Imaging crust and upper mantle beneath southern Africa: The southern Africa broadband seismic experiment

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The view from the rim of the Big Hole in Kimberley, South Africa, can only be described as spectacular (Figure 1). Both the size of that legendary kimberlite pipe and the prodigious amount of backbreaking labor that went into removing some 27 million tons of dirt to extract 14.5 million carats (2722 kilos) of diamonds are powerful testaments to the timeless allure of diamonds. The Big Hole, the largest hand-dug excavation in the world (820 m deep and 1.6 km across), lies at an improbable elevation above 1100 m (3500 ft) in the heart of the great Archean Kaapvaal craton of South Africa. The Kaapvaal, perforated with thousands of kimberlite pipes similar to that from which the Big Hole was dug, has a rich and colorful history of exhaustive and painstaking geologic study and exploration that the presence of exotic mantle samples and large quantities of gem quality diamonds inspires. In this classic Archean craton we launched the largest seismic investigation ever to probe the deep crust and upper mantle beneath the ancient continental nucleus (Figure 2).

The formation and long-term stability of the cratonic cores of continents remain among the more formidable puzzles in earth science. Cratons are the continental relicts from the early stages of Earth's differentiation and, through a little-understood process commonly referred to as "cratonization," they became fully stabilized by the end of the Archean, about 2.5 billion years ago. Archean cratons are unique relative to the younger continental masses accreted to them. First, they are associated worldwide with diamond formation. The reasons for this are related to the fact that cratons are underlain by thick (200+ km), cold, and highly melt-depleted mantle roots that are also Archean in age. These cold and very thick roots appear to be necessary ingredients for diamond stability in the mantle. Moreover, the thick roots appear to act as a barrier to magmatic upwelling from the deeper mantle so that only gas-rich, highly explosive magmas (kimberlite pipes) that originate at hundreds of km depth can bore through the thick cratonic root to the surface. These kimberlite magmas, which in southern Africa are mostly relatively young (~100 million years ago), carry with them mantle xenoliths, including diamonds, plucked from the wall rock at depths that can exceed 200 km and rafted to the surface. Tom Jordan adopted the term "tectosphere" in 1975 (*Reviews of Geophysics*) to describe this unique cratonic root and to distinguish it from the more usual lithospheric mantle beneath younger parts of the continent. He hypothesized that the tectospheric root remains attached to the cratonic crust through geologic time and does not mix with the rest of the mantle. The tectosphere appears to be buoyant, chemically distinct from the convecting mantle, and characterized by high strength and very low geothermal gradient. These properties serve to stabilize the tectosphere (and its diamonds) over billions of years of geologic time. There is no evidence in the geologic record that the conditions or processes that produced those continental cores and the deep root structures associated with them have been duplicated since Archean time. A second and more puzzling aspect of the cratons of southern Africa is that they tend to be characterized by crust that is both thinner and probably less mafic than that of post-Archean terranes. We will return later to the significance of that observation.

Figure 1. The Big Hole in Kimberley, South Africa. Abandoned since 1914 and now mostly filled with water, the Big Hole is the world's most famous diamond-mining locality and the source of much of Cecil Rhodes' fortune. Today diamond mining in Kimberley is confined largely to relatively small-scale underground and secondary recovery operations.

The Kaapvaal Project. Nowadays, it is common for large-scale seismic projects to be integrated into a much larger interdisciplinary research effort. In the present case, the southern Africa seismic experiment was a centerpiece of the broad-based multidisciplinary and multinational Kaapvaal Project. The project was aimed directly at the great unresolved problems of early continental evolution: What is the deep structure and the processes of formation of the ancient continental cratons and what accounts for the remarkable longevity of tectospheric mantle roots in an actively convecting upper mantle? Southern Africa is in many ways a "type locality" for probing these questions, a preeminent natural laboratory of early continental formation and evolution. It has the world's greatest concentration of relatively young kimberlite pipes by which an astonishing trove of crustal and mantle xenoliths have been carried to the surface. These xenoliths, moreover, are the most extensively studied of any in the world. From those studies we confirm that the cratonic tectosphere is geochemically depleted (by which we mean a large amount of partial melt has been removed) and intrinsically less dense than the rest of the (mobile) mantle and that it has a low geothermal gradient to depths in excess of 200 km. Radiometric dating shows, moreover, that the ages of mantle xenoliths erupted through the Kaapvaal are similar to those of the overlying crust over the entire 200+ depth range from which the xenoliths are derived, indicating that the mantle keel has been thermally and chemically stable for at least three billion years.

