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The role of extension in the Miocene denudation of the Nevado-Filábride Complex, Betic Cordillera (SE Spain)

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Abstract. The Internal Zone of the Betic Cordillera, SE Spain, consists of a nappe stack of three complexes, the deepest of which is the Nevado-Filábride Complex. The zone is separated from the overlying Alpujárride Complex by a crustal scale shear zone that has variously been interpreted as a thrust or an extensional detachment. A suite of 74 new apatite and zircon fission track results have been obtained from the Nevado-Filábride Complex and these have been used to define regional cooling patterns for the complex. Rapid cooling (105°C-200°C Ma^{-1}) is spatially related to the tectonic contact with the overlying Alpujárride Complex. Cooling to near-surface temperatures occurred first in the east (Sierra de los Filabres) during the mid-Serravallian (12±1 Ma) and was completed by the early Tortonian (9-8 Ma) in the west (Sierra Nevada). There is no correlation between fission track age and sample elevation. These results are consistent with tectonic unroofing of this complex, a finding that favors extension as the mechanism by which the two complexes were brought into contact. Extension spans the middle and earliest upper Miocene (12-8 Ma) in the study area and therefore lasted much longer than previously documented. A hypothesis is advanced which links oblique convergence between the Iberian plate and the Betic Internal Zones, resulting in crustal contraction at depth, with orogen parallel extension in the middle and upper crust.

Introduction and Regional Setting

The Betic Cordillera forms the westernmost branch of the European Alpine mountain belt which formed as a result of the ongoing collision between the African, European and other minor plates [*Dewey et al.*, 1973, 1989]. This mountain range forms part of an arcuate orogenic system across the Straits of Gibraltar with the North African Rif and Tell (Figure 1). Between the two, lies the Alboran Sea, a Neogene sedimentary basin floored by thinned continental crust whose oldest marine sediments are thought to be late Aquitanian (~21 Ma) in age [*Jurado and Comas*, 1992].

The Betic Cordillera itself has been subdivided into a nonmetamorphic External Zone in the north and northeast and a predominantly metamorphic Internal Zone in the south [*Egeler and Simon*, 1969; Figure 1]. The External Zone is subdivided into an autochthonous Pre-Betic whose Mesozoic facies consist largely of shallow water marine sediments and an allochthonous Sub-Betic consisting of Mesozoic deep water pelagic sediments [*Garcia-Hernandez et al.*, 1980]. The Mesozoic strata of the External Zones were deposited on an extended continental margin at the southern border of the Iberian plate [*Pacquet*, 1969; *Garcia-Hernandez et al.*, 1980]. The Internal Zones consist of three stacked tectonometamorphic complexes, (Figure 2) in ascending order, the Nevado-Filábride Complex, the Alpujárride Complex and the Malaguide Complex. The latter two are grouped as the Higher Betic Nappes [*Egeler and Simon*, 1969] in Figure 1.

The southern Iberian passive margin formed during Jurassic rifting which differentiated the Pre- and Sub-Betics. Further extension occurred during the Late Cretaceous but was followed by Tertiary compression [*Reicherter et al.*, 1994; *Lonergan*, 1993]. Compression emplaced the Sub-Betic upon the Pre-Betic together with the progressive emplacement of the Internal Zones upon the External Zones, a record of which is preserved within a piggyback basin sited between the two [*Lonergan and Mange-Rajetzky*, 1994].

During the late Oligocene to early Miocene period (~24-19 Ma) the metamorphic Alpujárride complex was exhumed from below the nonmetamorphic Malaguide Complex within the Internal Zones. This event was characterized by very high cooling rates in the Alpujárride Complex of up to 350°C Ma^{-1}, based on structural, stratigraphic, and radiometric data [*Zeck et al.*, 1992], consistent with unroofing at between 3 and 10 km Ma^{-1}. This cooling has been variously attributed to "late orogenic extension" [*Platt and Vissers*, 1989] or the thrusting of the Alpujárride Complex over cooler lithosphere [*De Jong*, 1991, 1992] (see below).

Following this dramatic phase of cooling, compression continued in the External Zones, with an important northerly directed component. During the late Miocene, dextral strike-slip faulting (not shown in Figures 1 and 2) and late, large-scale folding occurred within the Internal Zones, and these were in part responsible for the present-day topography [e.g., *Rodriguez-Fernandez and Sanz de Galdeano*, 1990].

The Nevado-Filábride Complex is exposed only in the eastern Betics, where it forms the principal topographic high along the southeastern Spanish margin (Figure 2). In the western part of the study area the Sierra Nevada contains Spain's highest mainland peak, Mulhacen (3482 m), while in the Sierra de los Filábres to the east, the principal peaks, Padilla (2062 m), Dos Picos (2086 m), Calar Alto (2168 m), and Tetica (2081 m), form a prominent east-west ridge. The Nevado-Filábride Complex is also exposed in the cores of a series of small sierras stretching from Almeria to Cartagena in the east.

The Nevado-Filábride Complex consists of a series of stacked thrust sheets of Palaeozoic graphite-bearing basement and an overlying metapelitic and metacarbonate sequence inferred to be of Triassic age [*De Jong and Bakker*, 1991]. No consensus exists on the timing of thrust stacking, with suggestions ranging from the Triassic and Jurassic [see *Egeler and Simon*, 1969] to as late as the early Miocene [*Frizon de Lamott et al.*, 1989]. More recent studies

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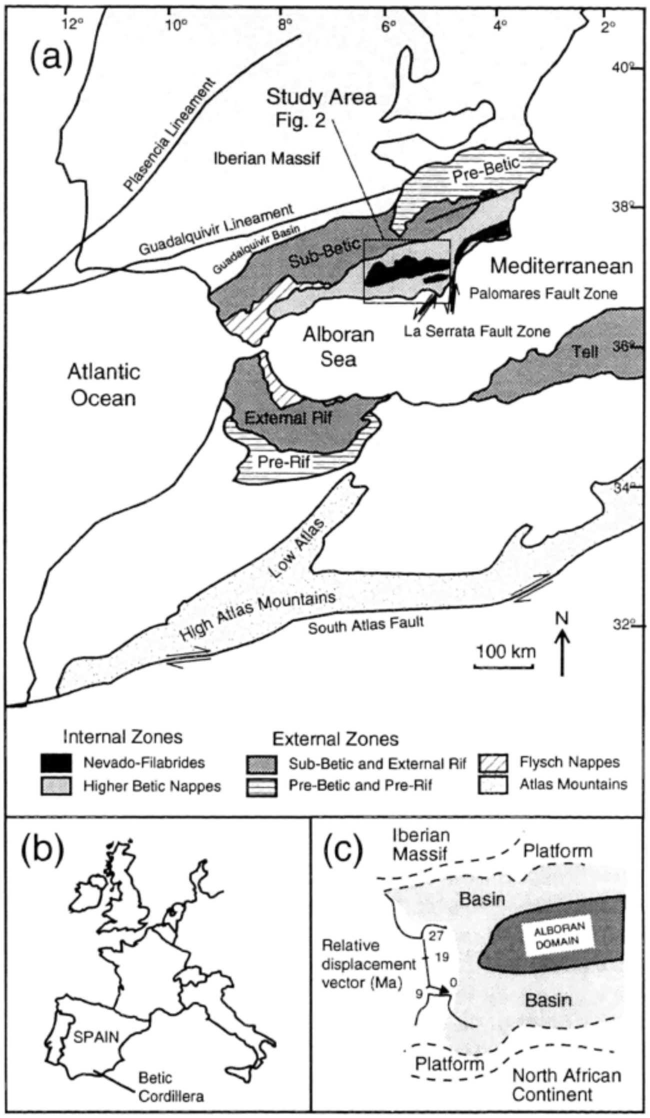

Figure 1. (a) Tectonic sketch map of southern Iberia and northwestern Africa showing the Alpine Betic-Rifian Arc, the Alboran Sea, and the Atlas Mountains. The study area in southeast Spain is indicated. (b) Sketch map of western Europe showing the location of the Betic Cordillera. (c) Cartoon illustrating relative Europe-Africa plate motions since the Oligocene. Platform deposits form the modern Pre-Rif and Pre-Betic units and the basinal sequences constitute the modern Sub-Betic, External Rif, and Tell. The Alboran Domain consists of continental crust that forms the modern Internal Zone nappes. Diagram is after *Platt and Vissers* [1989]

indicate either a mid-Cretaceous phase of subduction [e.g., *De Jong*, 1991] or Eocene-Oligocene crustal thickening [e.g., *Platt and Vissers*, 1989] as the cause for the stacking. Thrusting within the complex clearly predates the formation of the present-day contact between the Nevado-Filábride and overlying Alpujárride Complexes since this contact cuts across and down toward the west through the thrust stack [*Garcia-Dueñas et al.*, 1988; *De Jong*, 1991].

The plurifacial character of the Alpine metamorphism in the Nevado-Filábride Complex was first recognized by *Nijhuis* [1964]. Much work has since been done in detailing the metamorphic evolution of the complex [e.g., *Vissers*, 1981; *Gómez-Pugnaire and Fernandez-Soler*, 1987; *Bakker et al.*, 1989; *De Jong*, 1991; *Jabaloy Sánchez*, 1993] and despite disagreement over details, general agreement exists on its overall form. All workers recognize an early high pressure/low temperature metamorphism, followed by almandine-amphibolite facies conditions before regression to greenschist facies. During almandine-amphibolite facies conditions a main phase foliation was formed that has been variably overprinted [*De Jong*, 1991]. In much of the eastern part of the Nevado-Filábride Complex it forms the principle foliation, being only locally affected by later deformation. Moving westwards the overprint becomes increasingly regional and in the Sierra Nevada the principle foliation is a product of later deformation interpreted by some as having been formed during decompression and exhumation of this complex [*Galindo Zaldívar*, 1993; *Jabaloy Sánchez*, 1993].

This later foliation is marked by a penetrative stretching lineation that becomes increasingly pronounced as the contact with the overlying Alpujárride Complex is approached (Figure 3). The direction and sense of shear obtained from this ductile planolinear fabric is given by the stretching lineation together with a number of asymmetric kinematic indicators including schistosity-shear (S-C) fabrics, rotated porphyroblasts with their pressure shadows, and quartz c-axis fabrics [e.g., *Martínez-Martínez*, 1984; *Garcia-Dueñas et al.*, 1988; *Zevenhuizen*, 1989; *Soto et al.*, 1990; *González Lodeiro*, 1990; *Galindo Zaldivar*, 1993]. Within the area studied this data is broadly consistent with top-to-the-west shear. The trajectories, or flow lines, deduced from the variation in direction of maximum stretching [after *Jabaloy Sánchez*, 1993] do indicate systematic variation with the sense of shear swinging round in an anticlockwise direction from the northwest to the southwest as one moves from east to west.

Superimposed on this ductile deformation is later brittle deformation which has produced cataclasites, fault gouges and tectonic breccias at the Nevado-Filábride-Alpujárride contact, together with an extensive system of tension joints oriented perpendicular to the earlier formed stretching lineation [*Galindo Zaldivar et al.*, 1991; *Jabaloy Sánchez*, 1993; *Galindo Zaldivar*, 1993]. This brittle deformation exhibits a shear sense similar to that of the earlier ductile deformation (Figure 3) based upon fault fabrics and stria [*Galindo Zaldivar*, 1993].

Two groups of models have been advanced to account for the observed metamorphism and deformation within this complex which have strikingly different implications for denudation. In the first, metamorphism and the great majority of the structures result from a series of compressive deformation phases which produced a nappe pile [*Egeler and Simon*, 1969; *Rondeel and Simon*, 1974; *Kampschuur and Rondeel*, 1975; *Puga and Diaz de Frederico*, 1976; *Vissers*, 1981; *Bakker et al.*, 1989; *De Jong*, 1991]. However, as thrusting alone cannot result in the exhumation of any point in the footwall, it is implicit in these models that the structurally lowermost units presently exposed must have been exhumed by postdeformation erosion; that is deformation predates and is not the direct cause of denudation.

