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Lateral Isotopic Discontinuity in the Lower Crust: An Example from Antarctica

RUTH I. KALAMARIDES, JONATHAN H. BERG, ROBERT A. HANK

The lower continental crust is one of the least known variables in the crust-mantle evolutionary equation. In order to study the nature and compositional heterogeneity of the lower crust, more than 20 inclusions of lower crustal granulites in volcanic rocks from the McMurdo Sound region of Antarctica were analyzed for strontium and oxygen isotopes. These inclusions were erupted from volcanic centers covering an area of 12,000 square kilometers. Along with results from analyses of major and trace elements, the isotopic data reveal a profound discontinuity in the composition and probably the age of the lower crust that coincides with the boundary between the Transantarctic Mountains and the Ross Embayment. Although this topographic boundary between East and West Antarctica is largely a Cenozoic development, which apparently reflects a simple subvertical faulting relationship due to crustal rifting, the isotopic differences in the lower crust across the boundary suggest that the current faulting and rifting may coincide with an older crustal suture, the age of which is uncertain.

THE OVERALL COMPOSITION AND the degree and scale of heterogeneity of the earth's continental lower crust are vital to our understanding of the tectonic and petrologic evolution of continents and the development of the earth's crust-mantle system (*1*). Direct studies of the lower crust are rare, and studies that assess regional variation of the lower crust are rarer still. Most studies that purport to document regional chemical variation of the lower crust have involved uplifted and exposed granulite terranes (*2, 3*), which may or may not be representative of the lower crust. We report isotopic results determined directly on lower crustal inclusions transported to the surface over a broad region by relatively young (Cenozoic) volcanic eruptions. Because of the wide areal distribution of these inclusions, they play a crucial role in delineating horizontal variation in the composition of the lower crust.

The eastern boundary or "front" of the Transantarctic Mountains (TM), whose peaks in places rise from sea level to elevations greater than 5000 m, marks the boundary between East and West Antarctica. The nature of this boundary has been debated for many years. Since the advent of plate tectonic theory, most interpretations have fallen into two groups: one is a convergent-margin scenario of subduction, collision, and suturing, and the other is a divergent-margin scenario of continental rifting and block faulting. The geologic-tectonic history of the McMurdo Sound–Royal Society Range area of Antarctica is summarized in Fig. 1. Uplift of the TM and subsidence of the Ross Sea have apparently occurred primarily from the late Cretaceous to the present (*4, 5*). On the basis of gravity studies, which indicate that the thickness, density, and compositional characteristics of the crust change dramatically at the boundary between the TM and the Ross Sea, Smithson (*6*) suggested that this boundary marks a crustal suture that formed by continental collision during the convergence associated with the Ross Orogeny in the early Paleozoic. He suggested that the TM crust was thickened by underplating the margin of East Antarctica with the crust of West Antarctica [see also (*7*)]. Others (*8–12*) have suggested that the TM front is a normal fault boundary separating the uplifted block of the TM from the recently rifted and subsided Ross Embayment (RE). In this latter case, there is no lateral discontinuity in the geology across the front, only a subvertical displacement along a fault or faults, with the thinner crust of the RE having been caused by listric faulting and stretching.

Cenozoic volcanics of the Erebus Volcanic Province (*8*) were erupted through older crust that is partially exposed in the uplifted TM and completely unexposed in the RE (Fig. 2). The lavas have brought to the surface an extensive suite of crustal inclusions (*13*). These inclusions are the only direct evidence of the nature of the lower crust; in the case of the RE crust, the inclusions represent virtually the only evidence for the nature of the upper crust as well. The most abundant inclusions in both the TM and RE are lower crustal two-pyroxene granulites. Although rare relict igneous textures have been found, the more common textures range from an annealed texture with 120° angles at grain-boundary junctions, to a classic mortar texture, to a highly sheared and granulated texture with bent cleavages and lamellae. The TM two-pyroxene granulites locally contain garnet or spinel and do not contain coexisting primary olivine and plagioclase, indicating that they originated at depths ranging from about 17 to 45 km (*14, 15*). The RE two-pyroxene granulites commonly contain coexisting primary olivine and plagioclase, and spinel is present only locally, consistent with a crustal thickness of no more than 20 to 25 km (*14, 15*). Quantitative thermobarometry based on mineral compositions largely confirms the above conclusions and indicates that the geothermal gradient in the upper crust is very high, ranging from 60° to 100°C per kilometer (*14*).

