wang2013)]. However, the available data is consistent with imbrication of oceanic material [Tréhu, [1991](#ref-Trehu1991)] and a shallow slab tear adjacent to previously underplated material, at the approximate location of the coastline [Wilson et al., [2005](#ref-Wilson2005)]. Moreover, the 2º eastward dips of the underplated layer do not appear as steep as a stalled subduction zone would suggest.

A more serious objection to a continuous stalled slab beneath Salinia is that the proposed lateral translation of the slab is kinematically untenable. Subduction and rotation of the Monterey plate occured ~250 km south of the Salinian block. A dangling slab extending eastward beneath Salinia would have to retain its structure while being translated laterally through the sub-North America asthenosphere with the movement of the San Andreas fault. A young stalled slab requires mechanical dragging through the asthenosphere, which is unlikely, particularly for a young (and thus thin and mechanically weak) slab. Mechanical models of the system call for depths of slab tearing between 40 and 50 km [*Burkett and Billen*, [2009](#ref-Burkett2009); *Pikser et al.*, [2012](#ref-Pikser2012)]. A continuous Monterey plate would have to extend far deeper and more inland.

There is some evidence that the Monterey plate resisted breakoff for a time, rotating clockwise in concert with incipient transverse motion on the plate boundary. This torque localized on the plate boundary led to major effects on crustal structure. The clockwise rotation of the Transverse Ranges and outer continental borderland of southern California occurred atop of and in concert with the rotation of the Monterey microplate [**???**; *Nicholson et al.*, [1994](#ref-Nicholson1994)]. However, the cessation of crustal-block rotations in the early Miocene suggests that traction of the dragging slab ceased when the locus of transverse motion jumped inland of the trench interface. This suggests that the end of microplate rotation coincided with a shallow breakoff of the Monterey-plate slab.

Some workers have invoked the Isabella anomaly, a 300 km deep seismic high-velocity zone underlying the southeast Central Valley, as a signature of a stalled slab extending far inland [*Pikser et al.*, [2012](#ref-Pikser2012); *Van Wijk et al.*, [2001](#ref-Wijk2001); *Wang et al.*, [2013](#ref-Wang2013)]. However, this anomaly dwarfs the scale of the Monterey plate and requires it to project 300 km inland from the subduction interface . Further, xenolith studies, late-Cenozoic volcanism, thermo-mechanical modeling, and epeirogenic transients have demonstrated the likely formation of the Isabella anomaly by delamination of a dense crustal root underlying the Sierra Nevada Batholith [*Ducea and Saleeby*, [1996](#ref-Ducea1996); *Saleeby*, [2003](#ref-Saleeby2003); *Saleeby et al.*, [2012](#ref-Saleeby2012)]. Such evidence calls into question the major justification of a large-scale stalled slab. Still, the depth and eastern extent of the Monterey Plate is an open question. Crystal Knob is located 120 km inboard of the relict trench. If the Monterey microplate does indeed extend eastward, the slab may be sampled by the Crystal Knob xenoliths.

[[monterey\_plate|figure]]

### An older stalled slab

The idea that a stalled slab forms the basement of Salinia is not necessarily limited to the case of the Monterey plate. A stalled slab could have formed prior to this last gasp of subduction. Prior to the formation of a transverse margin in the Neogene, Salinia formed the upper plate of a subduction megathrust since at least the Cretaceous [*Chapman et al.*, [2016](#ref-Chapman2016); *Hall and Saleeby*, [2013](#ref-Hall2013)]. This configuration provided ample opportunities for the accretion of oceanic lithosphere beneath Salinia in response to slab rollback and foundering. This possibility of older underplated mantle lithosphere has been alluded to as a better explanation for apparent dislocations in seismic data [*Tréhu*, [1991](#ref-Trehu1991)].

One puzzle with the slab window model is said to be the relative lack of volcanism in the forearc, the apparent continuity of a mafic layer from the subducted oceanic crust inland, and the eastward-dipping nature of the Moho in regional seismic surveys. The stalled slab model has the feature of shielding the bottom of the continental crust from the high-temperature asthenosphere [*Brocher et al.*, [1999](#ref-Brocher1999)]. Thermal modeling (based on heat-flow data) shows that a young stalled slab explains the thermal structure of the Coast Ranges and Great Valley better than the slab window model [*Erkan and Blackwell*, [2008](#ref-Erkan2008)].

Older generations of stalled slab material may be an option. Density contrast of an old plate would be limited bullshit! Did they really say that, where, give me the page number! [*Wang et al.*, [2013](#ref-Wang2013)].

[[neogene\_sections|figure]][[cross\_sections|figure]]

The slab window seems to better fit the geodynamic and tectonic data. However, one of the major reasons for its attractiveness

Whether the migrating slab window caused wholesale replacement of underlying mantle lithosphere has been examined by several workers. *Erkan and Blackwell* [[2008](#ref-Erkan2008)] examined the possibility of wholesale ML replacement with upwelling asthenosphere, against a possible "stalled slab". They concluded the stalled slab was more likely. We agree with their primary assertion against the upwelling asthenosphere, but think that lithospheric nappes explain the data elegantly.

subducting slab or asthenospheric material underplated during a slab window event [*Van Wijk et al.*, [2001](#ref-Wijk2001)].

Regardless of whether this rock was emplaced at the last gasp of subduction, it is unlikely that the rock is part of the Monterey Plate proper, because this would imply that the 150 km of slip on the San Gregorio -- Hosgri fault is not continuous into the mantle {fig:cross-sections}.