In contrast, the second group of models ascribe many of the structures, and much of metamorphic evolution and subsequent denudation of this complex to crustal scale extension, whilst

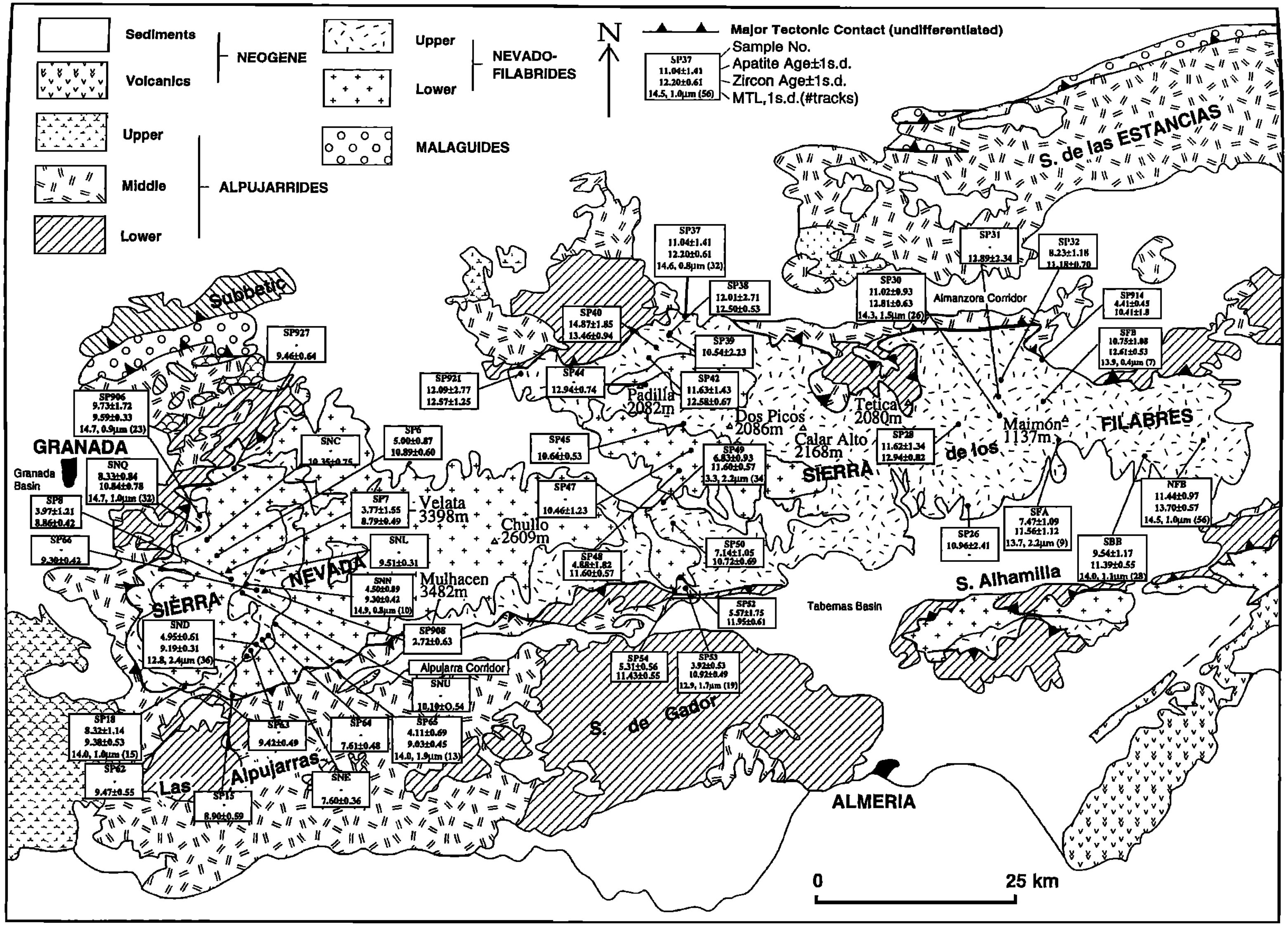

Figure 2. Geology of the eastern Betic Cordilleras together with the sample localities, apatite, and zircon apparent fission track ages and mean track length (MTL), standard deviation (1 s.d.), and number of measured tracks. All the samples come from the structurally lowermost complex, the Nevado-Filábride Complex, upon which rests the Alpujárride Complex and the Malaguide Complex in ascending order.

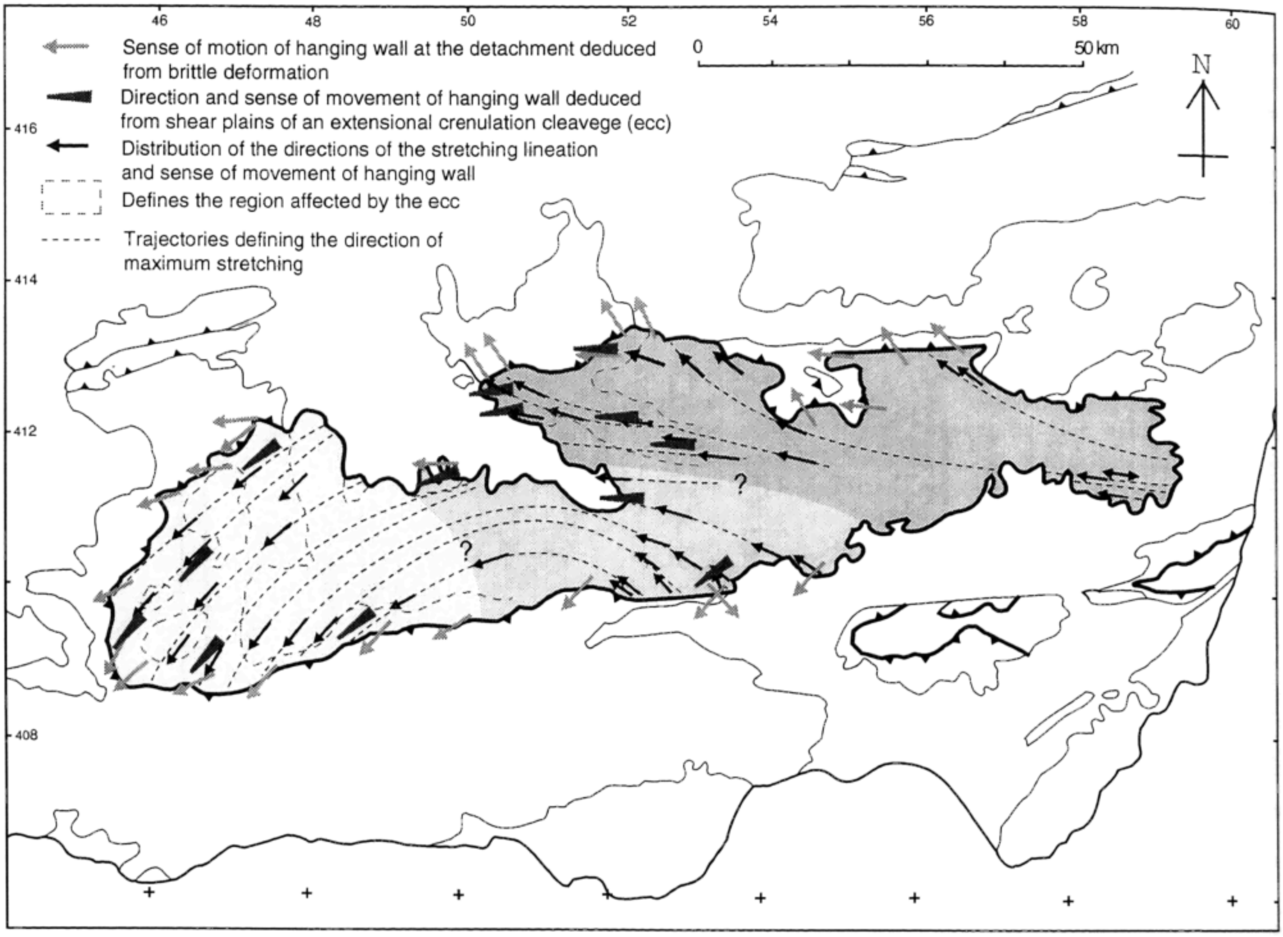

Figure 3. Summary of the structural data relating to the emplacement of the Alpujárride Complex upon the Nevado-Filábride Complex. The data is from the work of *Jabaloy Sánchez* [1993] which compiled the work of several authors. They suggest broadly east to west motion of the Alpujárride Complex with respect to the underlying Nevado-Filábride Complex (shown in grey shading). The significance of the shading is explained in the text.

retaining an early compressive phase of deformation causing thrust stacking and deep burial [*Platt and Behrmann*, 1986; *García-Dueñas and Martínez-Martínez*, 1988; *García-Dueñas et al.*, 1988; *Platt and Vissers*, 1989; *Galindo Zaldívar et al.*, 1989; *García-Dueñas et al.*, 1992]. In this second group of models, a genetic link exists between deformation and denudation, with denudation of the presently outcropping rocks achieved largely by crustal scale extension.

In this paper we address the nature and timing of cooling within the Nevado-Filábride Complex during the Neogene. This information provides the key to establishing the primary process responsible for Nevado-Filábride denudation. We then consider the implications that this denudational history has for Tertiary tectonics in the eastern Betic Cordillera. First, though, we examine the likely consequences of erosional and tectonic denudation on regional cooling patterns obtained from fission track data in orogenic belts, focusing in particular on those features that might distinguish the two processes.

Documenting Denudation Using Fission Track Data

Denudation may be accomplished either by surface processes, that is, erosion or by tectonic means, in which crust is thinned by extensional faults. Denudation of either kind will strongly influence the thermal state of the Earth's crust during orogeny [e.g., *Stüwe et al.*, 1994; *Ruppel et al.*, 1988], so determination of how crustal temperatures have varied temporally and spatially is one way of constraining the denudation history [e.g., *Cliff*, 1985; *Hurford et al.*, 1989; *Fitzgerald and Gleadow*, 1990; *Van der Beek*, 1995]. In orogenic belts it appears plausible that tectonic and erosive denudation should act together to help balance the effects of crustal shortening and thickening during orogenesis [e.g., *Platt*, 1986; *Jamieson and Beaumont*, 1988, 1989]. Whether it is possible to isolate these processes using fission track thermochronology depends on their relative importance over crustal length scales and geological timescales. Where one process

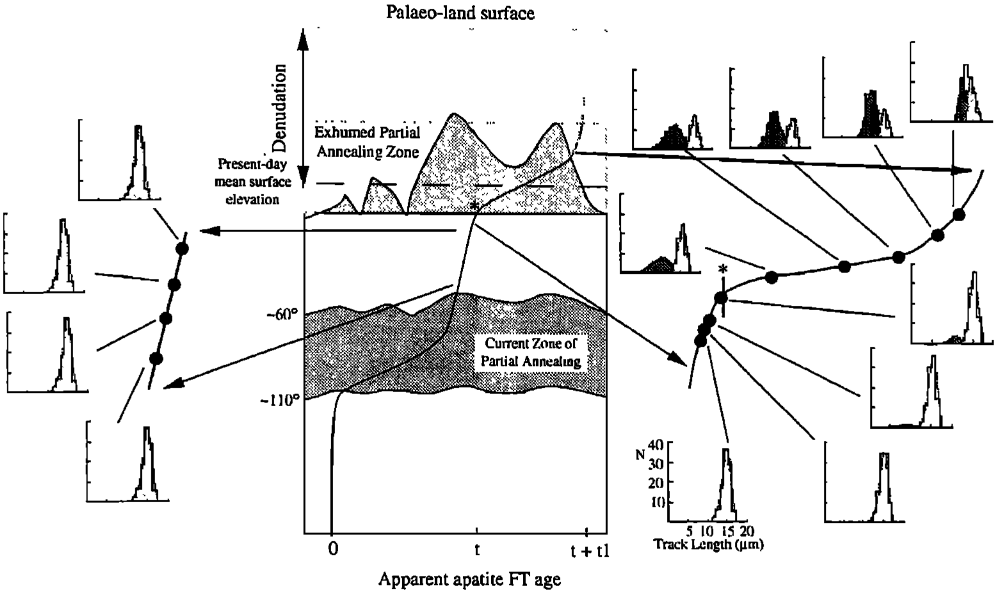

Figure 4a. Cartoon illustrating the variation of apparent age (specifically for apatites) with sample elevation (depth). A phase of accelerated denudation resulting from the action of Earth surface processes commenced at time *t*. This has promoted the development of a positive correlation between apparent fission track age and elevation. This relationship may be nonlinear, reflecting a combination of tracks that predate and postdate the onset of denudation (dark tracks and light tracks, respectively), or linear for samples at temperatures below ~60°C sourced from below the exhumed partial annealing zone [after *Fitzgerald et al.*, 1995]. The inflection in the apparent age-elevation profile marked by asterisk gives the time of onset of denudation. See text for discussion.

comes to dominate over the other, for some significant time interval, the regional cooling pattern should reflect that dominance. A description of the likely differences in cooling history resulting from denudation accomplished by either Earth surface or tectonic processes is given below.

Denudation by Earth Surface Processes

Fission track data from mountain belts is often presented by plotting apparent age as a function of elevation. Apatite ages, in particular, often show a positive correlation with elevation. In many cases the gradient of this trend has been interpreted as recording an "uplift" rate. *England and Molnar* [1990] and *Brown et al.* [1994] have demonstrated that this conclusion is often an oversimplification, since fission track analysis provides information, not on surface uplift, but on temperature histories and must therefore be interpreted as such.

