

Title:

LITHOSPHERIC PROCESSES

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Abstract

We used geophysical, geochemical, and numerical modeling to study selected problems related to Earth's lithosphere. We interpreted seismic waves to better characterize the thickness and properties of the crust and lithosphere. In the southwestern U.S. and Tien Shan, crust of high elevation is dynamically supported above buoyant mantle. In California, mineral fabric in the mantle correlate with regional strain history. Although "plumes" of buoyant mantle may explain surface deformation and magmatism, our geochemical work does not support this mechanism for Iberia. Generation and ascent of magmas remains puzzling. Our work in Hawaii constrains the residence of magma beneath Hualalai to be a few hundred to about 1000 years. In the crust, heat drives fluid and mass transport. Numerical modeling yielded robust and accurate predictions of these processes. This work is important fundamental science, and applies to mitigation of volcanic and earthquake hazards, Test Ban Treaties, nuclear waste storage, environmental remediation, and hydrothermal energy.

Background and Research Objectives

The Earth's *lithosphere* is its outer, rocky shell, comprising the crust and uppermost mantle. Typically, the lithosphere is 30 km thick beneath ocean basins and 100-200 km thick beneath the interiors of continents, but may be much thinner beneath regions affected by orogenic or rifting processes. Because the crust was derived from the mantle by partial melting, its composition is fundamentally different from that of the mantle. Whereas the upper mantle is made up mainly of the mineral olivine (Mg, Fe-orthosilicate), the crust is made up of a variety of minerals that contain much higher Si, Al, alkali metals, and other elements that do not readily fit into the structure of olivine.

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Continental crust, in particular, is composed mainly of rocks high in Si, Na, K, Rb, U, and many other *incompatible* (with olivine and other mantle mineral) elements. Because the rocks comprising continental crust are relatively buoyant ($\sim 2.7\text{-}2.8\text{ g/cm}^3$) compared to the mantle ($>3\text{ g/cm}^3$), they tend not to be churned back into the mantle by plate-tectonic processes. Therefore, continental crust contains a geologic record of most of the history of the planet.

The lithosphere is divided into about a dozen large and many smaller tectonic *plates*, which move about relative to each other on the underlying *asthenosphere*. The asthenosphere is relatively weak because it contains a few tenths of a percent of partial melt, mainly an H_2O -bearing silicate melt. The movement of lithospheric plates in response to buoyancy forces is referred to a *plate tectonics*.

Despite decades of study, many fundamental questions regarding the origin, structure, and properties of the lithosphere remain. A major uncertainty regards even the formation of the continental lithosphere. The prevailing paradigm is that the continental crust was formed by amalgamation of island arcs during *subduction*, the process by which plates sink into the mantle and are overridden by adjacent plates. A problem with this hypothesis is that the crust of many island arcs, such as the Aleutian arc, is more mafic (i.e., higher in Mg and lower in Si) than typical "mature" continental crust. If continental crust is formed during subduction, then it must undergo additional and poorly understood melting processes to transform it to normal continental crust. Additionally, the composition and physical properties of continental crust differ between the margins and the interiors of continents. Along the western margin of South America (the Andean orogen), new crust is being formed and old crust modified by intrusion and volcanism related to subduction. Here, the crustal structure is clearly different compared to the interior of North America. But, do other tectonically active regions such as the Tien Shan of China have a similar crustal structure to that of the Andes or to the midcontinent U. S.?

Other uncertainties include the inheritance of preferred fabrics (lithologic and structural inhomogeneities) and their later profound effect on continental tectonics, the strength of the lithosphere, seismic anisotropy in the subcontinental mantle, the thickness and composition of the lower crust, mechanisms of deformation, and even the process of extraction of magmas from the lower lithosphere and asthenosphere.

The objectives of this project, then, were to acquire a better understanding of the structure and characteristics (including seismic p-wave velocities) of the continental crust in several key localities, and to constrain process of melting and fluid flow, in order to answer some of these fundamental problems.

Importance to LANL's Science and Technology Base and National R&D Needs

A better understanding of the lithosphere--its composition, physical properties, and thermal state--is very important to a number of national needs. Characterization of the thickness and composition of the crust, and of anisotropy in the crust and mantle, will enable a more precise calculation of travel times for seismic waves emanating from distant earthquakes and explosions. This information, of relevance to seismic hazard mitigation and to treaty verification, will permit a more precise location of the source of the seismic event.