The Kaapvaal Project, which in many critical respects is a prototype for USArray both in scope and in all its multidisciplinary and multi-institutional modes (see Metlzer's companion paper on Earthscope/USArray in this issue), was many years in the making. Formal planning began 24 April 1995, when approximately 60 geoscientists from southern Africa and the United States gathered at the University of Capetown in the shadow of Table Mountain for the first Kaapvaal workshop. The workshop began almost a year to the day after the first democratic elections in South Africa and marked an important milestone in the re-emergence of

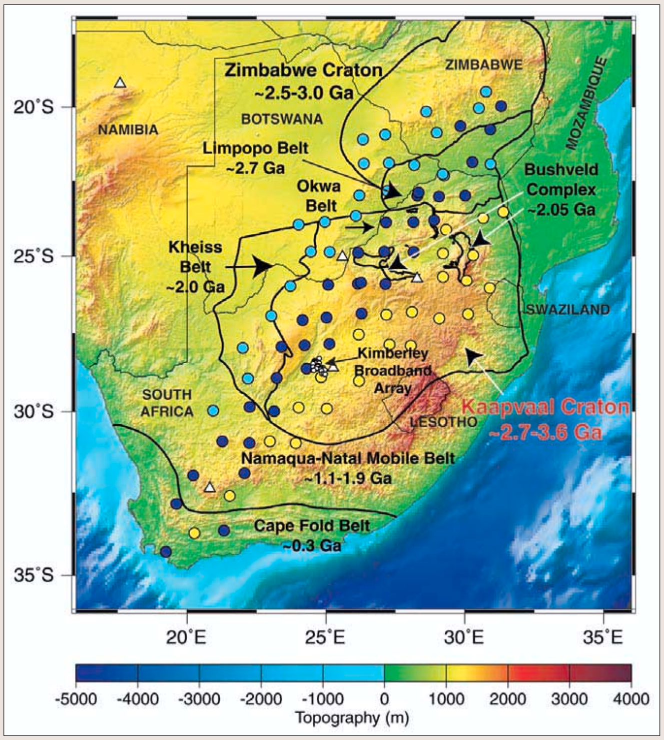

Figure 2. Map of seismic station locations (filled circles and white triangles), color-coded topography, and principal geologic provinces for the southern Africa seismic experiment. Fifty-four broadband (REFTEK/STS-2) stations were installed in April 1997, in South Africa, Botswana, and Zimbabwe and operated until July 1999. Colors denote different one-year deployments. The array covered age provinces spanning more than 3 billion years in three countries and measured some 1800 × 600 km at its greatest extent. It extended from the Cape Fold Belt of southernmost Africa, through the Namaqua-Natal mobile belt, a zone of Proterozoic plate convergence, and into the diamond-bearing region of the undisturbed southern Archean Kaapvaal craton. From there the array trended northeast through the great Bushveld layered complex that intruded into and disrupted the Kaapvaal craton 2 billion years ago, across the Limpopo Belt (the late Archean collisional zone between Zimbabwe and Kaapvaal cratons) and into the Zimbabwe craton. West to east, the array extended from the famously rich diamondiferous provinces of Botswana to the nondiamondiferous Barberton terrane on the east, the ancient (3.6 billion years old) core of the craton and where is found the type locality of the ultramafic komatiitic lava characteristic of the Archean.

South African geoscience to the international fold. Participating in the workshop were geologists, petrologists, geochemists, and geophysicists from both academia and the mineral exploration industry. The U.S. contingent consisted of Carnegie Institution and MIT. Among the numerous participants from academic institutions in southern Africa, the majority came from the University of Capetown (UCT) and the University of the Witwatersrand (WITS) in Johannesburg. Among the industry participants, those from giant Anglo-American/de Beers Corporation were a driving influence in shaping the scope of the project. As the project developed, both academic and industry involvement expanded to include active groups from both Zimbabwe and Botswana. A complete list of participants in the seismic experiment can be found in the Kaapvaal Web site at *www.ciw.edu/kaapvaal*.

Southern Africa Seismic Experiment. Readers of *TLE* are, of course, quite familiar with the fact that seismic reflection is an effective tool for exploring the shallow crust in both two and three dimensions. They are probably also familiar with the fact that it is a much tougher problem to probe the deep crust and upper mantle at anything approaching "geologically meaningful" resolution. In fact, until the development in the last decade of portable digital broadband seismic systems with continuous recording capabilities and accurate absolute timing capabilities (see companion papers by Jackson and by Owens and Fowler in this issue), high-resolution 3D imaging of the continental mantle was essentially beyond the reach of seismology. Shallow crustal 3D reflection seismology typically relies on thousands of closely spaced high-frequency sensors to record explosions, vibrators, or air guns all operating within a concentrated time window. Portable broadband seismology, on the other hand, relies on relatively few (50+ instruments is a major experiment), highly versatile, stand-alone seismic systems with very wide bandwidth capable of recording continuously for years. The seismic sources for broadband experiments are earthquakes of all kinds, from nearby local events to so-called teleseismic events with epicentral distances >27°. That means we deploy our instruments for considerable periods of time, typically 1-2 years, and wait for earthquake data to accumulate. In broadband seismology all three components of ground motion are recorded and the systems, like those of global seismic monitoring stations, are capable of observing virtually the whole of the radiated earthquake spectrum. This broadband capability, coupled with the ability to record for years at a stretch while maintaining all the while a GPS absolute time base, now makes it possible to image the deep structure of the continents. A burgeoning pool of broadband portable seismic instrumentation acquired by Incorporated Research Institutions for Seismology (IRIS) and (increasingly) by individual institutions has opened a wide range of formerly inaccessible seismic studies. Among the most obvious of these was a probe of the anatomy of Archean cratons—the Kaapvaal Project.

