GEOMETRY OF SUBDUCTED SLABS RELATED TO SAN ANDREAS TRANSFORM[1,2]

WILLIAM R. DICKINSON[3] AND WALTER S. SNYDER
Geology Department, Stanford University, Stanford, California 94305; and
Lamont-Doherty Geological Observatory, Columbia University,
Palisades, New York 10964

ABSTRACT

Development of the San Andreas transform by rise-trench encounter in coastal California influenced the structural evolution of a large region within the adjacent continent. Continuation of arc magmatism and tectonism depends upon the presence of a subducted slab of lithosphere at depth beneath an arc-trench system. The lack of subduction at the transform plate boundary along the California continental margin led to the growth of a slab-free region beneath the part of the continental block adjacent to the San Andreas transform. Geometric analysis based on ideal assumptions predicts that generation of a lengthening transform by rise-trench encounter will also generate an expanding triangular hole or window in the slab of lithosphere subducted beneath the continent. One leg of the slab-window is the adjacent transform, but the orientations and lengths of the other two legs depend upon the relative motions of the three plates involved. By inference, arc volcanism and tectonism cannot persist across the no-slab area at the surface above the slab-window. The actual configuration of the slab-free region adjacent to the transform will depart from ideal predictions where adjustments to the conditions of rise-trench encounter involve changes in the motions of surface plates or subterranean ruptures in subducted slabs. The extent of the expanding slab-free region adjacent to the San Andreas transform can be reconstructed through time from detailed knowledge of oceanic plate boundaries and motions offshore. The progressive switchoff of Neogene arc volcanism conformed to expected patterns in time and space when the age of oceanic lithosphere being consumed near the coast is taken into account. The extent of the growing no-slab area at the surface above the widening slab-window at depth has been largely coextensive with the gradually expanding Basin and Range province of extensional tectonism and bimodal volcanism. Diapiric upwelling of asthenosphere through the evolving slab-window in the subducted lithosphere probably influenced magma genesis and geodynamic behavior within the slab-free region. Bulk uplift of the adjacent Sierra Nevada and the nearby Colorado Plateau, as well as opening of the Rio Grande Rift, were possibly related to the same mantle processes.

INTRODUCTION

The evolution of the San Andreas transform along the California coast has major implications for the geometry of subducted slabs of lithosphere descending into the mantle beneath western North America. Although plate consumption continues to the north and to the south of the Mendocino and Rivera triple junctions at the ends of the San Andreas transform, no lithosphere is consumed along the transform plate boundary. Consequently, a slab-free region has developed beneath the continent where no subducted slab is present adjacent to the transform (Dickinson and Snyder 1975). The presence of a subducted slab at appropriate depth is required to sustain andesitic volcanism and associated magmatism related to subduction (Lipman et al. 1971). The existence of a slab-free region has important implications, therefore, for the areal distribution of volcanic provinces and related tectonic regimes. When the extent and configuration of the slab-free region changes through time as the coastal transform evolves, transitions in volcanic and tectonic behavior can be expected to sweep across parts of the continental block. Our purpose here is to outline a systematic scheme for the coordinate analysis of geologic events along the coast and within the interior, and to

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[2] Lamont-Doherty Geological Observatory contribution No. 0000.

[3] Presently at Department of Geosciences, University of Arizona, Tucson, Arizona 85721.

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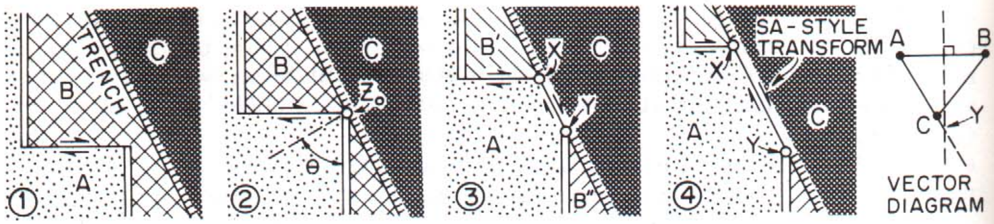

FIG. 1.—Generation of *SA*-style (San Andreas) transform by rise-trench encounter (plan view). Notation after Dickinson and Snyder (1979) is used also for succeeding figures. Main plates shown are analogs of the Pacific (*A*), Farallon (*B*), and American (*C*) plates, but small derivative plates (*B'*, *B''*) are designated separately adjacent to Mendocino (*X*) fault-fault-trench (*FFT*) and Rivera (*Y*) ridge-trench-fault (*RTF*) triple junctions, respectively. Angle θ is angle of incidence of ridge or rise segment (double lines) impinging on trench (hachures). Righthand figure is a diagram of controlling relative motion vectors in velocity space (McKenzie and Morgan 1969).

test our method against the chronology of key geologic episodes that affected both regions.

The subterranean configuration of subducted slabs beneath the western United States was complex throughout the Cenozoic (Dickinson 1979). Cretaceous plate consumption near the coast had nurtured the magmatism that built the great batholiths of the western Cordillera (Hamilton 1969). During the Paleogene, plate descent at a progressively shallow angle (Coney and Reynolds 1977, Keith 1978) triggered Laramide tectonism in the eastern Cordillera, and caused the Damon Null (Damon et al. 1964; Bikerman 1964; Mauger 1966) in arc magmatism within the intermontane region (Dickinson and Snyder 1978). The dip of the descending slab, which can be pictured as a moving belt, increased again through the Oligocene until an essentially continuous band of arc magmatism was again established down the length of the western Cordillera by the beginning of the Miocene (Snyder et al. 1976).

Meanwhile, an incipient San Andreas transform between the Pacific and American plates was generated along the coast late in the Oligocene (Atwater and Molnar 1973). The transform was initiated locally when a segment of the ancestral East Pacific Rise first encountered the subduction zone along the continental margin. The encounter took place when an intervening portion of the old Farallon plate was consumed at the Farallon-American trench. The resulting Pacific-American transform has since gradually lengthened by the simultaneous northward and southward migration of the two triple junctions that define the ends of the transform plate boundary (Dickinson and Snyder 1979). Figure 1 is a schematic representation of this style of plate interaction, which is a type of ridge subduction in the sense of DeLong and Fox (1977).

In this paper, we explore the successive configurations of subducted slabs implied by the progressive changes in plate geometry at the surface during the evolution of the San Andreas transform. We proceed by first defining an ideal geometric model based upon a set of simplifying assumptions. We next show how modifications to the ideal model allow predictions that are close approximations to inferred real behavior. We then compare predictions based on the modified model with data on the location and timing of key magmatic and tectonic provinces in the Neogene Cordillera.