Better numerical models of fluid flow, especially of hydrous fluids, and the accompanying transfer of heat and mass is critically important to predictions of the stability of high-level nuclear waste storage, to remediation of environmental sites, and to the potential for development of hydrothermal energy. It may also be relevant to the proposed sequestration of CO₂ in underground reservoirs.

Scientific Approach and Accomplishments

In this project we used a combination of geophysical, geochemical, and numerical modeling techniques to study selected problems to provide key information on lithospheric process. Geophysical techniques mainly involved study of earthquake waves to interrogate regions of crust and upper mantle. We selected three study areas, California, a region of the American Southwest from central Utah to west Texas, and the Tarim basin of China. Each of these regions had a specific rationale.

Seismic Anisotropy -- California. To investigate mantle seismic anisotropy, we took advantage of a vast amount of seismic data in California collected by several networks of seismometers. Mantle anisotropy is now widely used as an indicator of mantle flow and deformation. Experimental data and observations of mantle-derived xenoliths show that the anisotropy is the result of the aggregate orientation of the olivine within the mantle. Flow causes the olivine a-axes (fast axes) to align parallel to the flow direction, while compression causes the olivine b-axes (slow axes) to align along the compression direction. Seismic anisotropy can be inferred from travel time data. Anisotropic tomography uses travel time data from the P_n phase to solve for both lateral velocity variations and lateral anisotropy variations at the top of the mantle. The anisotropic tomography method was developed using data from the International Seismological Centre (ISC) data set for the western United States (Hearn, 1996).

More than 100,000 P_n arrivals were used in the inversion to image velocity and anisotropy lateral variations in the uppermost mantle beneath California and southwestern Nevada. The inversion was performed for a model with $1/8^\circ$ cells. Resolution tests show that 1% velocity and anisotropy variations can be imaged in areas with good ray coverage while the rms velocity and anisotropy error is less than .05 km/s. Low P_n velocities are imaged beneath Sierra Nevada, in the Cape Mendocino region, in the southern Great Basin, and along the Death Valley fault system; high P_n velocities were found beneath the Walker Lane Belt in western Nevada and most of the Great Valley (Fig. 1). High anisotropy was imaged along the coast of California, beneath Sierra Nevada, and beneath the Mojave block.

To better interpret our results, we have theoretically derived the variations of P-wave anisotropy for different orientations of olivine and compared them with the variations of S-wave anisotropy. The fast direction of both P- and S-wave anisotropy generally points toward the olivine a-axis. However, for some olivine orientations the fast P_n direction can be oriented perpendicular to the olivine b-axis. In this case, the fast direction of P_n can differ from that found by shear-wave splitting techniques. In addition, while shear-wave data are relatively insensitive to the b-axis orientation, travel-time data can be used to investigate the orientation of the olivine b-axis and detect regions of compression in the lithosphere.

The results obtained from the inversion of the California and southwestern Nevada data sets correspond well with the anisotropic tomography done using the ISC data set for the western United States as a whole and also to some of the shear-wave splitting directions that have been computed for the region. Moreover, the results show correlations with the tectonic regions of California. For example, anisotropy is oriented with its fast direction parallel to the San Andreas Fault, which suggests that simple-shear strain has oriented the olivine a-axis within the mantle there. In addition, the pattern of anisotropy shows major changes along the western margin of the Sierra Nevada Mountains where the fast direction changes to a northern direction, and the pattern also distinguishes the Coast Ranges north of San Francisco by its northeastern fast azimuth. This tomographic work has also given us a new picture of crust and mantle structure beneath northern California. New details of the low velocity region beneath the Sierra Nevada are imaged and the station delays show the dramatic thinning of the crust across the San Andreas Fault in central California.

Lithospheric structure -- Southwestern U.S. Despite decades of study, many fundamental processes affecting the geology of the southwestern United States remain poorly understood. This region, which includes the Basin and Range, Colorado Plateau, Rio Grande rift,

and Great Plains tectonic provinces, has undergone multiple episodes of compressional and extensional deformation.

The study area encompassed several Proterozoic crustal provinces, ranging in age from ~ 1.7 Ga to 1.0 Ga, that resulted from multiple episodes of crustal formation. In general, the crustal structure through the Southwest is only poorly constrained. Cenozoic extension across the region has nonuniformly thinned the lithosphere, allowing hotter asthenosphere to ascend closer to the surface (Livaccari and Perry, 1993), yet regions of significant extension, such as the axial grabens of the Rio Grande rift, do not necessarily correlate with regions of greatest upper mantle heat (Slack et al., 1996).