Where surface processes are solely responsible for cooling a suite of samples collected from different initial crustal depths, a progressive decrease in apparent age with paleodepth is observed as denudation results in their increasingly later passage through the Partial Annealing Zone (PAZ). Figure 4a, taken from *Fitzgerald et al.* [1995], illustrates this relationship by showing a PAZ that has been exhumed by a phase of denudation commencing at time *t*. Samples within and above the exhumed PAZ at time *t* contain varying proportions of tracks formed prior to and following this time, with greater numbers and therefore older ages at higher elevations. Samples collected below the exhumed PAZ contain only tracks formed after the onset of denudation, with the time at which samples passed into the PAZ causing lower samples to yield younger apparent ages. Thus, regardless of whether samples are taken from within or below the exhumed PAZ, a strong correlation between apparent FT age and sample elevation is to be expected if erosion is responsible for sample denudation.

Denudation by Tectonic Processes

Wheeler and Butler [1994] have argued that there are three types of criteria, structural, metamorphic, and geochronological, that should be used to identify crustal extension in orogenic belts. While the structural and metamorphic data presented above will be incorporated in the discussion of the results, it is the (thermo) geochronological data that will be considered here. Apatite and zircon FT thermochronology provides information on the low-temperature thermal history of crustal rocks. The temperature range which can be examined is estimated to be between 350°C and 60°C for geological timescales of 10^6-10^8 years [*Laslett et al.*, 1987; *Yamada et al.*, 1995], that is, largely within the brittle regime.

Previous studies indicate it is possible to identify three features that distinguish tectonic from erosional denudation in terms of the regional cooling patterns that each promote. These may be used for diagnosing the existence of tectonic denudation and, in addition to this, provide information for estimating its timing, rate, and geometry.

Samples from the footwalls of extensional faults such as those that bound the metamorphic core complexes of the western United

States reveal a poor correlation between apparent apatite age and elevation [e.g., *Dokka et al.*, 1986; *Foster et al.*, 1991]. The reason for this is probably that regional relief forms in response to isostasy [*Spencer*, 1984; *Wernicke and Axen*, 1988; *Block and Royden*, 1990] that is controlled by the position, amount, and timing of removal of crust at depth along the extensional fault (shear zone or detachment) and not by surface processes. Since cooling of the footwall rocks is similarly controlled by the extensional fault, neither a sample's apparent age nor its elevation will be related to surface processes. This relationship is illustrated in Figure 4b.

A second feature of tectonic denudation has been observed by workers in the western United States and the Alps. Progressive unroofing of the footwall rocks below a crustal scale shear zone or detachment results in asymmetric cooling patterns, with apparent ages decreasing in the direction of hangingwall transport [Figure 4b]. Correlations between apparent apatite age and distance in the inferred direction of hangingwall motion appear to be good [*Bradbury and Nolen-Hoeksema*, 1985; *Foster et al.*, 1991; *Foster et al.*, 1993; *John and Foster*, 1993] as are those with higher temperature thermochronometers [*Bradbury and Nolen-Hoeksema*, 1985; *Lee and Sutter*, 1991; *John and Foster*, 1993]. This feature has been exploited to estimate the slip rates of hangingwall rocks with respect to their footwall and has also been used to reconstruct the preextensional geometry of the fault system [*Foster et al.*, 1993; *John and Foster*, 1993].

A third feature of tectonic denudation is the very rapid cooling experienced by many footwall rocks, particularly those from the structurally highest sections of metamorphic complexes. Cooling rates inferred from rocks below major extensional faults vary from 40°C to 625°C Ma^{-1}, with the bulk of extensional terrains exhibiting rates between 50°C and 200°C Ma^{-1} [e.g., *Dokka and Lingrey*, 1979; *Dokka et al.* 1986; *Davis*, 1988; *Richards et al.*, 1990; *Carmignani and Kligfield*, 1990; *Baldwin et al.* 1993; *Foster et al.*, 1991, 1993; *John and Foster*, 1993].

Summary

Erosional denudation acting alone tends to promote a simple, positive correlation between apparent (apatite) FT age and elevation, whereas samples from the footwall to an extensional fault show little correlation between age and elevation. In addition, tectonic denudation promotes a negative correlation between apparent age and distance in the direction of hanging wall transport and high cooling rates which are spatially associated with the shear zone or detachment.

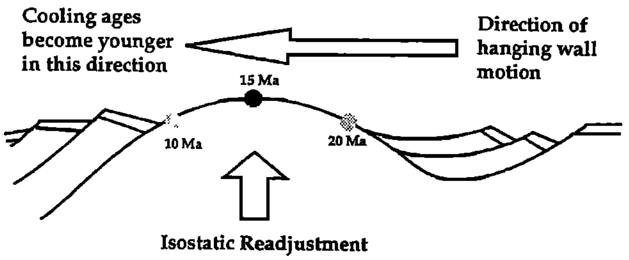

Figure 4b. Tectonic denudation causing excision of a section of crust results in isostatic readjustment of the footwall. Cooling ages in the footwall therefore acquire an elevation that is unrelated to the action of Earth surface processes. Slip on a low-angle normal fault results in cooling occurring progressively later down dip and isochrons running perpendicular to the dip direction.

Fission Track Data

A total of 46 samples were obtained from the Nevado-Filábride Complex, yielding 32 apatite and 42 zircon analyses. They were collected from three separate sectors in the study area: the Sierra de los Filábres in the east, the Northwestern Sierra de los Filábres-Eastern Sierra Nevada in the center, and finally, the Sierra Nevada in the west (Figure 2). All samples were taken from metasedimentary rocks, gneisses, and a metagranite of Triassic or earlier age.

Methodology

Standard heavy liquid and magnetic separation methods were used to extract apatite and zircon from their host rocks. These were analyzed using the external detector and zeta calibration approach [*Hurford and Green*, 1982]. Ages were calculated using the central age method of *Galbraith* [1992] which allows for non-Poissonian variation within a population of single-grain ages belonging to a single sample, and gives a measure of any such variation in the form of a relative error (RE). Where the RE is greater than ~15%, the possibility of more than one age population exists, and the sample is also likely to fail the χ^2 test. A significant number of FT ages from the Nevado-Filábride Complex do not appear to have single-grain age spreads consistent with a single-age population when assessed using the RE and the χ^2 test. The scatter in single-grain ages is thought to be due to the errors of commission and omission that result from the frequent presence of track-like crystal defects. The misidentification of very short tracks and spurious etch pits, while possibly small in number, have a significant effect because true spontaneous track numbers are low. The large numbers of crystals used and the likelihood that these two types of error are equally common means that they will tend to cancel out when the central age is calculated but produce a large single-grain age spread. This conclusion is supported by the age concurrence of closely spaced samples, some of which fail the single-population tests while their neighbors do not.

Track length data were obtained using a drawing tube and digitizing tablet. Typically, 100 track length measurements are made for the purpose of determining the mean track length and its standard deviation. However, this was not possible for any of the samples because of their low uranium content and late Tertiary cooling age. Of the 32 apatites analyzed, only 14 possessed any confined tracks. Of these analyses, five samples are thought to have adequate numbers of confined tracks for quantitative modeling purposes, the results of which are used to help interpret the less well constrained samples.

Quantitative modeling was undertaken using a robust optimization procedure which utilizes a genetic algorithm [*Gallagher and Sambridge*, 1994]. This is a Monte Carlo type scheme providing a highly efficient search of the model time/temperature space. In essence, the random sampling of thermal histories is progressively biased toward those which predict the observed data adequately. For this reason the approach adopted may be described as data driven, in contrast to a forward model approach which is constrained by a preset thermal history. Typically, 2000 to 3000 individual thermal histories are generated during the modeling procedure and examined for their consistency with the observed data. Since inversion of thermal indicator data cannot yield a unique solution [*Gallagher and Sambridge*, 1994], the results are ranked by statistical methods, maximum likelihood being the preferred choice. This approach is favored since, in addition to the best fit result, we also show the next 100 data fitting solutions. This population of solutions allows the better-constrained portions of the thermal history to be identified by examining the spread in the models.

Results

The fission track data and the sample details are given in Figure 2 and in an electronic supplement to this paper[1]. The zircon ages have a range of 13.7-7.6 Ma, while the apatite ages span 14.9-2.7 Ma. There is therefore considerable overlap, with many mineral age pairs lying within 2σ of one another. (Note all errors in Table 1 of the electronic supplement are given at the 1σ level.) The data will be examined in detail in this section before a discussion of its significance is given in the section on discussion and interpretation.

Zircon

Starting in the east, zircon ages in the Sierra de los Filábres range between 10.4 and 13.7 Ma and possess a weighted mean of 12.06±0.39 Ma. These overlap with Rb-Sr and K-Ar white mica and biotite ages reported by *Andriessen et al.* [1991] which span 12.5 Ma to 15.6 Ma. The ^{40}Ar-^{39}Ar dating of phengites from micaschists and a paragneiss from this region have yielded older cooling ages ranging from 21.5 Ma to 14.5 Ma [*De Jong*, 1991]. With the exception of sample SP31 (which consists of only one grain) the zircon analyses have maximum single-grain ages of between 15 Ma and 21 Ma and for five of the samples an asymmetrical distribution of ages about the central age (SP28, SP32, SP914, SBB, and SFB) skewed to older grains. This distribution of ages causes the failure of the χ^2 test and high relative error of samples SP28 and SP914. In contrast, the youngest single-grain ages are, with one exception, within the 8-9 Ma range (Figure 5). Attaching some special significance to the single-grain ages is problematic, and, in general, where the ages are most probably from a single population as indicated by the χ^2 statistic, it is prudent not to do so. However, the spread of "older" ages may have some significance. If the cooling rate during the early-middle Miocene was relatively low at the high temperature end of the zircon stability field (estimated as 170°C-390°C by *Yamada et al.* [1995]), a greater spread in older ages could result from differential annealing susceptibilities due to variations in single zircon crystal chemistry by analogy with apatites [*Green et al.*, 1986]. With the exception of sample SP28 the maximum single-grain age lies within the 15-18 Ma age range and thus coincides with the oldest white mica ages reported [*Priem et al.*, 1979; *De Jong*, 1991; *Andriesson et al.*, 1991] (except ALM 3). They also broadly coincide with the times for ^{40}Ar degassing in phengites, deduced by *De Jong* [1991] from modeling the ^{40}Ar release spectra, which fall in the 15-18 Ma age range.

The zircon ages from Western Sierra de los Filábres-eastern Sierra Nevada are identical to those from the Sierra de los Filábrides, having a range of 10.5-13.6 Ma, and a similar weighted mean (11.70±0.21 Ma). Like those from further east, these samples possess maximum single-grain ages of 15 to 25 Ma, although some samples from the southern section of the transect have younger minimum single-grain ages than previously encountered (Figure 5). The older zircon single-crystal ages are coincident with ^{40}Ar-^{39}Ar mica plateau ages of 16 and 17 Ma from the Northwestern Sierra de los Filábres [*Monié et al.*, 1991]. Hornblende and barriosite ^{40}Ar-^{39}Ar ages of 25 and 48 Ma are also reported from this region by *Monié et al.* [1991].

The 19 zircon analyses from the Western Sierra Nevada range in age from 7.6 to 10.9 Ma are consistent with belonging to a single-age population, and possess a weighted mean value of 9.17±0.39 Ma. Seven of the samples fail the χ^2 test because of the presence of older single-grain ages in the 15-20 Ma age range (Figure 5). Single-grain ages within the 15-20 Ma age range are also found in some of the other samples, although most have lower precisions. This age range is identical to that encountered in the samples in the eastern and central transects and is consistent with a relatively low cooling rate during the early-middle Miocene at the high-temperature end of the zircon stability field. In contrast, the range of minimum zircon ages (6-8 Ma) from the Western Sierra Nevada is the youngest encountered in the Nevado-Filábride Complex. These are for the most part within 1 s.d. of the mean age which suggests an increase in the cooling rate as the lower end of the zircon stability field is approached during the early Tortonian. This inferred cooling history is consistent with the single-zircon, confined track length measurement of 11.1±1.0 µm (sample SND).

There is no independent radiometric data from the Western Sierra Nevada. However, the similarity between the older zircon single-grain ages from this region and those to the east suggests that the Nevado-Filábres in this region were at temperatures of ~350°C for much of the lower Miocene.

In Figure 6 the zircon apparent ages are plotted as a function of their elevation. The results from the three transects are distinguished from one another, and the weighted mean for each is given. The slight negative correlation between age and elevation results from a lack of samples collected from elevations greater than 2100 m in the eastern and central transects. Apparent ages from individual transects are randomly distributed about their mean values, while the means themselves show a progressive younging from east to west.

Apatite

In contrast to the zircon analyses the apatite single-grain ages are far less likely to provide detailed information on a sample's cooling history because of the very low numbers of spontaneous tracks and possible errors of omission and commission in the track counts. This is largely due to the low uranium concentrations present within these apatites.