IDEAL GEOMETRY

Predicting the subterranean geometry of subducted slabs from a knowledge of surface plate motions is a speculative subject. The geometric rigor of plate theory is restricted to the spherical geometry of surficial slabs. To establish a kinematic framework for inferring the geometry of subducted slabs, we make a series of simplifying assumptions. Where these assumptions are unrealistic for a particular case, modifications to the ideal model can be made readily, as discussions below indicate. We use plane geometry for explanations and arguments, but spherical geometry obviously must be used to consider large regions with precision. We are able to

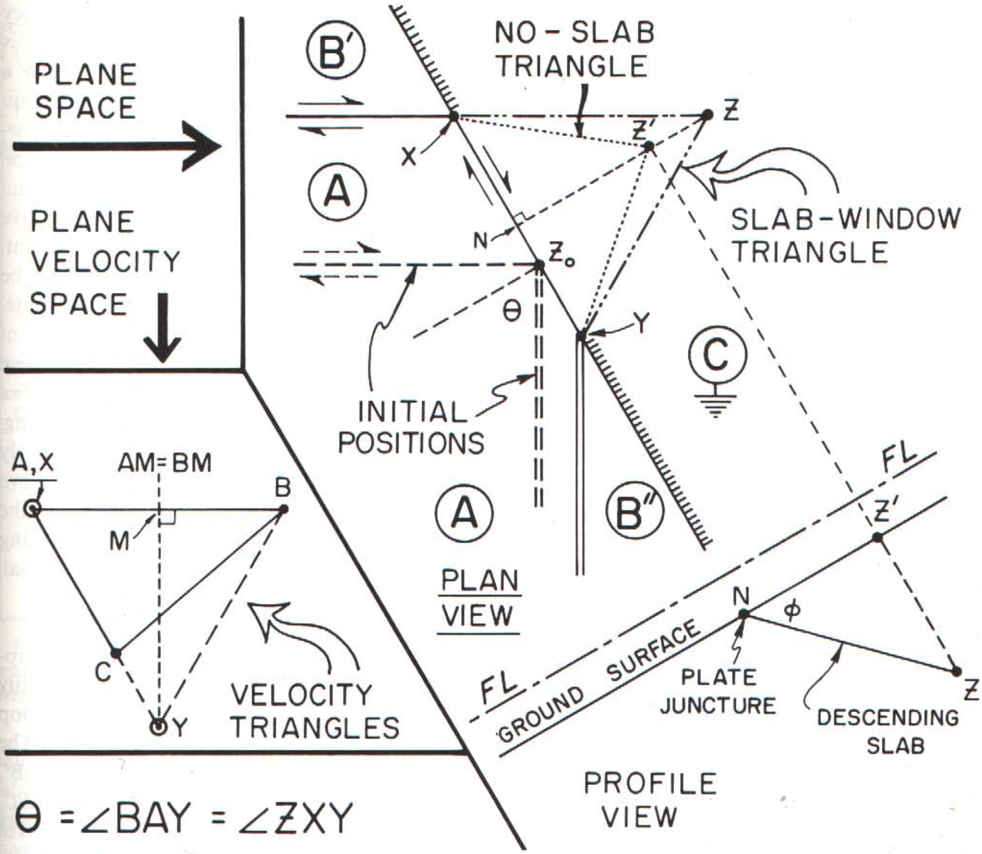

FIG. 2.—Ideal model of geometry (plan and profile views) and kinematics (velocity triangles) for triangular slab-free region adjacent to *SA*-style dextral transform. Letter designations of plates (A, B', B'', C) and triple junctions (X, Y) are the same as for figure 1 (after Dickinson and Snyder 1979). Plate C is arbitrarily held fixed (grounded symbol). Point Z is the inland apex of the triangular window in the subducted slab beneath plate C. In plan view, point Z is plotted as if the subterranean trajectory of the subducted slab were horizontal beneath plate C. In profile view, the subducted slab is shown dipping at the angle ϕ beneath plate C. Consequently, the projected point Z' in plan view is the inland apex of the triangular no-slab area located at the surface above the triangular slab-window at depth in the dipping slab. Point Z_0 marks the place where the slab-free region was originated at the time of initial rise-trench encounter (see figs. 1, 4).

proceed successfully using the simpler and more graphic plane geometry only because currently available data on the geochronology of pertinent volcanic suites and tectonic episodes are also imprecise.

Simplifying assumptions

The critical simplifying assumptions that underlie our ideal geometric model (figs. 2, 4) are the following:

1. Spreading is always symmetric and occurs exactly perpendicular to rise crests. This assumption is not strictly valid for slow-spreading ridges (Atwater and MacDonald 1977).

2. Relative plate motions are exactly parallel to the trends of transforms. Slight deviations from this rule are known, also.

3. The migratory triple junctions at either end of the transform generated by rise-trench encounter are both stable. This condition was not met in detail during the evolution of the San Andreas transform (Dickinson and Snyder 1979), but local instabilities of the triple junc-

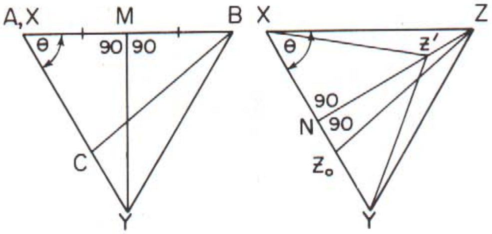

FIG. 3.—Diagram showing geometric similarity between velocity triangle AYB (on left) and slab-window triangle XYZ (on right). Refer to figure 2 for derivation and to text for discussion.

tions were not regionally significant beyond the coastal fringe of the continent.

4. Plates of lithosphere being consumed remain intact as contiguous slabs, partly surficial and partly subterranean. More complex behavior might include subterranean rupture of the slabs and subterranean displacement of detached slab fragments. We suppose, however, that such subterranean detachment is unlikely to occur during slab descent to the depths required to induce arc volcanism. The depth from the main line of arc volcanoes to the inclined seismic zone at the top of the descending slab is most commonly only 100 to 150 km (Dickinson 1975).

5. Strict continuity of motion is maintained between surficial and subterranean portions of the same slab. This inference implies that a subducted slab successfully negotiates the flexure associated with the subduction zone without losing its integrity or shape. General continuity of slab motion is required by all explanations of global plate motions that consider trench-pull to be a significant dynamic factor (Forsyth and Uyeda 1975, Chapple and Tullis 1977). However, the rigorous kinematic continuity that we assume here implies a complete lack of permanent plate deformation during subduction, and is not required to satisfy what is known or inferred about plate dynamics. We adopt the assumption only because we can imagine no alternate assumption that might represent a comparably general case upon which to base an ideal geometric model.

6. The small plates that lie beyond the triple junctions at either end of a transform generated by rise-trench encounter inherit perfectly the motion of the ancestral plate from which they were derived (see fig. 1). This assumption is merely an artifice to allow us to devise a logically coherent way to infer the configuration and size of the slab-free region from a knowledge of relative plate motions at the surface. Once an ideal model is constructed, actual changes in the relative motions of the derivative small plates can readily be taken into account.

7. Oceanic lithosphere of any age can be subducted as part of an intact oceanic plate. This assumption is implicit in the concept of triple junctions including a trench and a rise crest as two of the three plate boundaries involved. However, the subduction of young, hot lithosphere that is thin and has relatively low bulk density is probably difficult to achieve (Molnar and Atwater 1978). Moreover, the geodynamic effects of a subducted slab having such physical properties may well be abnormal.

Slab window

As shown by figure 2, the preceding assumptions predict that slab-free regions of roughly triangular shape in plan view will develop adjacent to SA-style transforms (fig. 1). The relative motions of the plates shown (A, B', B'', C) are specified by the velocity triangle ABC. These motions, coupled with the orientations of the plate boundaries depicted, not only generate the gradually lengthening *SA*-type transform XY, but also generate the gradually expanding triangular hole or window XYZ in the subducted slab. The subducted slab is composed of subterranean remnants of plate B and the derivative plates B' and B''. The slab window is produced, and enlarges through time, because no remnants of plate B are subducted along the transform boundary XY, which lengthens through time.