We fielded a passive seismic experiment, involving an array of approximately 70 broadband seismometers deployed along a main line extending 1200 km from West Texas to central Utah. The line extends from the Great Plains province at the southeast end across the Rio Grande rift to the Colorado Plateau at the northwest end. A second, and shorter, parallel line 350 km in length, crosses the central Rio Grande rift near Socorro, New Mexico. Our seismic studies of the Colorado Plateau in the western U. S. show that its high elevation (>1.8 km) is the result of dynamic support by a low-density mantle, not to a thickened root, and that the structure, density, and seismic properties of the crust vary by age provinces.

Crustal Structure -- Tarim Basin, China. Western China has some of the greatest subaerial topographic relief in the world. This tremendous vertical relief is a manifestation of the Indo-Asian collision and the consequent shortening, buckling, and thickening of the continental crust. A puzzling aspect of the crustal response is the nonuniformity of the deformation--strikingly illustrated by the topography. Within a distance of 1500 km west, southwest, and south of Urumqi lie the high mountains of the Tien Shan, Pamirs, Karakorum Range, and Kunlun Shan, the low-lying Tarim basin, and the high standing, but relatively flat, western Tibet. This study addresses the question *why the Tarim Basin has been relatively stable within this collage of deformation*. Secondary goals include investigation of regional propagation of seismic waves to WMQ (Urumqi, China), the closest broadband seismic station to the Chinese nuclear test site in Lop Nor, and a crustal comparison of the Tarim Basin, Tien Shan and, to the north, the Junggar Basin.

In this study we utilized regional broadband seismic data recorded at station WMQ to explore the crustal structure of the Tarim Basin and of the Tien Shan of Central Asia. Measurements of fundamental mode Rayleigh waves from pure Tarim Basin and Tien Shan paths we reanalyzed using a single station, multiple filtering technique to provide group velocity values for the two regions. Group velocity values were inverted to produce one-dimensional, shear wave velocity models for the Tarim Basin and Tien Shan (Fig. 2).

While group velocity measurements provide good resolution of shallow and middle crustal structure, a lack of adequate long period energy made it difficult to fully constrain the Moho depth or upper mantle structure using group velocity data alone. Thus, full waveform modeling is employed to further constrain and identify differences in Tarim Basin and Tien Shan crustal structures.

Group velocities for Tarim paths are lower than for Tien Shan paths in the 12 and 26 second period range, but group velocity curves from each region approach one another at longer periods. For periods sampling <20 km, the group velocities of the Tarim and Junggar Basin are at least 0.5 km/sec slower than for the Tien Shan. This variation is due to the presence of thick sediments deposited in that Tarim and Junggar basins. The nature of these sediments varies greatly within the respective basins. Typical group velocity curves for Junggar Basin paths are even lower than for Tarim Paths, but both Tarim and Junggar paths to WMQ generally have poor long period energy, making it difficult to confidently sample the deep crustal structure, the Moho depth, or upper mantle structure using group velocity data alone.

Results reveal significant variations in shallow (<20 km) velocity structure within the eastern Tarim Basin with a crustal thickness of about 50 to 55 km. Comparison of waveforms within the Tarim Basin suggest that either the Tarim crust thickens or the Tarim crustal velocity decreases to the east.

The Tarim velocity model is interpreted as a standard 42-km-thick "cratonic" crust overlain by about 9 km of metamorphosed sediments and 2 km of unconsolidated sediments. This crustal structure is consistent with the idea that the Tarim Basin remains relatively undeformed due to the presence of strong cratonic lithosphere. Several recent studies report that the Tien Shan crust also averages between 45 and 55-km-thick. Thus, the high elevation of the Tien Shan may be dynamically supported by low-density (hot) upper mantle. The question remains why the Moho depth of the Tarim Basin and Tien Shan appear to be similar despite the dramatic difference in average elevation.

Mantle Plumes -- Iberia. Mantle plumes, i.e., broad upwellings of (solid) mantle generally assumed to be rooted near the Earth's core/mantle boundary, are thought to drive large-scale volcanism and breakup of plates. Impingement of a plume on the base of the lithosphere has been proposed to explain volcanism and continental deformation in parts of the European plate. To test this idea, we chose a key area in the Iberian Peninsula to study. We measured Nd- and Sr-isotopic compositions and ^{40}Ar - ^{39}Ar dates of a suite of basaltic rocks from the Catalán volcanic field.