Ten samples from the Sierra de los Filabres yielded apatite ages. Despite the fact that six of the results fail the χ^2 test and possess high relative errors (RE>10) they all have unimodal single-grain trends (electronic supplement). Many of the apatites

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[1] Supporting data [table and zircon radial plots] are available on diskette or via Anonymous FTP from kosmos.aug.org, directory APEND (Username=anonymous, Password=guest). Diskette may be ordered from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009 or by phone at 800-966-2481; $15.00. Payment must accompany order.

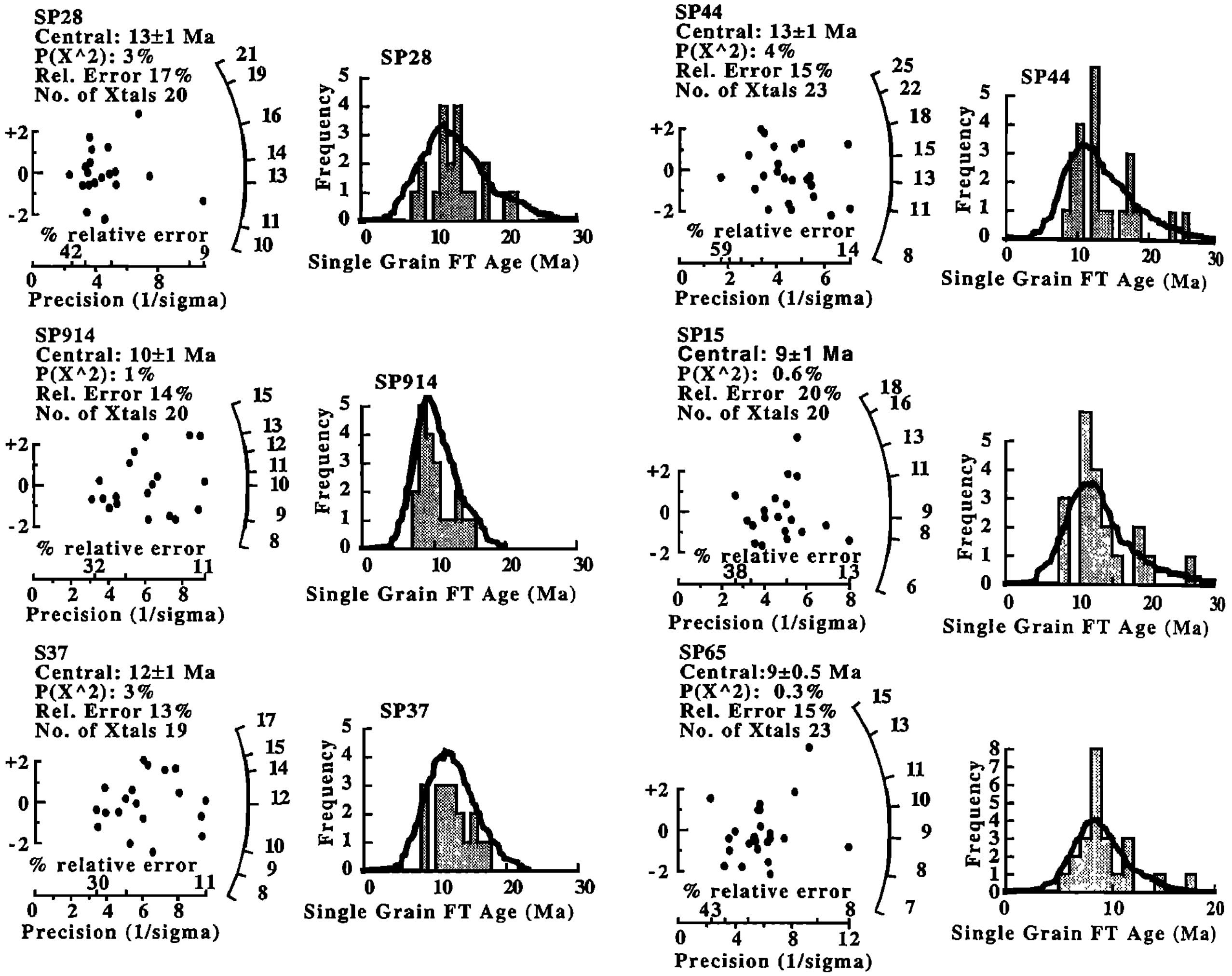

Figure 5. Six zircon samples (two each from the three transects) that fail the χ^2 test and demonstrate a marked asymmetry in their single-grain age distributions with late Oligocene to early Miocene aged grains that are coincident with the ^{40}Ar-^{39}Ar dates on phengites by *De Jong* [1991] and the ^{40}Ar-^{39}Ar mica plateau ages of *Monié et al.* [1991]. This is interpreted as evidence for slow cooling within the Nevado-Filábride Complex during the lower Miocene. Note the radial (y) scale is log time, and x scale is precision, with precision increasing away from origin. Single-grain ages can be estimated by projecting a line from the origin through the age plot to the y axis. The scales are variable.

have concordant ages with their coexisting zircons and generally long mean track lengths.

The oldest apatite age is 11.95±1.40 Ma (SP29), while the oldest for which a mean track length is available (14.51±0.15 μm, s.d.=1.00 μm) is 11.44±0.97 Ma (NFB). It is reasonable therefore to suppose that the oldest apatite ages are associated with mean lengths greater than 14 μm, particularly as these apatite ages are concordant with their coexisting zircon ages. Of the five apatite ages below 11 Ma, three have limited track length data associated with them. Corrected age estimates, although not definitive [*Green*, 1988; *Corrigan*, 1991], of 10.22-12.05 Ma for sample SBB and 11.62-13.04 Ma for sample SFB suggest cooling below ~110°C was contemporaneous with the cooling of the other samples with the exception of SFA whose corrected age of 8.15-10.53 Ma is more ambiguous. The scarcity of confined track lengths in all the samples analyzed means that modeling thermal histories cannot be attempted with the rigor generally desired. Two samples have had their cooling paths modelled (NFB and SP30, Figure 7). They have in common an initial phase of rapid cooling (~100°C Ma^{-1}) between approximately 12 and 10 Ma shortly after cooling through the zircon PAZ. Below 60° there is considerable scatter in the 100 better fitting-cooling paths because the model predictions are relatively insensitive to these temperatures.

The variation in apatite ages from the central transect is very different from that in the Sierra de los Filábrides. They range in value from 14.9 to 3.9 Ma and are not consistent with their belonging to a single age population (χ^2 fail at the 1% level). Using the statistical method of *Sambridge and Compston* [1994], this group of ages can be shown to be best described as a two-

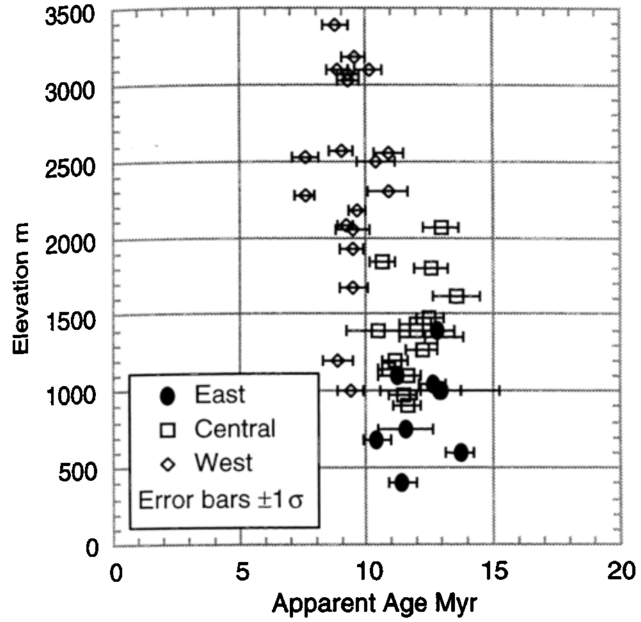

Figure 6. Plot illustrating the lack of any clear relationship between zircon apparent age and elevation.

component mixture having ages of 11.6 and 5.3 Ma. This statistical subdivision is reflected in the geographical distribution of the samples.

The older component (SP37, SP38, SP39, SP40, SP42, and SP921) is restricted to the Northwestern Sierra de los Filábres while the younger (SP48, SP49, SP50, SP52, SP53, and SP54) is restricted to the Eastern Sierra Nevada. The weighted mean age of the older group, 11.94±0.62 Ma, is statistically identical to the modelled value of 11.6 Ma and similar to the weighted mean of the three samples from the Sierra de los Filábres whose mean track lengths are ≥14 μm (10.81±0.53, all quoted at 1σ). Only one sample from this group yielded a mean confined track length [SP37], but its value of 14.59±0.14 μm (s.d.=0.8 μm) is probably representative of the others since they are concordant with one another and with their coexisting zircons (weighted mean 12.56±0.19 Ma). This indicates that the Nevado-Filábride Complex of the Northwestern Sierra de los Filábres cooled through the temperature range >350°C to <60°C at the same time as cooling in the Sierra de los Filábres farther east and that this occurred over a very restricted time interval of 1 to 2 Ma. This conclusion is supported by the quantitative modeling of sample SP37, shown in Figure 7, which indicates rapid cooling to a temperature below 60°C by 11-9 Ma.

The younger age group contains two samples with confined track information (SP49 and 53). Together they suggest a more protracted passage through the apatite partial annealing zone (~110°-60°C) than was the case with the older samples. Their corrected age estimates [*Green*, 1988; *Corrigan*, 1991] of 7.70 to 10.03 Ma and 4.57 to 5.72 Ma, respectively, indicates that these samples were at depths consistent with temperatures >110°C but less than 180°C at the time of cooling to below 60°C in the Northwestern Sierra de los Filábrides.

The 10 apatites from the Western Sierra Nevada range in age from 2.7 to 9.7 Ma. This range is not consistent with a single age population, and they can be subdivided loosely on the basis of a combination of age and length into two groups. The first of these possesses ages concordant with their coexisting zircons and have long mean track lengths (SP18, SP906, and SPQ). These are all located close to the boundary with the overlying Alpujárride Complex, that is, within the structurally uppermost part of the

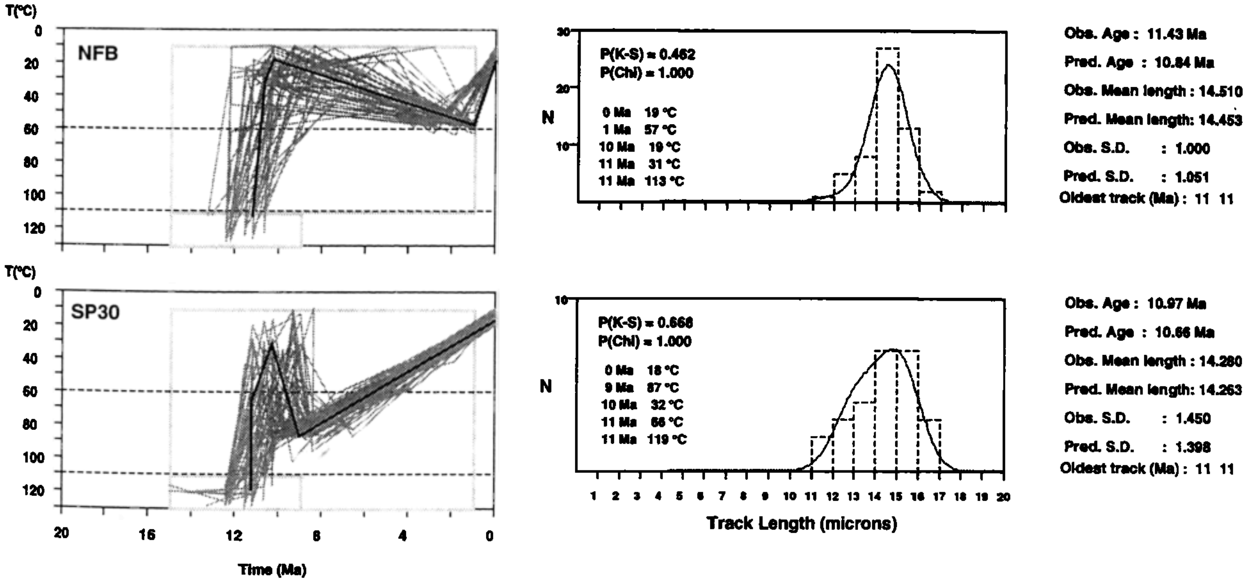

Figure 7. Results of quantitative modeling of apatite data. In left-hand plots the black line is the best fit solution, while the grey lines are the 100 better-fitting solutions. These are included to help identify the better-constrained portions of the cooling history. Note that for temperatures above ~110°C and below ~60°C, the fission track data provide no effective constraint on model evolution. In the right-hand plots the measured confined track length distribution is given by the histogram, while the modeled distribution is given by the curve. Observed and predicted parameters are listed on the right hand side.