For clarity, the window in the subducted slab is shown in plan view (fig. 2) as if the slab slid horizontally beneath the overriding plate C. This pictorial device illustrates how the shape and dimensions of the subterranean slab-window triangle in the subducted slab are controlled by the relative motions of the plates at the surface (fig. 3). In general, the slab-window triangle XYZ in plane space is geometrically similar to the velocity triangle AYB in

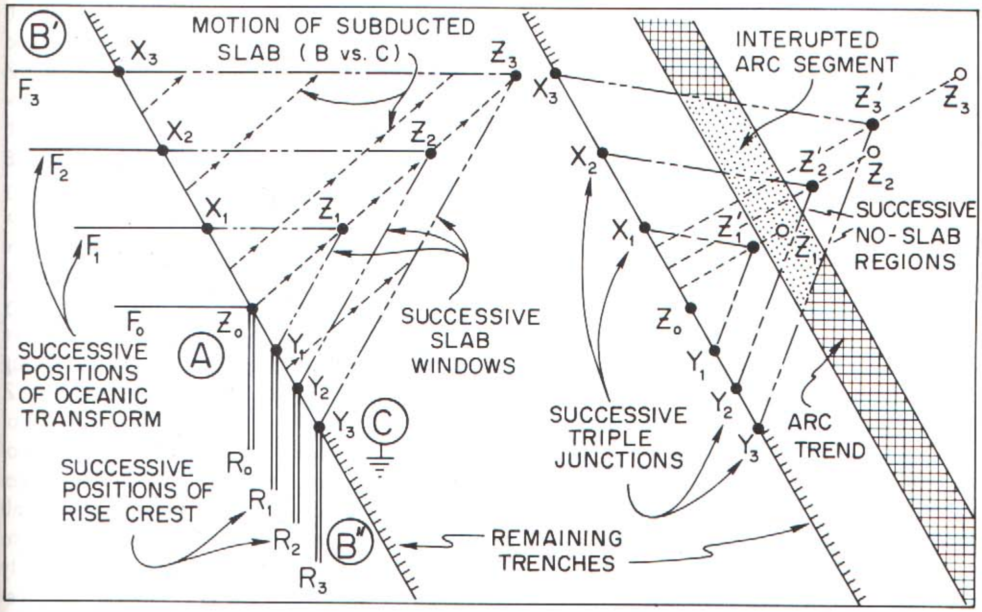

FIG. 4.—Diagrams showing sequential configurations of horizontally subducted (see fig. 2) slab-window triangle XYZ (on left), and coordinate incremental extinction of a magmatic arc as the commensurate no-slab area XYZ' (on right) coevally transects the arc trend parallel to the subduction zone.

velocity space because the following geometric relations hold: (a) the sides XY (the SA-type transform) and AY are parallel by definition (see velocity triangles of fig. 2); (b) by the rules of mutual perpendicularity, angles BAY and ZXY are both equal to θ, the angle of incidence between the A-B rise crest and the normal to the B-C trench (see fig. 1); (c) the line Z_0Z represents the direction of subduction of plate B beneath plate C and is thus by definition parallel to BC; and (d) the lines from Z_0 to points X, Y, and Z are by definition proportional in length to the lines from point C to A, Y, and B in velocity space.

Note further on figure 3 that lines AY and BY are of equal length in velocity space because the point Y is located, on line AC extended, by the perpendicular bisector MY of line AB (the line MY is parallel to the trend of the A-B rise crest). In plane space, therefore, the slab-window triangle is isosceles with legs XY and YZ of equal length. Although leg YZ is hidden from view in the subsurface, leg XY is the SA-type transform, a directly mappable feature. Moreover, $AB = 2AY \cos \theta$ in velocity space; hence, by similarity, $XZ = 2XY \cos \theta$ in plane space. These relations allow the lengths of the subterranean legs of the slab-window triangle to be predicted inland from mapped relations along the coastal transform and postulated plate motions at sea. With the slab-window triangle XYZ in horizontally subducted position, leg XZ is a colinear projection of the oceanic A-B' transform involved in triple junction X, but leg YZ is canted with respect to the trend of the A-B'' rise crest involved in triple junction Y by an angle that is a combined function of the incident angle θ and the A-B spreading rate given by motion vector AB.

The slab-free region beneath plate C is a triangular prism whose vertical sides include the legs of the slab-window triangle. Introduction of a realistic dip angle, ϕ, for the subducted slab in profile view (fig. 2) allows projection of the slab-window triangle XYZ to the surface. This projection defines a triangular no-slab area in the plan view of plate C (see fig. 2). The resulting projected no-slab triangle XYZ' at the surface is foreshortened with respect to the subsurface slab-window triangle XYZ.

The altitude NZ' of the no-slab triangle equals $NZ \cos \phi$ where NZ is the altitude of the slab-window triangle. As the coastal transform XY lengthens through time, the growing distance from the coastal transform to the inland apex of the expanding no-slab area of plate C is given by the expression $NZ' = 2XY \sin \theta \cos \theta \cos \phi$, where NZ' is the altitude of the no-slab triangle.

Arc magmatism

If rates of plate motion can be specified as the vectors forming velocity triangle ABC, the location and dimensions of the slab-window triangle can be inferred for any given time after initial generation of the transform. The only other information required is the location of the initial rise-trench contact point Z_0 or the locations of triple junctions X and Y for the time in question. The location of point Z', and thus the position and dimensions of the no-slab area at the surface, can also be inferred if the dip angle ϕ can be estimated for the subducted slab. By inversion, the nature of the velocity triangle can be reconstructed for a given span of time if the location and size of the no-slab area is known independently from geologic evidence on land.

Figure 4 depicts the manner of growth of the slab-window and no-slab triangles that define the slab-free region. In time, the expansion of that region where no subducted slab is present at depth can be expected to extinguish arc magmatism along a progressively lengthening segment of the magmatic arc related to subduction. Relations between the location and length of the arc segment that has been interrupted and the position of the coastal transform are geometrically systematic. Figures 2 and 4 thus constitute a closed logical system by which data on the timing, distribution, and nature of inland volcanism within the Cordillera can be related to postulated plate motions at sea and to the evolution of the San Andreas transform along the coast.

Before turning to applications, one geometric peculiarity of figures 2 and 4 deserves special emphasis. Although the sides XZ and YZ of the slab-window move laterally through time with respect to plate C, there is no strictly corresponding lateral motion of the subducted slab itself beneath plate C. As indicated by dashed arrows on figure 4, each point on the lines XZ and YZ, which are trailing edges of the subducted slab, moves strictly in accordance with the vector of relative motion between plates B and C. That vector is the line BC in velocity space and is parallel to the line Z_0Z in plan view (see fig. 2). In our case, this direction of relative plate motion is almost normal to the margin of plate C. The origins of the dashed trajectory arrows systematically represent the successive positions of the migratory triple junctions along the boundary of plate C. The sides XZ and YZ of the slab-window in its horizontally subducted position are thus the loci of the heads of the successive trajectory arrows. Thus, the edges of the slab-window triangle, and of the no-slab triangle also, migrate laterally with respect to plate C, as the slab-free region expands, simply because the migratory triple junctions progressively eliminate successive increments of the trench (Dickinson and Snyder 1979).