Figure 3. Some standard hazards of field work in Africa. A leopard's lair (left) near one of the stations in Botswana proved highly effective at discouraging vandalism. An irritated young bull elephant on the road in Zimbabwe (right). These lone bulls, driven from the herd by more dominant males and forced into a solitary existence, are commonly in a bad mood.

With the support of NSF and both industry and academic partners in southern Africa, the first deployments for the seismic experiment were undertaken in April 1997, exactly two years after the first planning workshop. The initial station deployment was preceded, however, by six months of intense effort to locate secure sites and to construct the vaults and housing for the broadband instruments. The search for quiet sites across southern Africa was spearheaded by Rod Green, a former professor at the University of the Witwatersrand (WITS) in Johannesburg and equally at home advising seismology students, sleeping under a truck in the bush, or dismantling the temperamental microelectronics of broadband feedback seismometers. Such diverse expertise is essential in Africa, where more than the usual hazards await the field seismologist (Figure 3). Seismograph systems were installed on Afrikaans (and a few English) farms, public and private game parks, native communal lands and exploration company camps across a swath of South Africa, Zimbabwe, and Botswana that ultimately came to encompass nearly 1 million km^2 in the two-year deployment (Figure 2). A major

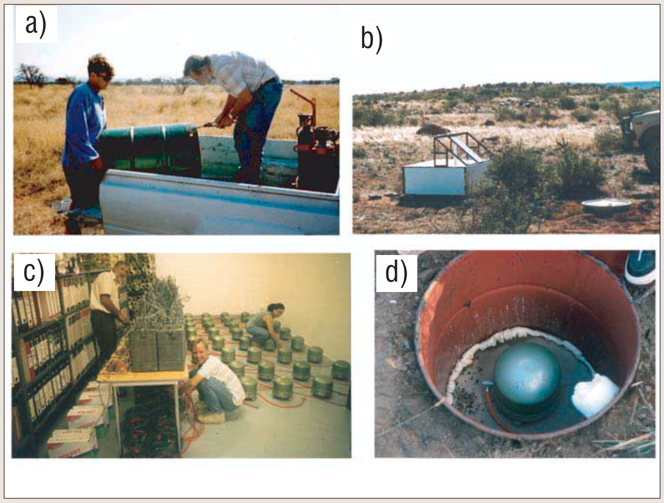

Figure 4. *(a) Rod Green torching off the bottom of a perfectly good 55 gallon drum in preparation for turning it into a seismic vault. (b) A prepared site ready for installation. The drum, the top of which is seen at the right, is installed on bedrock and when capped and covered with a foot or so of dirt will be an effective constant temperature vault for the sensor. The sheet metal housing for the recording electronics is internally mounted to a concrete base to discourage vandalism. (c) Preparation for field installation includes a comprehensive "huddle" test where all of the equipment is removed from shipping containers and operated for a period of one to two days to assure that it has survived the journey. This huddle test was carried out in the Green's Geophysics enclave in the de Beers offices in Kimberley, South Africa. The Dairy Farm, at which the de Beers Geology Division is headquartered, served as the logistical center of operations for the two-year seismic experiment. de Beers shouldered much of the burden of hosting the experiment as well as providing massive logistical support for field operations and shop facilities for construction of the station hardware. (d) Setting up the STS-2 broadband sensor in the drum vault. Once the sensor is oriented correctly (with north set to true north, not magnetic north, within 1-2°) and leveled, a close-fitting styrofoam cover is placed over it to reduce the effects of thermal convection in the vault.*