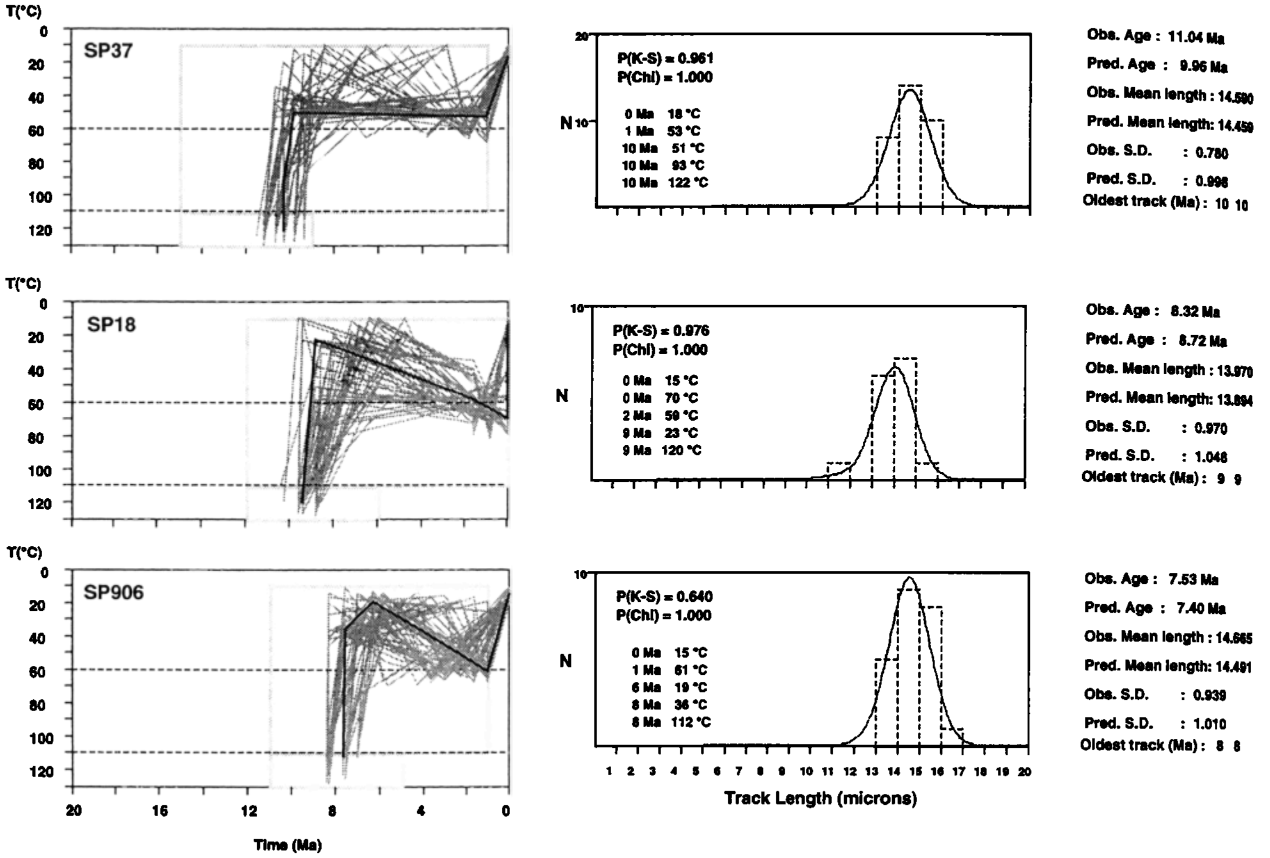

Figure 7. (continued)

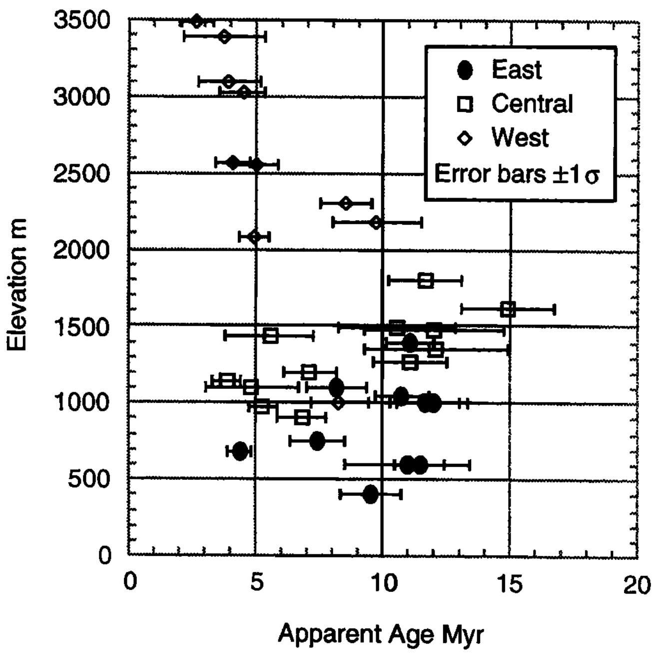

Figure 8. Plot illustrating the lack of any clear relationship between apatite apparent age and elevation.

Nevado-Filábride Complex. The second group possess ages that are younger and discordant with their coexisting zircons. These samples come from structural depths below the contact with the overlying Alpujárride Complex, estimated to be up to 3.6±1.5 km [*Johnson*, 1995], with the youngest age (2.7±0.6 Ma) obtained from the sample with the highest elevation but the greatest structural depth (SP908).

Quantitative modeling of samples SP18 and SP906 (Figure 7) in conjunction with the zircon results indicate that cooling over the temperature interval 350°C - 60°C in the western Sierra Nevada region immediately below the Alpujárride/Nevado-Filábride contact occurred between approximately 10 and 8 Ma.

In Figure 8 the apatite results are plotted as a function of their elevation. Taken together, no trend can be recognized, although the samples from the western transect do have a negative correlation between their apparent ages and elevation (R=0.74). Since the cooling of these higher-elevation samples postdates the phase of rapid cooling identified within the structurally uppermost part of the complex, they cannot possess thermal history information that relates to the processes responsible for the rapid cooling.

Discussion and Interpretation

In this section we seek to establish the dominant denudational process and its time of action by concentrating on three issues.

First, the time of cooling in the Nevado-Filábride Complex and that of other geological phenomena and their possible relationships are dealt with. Second, the rates of cooling within the complex are deduced and considered in conjunction with the structural setting of individual samples. Third, the kinematics of the cooling history for the Alpujárride/Nevado-Filábride contact are considered.

Timing

The time of cooling to near-surface temperatures in the Nevado-Filábride Complex has been shown to decrease from east to west. This is best illustrated by the weighted mean zircon ages from the three transects, together with the results of the five apatite quantitative thermal modeling exercises. The weighted mean zircon age in the Sierra de los Filabres is 12.06±0.39 Ma, 11.7±0.39 Ma in the eastern Sierra Nevada/Western Sierra de los Filabres, and 9.17±0.39 Ma in the Sierra Nevada. The apatite modeling indicates that cooling was more or less complete in the structurally uppermost parts of the complex by 11 Ma in the east and 8 Ma in the west.

This timing, and its variation from east to west, is closely matched by the first appearance in the surrounding intermontane basins of clastic detritus shed from the Nevado-Filábride Complex. Neogene sediments in the Almanzora corridor in the east of the study area (Figure 2) consist of a number of unconformable units [*Braga and Martín*, 1988]. The first of these, lying on Alpujárride basement, is a thick (>100m) red, continental conglomerate believed to be Serravallian in age (14.2-10.4 Ma). It contains clasts predominantly from the upper (Mulhacen) nappe of the Nevado-Filábride Complex together with lesser amounts of Alpujárride material. Toward the end of the Serravallian and during the early Tortonian a transition to marine sedimentation took place within the eastern Betic basins [*Weijermars et al.*, 1985]. In the Tabernas Basin the first influx of Nevado-Filábride detritus occurred at this time [*Weijermars et al.*, 1985]. Farther west in the Alpujárra Corridor, middle Miocene clastics are dominated by Alpujárride detritus with a secondary Maláguide component [*Rodríguez Fernández and Sanz de Galdeano*, 1990]; however, Nevado-Filábride material is never recorded.

Following the lower Tortonian transgression, a phase of major tectonic activity took place that resulted in terrigenous sedimentation throughout the eastern Betics [*Sanz de Galdeano and Vera*, 1992]. This has led to the distinction in the literature between a eustatic-controlled, transgressive sedimentary unit (Tortonian I) and a later succession whose origin is essentially tectonic (Tortonian II) [*Sanz de Galdeano and Vera*, 1992]. The Tortonian I and II sequence boundary age is inferred to be 8.5 Ma from *Haq et al.* [1989]. Of the Betic basins peripheral to the study area, the most westerly of these, the Granada Basin, was the last to receive Nevado-Filábride detritus. This took place at the onset of Tortonian II sedimentation during which mean deposition rates were in excess of 0.5 mm yr^{-1} [*Rodríguez Fernández et al.*, 1989].

These observations indicate that the appearance of Nevado-Filábride material within the sedimentary record is diachronous within the eastern Betic basins by perhaps as much as 6 Ma and that unroofing of this complex occurred from east to west, complimenting, both temporally and spatially, the findings of this study. This contrasts with the record of siliciclastic sedimentation within the basins of the eastern Betics in which change is regionally contemporaneous. This suggests that surface processes (in conjunction with eustacy) were not major factors in the initial unroofing of the Nevado-Filábride Complex in the middle and upper Miocene. This conclusion is supported by the absence of any positive correlation between apparent age and sample elevation noted in the previous section. Instead, the westerly younging observed for the rapid cooling in this complex is consistent with tectonic denudation.

Subsequent to the tectonic unroofing of the Nevado-Filábride Complex, surface processes must have played an important role in the denudation of its presently outcropping rocks. This is illustrated by the presence of large volumes of Nevado-Filábride detritus within the peripheral basins and explains the apatite ages from the southwest margin of the Sierra de los Filabres and the central Sierra Nevada. The negative correlation between elevation and apparent apatite age observed in the latter region is interpreted in terms of the interaction between erosional denudation and late, large scale folding by C. Johnson (Resolving denudational histories in Orogenic Belts with AFTT; some problems and solutions, submitted to *Geology*) and is not dealt with here.

The clear inference to be drawn from the discussion above is that tectonic denudation ceased in the eastern Betics between 9 and 8 Ma and that the tectonic events at that time, which resulted in the initial structuration of the intermontane Betic basins and development of the modern topography, are somehow linked to this change. Relative plate motions between Africa and Iberia were broadly north-south convergent throughout the Tertiary until chron 5 (9 Ma), after which they became dextrally transpressive [*Dewey et al.*, 1989], remaining so until the present day [*Argus et al.*, 1989]. This timing may therefore have a wider implication, suggesting a possible causal link between relative Africa-Europe (Iberia) plate motion and extension within the mountain belt.

Cooling Rate

Reconstructing cooling rates generally depends on the adoption of "closure temperatures" for two or more thermochronometers, the common exception to this approach being apatite fission track analysis. With this technique, age and confined track length data in conjunction with an annealing equation permit rates to be estimated directly. It is theoretically now possible to adopt this same approach with zircons using the annealing equation of *Yamada et al.* [1995], although this is not attempted here. The zircon partial annealing zone [PAZ] was estimated by *Yamada et al.* [1995] to be approximately 390°C-170°C but for this exercise we adopt the rather more conservative figure of 230°C±25°C [*Hurford*, 1986] as a nominal closure temperature.

The results of ^{40}Ar-^{39}Ar analyses on phengites from the eastern Sierra de los Filabres by *De Jong* [1991] yielded plateau ages of 14 to 29 Ma. These results were interpreted in terms of a Miocene regional thermal overprint causing partial resetting of older cooling ages that postdated a proposed Cretaceous subduction of this complex. Whether this is the case or not, it is clear that temperatures during the late Oligocene and throughout much of the lower and middle Miocene were within the 350°C±50°C temperature range; an observation supported by the presence of similarly aged zircon single-grain ages. Cooling throughout this period was therefore slow, although difficult to quantify. A similar cooling pattern exists in the Western Sierra de los Filabres based on the more limited ^{40}Ar-^{39}Ar results of *Monié et al.* [1991]. The lack of other published thermochronology data from the Sierra Nevada prevents a similar judgement about this region being made. However, the presence of older zircon single-grain ages in the range of 15-20 Ma within grain populations that fail the χ^2 test does suggest that these samples probably experienced a similar slow cooling history during the lower and middle Miocene.