MODIFIED GEOMETRY

Some assumptions that underlie the ideal geometric model are unrealistic for the San Andreas system. The model thus requires modification before it can be tested against actual geologic data. There are two key discrepancies: (1) Relative plate motions changed through time during the evolution of the San Andreas transform; accordingly, the shapes of the slab window and the corresponding no-slab area were more irregular than the triangles shown in figure 2; and (2) Subterranean slabs representing oceanic lithosphere having different age at the time of subduction may well behave differently in the subsurface; consequently, relations between the extent of the slab-free region and the extinction of arc magmatism need not have been as simple as depicted by figure 4.

We discuss these two points in turn, and discuss methods for dealing with each. Resulting procedures lead to a modified geometric model, which is used for the reconstructions of figure 5 and to show the present configuration of the slab-free region in figure 6.

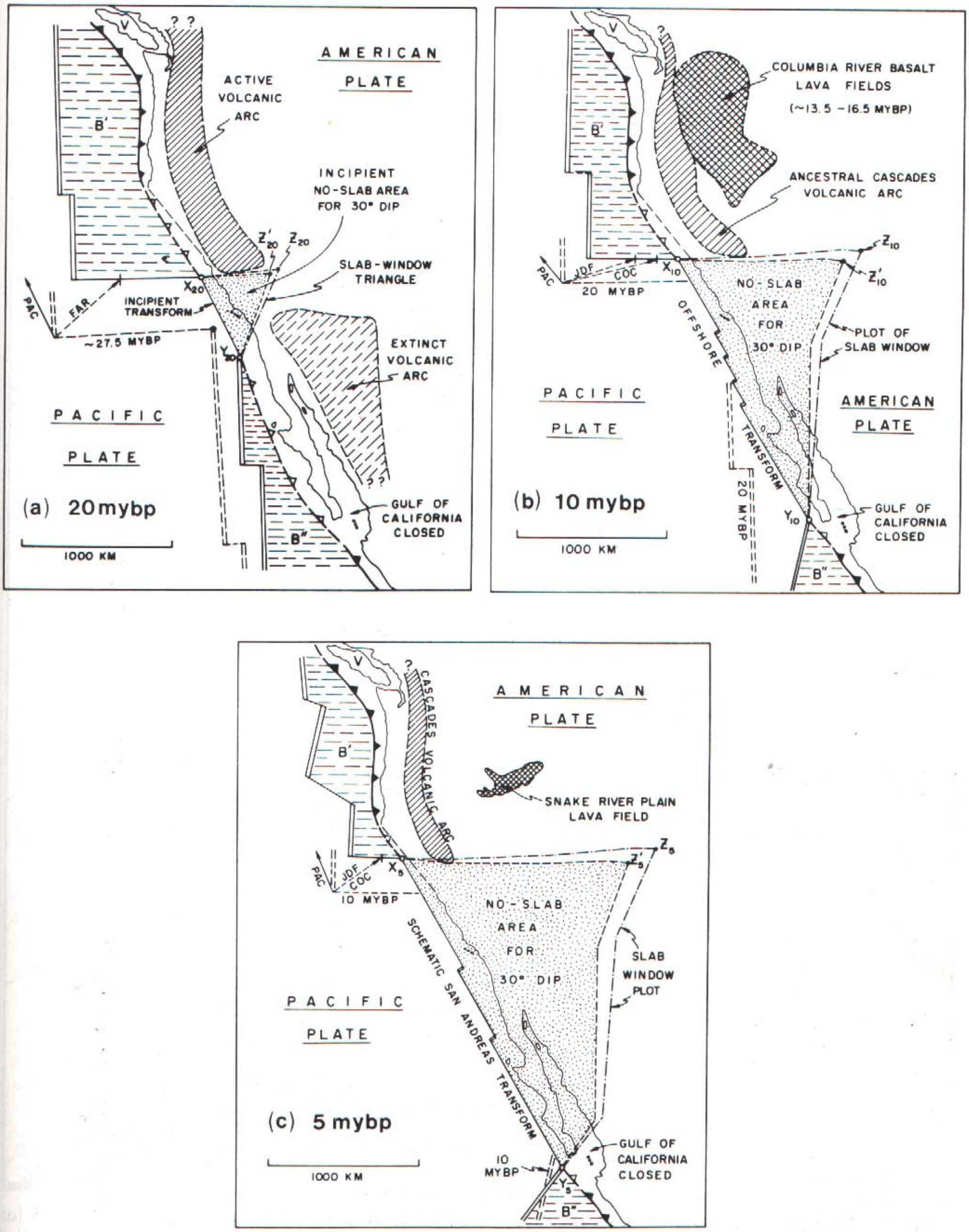

FIG. 5.—Inferred slab-free regions (stippled) adjacent to San Andreas transform at 20, 10, and 5 m.y.b.p. (*a*, *b*, *c*, respectively), as reconstructed using modified geometric model (see text). See figure 2 for notation (i.e., *B'*, *B''*, *X*, *Y*, *Z*, *Z'*).