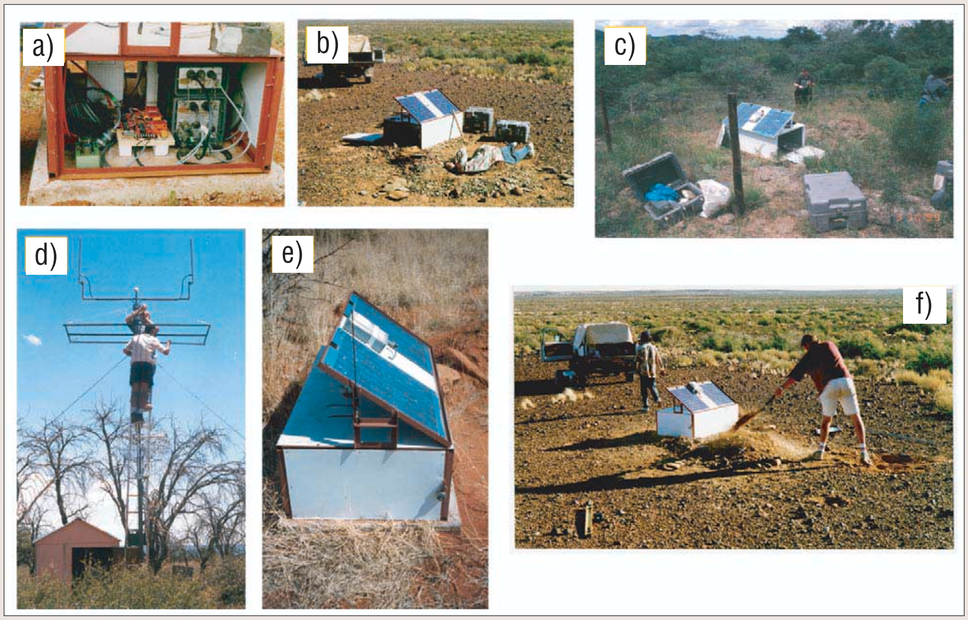

Figure 5. *(a) Electronics inside the doghouse. Datalogger and disk unit are on right, connector board for power is in the middle, broadband seismometer control box is on left, and batteries are in back. (b) Orienting, leveling, and connecting the sensor. (c) A site in Zimbabwe being fenced to prevent range cattle from trampling the station. (d) Green preparing an antenna for the telemetered array around Kimberley. (e) An operational telemetered station. (f) A completed station site.*

enhancement to the project was the inclusion in the last six months of the experiment of a high-density PASSCAL broadband telemetered array (31 stations in an area 60 × 40 km^2 indicated on Figure 2) that we installed in the vicinity of Kimberley, South Africa.

The sheer scale of the southern Africa deployment required the establishment of four more or less independent servicing centers—in Capetown (UCT), Kimberley (de Beers, Geology Department headquarters at the Dairy Farm), Johannesburg (WITS) in South Africa, and Masvingo (Rio Tinto Zimbabwe and the University of Zimbabwe) in Zimbabwe. In addition, station deployment and servicing in Botswana included the participation of the Botswana Geological Survey in Gaborone. With the exception of Kimberley, which functioned as headquarters for the experiment and where logistics and manpower were provided entirely by de Beers Geology Department, the servicing centers involved a partnership between academic participants (who provided the field crews) and industry (who provided vehicle and other logistical support). A vital element of the whole experiment was the support and active participation of African students. Several PhD and MSc students and a large number of honors students from South Africa, Zimbabwe, and Botswana have either completed or are currently engaged in project research. The strengthening of earth sciences in southern Africa has been a major objective of the multinational study.

An array of 55 portable broadband REFTEK/STS-2 seismic stations was deployed from April 1997 to July 1999 on an approximately 100-km grid along a NNE-SSW transect 1800 km long by about 600 km wide in southern Africa (Figure 2). Approximately half the stations were redeployed to new sites in April/May 1998 for a total of 82 stations. The station configuration shown in Figure 2, outlined during the course of the first workshop and refined in subsequent strategy sessions, assures coverage of critical regions both within and outside the boundaries of the craton. Station grid density of about 100 km was designed both to sample the geologic terranes of interest and to optimize resolution of P and S velocity structure of the deep craton at depths between 100 and 500 km. In addition, the 100-km station spacing is sufficient (barely) to map discontinuity and anisotropy structures of crust and mantle at scales significantly smaller than the terranes being studied. A significant portion of the region covered by seismic stations, both on and off craton, is perforated by an abundance of xenolith-bearing kimberlite pipes. The compositions of these mantle samples provide a critical yardstick for interpreting the results of the seismic analysis.

The better portable broadband installation does not differ significantly in functional capability from a state-of-the-art global seismic station and because of its placement in very remote locations is commonly superior in performance.