Basalts act as probes of the composition and physical state of the mantle, allowing lithospheric thicknesses to be inferred based on source characteristics of basalts. Furthermore, by using basalts of different ages, the evolution of mantle reservoirs beneath rifts can be tracked through time.

The Catalán volcanic zone of northeastern Spain encompasses dozens of Miocene to Quaternary alkaline basaltic flows and pyroclastic deposits in a region of less than 6000 km². The volcanic zone is located in an intraplate tectonic setting within the Catalán margin of Iberia adjacent to major extensional basins of the western Mediterranean (the València Trough and the Gulf of Lion). Alkaline basaltic volcanism is associated in this region with crustal extension, which began in Miocene time and continues today. Flows generally erupted along NW-SE-striking normal faults, describing a migration of volcanic and extensional activity from the coast towards the interior of the peninsula (e.g., Saula et al., 1994). The volcanic outcrops are typically grouped into three sub-zones, L'Empordà, La Selva and La Garrotxa, which correspond to extensional basins. Quaternary volcanism and extension are confined to La Garrotxa.

Two principal mechanisms have been proposed to explain alkaline basaltic volcanism in the Catalan volcanic zone: 1) extension-driven decompression (Martí et al., 1992), and 2) lithospheric thinning caused by impingement of a mantle plume on the base of the lithosphere (Hoernle et al., 1995; Neumann et al., in press). Differences in the Sr isotopic characteristics of basalts from NE Spain led to the inference that basaltic volcanism resulted from decompression melting associated with extension (Martí et al., 1992). An inferred progressive increase in the extension rate during the period of alkaline volcanism is thought to have favored interaction of two mantle sources (Martí et al., 1992). However, many authors have concluded that changes through time in basalt geochemistry and significant thermal uplift were caused by thinning of the deep lithosphere beneath northeastern Iberia (e.g., Morgan and Fernández, 1992; Watts and Torné, 1992; Janssen et al., 1993). In this case, changes in source characteristics of the basalts, from mantle lithospheric to asthenospheric signatures, might be due to progressive thinning of the lithosphere, as proposed for the Rio Grande rift (USA; e.g., Perry et al., 1988).

The question of whether lithospheric thinning has occurred beneath northeastern Spain was best addressed by studying the geochemistry of Miocene to Recent alkaline volcanic rocks in the Catalán volcanic zone. The composition of primitive basalts was used to obtain information about their source regions and the processes involved in magma generation (e.g., Asmerom and Edwards, 1995; Asmerom et al., 1994; Sun and McDonough, 1989).

It is widely accepted, for example, that alkali olivine basalts equilibrate at depths corresponding to pressures of 11 kb (Kushiro, 1968; Nicholls et al., 1971; Takahashi and Kushiro, 1983), a depth range of about 40-70 km. Gravity and geoid modeling show that present-day lithospheric thicknesses vary from about 65 km beneath the Catalan margin to about 50 km within the València Trough (Ayala et al., 1996). At least the Quaternary alkaline basalts in this region should come dominantly from the asthenospheric mantle.

We determined two marked spatial and temporal trends in the Nd-Sr isotopic results from the basalts of the Catalán volcanic zone. Miocene basalts are relatively depleted (i.e., have undergone prior melting events) compared to Quaternary basalts, which were derived from a separate mantle source. Miocene flows have ϵ_{Nd} values from +3.2 to +4.7 and $^{87}Sr/^{86}Sr$ ratios from 0.70345 to 0.70511, whereas Quaternary flows give ϵ_{Nd} values between +1.1 and +2.7 and $^{87}Sr/^{86}Sr$ ratios from 0.70362 to 0.70384. Flows from the eastern part of the volcanic zone are relatively depleted, whereas flow from the western part are more enriched. The relatively depleted isotopic signature of Miocene rocks suggests derivation from a depleted asthenospheric source. By contrast, the more enriched signature of the Quaternary basalts may derive from mixing of depleted asthenospheric mantle and enriched Proterozoic lithospheric mantle.