The studied samples cover as much as possible of the range of two-pyroxene–granulite compositions in order to evaluate the extent of compositional diversity. Those samples analyzed represent a wide range in mineralogy, and the selection of samples for analysis has been weighted in a manner that would probably overemphasize the similarities between the two suites.

Plots of Rb-Sr data for the granulite inclusions are shown in Fig. 3A. A previous Sr isotope study of the RE granulites (*16*) indicated an age for the xenoliths (158 million years) that was roughly contemporaneous with the Jurassic Ferrar magmatism evident at or near the surface in this region. However, data on a large number of inclusions were disregarded, and we believe that the determined age is fortuitous. Our data do not form an isochron for either the RE or TM granulites. Because the samples have a wide areal distribution and are derived from varying depths within the crust, the lack of an isochron is not unreasonable.

In the following discussion on Sr initial ratios (I_{Sr}), all such ratios were calculated from a selected age of 900 million years. This age is arbitrary, but is probably close to the minimum age for the TM granulites, which we assume to be represented by the maximum age of the overlying metamorphic rocks, that is, 675 to 950 million years (*17*).

Department of Geology, Northern Illinois University, DeKalb, IL 60115.

There is no reason to expect the RE and TM granulites to be the same age—other than their proximity—and, in fact, we suggest below that they probably have different ages. Most of the samples have such a low $^{87}Rb/^{86}Sr$ ratio that little error is introduced by errors in age assumptions.

A combined plot of I_{Sr} and $\delta^{18}O$ (Fig. 3B) reveals several points. First, with the exception of one RE and one TM inclusion, the two suites are isotopically distinct. The atypical RE inclusion falls within the TM grouping and away from the other RE inclusions regardless of geochemical, textural, or mineralogical criteria. The atypical TM inclusion is actually a biotite-rich ultramafic granulite and quite unlike most of the TM granulites. Second, neither suite shows any isotopic similarity to the Jurassic magmatic rocks. Third, all of the TM inclusions have high $\delta^{18}O$ values, some of which are unusually high. The TM suite also shows an unusual, albeit weak, negative correlation between $\delta^{18}O$ and I_{Sr}. Correlation between $\delta^{18}O$ and many major and trace elements (*18*) indicates that the $\delta^{18}O$ values are primary and they were not elevated by some type of fluid alteration. The I_{Sr} ratios of the TM suite overlap those of the Ordovician Granite Harbour Intrusives [0.707 to 0.719 (*19*)], but $\delta^{18}O$ data are unavailable for these granitoids; hence a direct comparison cannot be made. Nevertheless, if our assumption is correct that the TM lower crust is older than the upper crustal metamorphic rocks that are intruded by the Granite Harbour Intrusives, then the TM lower crust is also older than these intrusives. Therefore, a primary relationship is not to be expected unless the intrusives were formed by partial melting of the TM lower crust. A relationship between the RE inclusions and the Granite Harbour Intrusives appears to be precluded on the basis of the Sr isotope data.

Plots of $\delta^{18}O$ and I_{Sr} versus major and trace elements and element ratios (Fig. 4) further demonstrate that most samples of the TM and RE suites form separate groupings, with no indication of a transition from one to the other (*18*). Therefore, it seems unlikely that one could have been derived from the other or that one could have been modified to produce the other. Furthermore, relations between isotopes and major or trace elements are generally weak in the RE suite; these rocks either have multiple origins or were modified by multiple processes. However, relations within the TM suite are stronger and suggest a simpler history and origin. For the most part, the TM compositional trends are at high angles to theoretical mixing lines between the TM and RE groups.