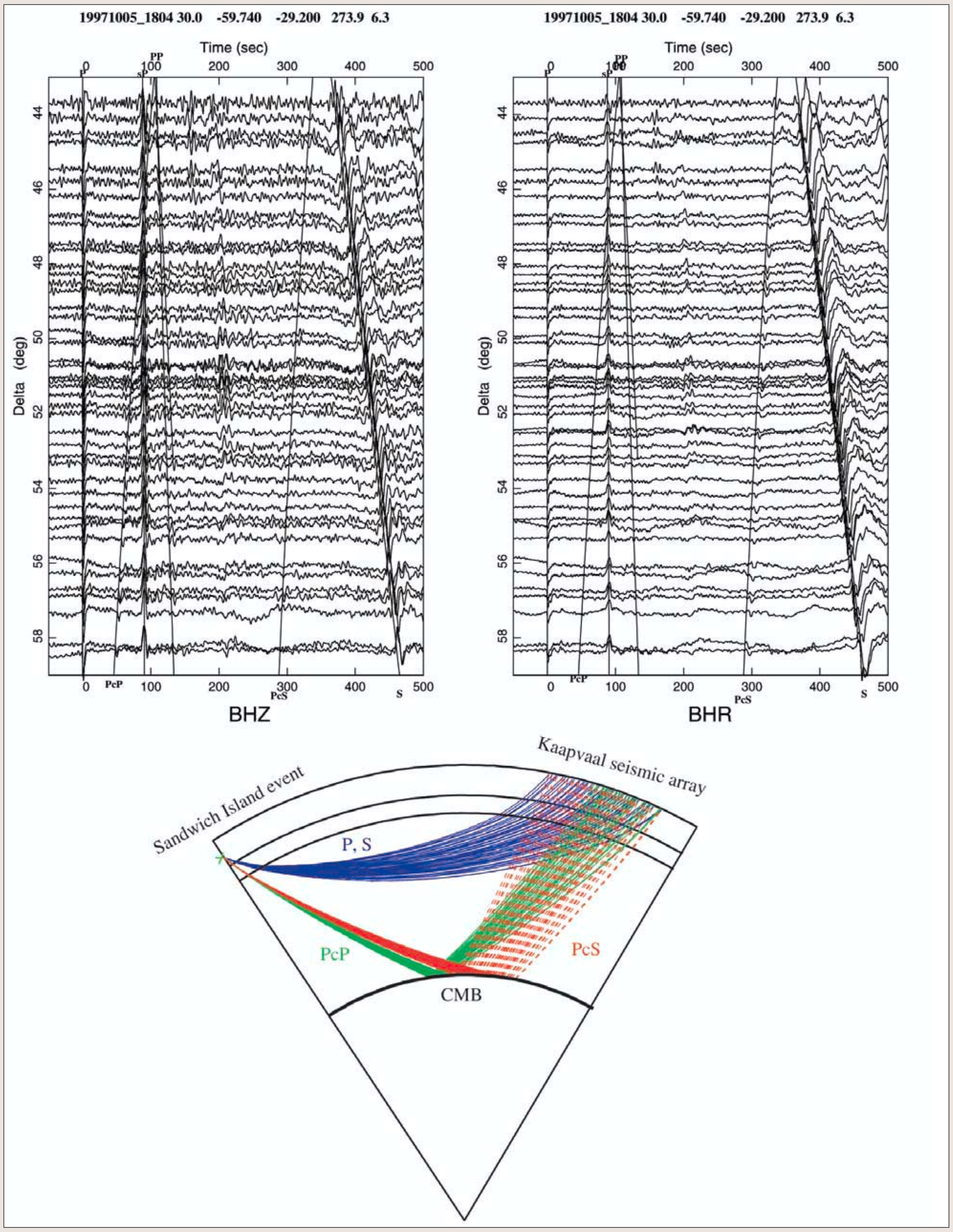

Figure 6. *Ground displacement seismograms across the southern Africa array for an intermediate depth event in the South Sandwich Islands (courtesy of Fenglin Niu, Rice University). The upper frames are vertical (left) and radial (right) component seismograms. Time is on the horizontal axis in seconds relative to the first arriving P-wave. Distance is in degrees on the vertical axis. Solid line overlays show the predicted arrival times based on the IASPEI91 standard earth model for the phases indicated. The small but very clear phase labeled PcS is a P wave that is converted to an S wave upon reflection at the core-mantle boundary and is very rarely observed.*

Each of the broadband sites, constructed of concrete and steel, constituted a semipermanent mini-observatory. The broadband sensor, comprised of three matched components (in most cases a Streckeisen STS-2 with flat velocity response between 50 and 0.008 Hz), was buried in a constant temperature vault constructed of a 55 gallon steel drum with the bottom torched off (Figure 4). A thin concrete layer, laid down to provide a level surface for sensor installation, was poured atop bedrock at the base of the drum and mechanically isolated from the drum wall. The base of the sensor vault was generally some 60-80 cm beneath ground level. The station electronics, housed in a secure sheet metal structure (the "doghouse," constructed in the de Beers machine shop in Kimberley), were powered by standard marine deep cycle batteries charged by a pair of 30 watt solar panels mounted on top of the doghouse (Figure 5). Seismic signals were recorded with 24-bit dynamic range at a continuous sampling rate of 20 samples/s. A number of stations in the vicinity of the deep gold mines (an approximately 5000 km^2 region centered near 27° S. latitude, 28° E. longitude), where local earthquakes are a common occurrence, additionally recorded 100 samples/s in event triggered mode. The data were written to an interchangeable disk drive with several months recording capacity. An external GPS unit mounted atop the doghouse provided millisecond absolute timing accuracy and highly accurate station coordinates. Our African collaborators serviced the stations at 6-8 week intervals, swapped out data disks and returned them to one of the four operational centers for tape copying. One tape was returned to the United States for database processing and subsequent transmission to the IRIS Data Management Center (DMC) for permanent data archiving, and where PASSCAL data are publicly available to the research community. The total data volume for the experiment was approximately 300 GBytes. All research groups involved in the experiment obtained working copies of the seismic data of interest directly from DMC via a highly efficient system of electronic requests.