What the results of this study demonstrate so very clearly is that following the relatively slow cooling phase described above, rates increased dramatically as temperatures decreased. In the Eastern Sierra de los Filabres a cooling rate of 200°C Ma^{-1} can be estimated on the basis of the combined weighted mean zircon age and the apatite quantitative modeling (Figure 9). In the Western Sierra de los Filabres a minimum cooling rate of 105°C Ma^{-1} is obtained, while in the Sierra Nevada this rate is 170°C Ma^{-1} and may have been much higher. The Nevado-Filábride Complex thus underwent cooling at a rate identical in magnitude to that estimated for the Alpujárride Complex [*Zeck et al.*, 1992] but between 7 and 10 Ma later than the time at which cooling in this overlying complex took place (19 Ma). It is concluded here that these high rates of cooling are most readily explained by tectonic denudation of the Nevado-Filábride Complex during the middle to late Miocene.

Kinematics

Mylonitic and ultramylonitic fabrics develop at temperatures of 300°C to 620°C [e.g., *Anderson*, 1988; *Koch et al.*, 1989; *Hurlow et al.*, 1991], whereas fission tracks in zircon anneal over a temperature range of approximately 390°C-170°C (preferred model of *Yamada et al.* [1995]). Therefore zircon fission track thermochronology spans the transition between ductile and brittle deformation. If cooling is accomplished by tectonic denudation, then the zircon ages can be said to "date" the cessation of ductile deformation within the contact zone between the hanging and footwall rocks. The end of ductile deformation occurred first in the Eastern Sierra de los Filabres before eventually finishing in the Western Sierra Nevada. The distribution and sense of hangingwall motion of the noncoaxial ductile deformation given in Figure 3 is consistent with this cooling history obtained in this study and thus with tectonic denudation.

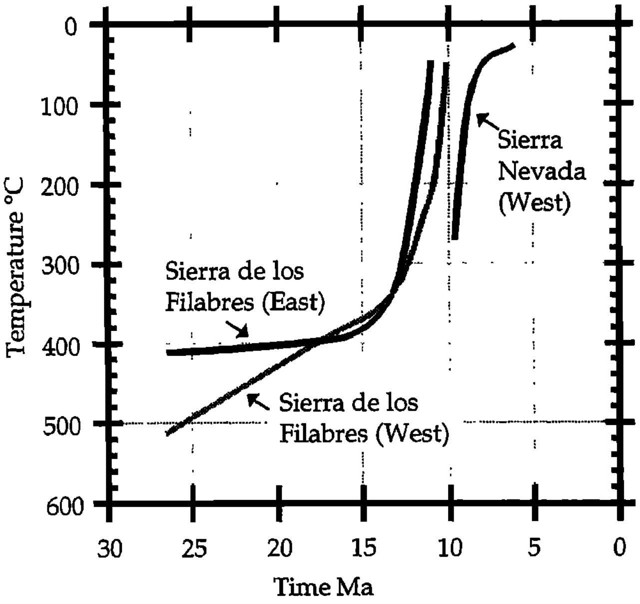

Figure 9. Summary plot showing representative cooling curves for each of the three transects for the uppermost structural levels within the Nevado-Filábride Complex obtained from published radiometric data [*De Jong*, 1991; *Monié et al.*, 1991] and the FT results presented here. (1) Sierra de los Filabres, (2) Western Sierra de los Filabres, and (3) Sierra Nevada.

The progressive increase in the noncoaxial ductile deformation from east to west, noted in the introduction, is also consistent with tectonic unroofing. This is because movement along the tectonic contact with the overlying Alpujárride Complex must have lasted longer in the west than in the east.

Calculating hangingwall slip rates in the manner of *John and Foster* [1993; see above] is complicated in this study by the distribution of samples. Because they are grouped in transects which run perpendicular to the apparent direction of hangingwall motion, there are effectively only three time-distance points. Simply taking the Sierra Nevada and eastern Sierra de los Filabres results yields a general estimate for the slip rate of 40 mm yr^{-1}. This is an order of magnitude greater than the rates estimated for the metamorphic core complexes of the western USA using apatite fission track analysis [*Foster et al.* 1991; *Foster and Gleadow*, 1993; *John and Foster*, 1993] but the rates are broadly similar to estimates given by *Wernicke* [1992]. Cooling in the Eastern Sierra de los Filabres was contemporaneous with cooling in the west of this range over geological timescales, suggesting mean slip rate obscures considerable local variation.

This cooling pattern seems best explained by tectonic unroofing accompanied by the dismembering of the overlying Alpujárride Complex, whose upper surface was unconstrained by this time. A first phase brings the region with heavy stipple in Figure 3 to the Earth's surface and leaves the region marked by moderate stipple at temperatures between 110°C and 180°C, suggesting that unroofing was episodic rather than continuous, with a pause during the late Serravallian (~11 Ma). Without an independent estimate of the palaeogeothermal gradient at this time, reconstruction of the geometry of the brittle detachment separating the Alpujárride and Nevado-Filábride Complexes is difficult. In the Sierra Nevada, *Johnson* [1995] obtained an estimate of 50°C km^{-1} for the early Tortonian, which if applicable to the western Sierra de los Filabres, places the detachment at between 2 and 3 km depth. The two closest apatite ages from groups 1 and 2 of the central transect (SP42 and SP48) are at a distance from one another of approximately 10 km, which yields minimum angles of dip on the detachment of between 11° and 17° in the late Serravallian. At this time the samples immediately below the detachment in the Sierra Nevada, indicated by the light stipple in Figure 3, were at temperatures of perhaps 300°C and a depth of 6 km.

Tertiary Tectonics in the Eastern Betic Cordillera

It has been established in the section on discussion and interpretation that the Miocene denudation of the Nevado-Filábride Complex has been achieved by tectonic unroofing or extension. What has yet to be established is the form that this extension took and the driving mechanism responsible for it. There is little unequivocal evidence for net crustal thinning within the eastern Betics during the Miocene, as is the case in the adjoining Alboran Sea to the south. Indeed, the present crustal thickness (40 km just to the north of the Sierra Nevada) and the existence of a lithospheric root to the orogen point, instead, to net thickening [*Marillier and St. Mueller*, 1985]. Thus extension within the upper crust must have acted coincidentally with lower crustal contraction.

It is our contention that the relationship between extension and contraction is a causal one, with the former resulting from the latter. A well-established mechanism for allowing lower crustal contraction to drive upper crustal extension is that of underplating of the crust during subduction of a lower plate [*Platt*, 1986;

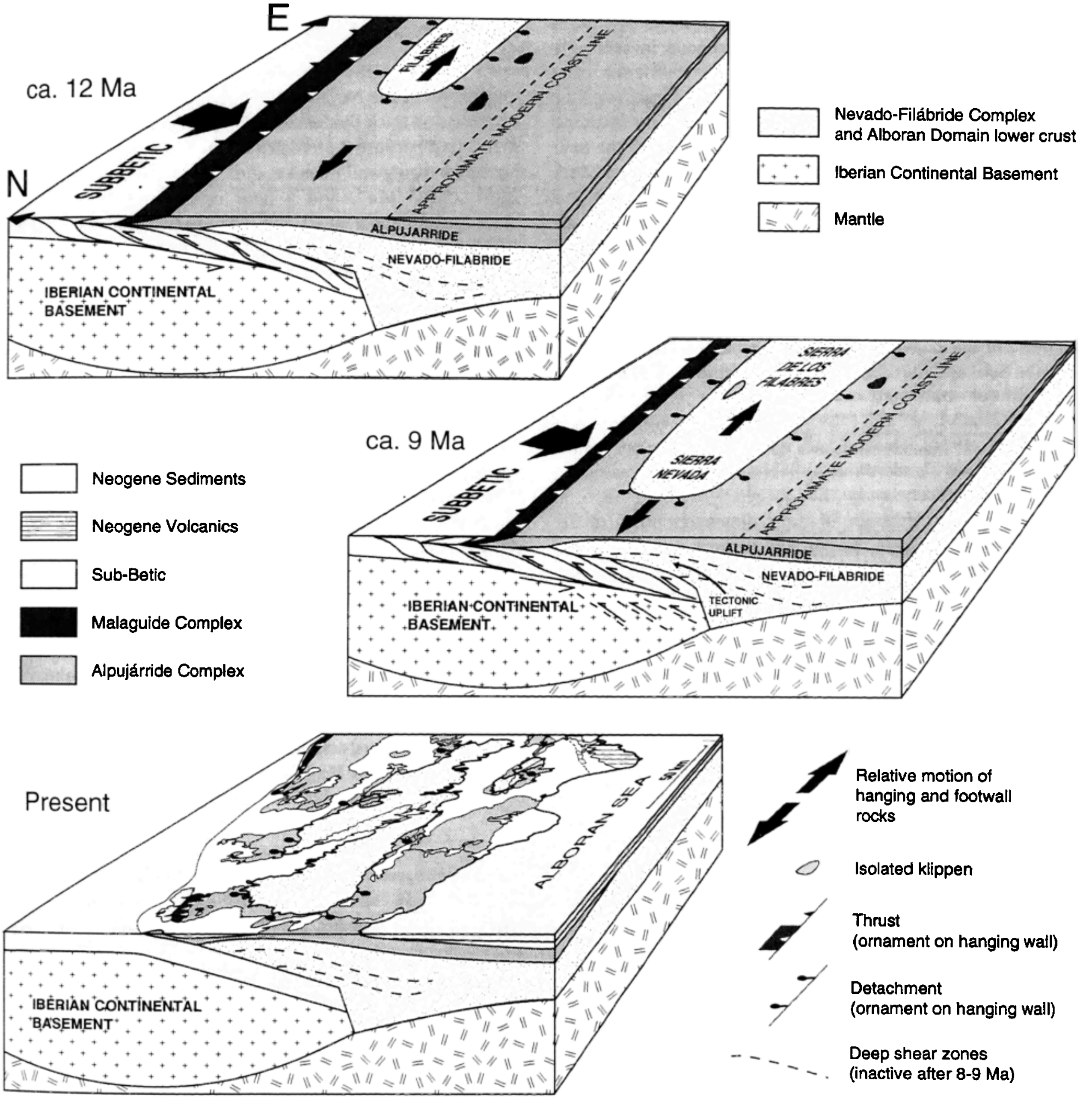

Figure 10. Cartoons illustrating the tectonic denudation of the Nevado-Filábride Complex during the middle-upper Miocene to present day. In this hypothesis, underthrusting of the Internal Zones by the Iberian basement caused contraction at depth, driving extension in the upper crust. Because convergence between the Internal Zones and Iberia was slightly oblique, as indicated by the broad arrow, extension was orogen parallel. Extension probably began during the early Miocene, since farther east of the study area there is evidence that the complex was unroofed by Langhian times [*Lonergan and Mange-Rajetzky*, 1994]. In the study area however it was not until the Serravallian (~12 Ma) that this complex was exposed. By approximately 9 Ma the Sierra Nevada in the west of the study area had been exposed, at which point extension ceased. The present-day disposition of the major geological units is also given to illustrate the relationship between the conseptual model and Figure 2.

Jamison and Beaumont, 1988]. However, there is no clear evidence for subduction below the Betic Cordilleras, since the Alboran Sea is an extensional basin whose northern margin possesses a half-graben morphology [*Comas et al.*, 1992].

A potential solution to this problem lies in considering relative plate motions and plate boundary changes in this region. While overthrusting of the Mesozoic passive margin of Iberia by crust of the Internal Zone "Alboran block" commenced in the early Tertiary [*Reicherter et al.*, 1994; *Lonergan*, 1993], the most important phase of orogenesis in terms of cooling that affected the Betic Cordillera occurred in the late Oligocene-early Miocene [*Zeck et al.*, 1989, 1992]. This phase is coincident with the final closure of the northern King's Trough-Azores Biscay Rise-North Spanish Trough-Pyrenees plate boundary to the north of the Iberian plate, which left the Azores-Gibraltar Fracture Zone to its south as the sole plate boundary separating Europe and Africa [*Srivastava et al.*, 1990; *Srivastava and Roest*, 1992].

The north-south convergence between Iberia and Africa that had preceded this change in plate boundaries continued after it. A component of this convergence was accommodated by shortening within the Sub- and Pre-Betic and by backthrusting of elements of the Sub-Betics southward over the Internal Zones in the east [*Frizon de Lamotte et al.*, 1989; *Banks and Warburton*, 1991; *Allerton et al.*, 1994]. This indicates that the Internal Zones of the eastern Betics were underthrust by Iberian continental basement after the late Oligocene-early Miocene phase of deformation. In this analysis, what remained of the sedimentary prism of the Mesozoic Iberian passive margin, and perhaps sections of the basement as well, underwent further shortening during the lower and middle Miocene. It is these sedimentary rocks and Iberian basement that were effectively accreted at depth to the Internal Zone wedge and were responsible for upper crustal extension, a hypothesis strengthened by the coincidence between the cessation of extension within the Betic Cordilleras and the change in relative Europe-Africa plate motions that occurred at 9-8 Ma during the early Tortonian. Thus, crustal thickening, convergence, and shortening were compensated by extension parallel to the orogen. This hypothesis is illustrated in cartoon form in Figure 10.