Although 675 to 950 million years was given as a reasonable minimum age for the TM lower crust, the actual age could be significantly older. By using different ages to calculate different sets of I_{Sr} values, similar to the strategy used by Rudnick *et al.* (*20*), we found that the correlation coefficients for I_{Sr} versus various elements degenerated rapidly for ages younger than about 1500 to 2000 million years. In conducting this analysis we neglected the sample with a very high $^{87}Rb/^{86}Sr$ ratio (Fig. 3A) because it is biotite-rich and ultramafic and may have undergone relatively late Rb enrichment. Possibly supporting these age inferences is a model Sm-Nd age on clinopyroxene of 1800 to 2100 million years for closely associated lower crustal or upper mantle clinopyroxenite xenoliths from the TM (*21*). For ages

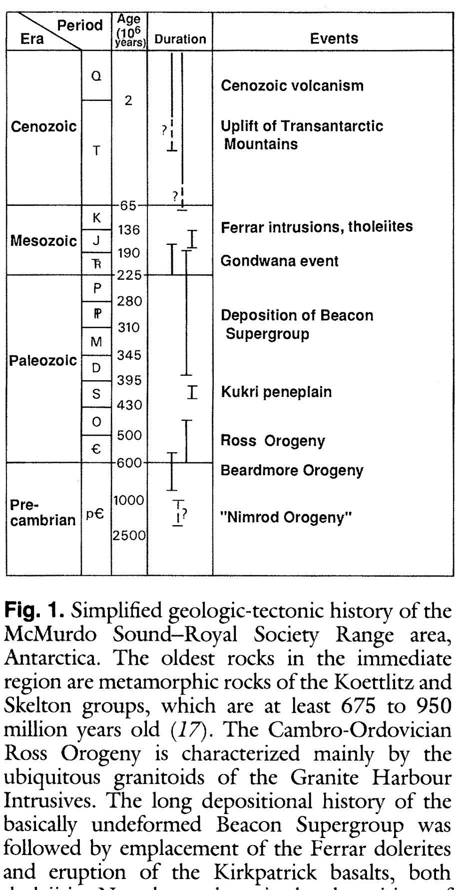

Fig. 1. Simplified geologic-tectonic history of the McMurdo Sound–Royal Society Range area, Antarctica. The oldest rocks in the immediate region are metamorphic rocks of the Koettlitz and Skelton groups, which are at least 675 to 950 million years old (*17*). The Cambro-Ordovician Ross Orogeny is characterized mainly by the ubiquitous granitoids of the Granite Harbour Intrusives. The long depositional history of the basically undeformed Beacon Supergroup was followed by emplacement of the Ferrar dolerites and eruption of the Kirkpatrick basalts, both tholeiitic. Not shown here is the deposition of sediments in the Ross Sea since at least the late Oligocene, but perhaps even the late Cretaceous, at least locally (*4*). The Cenozoic volcanism is represented by the alkaline volcanics of the Erebus Volcanic Province (*8*) and dates from at least the Miocene.