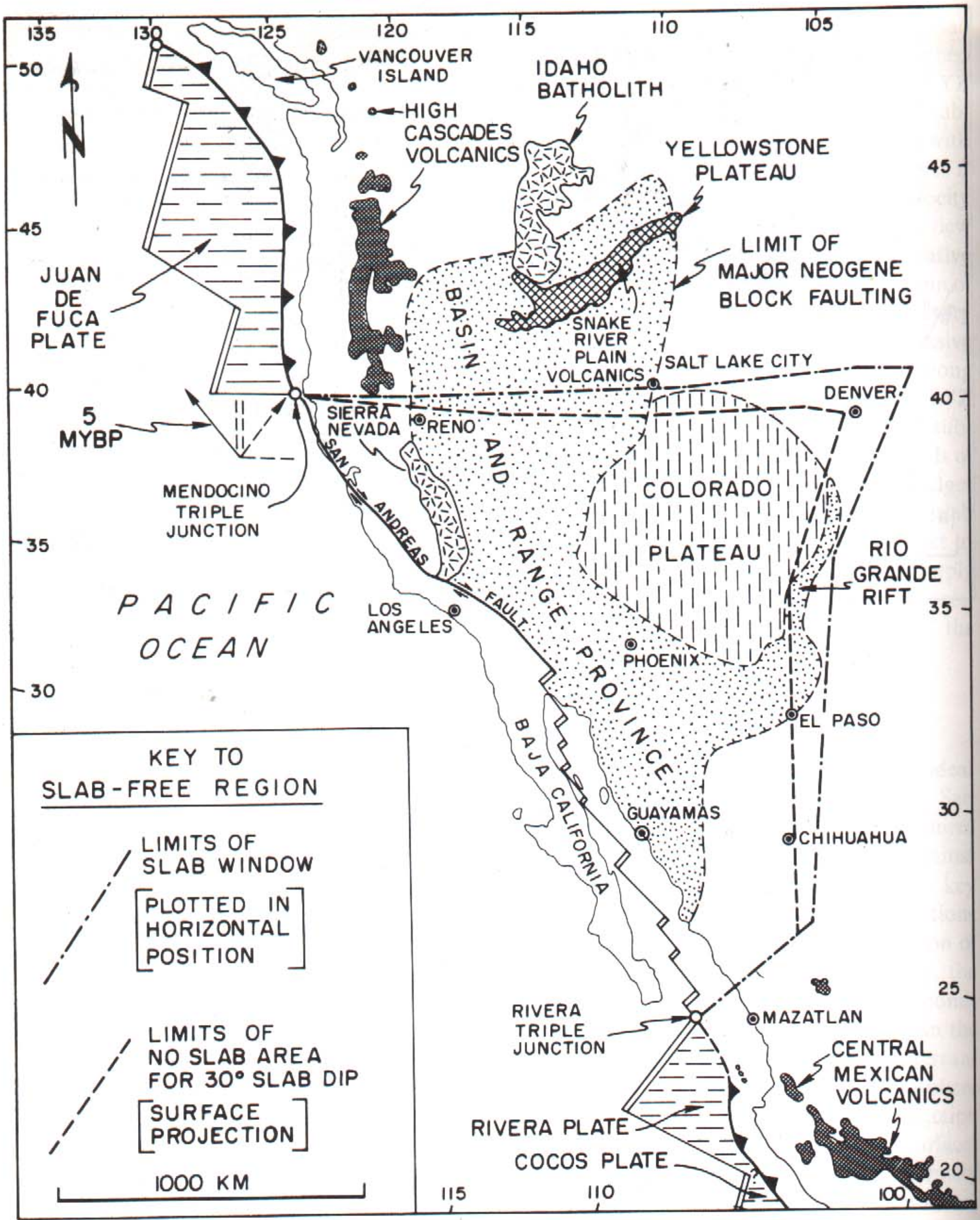

FIG. 6.—Inferred extent of present slab-free region adjacent to San Andreas transform. See figure 5 for derivation.

Plate motions

We allow for changes in the relative motion between the Pacific and American plates by using the results of Atwater and Molnar (1973). They plotted the calculated positions of the edge of the Pacific plate with respect to the margin of the continent for the times represented by magnetic anomalies 1, 3, 6, 8, and 13 on the seafloor. Their maps thus show the approximate locations of key oceanic transforms and rise crests at about 0, 5, 10, 20, and 27.5 m.y.b.p. (La Brecque et al. 1977). The trends of these offshore features define the successive positions of the two triple junctions at the ends of the San Andreas transform near the coast. On figure 5, we show the continental margin in a schematic Miocene configuration with the Gulf of California closed, and with enough left slip restored on the Garlock fault to straighten the San Andreas trend in California. The actual configuration of the coastal region was more complex than that depicted by figure 5 (e.g., Blake et al. 1978).

We infer changes in the relative motions between the Pacific plate and derivatives of the Farallon plate from the spacing of known magnetic anomalies on the Pacific seafloor (Atwater and Menard 1970). Some interpretations are complicated in detail by the pivoting subduction of small plates (Menard 1978) and the complex evolution of plate boundaries (Lynn and Lewis, 1976). In general, rates of subduction beneath the American plate were not identical to the north and to the south of the San Andreas transform. These differences imply probably rupture of the subducted slab at depth beyond the slab-free region.

On figure 5, barbed arrows attached to reconstructed rise-transform intersections at sea show net relative plate motions for the intervals of time represented. Division of the scalar lengths of each arrow by the duration of the different time intervals represented would give successive averages for the relative plate motions as they changed slightly through time. Solid arrows indicate incremental motions of the Pacific (PAC) plate relative to the American plate. Note that each successive rise-transform intersection lies exactly midway between the head of a solid arrow and the tick mark toward which a corresponding dashed arrow points. This is simply a consequence of vector addition. The dashed arrows show coordinate motions of the Farallon (FAR) plate, or Juan de Fuca (JDF) and Cocos (COC) plates, with respect to the American plate. The incremental motions specified by the dashed arrows were used to delimit the outline of the slab window as it evolved through time. The extent of the growing no-slab area was inferred using an arbitrary dip of 30° for the subducted slab. Although this value is compatible with geochemical parameters for the active Cascades volcanoes (Dickinson 1970), we do not know the actual behavior of the slab and cannot estimate its true dip through time.

Slab ages

DeLong (and Fox 1977, et al. 1977) has suggested that young lithosphere is too hot and too thin to generate normal arc volcanism when subducted. The thickness of the subducted plate approaches zero at a rise-trench intersection (i.e., Y of figs. 2, 4–6), where the asthenosphere just beneath the rise crest encounters the trench. In principle, therefore, the leg YZ of the slab window cannot be as discrete a boundary of the subducted slab as is the leg XZ where the lithosphere undergoing subduction is inherently older. Whereas leg XZ is a sharp receding plate edge, leg YZ is more likely to be a diffuse transition zone or tapering wedge. The effective boundary of the slab window perhaps can be defined as some critical isochron lying farther inland within the subducted slab, rather than along the leg YZ as plotted here.

The critical aging period for cooling of lithosphere before it can be subducted effectively to trigger arc volcanism can be inferred from the spacing of magnetic anomalies offshore from the modern High Cascades and Central Mexican volcanic arcs (fig. 6). The sporadic and discontinuous Cascades arc and the western extremity of the Mexican arc are inferred here to represent segments of arcs now in a terminal phase of waning activity. In both areas, reconstructed plate motions (figs. 5, 6) imply that lithosphere now at depth beneath the volcanoes was formed at the rise crest about 17.5 m.y.b.p. and was subducted at the trench about 7.5 m.y.b.p. The transit time for aging on the seafloor prior to subduction was thus about 10 m.y. Lithosphere that is 10 m.y. old has a thickness of about 35 km (Crough 1975), or roughly half that of a thermally mature plate.

Arc switchoff

The distribution of arc volcanism through the Tertiary is now well known for the continental region adjacent to the evolving San Andreas transform (Snyder et al. 1976; Cross and Pilger 1978; Armstrong 1978; Lipman 1979). In the latest Oligocene and earliest Miocene (20–25 m.y.b.p.), an active magmatic arc extended unbroken parallel to the coastal subduction zone from Canada to Mesoamerica, except for a minor gap centered on southernmost Nevada. To the north, the igneous belt followed the ancestral Cascades trend down along the Sierra Nevada block and the western fringe of the Great Basin. To the south, the igneous belt extended from southern Arizona down the trend of the Sierra Madre Occidental in Mexico.

Starting about 20 m.y.b.p. (Snyder et al. 1976), the slab-free region associated with the evolving San Andreas transform began to terminate this arc activity (fig. 5). On the north, the southern end of the Cascades arc retreated through the Neogene in a manner that closely matches behavior predicted by our modified geometric model. At each key stage (20, 10, 5, 0 m.y.b.p.) in this retreat, the southern limit of the Cascades arc and the northern edge of the no-slab area are coincident within the limits of the data (figs. 5, 6). In southern Arizona and New Mexico, arc volcanism was extinguished abruptly at about 20 m.y.b.p. throughout the so-called Arizona locus of magmatism (Snyder et al. 1976). Moreover, arc volcanism farther south in Mexico similarly ended between 20 and 25 m.y.b.p. in the Sierra Madre Occidental near Chihuahua and east of Mazatlan (McDowell and Clabaugh 1976, McDowell and Keizer 1977). As shown by figure *5a*, the broad southern region where arc activity was terminated at about 20 m.y.b.p. lay well outside the slab-free region for that time. Recall, however, that the leg *YZ*, as plotted here, does not mark the effective edge of the slab window because the lithosphere of the slab adjacent to it was so young.