A six-month deployment of a high-density broadband array near Kimberley, South Africa, proved an invaluable high-resolution complement to the wide-aperture deployment. The broadband system, which was designed and operated by PASSCAL, consisted of 31 real-time telemetered broadband seismic stations deployed within an area approximately 60 × 40 km. The telemetered array recorded at 40 samples/s, with signals transmitted in real time to a central recording site within the Green's Geophysics enclave at the de Beers Dairy Farm. From there data were retransmitted in near real-time over the Internet to Carnegie Institution and to Frank Vernon's lab at the University of California at San Diego, partners with IRIS/PASSCAL in development and operation of the telemetered array. The high-quality seismic data collected as part of that deployment have provided a unique opportunity to image the fine structure of the crust and Moho in a cratonic "type locality."

Selected seismic results. We describe here representative

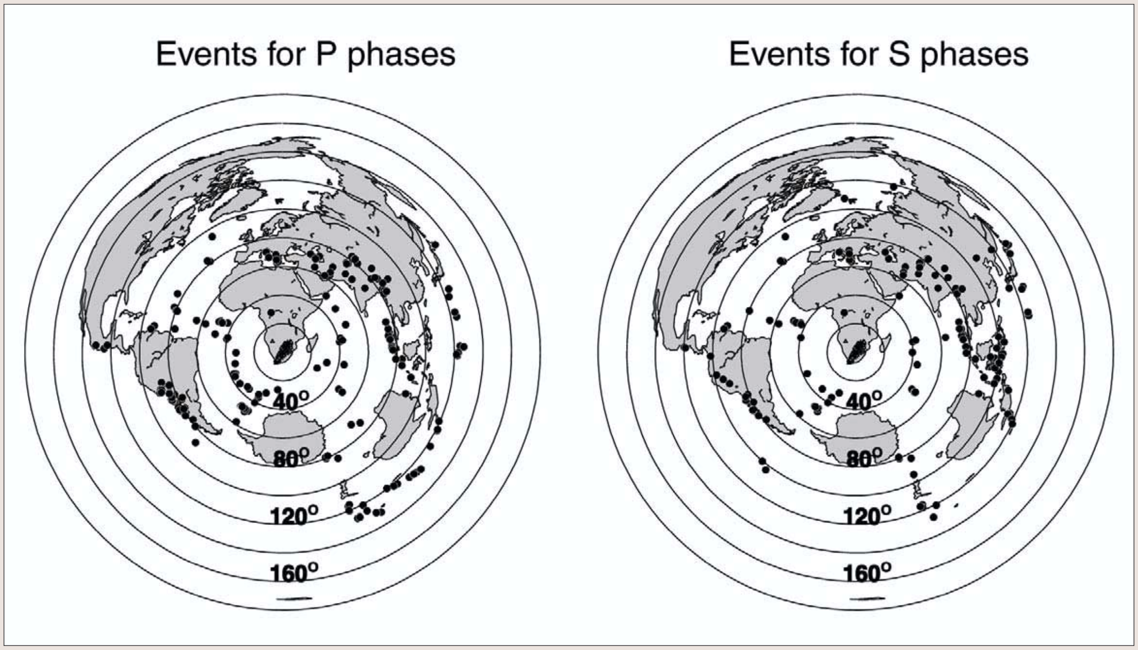

Figure 7. *Map of earthquakes used for P wave and S wave tomographic inversions. The map is centered on the southern Africa array and extends to the antipodes.*