Using $^{40}Ar/^{39}Ar$ geochronology and Nd and Sr isotopic compositions of alkaline basalts from the Catalan Volcanic Zone, our work on isotopic compositions of mantle-derived lavas in eastern Spain confirms that lithosphere was thinned prior to 10 million years ago. Our Nd-Sr isotopic data indicate depleted asthenospheric sources, and therefore lithospheric thicknesses of <70 km, as early as 13 Ma, strongly suggesting tectonic or convective removal of mantle lithosphere by this time. New $^{40}Ar/^{39}Ar$ geochronology and Nd-Sr isotopic analyses of alkaline basalts from the Catalan Volcanic Zone (NE Spain) require reinterpretation of the Neogene geodynamic evolution of the western Mediterranean. Our geochronology indicates that asthenosphere-derived alkaline volcanism began as early as ~14 Ma, implying thinning of the lithosphere much earlier than previously thought. Therefore, lithospheric thinning beneath NE Spain is not a distinct tectonic or thermal event but is linked in time with formation of the Gulf of Lion, Valencia trough, and Provençal basin. We propose that mantle lithosphere was thinned during extension behind a retreating subduction zone (Fig. 3). The thermal anomaly associated with lithospheric thinning appears to be migrating into the Iberian Peninsula, producing seismicity, extension, volcanism, high heat flow, and elevated topography supported by buoyant mantle. No deep mantle plume is required, as has been hypothesized.

Mantle melting -- Hawaii.

Because geochemical and isotopic data from magmatic rocks are typically "inverted" to interpret the composition of the mantle, it is important to understand processes by which magmatic composition evolve in the upper crust. We studied selected lavas from Hawaii to understand how long magma resides in upper level chambers. Hawaii is one of the best natural laboratories for investigation of basalt genesis. Despite the resulting abundance of geochemical and geophysical information, there is continuing uncertainty about the origin and physicochemical evolution of Hawaiian magmas, as is amply demonstrated by recent U-series disequilibrium analyses. Data for Hawaiian basalts (Sims *et al.*, 1996; Sims *et al.*, 1999) suggest that both the trend and magnitude of covariations in ^{231}Pa - and ^{230}Th -enrichment with respect to U are qualitatively those expected of variable degrees of partial melting. On the other hand, ^{226}Ra , the half-life of which may be comparable to magmatic residence times (Volpe and Hammond, 1991; Bourdon *et al.*, 1994), could have been affected by processes other than melt generation and extraction (Hémond *et al.*, 1994; Volpe and Hammond, 1991; Condomines *et al.*, 1987). It is notable, therefore, that magnitudes of ^{230}Th - ^{226}Ra disequilibria in Hawaiian basalts have been variously attributed to melt extraction by porous flow (Sims *et al.*, 1996), to crustal contamination (Hémond *et al.*, 1994), and to dynamic melting processes (Cohen and O'Nions, 1993). We measured ^{238}U -series and ^{235}U -series nuclides in Hawaiian alkalic and tholeiitic basalts selected specifically for the purpose of constraining magma residence times from mineral-mineral and mineral-glass decay-series disequilibria, and evaluating the role of shallow-level contamination in the genesis of ^{238}U -series and ^{235}U -series disequilibrium and its implications for the chemical evolution of Hawaiian basalts. Our mineral analyses build a strong foundation for a study of the utility of ^{230}Th - ^{226}Ra and ultimately ^{235}U - ^{231}Pa for dating late Pleistocene to Holocene lava.

A priori estimates of the residence times of Hawaiian magmas are difficult to assess and, for Kilauea, the subject of debate, with estimates ranging from tens (Mangan, 1990) to thousands (Clague, 1996) of years. Some alkalic basalts of Hualalai entrain xenoliths of lower crustal/upper mantle origin, suggesting that the basalts ascended relatively rapidly from mantle depths. Despite this indication of rapid ascent, the composition of the host basalts is not that expected of primary mantle melts,

and thus requires some period of time for the primitive melts to evolve to the erupted compositions. These time scales should be resolvable using ^{226}Ra - ^{230}Th disequilibria in lava samples from the two volcanoes. The extent of similarity and difference in inferred residence times for the two types of basalt have important implications for models of melt transport beneath Hawaii, which, in turn, may lead to a better understanding of melt generation processes in other intraplate tectonic settings, including those of the continents.