We don't really have too much of an idea exactly how far the trench was offshore pre-Neogene

### Late Cretaceous rollback underplating

A third scenario that hasn’t been explored significantly in the geodynamics literature:

* Late-Cretaceous breakup of southern-California arc
* Associated with subduction of Farallon plate
* Continental underplating by remnant Farallon slab recorded in Mojave [*Luffi et al.*, [2009](#ref-Luffi2009)]
* This goes along with subduction channel facies (Rand schist) exposed at the surface in the Mojave

At these locations, *Luffi et al.* [[2009](#ref-Luffi2009)] identified underplated nappes of Farallon-plate mantle lithosphere. The timing and character of underplating is constrained by surface exposures of the Pelona and Rand schists, subduction-channel facies that mark a relict plate interface during flat-slab subduction [*Chapman et al.*, [2010](#ref-Chapman2010)]. Taken together, crustal structure and xenoliths show that the Farallon mantle lithosphere was underplated during extensional collapse in the late Cretaceous to Paleocene.

When restored for Neogene transform offset, the Crystal Knob xenoliths provide a distal addition to the lithospheric mantle transect anchored by the Dish Hill and Cima Dome xenolith suites in the Mojave . The Salinian block is a displaced fragment of the Mojave block [*Johnson and Normark*, [1974](#ref-Johnson1974)], so it should not be surprising that similar surface features are observed. Subduction channel facies are likewise juxtaposed against arc plutonic rocks. This relationship is particularly impressive in the case of the Sierra de Salinas schist, which is exposed near the granites of the Santa Lucia range. Geochemical markers of age and magma source (e.g. U-Pb ages and ratios) imply that the plutons have a similar origin to Mojave [*Dickinson et al.*, [2005](#ref-Dickinson2005)].

The repetition of the pattern of schist underplated against deep plutonic rocks within the Salinian block implies formation during the same flat-slab episode that disturbed the Mojave [*Kidder and Ducea*, [2006](#ref-Kidder2006)]. Accordingly, replacement of the mantle lithosphere beneath inland locales implies that the same process acted in the forearc.

Absent wholesale replacement due to later events, it is likely that the sub-Salinia mantle lithosphere is largely composed of Farallon-plate remnants. This series of events that led to underplating has much more geologic justification

In Figure we present an endmember model for Farallon plate mantle lithosphere having tectonically underplated the Salinia-Mojave segment of the Cordilleran batholithic belt at ca. 70 Ma. This is shown to have occurred in conjunction with shallow flat subduction that was induced by the subduction of a major oceanic plateau that was embedded in the Farallon plate (after Saleeby, 2003; Liu et al., 2010). Crustal deformation, timing and thermal conditions, as applied to our thermal modeling (Fig. Y), are integrated from Kidder and Ducea (2007) and Chapman et al. (2010). Figure Xa and Xb show the arrival of the oceanic plateau into the subducting trench, and plateau buoyancy driven shallowing of the subduction megathrust. Temperature conditions along the flat subduction megathrust initiated at ~900ºC, ambient conditions within the deep levels of the then-active arc, and retrogressed to ~715ºC, peak temperatures recorded in shallowly subducted metaclastic rocks of the Rand-Sierra de Salinas schist [*Kidder and Ducea*, [2006](#ref-Kidder2006)].

In Figures c and d we adopt the focused slab rollback and mantle lithosphere underplating models of *Saleeby* [[2003](#ref-Saleeby2003)] and *Luffi et al.* [[2009](#ref-Luffi2009)] for the dynamic response of normal thickness oceanic lithosphere following the crustal thickened oceanic plateau down the subduction zone. Principal crustal responses are shown as large magnitude trench-directed extension coupled to extrusion of the Rand-Sierra de Salinas schist, which was driven by suction forces of the retreating slab. In the Figure c to d transition, accelerated rollback is accomplished by duplex formation from Farallon plate mantle nappes. The idealized locus of mantle xenolith entrainment by the Crystal Knob eruption is shown in Figure d. The approximate age of oceanic lithosphere entering the trench is denoted along the base of the oceanic crust in each frame [after *Seton et al.*, [2012](#ref-Seton2012)]. This is considered an endmember model in terms of the maximum plausible age of mantle tectonic underplating, and the highest plausible upper plate geothermal gradient.

First, the depth at which the Monterey plate slab broke after the cessation of subduction is unknown. There is significant ambiguity in seismic reflection data as to whether the high-density layer underlying Salinia is continuous with the outboard Monterey plate. The partially subducted slab is clearly visible in offshore seismic surveys [Nicholson et al., [1992](#ref-Nicholson1992); Tréhu, [1991](#ref-Trehu1991)]. Workers differ on how to interpret an apparent dislocation near the current coastline, with oceanic material dipping eastward at 16º offshore and abruptly flattening to 2º beneath the coast (Figure gives the rough configuration). Some interpret this data to show a single continuous slab [Brink et al., [1999](#ref-tenBrink1999); Brocher et al., [1999](#ref-Brocher1999); Pikser et al., [2012](#ref-Pikser2012); Van Wijk et al., [2001](#ref-Wijk2001); Wang et al., [2013](#ref-Wang2013)]. However, the available data is consistent with imbrication of oceanic material [Tréhu, [1991](#ref-Trehu1991)] and a shallow slab tear adjacent to previously underplated material, at the approximate location of the coastline [Wilson et al., [2005](#ref-Wilson2005)]. Moreover, the 2º eastward dips of the underplated layer do not appear as steep as a stalled subduction zone would suggest.

### *Reheating of older stalled-slab material*

We know that the slab window must have been present. We know that a young stalled slab, though more thermally favorable, is kinematically impossible. And an older stalled slab is by itself too cold. But with reheating by the slab window, it might be warmer.