Consideration of plate boundaries and motions for the mid-Tertiary indicate that lithosphere of the subducted slab that lay beneath the Sierra Madre Occidental at 20 m.y.b.p. had formed along the offshore rise crest at about 40 m.y.b.p. and was subducted along the coast at about 30 m.y.b.p. Its transit time on the seafloor was thus about 10 m.y., the critical aging period for effective subduction of lithosphere. We infer that arc magmatism was terminated abruptly at about 20 m.y.b.p. over the whole region to the southeast of the no-slab area, as plotted here, because the critical isochron of the subducted slab of lithosphere passed beneath the igneous belt at that time. However, the significance of younger Miocene volcanism in Baja California remains uncertain (Gastil et al. 1975).

Within the slab-free region of the continent, extinction of mainly andesitic-dacitic arc volcanism was followed by widespread basalt-rhyolite volcanism of bimodal character (Christiansen and Lipman 1972, Lipman et al. 1972). During arc activity, a thick slab of subducted lithosphere was present in the mantle beneath the region. We attribute the subsequent outbreak of bimodal volcanism to effects produced by upwelling of asthenosphere into and through the slab window to replace the volume of space formerly occupied by the descending slab. Partial melting of rising mantle could produce basaltic magmas and advective heating of crust could produce rhyolitic magmas. Note, however, that the extensive Neogene basalt fields of the Columbia River plateau (fig. *5b*) and the Snake River plain (figs. *5c*, 6) had other origins, for they were erupted behind the Cascades arc outside of the slab-free region.

Where the arc volcanism was extinguished by the passage of a critical isochron of the subducted slab beneath the igneous belt, the transition in magma genesis may have been complex. In southern Arizona and New Mexico, for example, there are still uncertainties regarding the timing and the nature of the magmatic transition, as well as its relation to local tectonics (Elston 1976). Moreover, in the California Continental Borderland and adjacent parts of the mainland in southern California and Baja California, mixed suites of Miocene basaltic and andesitic-dacitic volcanics occur over a wide area (Hawkins 1970, and Divis 1975). Perhaps these puzzling joint occurrences of contrasting rock assemblages reflect a transient phase of magmatism associated with subduction of young lithosphere, thin and hot but not wholly absent, in the interval from 12.5 to 17.5 m.y.b.p. (see figs. *5a*, *b*).

TECTONIC IMPLICATIONS

As indicated by figure 6, the present extent of the inferred no-slab area includes the Sierra Nevada block, most of the Basin and Range province, and the bulk of the Colorado Plateau east as far as the Rio Grande rift. This region of the continent has been subjected to regional uplift and locally marked crustal extension during the Neogene (Thompson and Zoback 1979). The Sierra Nevada block and the Colorado Plateau have experienced bulk uplift without prominent internal deformation, whereas the Basin and Range province and the Rio Grande rift have suffered extensional fracturing as well as uplift. The net effect of the deformation has been fragmentation of the American plate into a complex field of subplates whose boundaries are ill-defined (Smith and Sbar 1974; Suppe et al. 1975; Smith 1977, 1978). The fragmented region also includes the area of the Snake River plain and the Yellowstone hotspot or plume outside the inferred no-slab area (Matthews and Anderson 1973).

Slab-window tectonics

We suggest that regional uplift and widespread extension within the Neogene slab-free region may have been triggered by upwelling of asthenosphere through the gradually enlarging slab window at depth below the American plate (cf. Stewart 1978, Best and Hamblin 1978). This idea is speculative because we do not know whether the development of the slab window occurred at a depth shallow enough in the asthenosphere to produce the surficial tectonics observed at the surface. On the one hand, we argue that sinking of the receding edge of the descending Farallon plate and its derivatives, as they swept beneath the continent to generate the slab-free region, forced upwelling of asthenosphere to replace the volume of mantle formerly occupied by the subducted slab of lithosphere. Ideally, however, the asthenosphere has a perfectly adiabatic temperature gradient (e.g., Verhoogen 1973). If so, motions within the asthenosphere would not normally be detected by overlying lithosphere. But in the present case, we are dealing with asthenosphere through which a descending slab of lithosphere had been moving for a long period. Under such conditions, we believe that the portions of the asthenosphere above and below the subducted slab would attain different thermal conditions. Thus, opening of the window in the cold slab, which had previously shielded the uppermost mantle and crust from warmer regions below, may have allowed abnormally hot asthenosphere, upwelling from depth below the slab, to impinge on the base of the American plate. This notion implies, of course, that the slab window developed at a depth shallower than the level below which the lithosphere of the slab could have been resorbed thermally to become indistinguishable from surrounding asthenosphere.

Despite the uncertainties involved, we think the possible tectonic implications of the slab-window concept are worth pursuing, because previous explanations for the structural evolution of the region in question are incomplete. The association of regional uplift with extensional tectonics has led to two classes of explanations for their joint development:

1. Mantle diapirism is regarded as the root cause, with crustal extension an auxiliary effect (Scholz et al. 1971; Best and Brimhall 1974; Thompson 1977). The diapirism is commonly viewed as a form of backarc spreading to form an ensialic interarc basin within the continent. However, crustal extension has continued through the Neogene despite the extinction of arc volcanism along most of the continental margin as subduction was supplanted by transform shear. Our concept of upwelling through the subterranean slab window seemingly leads to a more appropriate timing for any requisite diapiric effects.

2. Oblique crustal extension in response to lateral drag along the San Andreas transform is viewed as the basic process, with induced mantle diapirism a secondary result (Atwater 1970; Heptonstall 1977; Christiansen and McKee 1978). The whole region is thus regarded as a wide transform boundary within which diffuse shear fosters complex deformation. The reasons for this behavior are unclear. Perhaps upwelling of mantle through the slab window led to enough softening or weakening of the American plate to allow the broadly distributed deformation that is observed.

Our hypothesis that the existence of a window in the subducted slab triggered tectonism at the surface is in some respects analogous to the earlier idea that an oceanic rise crest extends into (Cook 1969), was overridden by (Palmer 1968), or has been subducted beneath (McKee 1971) the continent. We would argue, however, that the persistence of a discrete