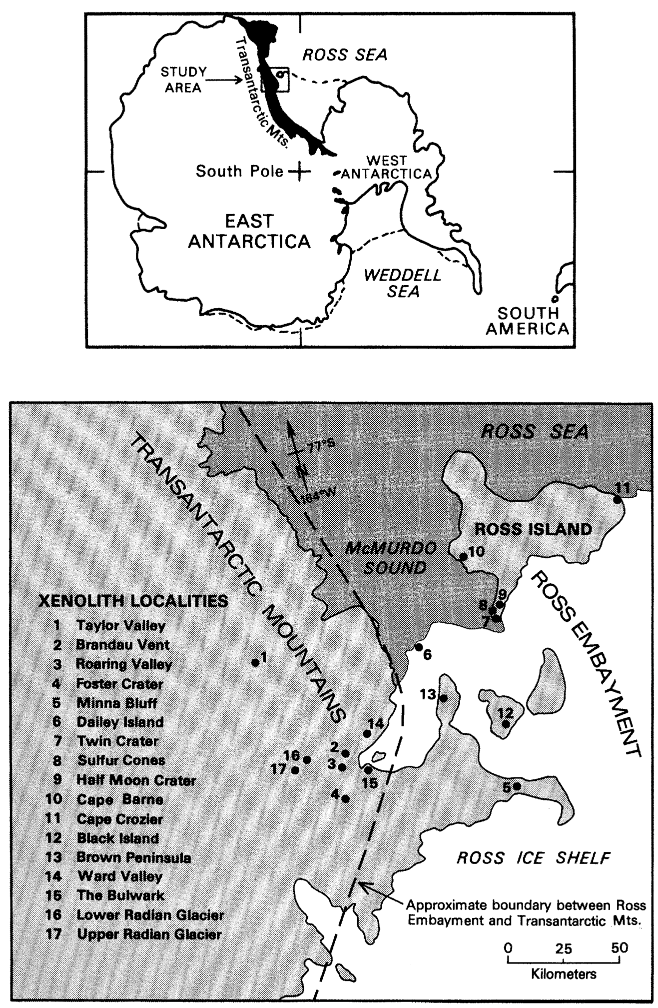

Fig. 2. (**Top**) Map of Antarctica showing study area. (**Bottom**) Generalized map of the McMurdo Sound–Royal Society Range region, showing the locations of the xenolith-bearing volcanic centers located on either side of the RE-TM boundary.

older than 900 million years, some of the RE granulites yield I_{Sr} ratios that are unreasonably low, unless they have suffered late Rb enrichment. Therefore, we suggest that the RE lower crust is possibly younger than the TM lower crust.

The dramatic isotopic, compositional, and possible age differences between the lower crustal two-pyroxene granulites from the RE and the TM indicate that they had very different origins. This finding suggests that the TM front marks an ancient crustal suture, the age of which cannot be precisely determined. Because no rocks with younger metamorphic ages have been found in the immediate region, the suture must be at least as old as the Ross Orogeny (early Paleozoic) and could perhaps be Precambrian. The nature of the TM front must change to the north of this region, because sutures with apparently younger ages cross the TM at moderate angles to the front in northern Victoria Land (*22*).

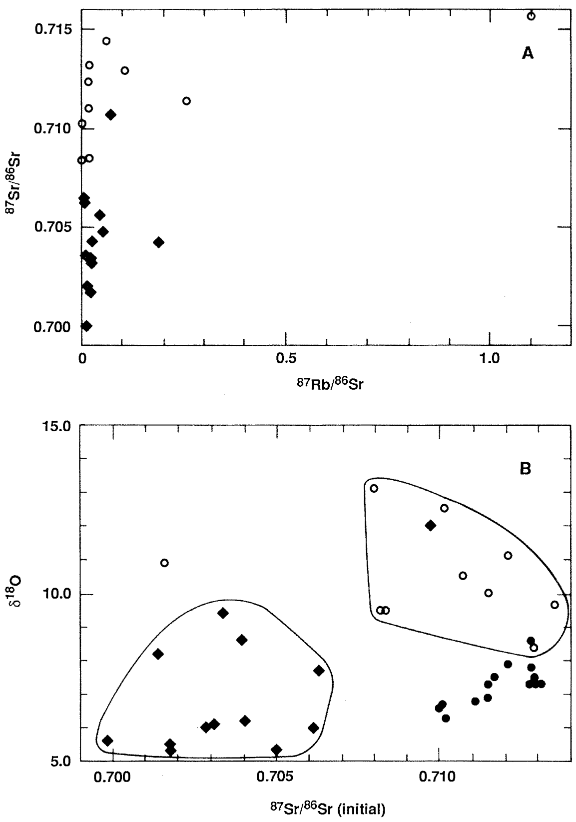

Fig. 3. (**A**) Plot of $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ for the lower crustal two-pyroxene granulite xenoliths. The Rb-Sr analyses are reported at the 95% confidence level of ±2 SD. For $^{87}Rb/^{86}Sr$, 2 SD = 0.0014; for $^{87}Sr/^{86}Sr$, 2 SD = 0.0009. (**B**) A combined plot of I_{Sr} (explanation of assumed age in text) and $\delta^{18}O$ shows two distinct groupings, both of which differ significantly from the Jurassic Ferrar magmatism (*23*). The host lavas from the RE have restricted isotopic values of $^{87}Sr/^{86}Sr$ = 0.7031 to 0.7034 (*16*), and we determined $\delta^{18}O$ values of +6.1 on both sides of the RE-TM boundary. The average of the mean deviations for all whole rock oxygen isotope analyses is ±0.2 per mil. The value of the silicate standard NBS-28, relative to standard mean ocean water, obtained by our laboratory is 9.6 ± 0.1 per mil. Symbols: closed diamonds, RE xenoliths (900 million years); open circles, TM xenoliths (900 million years); closed circles, Kirkpatrick basalts (Jurassic) (*23*).