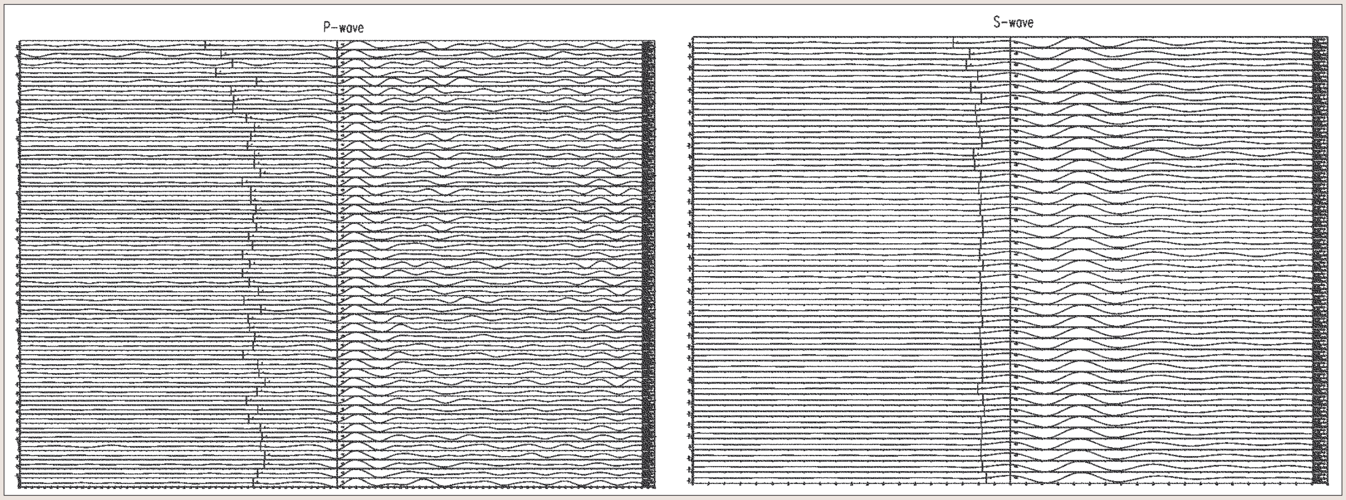

Figure 8. *Example of P wave and S wave cross-correlation for a relatively small (Mb=5.2) event in the South Sandwich Islands. Left = 20 s record section of vertical component P-wave arrivals organized by station from south (top) to north (bottom). The records have been band-passed between 0.5 and 1.5 Hz and time shifted into alignment according to the statistical best fit of the cross correlation. The relative delay times for the stations of the array are used as input for tomographic inversion. The short vertical dashes preceding the P arrivals are the predicted P wave arrival time based on the IASPEI91 standard earth model. Right = 80 s record section of transverse component S-wave arrivals organized south-north as for the P-waves. The records have been band-passed between 0.04 and 0.125 Hz and aligned by cross-correlation.*

results of tomographic and crustal studies from southern Africa that may be of interest to *TLE* readers. Published analyses have also included studies of surface waves, mantle anisotropy, and deep discontinuity structure, and the interested reader can find references and other information at the Kaapvaal Project Web site *www.ciw.edu/kaapvaal* and in *Suggested reading* at the end of this article. Other recent work has made use of the teleseismic data to examine the deep mantle and core-mantle boundary beneath Africa, including the so-called African superplume in the deep mantle.

Figure 6 shows good examples of seismic record gathers across the wide aperture array. We have analyzed the teleseismic P and S waves using both tomography and receiver functions to obtain crustal and upper mantle structure. Other data such as core-interacting phases (PcP, PcS and diffracted P and S, for example) are also being used to examine the deep mantle structure and the nature of the core-mantle boundary. Seismic records such as those in Figure 6 were obtained during the course of the experiment from all azimuths and distances and provided the raw data for tomographic imaging of the earth beneath southern Africa. One critical requirement for tomography (besides high quality data) is a good distribution of earthquakes in both azimuth and distance. For southern Africa the earthquake distribution was reasonably good (Figure 7).

Tomographic methods and results. The form of tomographic imaging we use in the southern Africa studies involves the analysis of relative arrival times (delay times) for many thousands of crossing rays from teleseismic earthquakes and the mapping of relative velocity variations (velocity perturbations) in the earth beneath the array. A simple rule of thumb is that we can obtain good image resolution to depths equal to about half the dimension of the array, or 900 km in this case. The input data for the analysis are the delay times of teleseismic P and S wave records of broadband waveforms observed during the continuous two-year operation of the southern Africa array. In practice, relative arrival times of phases P, PKPdf, S, and SKS were retrieved via a multichannel cross-correlation procedure using all possible pairs

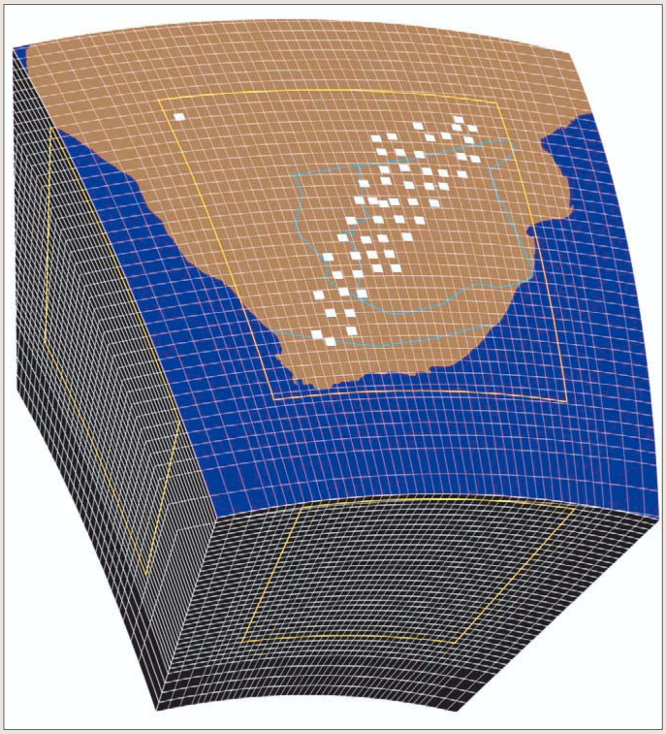

Figure 9. Three-dimensional perspective of grid knots that constrain the velocity perturbation model. Velocity perturbations associated with each grid element are with reference to a global 1D velocity-depth model, typically IASPEI91, a widely used standard earth model. The yellow lines indicate regions to which the tomographic horizontal and vertical cross-sections are confined.