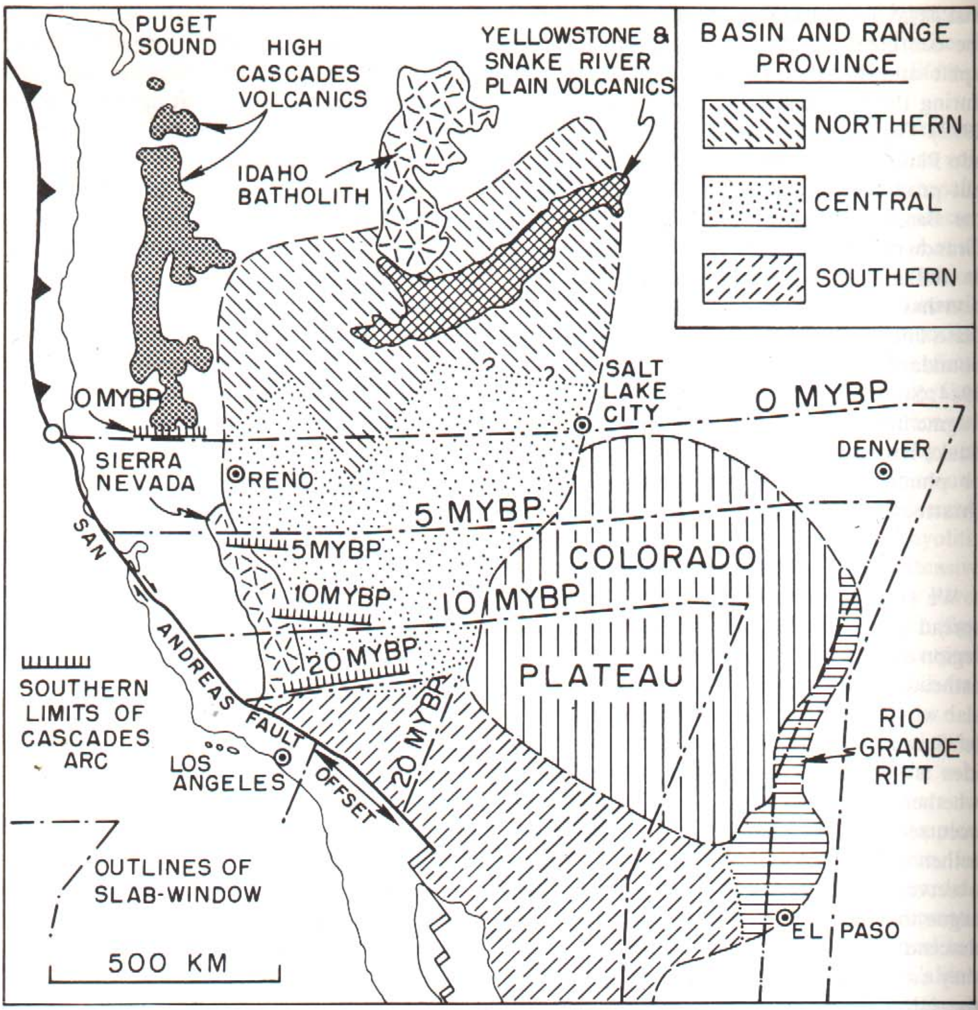

FIG. 7.—Sketch map showing Neogene growth of slab-free region beneath the Basin and Range Province and Colorado Plateau. See text for discussion.

spreading center is dependent upon the continued creation of new lithosphere, which can only form by chilling at the surface. Consequently, the broad and diffuse upwelling that we envision through the subterranean slab window should not be described as a rise crest, nor attributed the properties and behavior associated with such a feature.

Basin and range province

As the slab window beneath the region expanded through time (fig. 7), any tectonic effects associated with it should be diachronous. We can test for this relationship by examining the timing of extensional deformation within the Basin and Range province. Except for the part of the province lying to the south of the Colorado Plateau, the northern edge of the slab-free region swept monotonically northward across the province. Several general relations are compatible with a tectonic evolution from south to north (cf. Proffett 1977):

1. There is general agreement that the ranges in the southern part of the province are geomor-

phically older, as a rule, than those to the north (Lustig 1969).

2. The southern end of the Cascades arc retreated northward in harmony with the advance of the slab-free region, and the arc volcanics have subsequently been displaced by block faults along the western margin of the province (fig. 7).

3. The uplift of the Sierra Nevada block bounding the province on the west has been modeled successfully by assuming that a cold descending slab of lithosphere in the mantle below was replaced in the Neogene by asthenosphere; the range crest slopes suitably downward, from south to north (Hay 1976, Crough and Thompson 1977).

Data on the specific timing of extensional deformation in different areas of the Basin and Range province is meager. The prevailing view that characteristic basin-range tectonism began over a wide area shortly before 15 m.y.b.p. is based upon extrapolation from quite limited data within the Great Basin west of the Colorado Plateau (Stewart 1971, Noble 1972). In reality, the dominant structural grain of the present ranges and basins was not established until about 10 m.y.b.p. or later, although older extensional faulting began locally as early as about 17.5 m.y.b.p. (Stewart 1978). Figures 8 and 9 are a summary of our interpretations for 15 separate localities within the province, which can be divided into three subprovinces (see fig. 7). In the southern subprovince (locations 1–4, figs. 8, 9), the poorly defined eastern margin of the slab-free region migrated eastward through time as the diffuse edge of young lithosphere receded back under the continent. In the central subprovince (locations 5–11, figs. 8, 9), the sharply defined northern margin of the slab-free region migrated northward through time as a discrete edge of subducted lithosphere descended into the mantle. The northern subprovince (locations 12–15, figs. 8, 9) lies outside the no-slab area but within the region where migration of the Yellowstone hotspot or plume may have influenced local tectonics (Smith and Sbar 1974).

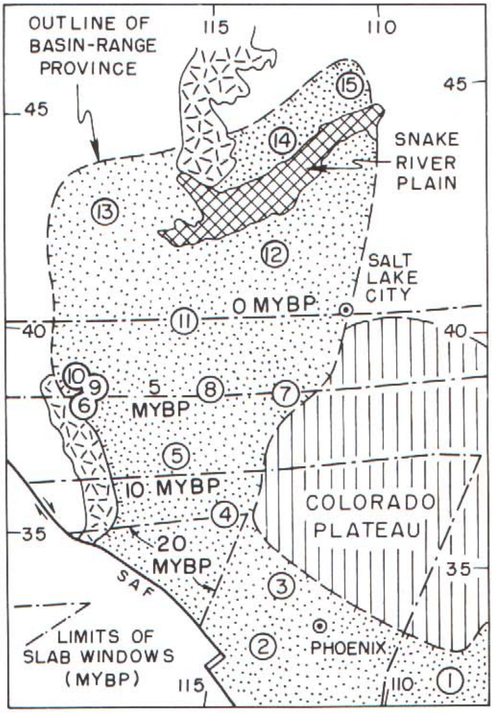

FIG. 8.—Sketch map showing northward migration of northern limit of slab-free region in the Basin and Range Province (refer to fig. 7). Circled numbers denote localities for data in figure 9.

In many areas, it is difficult to distinguish between (a) normal faults that reflect true basin-range tectonism associated with regional extension, and (b) older normal faults associated with local volcano-tectonic subsidence during arc magmatism (e.g., Crowe 1978). We cannot be sure that we have made this distinction correctly in every case. On figure 9, we have shown the time spans of fault movements that helped to define the main horsts and grabens, or tilted blocks, as solid lines indicative of true basin-range tectonism. Older extensional faulting defined by structures exposed entirely within the ranges is denoted by dashed lines. Typically, the older faults not related directly to modern range fronts display low angles of dip suggestive of denudational structures (e.g., Proffett 1977). The earlier faulting is roughly coordinate in timing with the eruption of Columbia River basalts in the Pacific Northwest (see fig. 9), and may represent a tectonic and magmatic episode prior to development of the modern Basin and Range province (Zoback