Although the gross crustal structure of the region, the evidence for block faulting, and the extremely high geothermal gradient seemingly confirm the divergent-margin scenario for the origin of the TM and RE, a simple rift cannot explain the striking lateral discontinuity in the composition of the lower crust between the TM and the RE. Our isotopic and major- and trace-element data on granulite xenoliths from the lower crust support Smithson's (*6*) contention that the RE crust is fundamentally different from the TM crust. Although these data support the interpretation of a collisional suture between the RE and the TM, we suggest that this suture, rather than playing a direct role in the origin and uplift of the TM, has merely provided a convenient dislocation surface in the crust of this region for the rifting and divergence to follow.

The data presented show the lower crust to be heterogeneous. Furthermore, these results imply that over a given region lateral (intersite) compositional variation may likely exceed vertical (intrasite) variation. This finding could indicate that lateral accretion is more important than vertical accretion in the development of the lower crust. Additional regional studies of lower crustal inclusions may help constrain our knowledge of heterogeneity in the lower crust and of crustal evolution models.

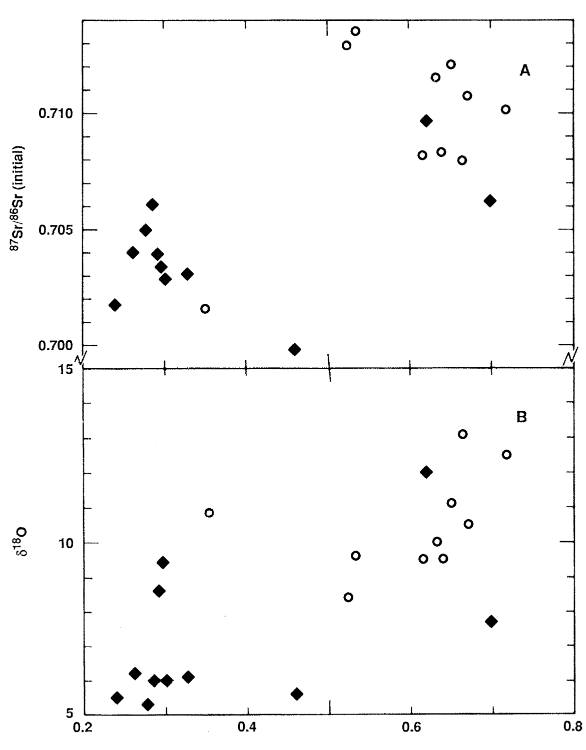

Fig. 4. (**A**) Plot of Fe/(Fe + Mg) versus I_{Sr} for the lower crustal xenoliths from either side of the RE-TM boundary. (**B**) Plot of Fe/(Fe + Mg) versus $\delta^{18}O$ for the same samples as in (A). Symbols: open circles, TM; closed diamonds, RE.

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Japanese Quail Can Learn Phonetic Categories

KEITH R. KLUENDER, RANDY L. DIEHL, PETER R. KILLEEN

Japanese quail (*Coturnix coturnix*) learned a category for syllable-initial [d] followed by a dozen different vowels. After learning to categorize syllables consisting of [d], [b], or [g] followed by four different vowels, quail correctly categorized syllables in which the same consonants preceded eight novel vowels. Acoustic analysis of the categorized syllables revealed no single feature or pattern of features that could support generalization, suggesting that the quail adopted a more complex mapping of stimuli into categories. These results challenge theories of speech sound classification that posit uniquely human capacities.

LACK OF INVARIANCE IN THE RELATION between linguistic categories and the acoustic signal poses a central problem in the study of speech perception. Acoustic information specifying a phonetic segment varies substantially depending on surrounding segments, and the ease with which humans identify speech sounds in the face of this variability has encouraged many researchers to invoke uniquely human perceptual processes that give rise to phonetic categories.