The orogen parallel extension suggests that Iberian underthrusting was oblique to the trend of the mountain belt. This is consistent with the clockwise rotation of thrust sheets in the Sub-Betic deduced from palaeomagnetic studies [*Platzman*, 1992]. It implies, however, that the amount of underthrusting of the Internal Zones increased toward the east. This motion appears to have been accommodated by the development of a series of sinistral strike-slip faults in the eastern Betics of which the Palomares is perhaps the best known (Figure 1). This fault system now juxtaposes thick (~40 km), "Meseta Type" crust to the west with thin (~20 km), "Cartagena Type" crust to the east (terms from *Larouzière et al.* [1988]), suggesting southerly motion of the Iberian basement to the west of this fault system and the carriage of the eastern Betics as a "piggyback" orogen.

Summary and Conclusions

In this study the role played by extension in the Miocene denudation of the Nevado-Filábride Complex has been examined using fission track thermochronology. Tectonic denudation can be recognized because it promotes a correlation between apparent FT age and hangingwall transport direction, rapid cooling typically at rates >50°C Ma^{-1}, and a poor correlation between sample elevation and apparent FT age. The results show that (1) cooling within this complex was rapid (105°C-200°C Ma^{-1}) and spatially related to the tectonic contact with the overlying Alpujárride Complex, (2) the rapid cooling in the study area to near surface temperatures occurred first in the east (Sierra de los Filabres) during the Serravallian (12±1 Ma) and was completed by the early Tortonian (9-8 Ma) in the west (Sierra Nevada), and no correlation exists between FT age and sample elevation. On the basis of these findings it is considered that the denudation of the Nevado-Filábride Complex can be best explained by tectonic means rather than by Earth surface processes.

In conjunction with other thermochronological, structural and sedimentological data and placed in the broader context of relative Africa-Iberia plate motions during the Tertiary, the following conclusions have been drawn: (1) Upper crustal extension is contemporaneous with lower crustal contraction within the eastern Internal Zones. (2) The driving mechanism for extension is thought to be shortening and accretion of the sedimentary prism of the paleo-Iberian passive margin to the overlying Internal Zone wedge during lower and middle Miocene underthrusting of the Iberian plate. (3) Extension in the Betic Cordilleras lasted much longer that previously thought, only coming to an end during the early Tortonian (9-8 Ma). (4) There is a causal link between the cessation of extension and a change in plate boundary conditions.

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References

Allerton, S., K. Reicherter, and J.P. Platt, A structural and palaeomagnetic study of a section through the eastern Subbetic, southern Spain, *J. Geol. Soc. London*, *151*, 659-668, 1994.

Anderson, J.L., Core complexes of the Mojave-Sonoran desert: Conditions of plutonism, mylonitisation, and decompression, *Metamorphism and Crustal Evolution in the Western United States*, Ruby vol. II, edited by W.G. Ernst, pp. 328-344, Englewood Cliffs, Prentice-Hall, 1988.

Andriessen, P.A.M., E.H. Hebeda, O.J. Simon, and R.H. Verschure, Tourmaline K-Ar ages compared to other radiometric dating systems in Alpine anatectic leucosomes and metamorphic rocks (Cyclades and southern Spain), *Chem. Geol.*, *91*, 33-48, 1991.

Argus, D.F., R.G. Gordon, C. DeMets, and S. Stein, Closure of the Africa, Europe, North America plate motion circuit and tectonics of the Gloria fault, *J. Geophys. Res.*, *94*, 5585-5602, 1989.

Bakker, H.E., K. De Jong, H. Helmers, and C. Biermann, The geodynamic evolution of the Internal Zone of the Betic Cordilleras (south-east Spain): A model based on structural analysis and geothermobarometry, *J. Metamorph. Geol.*, *7*, 359-381, 1989.

Baldwin, S. L., G.S. Lister, E.J. Hill, D.A. Foster, and I. McDougall, Thermochronologic constraints on the tectonic evolution of active metamorphic core complexes, d'Entrecasteaux Islands, Papua New Guinea, *Tectonics*, *12*, 611-628, 1993.

Banks, C.J., and J. Warburton, Mid-crustal detachment in the Betic system of southeast Spain. *Tectonophysics*, *191*, 275-289, 1991.

Block, L., and L.H. Royden, Core complex geometries and regional scale flow in the lower crust, *Tectonics*, *9*, 557-567, 1990.

Bradbury, H. J., and R.C. Nolen-Hoeksema, The

Lepontine Alps as an evolving metamorphic core complex during A-type subduction: Evidence from heat flow, mineral cooling ages, and tectonic modeling, *Tectonics*, *4*, 187-211, 1985.

Braga, J.C., and J.M. Martín, Neogene coralline-algal growth-forms and their palaeoenvironments in the Almanzora river valley (Almeria, S.E. Spain), *Palaeogeog., Palaeoclimatol., Palaeoecol.*, *67*, 285-303, 1988.

Brown, R.W., M.A. Summerfield, and A.J.W. Gleadow, Apatite fission track analysis: Its potential for the estimation of denudation rates and implications for models of long-term landscape development, *Process Models and Theoretical Geomorphology*, edited by M.J. Kirkby, pp. 23-53, John Wiley, Chichester, UK, 1994.

Carmignani, L., and R. Kligfield, Crustal extension in the northern Apennines: The transition from compression to extension in the Alpi Apuane core complex, *Tectonics*, *9*, 1275-1303, 1990.

Cliff, R.A., Isotopic dating in metamorphic belts, *J. Geol. Soc. London*, *142*, 97-110, 1985.

Comas, M. C., V. Garcia-Dueñas, and M.J. Jurado, Neogene Tectonic evolution of the Alboran Sea from MCS data, *GeoMar. Lett.*, *12*, 157-164, 1992.

Corrigan, J., Inversion of apatite fission track data for thermal history information, *J. of Geophys. Res.*, *96*, 10347-10360, 1991.

Davis, G. A., Rapid upward transport of mid-crustal mylonitic gneisses in the footwall of a Miocene detachment fault, Whipple Mountains, southeastern California. *Geol. Rundsch.*, *77*, 191-209, 1988.

De Jong, K., Tectono-metamorphic studies and radiometric dating in the Betic Cordilleras (S. E. Spain), Ph.D.thesis, 204 pp., Free Univ., Amsterdam, 1991.

De Jong, K., Comment on "Very high rates of cooling and uplift in the Alpine belt of the Betic Cordilleras, southern Spain". *Geology*, 20, 1052-1053, 1992.

De Jong, K., and H. E. Bakker, The Mulhacen and Alpujárride Complex in the eastern Sierra de los Filábres, SE Spain: Litho-stratigraphy, *Geol. Mijnbouw,*. *70*, 93-103, 1991.

Dewey, J.F., W.C. Pitman, W.B.F. Rayan, and J. Bonnin, Plate tectonics and the evolution of the Alpine system, *Geol. Soc. Am. Bull.*, *84*, 3137-3180, 1973.

Dewey, J. F., M.L. Helman. E. Turco, D.W.H. Hutton, and S.D. Knott, Kinematics of the western Mediterranean, *Alpine Tectonics*, edited by M.P. Coward and D. Dietrich, and R. G. Park, *Geol. Soc. Spec. Publ.*, *45*, 265-283, 1989.

Dokka, R.K., and S. H. Lingrey, Fission track evidence for a miocene cooling event, Whipple mountains, southern California, *Cenozoic Paleogeography of the Western United States: Pacific section*, edited by J. Armentrout et al., *Soc. of Econ. Paleontol. and Mineral. Paleogeog. symp.*, *3*, 141-145, 1979.

Dokka, R.K., M.J. Mahaffie, and A.W. Snoke, Thermochronological evidence of major tectonic denudation associated with detachment faulting, Northern Ruby Mountains - East Humbolt Range, Nevada, *Tectonics*, *5*, 995-1006, 1986.

Egeler, C. G., and O.J. Simon, Sur la tectonique de la Zone Betique, *Verh. K. Ned. Akad. Wet. Nat. XXV*, *3*, 1-90, 1969.

England, P., and P. Molnar, Surface uplift, uplift of rocks, and exhumation of rocks, *Geology*, *18*, 1173-1177, 1990.

Fitzgerald, P.G., and A.J.W. Gleadow, New approaches in fission track geochronology as a tectonic tool: Examples from the Transantarctic Mountains, *Nucl. Tracks Radiat. Meas.*, *17*, 351-357, 1990.

Fitzgerald, P. G., R. B. Sorkhabi, T. F. Redfield and E. Stump, Uplift and denudation of the central Alaska Range: A case study in the use of apatite fission track thermochronology to determine absolute uplift parameters, *J. Geophys. Res.*, *100*, 20175-20191, 1995.

Foster, D.A., D.S. Miller, and C.F. Miller, Tertiary extension in the Old Women Mountains area, California: Evidence from apatite fission track analysis, *Tectonics*, *10*, 875-886, 1991.

Foster, D.A., A.J.W. Gleadow, S.J. Reynolds, and P.G. Fitzgerald, Denudation of metamorphic core complexes and the reconstruction of the transition zone, west central Arizona: Constraints from apatite fission track thermochronology, *J. Geophys. Res.*, *98*, 2167-2185, 1993.

Frizon de Lamotte, D., J.-C. Guézou, and M.-A. Albertini, Deformation related to Miocene westward translation in the core of the Betic zone: Implications on the tectonic interpretation of the Betic orogen (Spain), *Geodin. Acta*, *3*, 267-281, 1989.

Galbraith, R.F., Statistical models for mixed ages, Paper presented at 7th International Workshop on Fission Track Thermochronology, Univ. of Pennsylvania., Philadelphia, July 13-17, 1992.

Galindo Zaldivar, J., Geometría de las deformacions Neógenas en Sierra Nevada (Cordilleras Béticas), *Monográfica Tierras del Sur, vol. 8*, 249 pp., Univ. de Granada, Granada, 1993.

Galindo Zaldivar, J., F. González Lodeiro, and A. Jabaloy Sánchez, Progressive extensional shear structures in a detachment contact in the western Sierra Nevada (Betic Cordilleras, Spain), *Geodin. Acta*, *3*, 73-85, 1989.

Galindo Zaldivar, J., F. Gonzalez Lodeiro, and A. Jabaloy Sánchez, Geometrá y cinemática de las deformaciones frágiles post-Aquitanieses en los materiales alpujárrides y su relación con el contacto Alpujárride/Nevado-Filábride, *Geogaceta*, *10*, 130-134, 1991.

Gallagher, K., and M. Sambridge, Genetic algorithms: A powerful method for large scale non-linear optimisation problems, *Comput. Geosci.*, *20*, 1229-1236, 1994.

Garcia-Dueñas, V., and J.M. Martinez-Martinez, Sobre el adelgazamiento Mioceno del Dominio Cortical de Alborán, el despegue extensional de Filábres (Béticas orientales), *Geogaceta*, *5*, 53-55, 1988.

Garcia-Dueñas, V., J.M. Martinez-Martinez, M. Orozco, and J.I. Soto, Plis-nappes, cisaillements syn- à post-metamorphiques et cisaillements ductiles-fragiles en ditension dans les Nevado-Filábrides (Cordillères Bétiques, Espagne), *C. R. Acad. Sci. Ser. 2*, *307*, 1389-1395, 1988.

Garcia-Dueñas, V., J.C. Balanyá, and J.M. Martinez-Martinez, Miocene extensional detachments in the outcropping basement of the northern Alboran basin (Betics) and their tectonic implications. *GeoMar. Lett.*, *12*, 88-95, 1992.

Garcia-Hernandez, M., A.C. Lopez-Garrido, P. Rivas , C. Sanz De Galdeano, and J.A. Vera, Mesozoic paleogeographic evolution of the External Zones of the Betic Cordillera, *Geol. Mijnbouw*, *59*, 155-168, 1980.

Gómez-Pugnaire, M.T., and J.M. Fernandez-Soler, High pressure metmorphism in metabasites from the Betic Cordilleras (SE Spain) and its evolution during the Alpine orogeny, *Contrib. Minerol. Petrol.*, *95*, 231-244, 1987.

González Lodeiro, F., J. Galindo Zaldivar, and A. Jabaloy Sánchez, Las deformaciones alpinas en los materiales Nevado-Filábrides. in *II Reunión de la Comisión de Tectónica Sociedad Geologíca de España*. 174 pp., Univ. de Granada, Granada, 1990.