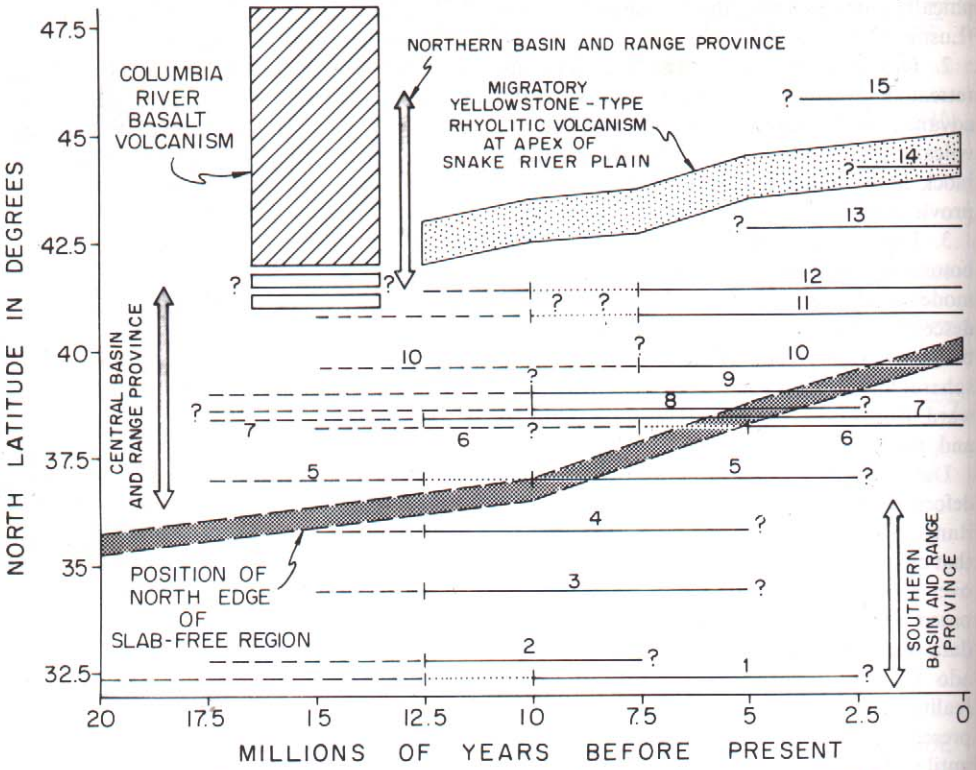

FIG. 9.—Time-space diagram showing inferred duration of Basin and Range deformation at 15 selected localities (see fig. 8). Solid lines show faulting related to main range fronts. Dashed lines show earlier extensional deformation. Tick marks and/or dotted lines denote times of transition between those two tectonic regimes (see text for discussion). Timing of Columbia River Plateau eruptions after Watkins and Bakshi (1974) and Snake River Plain eruptions after Armstrong et al. (1975). Other localities and references: (1) Southwest New Mexico (Elston et al. 1973, Chapin and Seager 1975); (2) Southern Arizona (Eberly and Stanley 1978); (3) Central Arizona (Elston 1978; Otton 1978; Peirce et al. 1978); (4) Lake Mead area (Anderson 1971; et al. 1972; Lucchitta 1972; Damon et al. 1978); (5) Nevada test site (Ekren et al. 1968, Marvin et al. 1970); (6) Mono Lake area (Gilbert et al. 1968, Gilbert and Reynolds 1973); (7) Southwest Utah (Rowley et al. 1978); (8) Eastern Nevada (Moores et al. 1968); (9) Yerington district (Proffett 1977); (10) Steamboat Springs area (Thompson and White 1964); (11) Central Nevada (Zoback and Thompson 1978); (12) Northwest Utah (Compton et al. 1977); (13) Southeast Oregon (Walker 1977); (14) Central Idaho (Dort and Knoll 1973); (15) Southwest Montana (Kuenzi and Fields 1971).

and Thompson 1978). From the data presented, we infer the following key relations:

1. In the southern Basin and Range province, the earlier faulting of uncertain character occurred mainly within the interval 12.5–17.5 m.y.b.p. The main period of basin-range tectonism began about 12.5 m.y.b.p. and was essentially complete by the end of the Miocene about 5 m.y.b.p. The timing of either or both events allows correlation with the development of a slab window at depth.

2. In the central Basin and Range province, the earlier faulting of uncertain character occurred within the interval 10–17.5 m.y.b.p. The main basin-range tectonism began during the period 5–10 m.y.b.p., later than farther south, and continues today in many areas. Only the latter deformation could be correlated with development of a slab window, for the earlier deformation is much too old.

3. In the northern Basin and Range province, lavas erupted about 15 m.y.b.p. form the bulk of

many scarps. Basin-range tectonism did not begin until 5 m.y.b.p. or later, for ignimbrites erupted only 5–10 m.y.b.p. mantle the sloping backs of many tilted blocks right to the crests of ranges. None of the deformation can be linked directly to development of a slab window unless the mantle diapirism is inferred to affect a larger area at the surface than is represented by the slab window at depth.

We conclude that the inception of the main period of basin-range tectonism was distinctly diachronous, from south to north as predicted by the slab-window concept, and had actually ended in the south before it began in the north. It is equally clear, however, that better data on the timing of fault movements generally, and better understanding of the significance of local structures, are required before any hypothesis can be put to a rigorous test. We also have not discussed the strike-slip faulting reported along the southwestern (Stewart et al. 1968) and northwestern (Lawrence 1976) fringes of the Basin and Range province.

Colorado plateau

The Colorado Plateau is an elevated block, largely amagmatic and unfaulted, lying between the Great Basin and the Rio Grande rift (fig. 6). Its bulk uplift without marked extension may also have been related to the upward flow of asthenosphere through the slab window. After Middle Miocene time about 15 m.y.b.p., the inferred slab-free region expanded to include most of the Colorado Plateau by the end of the Miocene at 5 m.y.b.p. Regional geophysics indicates that the crustal thickness beneath the Colorado Plateau is insufficient to explain its present elevation, and that mantle material of anomalously low density must exist at depth (Thompson and Zoback 1979). During the Paleogene, the region was a lowland with large ponded lakes (Hunt 1956). The principal time of uplift was aparently during the Late Miocene, 5–10 m.y.b.p. (McKee and Anderson 1971, McKee and McKee 1972), as our concept of upwelling through the slab window would predict (fig. 7).

Relations along the Rio Grande rift are more equivocal. For example, there is clearcut evidence for some basaltic volcanism, block-faulting, and bolson sedimentation along the trend of the rift as early as 25–30 m.y.b.p. during the Late Oligocene (Chapin and Seager 1975, Lipman and Mehnert 1975). However, thick sedimentary sequences deposited subsequently in local Miocene paleobasins were disrupted severely by an apparent culmination of rift faulting in Late Miocene to mid-Pliocene times (Chapin and Seager 1975). Basaltic lavas intercalated within sediment piles that are ponded beneath the floor of the present rift depression date back no farther than about 5 m.y.b.p. (Lipman and Mehnert 1975). The potential influence of a slab window on Rio Grande tectonics seemingly would be restricted to the past 5 m.y. if the limits of the slab-free region depicted by figure 7 are interpreted strictly. Recall, however, that the eastern limit of the slab-free region may be poorly represented by the conventions we have adopted. This limit is actually marked by a tapering wedge of young lithosphere whose effective edge is difficult to infer within a broad gradational zone. Conceivably, local mantle diapirism may have been induced sooner than we imply.

CONCLUSIONS

1. The distribution of Neogene magmatic and tectonic provinces within the continental block display systematic relationships in time and space to the structural evolution of the San Andreas transform along the coast.

2. Lengthening of the coastal transform was accompanied by the gradual enlargement of an adjacent region where no subducted slab of lithosphere was present at depth in the mantle beneath the continent.

3. Adoption of a simple set of kinematic assumptions allows development of an integrated geometric model for reconstructing the growing extent of the slab-free region adjacent to the coastal transform.

4. By taking various changes in plate motions and slab ages into account, a modified geometric model for the slab-free region successfully explains the progressive switchoff of arc volcanism within the Cordillera.

5. Extensional deformation within the Basin and Range Province and bulk uplift of the Colorado Plateau have been largely coordinate

with the extent of the slab-free region where Neogene upwelling of asthenosphere can be inferred.

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