We analysed Ra, Ba, Th, and U from mineral separates and a whole-rock sample from a xenolith entrained in the most recent (1800 A.D.) eruption of Hualalai Volcano (Fig. 4). All samples have disequilibrium between ^{230}Th and ^{226}Ra activities, and the three samples show a correlation between Ra/Ba and Th/Ba. The observed degree of disequilibrium between ^{230}Th and ^{226}Ra indicates that fractionation of Ra (and Ba) from Th occurred within the past 1500. Further, the slope of the best-fit line to the data is equivalent to an age of 420 ± 100 y. However, the data do not strictly define a single line (within analytical uncertainty), indicating either that the samples did not have the same initial Ra/Ba ratio or that the system has not remained closed since crystallization. Several explanations for the data array in terms of crystallization and/or open-system processes are geologically plausible. Crystallization of the xenolith from a tholeiitic magma only 420 y ago would require that tholeiitic magma crystallized beneath Hualalai more than 100 ka after the last eruption of magma of that composition. If previous interpretations of this type of xenolith as tholeiitic are however in error and they are in fact cumulates from alkalic magma, the measured disequilibria could represent fractionation of Ra from Th during crystallization; the failure of the analyses of separates to define a line could be due to crystallization of minerals from the same magma over a time period greater than 100 y. Alternatively, post-crystallization mobility of Ra and Ba, and potentially Th, could have occurred through interaction with a hydrous or CO_2 -rich fluid, possibly either magmatic or hydrothermal in origin. In any case, from study of short-lived U-series isotopes, we determined that holding times in shallow magma chambers are relatively short (few hundred years to c. 1000 years), and that contamination of melts by crustal wall rocks is not a major problem.

Hydrothermal Processes -- Numerical Studies. Hydrothermal processes in pyroclastic rocks are driven by two types of heat sources: (1) initial magmatic heat retained at time of deposition (primary heat), and (2) reheating by subsequent magmatic intrusions into the deposits (secondary heat).

We studied systems driven by both primary and secondary heat sources. At shallow depths these hydrothermal processes involve multiphase flow and can be quite complicated. We used numerical modeling techniques combined with field data on alteration histories and with paleomagnetic data to quantify the temporal and spatial characteristics of these systems. For systems driven by primary heat we focus on cooling ignimbrites. In order to build on previous modeling that assumes heat transport only by conduction and mass transport only by single-phase (vapor or liquid) flow, we fully coupled multiphase heat and mass transport. The numerical modeling work (Fig. 5) modified and applied the Los Alamos finite-element code, FEHM, which accounts for time-dependent, multiphase, multicomponent flow in complex 3-dimensional porous and fractured media with heat transport. This allowed us to study effects of water input to ignimbrites: rain infiltration on the top, overrun water bodies on the bottom, and phreatic infiltration on the lateral boundaries.

For systems driven by secondary heating, we focused on the shallow (200 m depth) intrusive system at Paiute Ridge, Nevada. This intrusive system contains basaltic dikes and sills that were emplaced into fallout tuffs and ignimbrites. Independent studies have produced a wealth of data on intrusion geometries, alteration histories, and paleomagnetic characteristics that can all be combined with our numerical modeling to produce a thorough understanding of the hydrothermal processes that resulted from these intrusions. An added benefit is that the intrusions and the altered host tuffs record a complete reversal of the geomagnetic field and the directional morphology of the reversal. Our numerical modeling, coupled with paleomagnetic sampling and analysis, defined the temporal history of the reversal and therefore ties directly with current efforts at modeling the geodynamo.

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Figure Captions

Fig. 1. Variations in P_n velocities in California and southwestern Nevada (preliminary results).

Fig. 2. An initial one-dimensional velocity model for the vicinity of the Lop Nor Test Facility based upon group velocity inversion. This model is interpreted as a standard 42-km thick "cratonic" crustal column overlain by about 9 km of metamorphosed sediments and 2 km of unconsolidated sediments. The Moho boundary is interpreted as a transition zone of increasing velocity ranging from a depth of 55 km to 60 km.

Fig. 3. Lithospheric model across the Catalán volcanic zone. A shift in the mantle source regions of basaltic rocks after ~12 Ma may record a significant translation of the zone of magma genesis and reactivation of rifting due to thermal thinning of the mantle lithosphere.

Fig. 4. Ra-Tb isochron diagram for Hualalai xenolith sample. A line with slope=1, representing radioactive equilibrium, is shown for reference. Pl = plagioclase, px = pyroxene, wr = whole rock. Size of symbols is equivalent to measurement error.

Fig. 5. Results from the conduction-only model for a 10-m wide, 1200°C basaltic dike in tuffaceous host rock. Profiles represent the thermal evolution for rock at various distances (in meters) from the dike/host rock contact. Profiles with negative distances represent positions within the dike. The horizontal lines enclose the temperature range (300-585°C) in which magnetic mineral lock in a thermoremanent magnetization direction parallel with the ambient field. These results are interpreted to predict that the first 10 m of the host rock