Green, P.F., I. R. Duddy , A.J.W. Gleadow, P.R. Tingate, and G. M. Laslett, Thermal annealing of fission tracks in apatite, 1, A qualitative discription, *Chem. Geol.*, *59*, 237-253, 1986.

Green, P.F., The relationship between track shortening and fission track age reduction in apatite: Combined influences of inherent instability, annealing anisotropy, length bias and system calibration, *Earth Planet. Sci. Lett.*, *89*, 335-352, 1988.

Haq, B.U., J. Hardenbol, and P.R. Vail, Mesozoic and Cenozoic chronostratigraphy and cycles of sea level change, *Sea level changes - An Integrated Approach*, edited by B. E. Lidz, *SEPM Spec. Publ.*, *42*, 71-108, 1989.

Hurford, A.J., Cooling and uplift patterns in the Lepontine Alps South Central Switzerland and an age of vertical movement on the Insubric fault line, *Contrib. Mineral. Petrol.*, *93*, 413-427, 1986.

Hurford, A.J., and P.F. Green, A users' guide to fission track dating calibration, *Earth Planet. Sci. Lett.*, *59*, 343-354, 1982.

Hurford, A.J., M. Flisch, and E. Jäger, Unravelling the thermo-tectonic evolution of the Alps: A contribution from fission track analysis and mica dating. *Alpine Tectonics*, edited by M.P. Coward and D. Dietrich, and R. G. Park, *Geol. Soc. Spec. Publ.*, *45*, 369-398, 1989.

Hurlow, H.A., A.W. Snoke, and K.V. Hodges, Temperature and pressure of mylonitization in a Tertiary extensional shear zone, Ruby Mountains-East Humbolt Range, Nevada: Tectonic implications, *Geology*, *19*, 82-86, 1991.

Jabaloy Sánchez, A., La estructura de la región occidental de la Sierra de los Filábres (Cordilleras Béticas), in *Monográfica Tierras del Sur, vol. 9*, 200 pp., Univ. de Granada, Granada, 1993.

Jamieson, R.A., and C. Beaumont, Orogeny and metamorphism: A model for deformation and pressure-temperature-time paths with applications to the central and southern Appalachians, *Tectonics*, *7*, 417-445, 1988.

Jamieson, R.A., and C. Beaumont, Deformation and metamorphism in convergent orogens: A model for uplift and exhumation of metamorphic terrains, in Evolution of Metamorphic Belts, edited by J.S. Daly, R.A. Cliff, and B.W.D. Yardley, *Geol. Soc. Spec. Pub.*, *44*, pp. 117-129, 1989.

John, B.E., and D.A Foster, Structural and thermal constraints on the initiation angle of detachment faulting in the southern Basin and Range: The Chemehuevi Mountains case study, *Geol. Soc. Am. Bull.*, *105*, 1091-1108, 1993.

Johnson, C., Neogene tectonics in S.E. Spain: Constraints from fission track analysis, Ph.D. thesis, pp. 381, *Univ. of London*, 1995.

Jurado, M.J., and M.C. Comas, Well log interpretation and seismic character of the Cenozoic sequence in the northern Alboran Sea, *GeoMar. Lett*, *12*, 129-136, 1992.

Kampschuur, W., and H.E. Rondeel, The origin of the Betic Orogen, southern Spain, *Tectonophysics*, *27*, 39-56, 1975.

Koch, P.S., J.M. Christie, A. Ord, and R.P. George, Effect of water on the rheology of experimentally deformed quartzite, *J. Geophys. Res.*, *94*, 13975-13996, 1989.

Larouzière, F-D., J. Bolze, P. Bordet, J. Hernandez, C. Montenat, and P. Ott D'Estevou, The Betic segment of the lithospheric shear zone during the Late Miocene, *Tectonophysics*, *152*, 41-52, 1988.

Laslett, G.M., P.F. Green, I.R. Duddy, and A. J. W. Gleadow, Thermal annealing of fission tracks in apatite, 2, A quantitative discription, *Chem. Geol.*, *65*, 1-13, 1987.

Lee, J., and J. F. Sutter, Incremental 40Ar/39Ar thermochronology of mylonitic rocks from the Snake Range, Nevada, *Tectonics*, *10*, 77-100, 1991.

Lonergan, L., Timing and kinematics of deformation in the Malaguide Complex, Internal Zone of the Betic Cordillera, southeast Spain, *Tectonics*, 12, 460-476, 1993.

Lonergan, L., and M.A. Mange-Rajetzky, Evidence for Internal Zone unroofing from foreland basin sediments, Betic Cordillera, SE Spain, *J. Geol. Soc. London*, *151*, 515-529, 1994.

Marillier F., and St. Mueller, The Western Mediterranean region as an upper-mantle transition zone between two lithospheric plates, *Tectonophysics*, *118*, 113-130, 1985.

Martínez-Martínez, J. M., Evolución tectono-metamórfica del Complejo Nevado-Filábride en el sector de unión entre Sierra Nevada y Sierra de los Filabres, Cordilleras Béticas (España), *Cuad. Geol. Univ. Granada*, *13*, 1-198 , 1984.

Monié, P., J. Galindo-Zaldivar, F. Gonzalez Lodeiro, B. Goffé, and A. Jabaloy Sánchez, Ar-Ar geochronology of Alpine tectonism in the Betic Cordillerar (southern Spain). *J. Geol. Soc. London*, *148*, 289-297, 1991.

Nijhuis, H.J., Plurifacial alpine metamorphism in the south-eastern Sierra de los Filábres south of Lubrin, SE Spain, Ph.D. thesis, pp. 151, Univ. of Amsterdam, 1964.

Pacquet, J., Etude géologique de l'ouest de la province de Murcie (Espagne). *Mém. Soc. Géol. Fr.*, *48* (111), 1-270, 1969.

Platt, J.P., Dynamics of orogenic wedges and the uplift of high pressure metamorphic rocks, *Bull. Geol. Soc. Am.*, *97*, 1037-1053, 1986.

Platt, J. P., and J. H. Behrmann, Structures and fabrics in a crustal-scale shear zone, Betic Cordillera, SE Spain, *J. Struct. Geol.*, *8*, 15-33, 1986.

Platt, J.P., and R.L.M. Vissers, Extensional collapse of thickened continental lithosphere: A working hypothesis for the Alboran Sea and Gibraltar Arc, *Geology*, *17*, 540-543, 1989.

Platzman, E.S., Paleomagnetic rotations and the kinematics of the Gibraltar arc, *Geology*, *20*, 311-314, 1992.

Priem, H.N.A., N.A.I.M. Boelrijk, E.H. Hebeda, I.S. Oen, and R.H. Verschure, Isotopic age determinations on tourmaline granite-gneiss and a metagranite in the eastern Betic Cordilleras (southeastern Sierra de los Filabres), SE Spain, *Geol. Mijnbouw*, *45*, 184-187. 1979.

Puga, E., and A. Díaz de Frederico, Metamorfismo polifásico y deformaciones alpinas en el Complejo de Sierra Nevada, implicaciones geodinámicas. In. *Reunión sobre la geodinámica de las Cordilleras Béticas y del Mar Alborán*, pp. 79-111, Univ. de Granada, Granada, 1976.

Reicherter, K., T. Pletsch, W. Kuhnt, J. Manthey, G. Homeier, J. Wiedmann, and J. Thurow, Mid-Cretaceous paleogeography and paleoceanography of the Betic Seaway (Betic Cordillera, Spain), *Palaeogeog., Palaeoclimatol. Palaeoecol.*, *107*, 1-33, 1994.

Richards, S.M., J.E. Fryxell, and J.F. Sutter, Tertiary structure and thermal history of the Harquahala and Buckskin Mountains, west central Arizona: Implications for denudation by a major detachment fault system, *J. Geophys. Res.*, *95*, 19973-19987, 1990.

Rodríguez Fernández, J., and C. Sanz de Galdeano, Le Couloir des Alpujarras, in *Les Bassins Neogenes du Domaine Betique Oriental (Espagne)*, edited by C. Montenat, *Doc. et Trav. Instit. Geol. Albert-de-Lapparent*, *12*, 87-100, Paris, 1990.

Rodríguez Fernández, J., C. Sanz de Galdeano, and J. Fernández, Genesis and evolution of the Granada Basin (Betic Cordilleras, Spain), *Intermontane Basins: Geology and Resources*, edited by T. P. Thauasuthipitak and P. Ounchanum, Chiang-Mai Univ., Chiang-Mai, Thailand, 294-305, 1989.

Rondeel, H.E., and O.J. Simon, Betic Cordilleras, in *Mesozoic-Cenozoic Belts: Data for Orogenic Studies*, edited by A.M. Spencer, *Spec. Publ. Geol. Soc. London*, *4*, 23-35, 1974.

Rupple, C., L. Royden, and K.V. Hodges, Thermal modeling of extensional tectonics: Application to pressure-temperature-time histories of metamorphic rocks, *Tectonics*, *7*, 947-957, 1988 .

Sambridge, M.S., and W. Compston, Mixture modeling of multi-component data sets with application to ion-probe zircon ages, *Earth Planet. Sci. Lett.*, *128*, 373-390, 1994.

Sanz de Galdeano, C., and J. A. Vera, Stratigraphic record and Palaeogeographical context of the Neogene basins in the Betic Cordillera, Spain, *Basin Res.*, *4*, 157-165, 1992.

Soto, J.L., V. Garcia-Dueñas, and J. M. Martinez-Martinez, El valor de la deformación dúctil asimétrica en el ortogneis de Lubrín, Almeria (Manto de Bédar-Macael, Complejo Nevado-Filábride), *Geogaceta*, *7*, 92-94, 1990.

Spencer, J.E., Role of tectonic denudation in warping and uplift of low-angled normal faults, *Geology*, *12*, 95-98, 1984.

Srivastava, S.P., and W.R. Roest, Kings Trough: reactivated pseudo-fault of a propagating rift, *Geophys. J. Int.*, *108*, 143-150, 1992 .

Srivastava, S.P., W.R. Roest, L.C. Kovacs, G. Oakey, S. Lévesque, J. Verhoef, and R. Macnab, Motion of Iberia since the late Jurassic: Results from detailed aeromagnetic measurements in the Newfoundland Basin, *Tectonophysics*, *184*, 229-260, 1990.

Stüwe, K., L. White, and R. Brown, The influence of eroding topography on steady-state isotherms. Application to fission track analysis, *Earth Planet. Sci. Lett.*, *124*, 63-74, 1994.

Van de Beek, P., Tectonic evolution of continental rifts: Inferences from numerical modeling and fission track thermochronology, Ph.D. thesis, 232 pp., Free Univ. Amsterdam, 1995.

Vissers, R.L.M., A structural study of the central Sierra de los Filábrides (Betic Zone, SE Spain), with emphasis on deformational processes and their relation to the Alpine metamorphism, *GUA Pap of Geol.*, Ser. 1, *15*, 154 pp., Univ. Amsterdam, Amsterdam, 1981.

Weijermars, R., T.B. Roep, B. van den Eeckhout, G. Postma, and K. Kleverlaan, Uplift history of a Betic fold nappe inferred from Neogene-Quaternary sedimentation and tectonics (in the Sierra Alhamilla and Almeria, Sorbas, and Tabanas Basins of the Betic Cordillera, SE Spain), *Geol. Mijnbouw*, *64*, 397-411, 1985.

Wernicke, B., Cenozoic extensional tectonics of the U.S. Cordillera, in *The Cordilleran Orogen: Conterminous U.S.*, edited by B.C. Burchfiel, P.W Lipman, M.L. Zoback, *Geol. Soc. Am.*, *The Geology of North America*, *G-3*, 553-581, 1992

Wernicke, B., and G. A. Axen, On the role of isostasy in the evolution of normal fault systems. *Geology*, 16, 848-851. 1988.

Wheeler, J., and R.W.H. Butler, Criteria for identifying structures related to true crustal extension in orogens, *J. Struct. Geol.*, *16*, 1023-1028, 1994.

Yamada, R., T. Tagami, S. Nishimura, and H. Ito, Annealing kinetics of fission tracks in zircon: An experimental study, *Earth Planet. Sci. Lett.*, *122*, 249-258, 1995.

Zeck, H.P., F. Albat, B.T. Hansen, R.L. Torres-Roldán, A. Garciá-Casco, and A. Martín-Algarra, A 21±2 Ma age for the termination of the ductile Alpine deformation in the Internal Zone of the Betic Cordilleras, south Spain, *Tectonophysics*, *169*, 215-220, 1989.

Zeck, H.P , P. Monie, I.M. Villa, and B.T. Hansen, Very high cooling and uplift in the Alpine belt of the Betic Cordilleras, southern Spain, *Geology*, *20*, 79-82,1992.

Zevenhuizen,W.A., Quartz fabrics and recumbent folds in the Sierra de Los Filábres (SE Spain), *Geodin Acta*, *3*, 95-105, 1989.

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