Some have hypothesized the existence of a system, biologically distinct from the general human auditory system, that automatically assigns acoustically different speech sounds to the same category on the basis of common underlying articulatory events (*1*). Others suggest that, although a separate system is not necessary, humans may have evolved special sensitivities or sensory discontinuities in the auditory system to facilitate classification of linguistically significant vocal tract output (*2*). Finally, a logical possibility is that phonetic categories have no natural basis in either audition or articulation. Perhaps the human listener learns to group physically diverse speech tokens together on purely functional grounds. By this view, learning that [di] and [du] have the same initial segment is much like learning that upper- and lowercase "A" belong to the same orthographic category.

Experiments with nonhuman animals are particularly informative in assessing whether uniquely human processes are required for speech categorization. In almost all previous research with nonhumans, monkeys or chinchillas were trained in tasks that generally involved simple classification or discrimination of synthetic speech sounds varying on a well-defined dimension (*3*). In contrast, the present study examines the ability of an avian species to categorize naturally produced speech stimuli that vary on several relevant acoustic dimensions (*4*). None of the above hypotheses predicts appropriate phonetic categorization by nonhumans, which obviously lack both specific adaptations for perceiving human speech and the extensive exposure to language required to learn phonetic categories on a purely functional basis.

Japanese quail (*Coturnix coturnix*) were used as subjects in a categorization experiment (*5*). Three females were taught to discriminate natural [d]-vowel-[s] syllables from [b]-vowel-[s] and [g]-vowel-[s] syllables (*6*). The phonetic segments [b], [d], and [g] are all voiced stop consonants that differ only in place of articulation. In particular, [d] was chosen because it represents "the paradigm case of lack of acoustic invariance" (*7*). Despite extensive examination of the signal, researchers have not found a reliable acoustic correlate of [d] (*8*).

Quail first learned to discriminate [dis], [dus], [dæs], and [das] from [bis], [bus], [bæs], [bas] and from [gis], [gus], [gæs], [gas] in training sessions consisting of 48 positive and 48 negative trials (*9*). During positive trials, birds received food reinforcement for pecking a single lighted key during repeated presentation of [d] syllables; during negative trials, they were required to refrain from pecking for 10 seconds for presentation of [b] and [g] syllables to be terminated (*10*).

After reaching asymptotic performance for the [i], [u], [æ], and [a] contexts (*11*), birds were tested on novel syllables containing the vowels [ɪ], [ʊ], [ɛ], and [ʌ]. Each of eight novel vowel tokens was presented three times in a test session, with every novel vowel appearing in one positive and one negative syllable. For example, during one test session, the novel tokens were [dɪs], [dʊs], [dɛs], [dʌs], [bɪs], [bɛs], [gʊs], and [gʌs]. Birds could not receive food on novel [d] stimuli, and they did not need to cease pecking for presentation of the novel [b] and [g] stimuli to terminate. The 24 nonreinforced novel stimulus trials were interspersed with 96 nonnovel stimulus trials presented with the same reinforcement contingencies in effect as those during training sessions. Eight test sessions were carried out 2 or 3 days apart, separated by normal nonnovel sessions (Fig. 1 and Table 1).

All three quail pecked significantly more often to novel stimuli beginning with [d] than to those beginning with [b] or [g]. Bird 716 did not peck at all to the [gʊs] syllable. Quail recognized novel [d] stimuli as belonging to the same category as the [d] stimuli on which they were trained (*12*).

It could be argued that the vowel environments [ɪ], [ʊ], [ɛ], and [ʌ] were not sufficiently novel, since they may be loosely characterized as short or lax versions of the vowels used in training. Demonstration of category formation requires that discriminably different items be classified equivalently by the perceiver. To address this point, two of the same birds were tested in a second experiment with four more novel vowel environments including the diphthongs [e^{y}], [o^{w}], [o^{y}], and retroflex [ɝ] (*13*). These vowels are acoustically quite distinct from the eight formerly used. Quail were trained for a few days on the test stimuli used in the first experiment. Critical test sessions were then carried out as before, except that trials with the four new test

K. R. Kluender and R. L. Diehl, Department of Psychology, University of Texas, Austin, TX 78712.
P. R. Killeen, Department of Psychology, Arizona State University, Tempe, AZ 85287.