of waveforms (VanDecar and Crosson, 1990). This procedure produces highly accurate delay times, with typical standard errors for the southern Africa data approximately 0.03 s for P-waves and 0.06 s for S-waves. Figure 8 shows examples of cross-correlated P and S waves. Tomographic images for P, based on 8693 rays from 234 events, are higher resolution than those for S, based on 4834 rays from 148 events. In all cases, however, the key to robust tomographic images is a quality-controlled data set. For the southern Africa data, each event was individually analyzed with various filter and cross-correlation settings and every record and record section examined by eye for waveform consistency. In the few cases where absolute clock accuracy could not be assured to at least 0.01 s, the records were discarded.

The dominant assumption implicit in tomographic inversion is that although the waves we record have limited bandwidth, infinite-frequency approximations are valid so that we can assume energy from earthquake to station travels solely along a raypath. This approximation is valid when material properties are varying slowly with respect to wavelength. In this case, the dominant wavelength for the observed P waves is about 8 km and the dominant wavelength for the observed S waves is about 35 km, whereas the smallest imaged structures are about 50-100 km. We also assume that the starting structure is sufficiently close to the final structure such that we can iteratively perform linear inversions to converge on the correct solution. By restricting our data set to teleseismic events we minimize nonlinear effects by excluding events with turning rays in the upper mantle transition zone above 660 km where velocity gradients are anomalously steep.

The structure beneath the region of the seismic array is parameterized as a three-dimensional smoothly varying grid (Figure 9). In our tomographic method, the data are simultaneously inverted for velocity perturbation (within each grid element through which rays pass), earthquake relocation, and station corrections. Station corrections are distinct from corrections for station elevation and crustal thickness that are incorporated directly into the inversion. The inclusion of earthquake relocation and station corrections minimizes systematic errors in the data and assures that they are not mapped into structure. The resulting velocity model thus contains the least amount of structure required to satisfy the observations within their estimated standard errors. The key to understanding which structural images are robust is in the density distribution of crossing rays within each grid element. Beneath the Africa array, the region of maximum intersecting raypaths is in the depth range 100-500 km, in the interior of the array, and this is where we achieve our maximum resolution. The station spacing of about 100 km means that there are essentially no crossing rays at depths shallower than about 50 km and thus any structural variations in that region are folded into station corrections.

Results for the linear, smoothed traveltime inversion for P and S waves are summarized in Figure 10 (see also James et al., 2001). The independently computed P and S models are similar within the limits of resolution. High mantle velocities in both P and S coincide with the interiors of the Kaapvaal and Zimbabwe cratons. An extensive region of maximum positive velocity perturbations (blue regions) is concentrated in the present-day heart of the Kaapvaal craton, which extends from the southern edge of the Bushveld province SSW to the contact with the Namaqua-Natal mobile belt (see Figure 2). In this region, the undisturbed cratonic keel may attain depths of 250-300 km and perhaps more. The evidence for root structures deeper than ~300 km beneath the array is sparse, although excepting regions of disrupted craton (as in the Bushveld), the tectospheric root attains a thickness of ~200-250 km almost everywhere beneath the cratons, including the Archean Limpopo mobile belt.

The most remarkable "disrupted" feature of the Kaapvaal craton is associated with the Bushveld province. Distinctly lower mantle velocities, strikingly evident for P but also seen in S, are associated with the larger Bushveld province, extending at least into the southern part of the rich diamondiferous terrane of the Okwa and Magondi belts in Botswana. While these low mantle velocities are well-resolved overall, the localized "patchiness" of the low velocity perturbations seen in Figure 10 is not. The tomographic results may be consistent with the fact that age dating of the mantle xenoliths from the Bushveld region shows a clear Proterozoic overprint on the original Archean mantle (Carlson et al., 2001; Shirey et al., 2002). Overprinting that involves infiltration of fertile (more iron-rich) material into depleted mantle or an overall increase in the geothermal gradient will result in lower seismic velocities.

Within the resolution of the data, the mantle structure of the Archean Limpopo belt does not differ significantly from that of the adjacent cratons. The similarity with cratonic mantle structure contrasts sharply with the results of crustal structure determinations (see below) which show the Central Zone of the Limpopo belt to be characterized by thick crust and poorly developed Moho relative to the adjacent cratons. Interestingly, Silver and colleagues (2001) have shown from analysis of SKS shear wave splitting that the Limpopo belt exhibits a consistent E-W mantle fabric, which they hypothesize was acquired at the time of craton collision 2.7 billion years ago.

The Proterozoic Namaqua-Natal mobile belt, thought to be the remnants of a major N-S convergent margin that

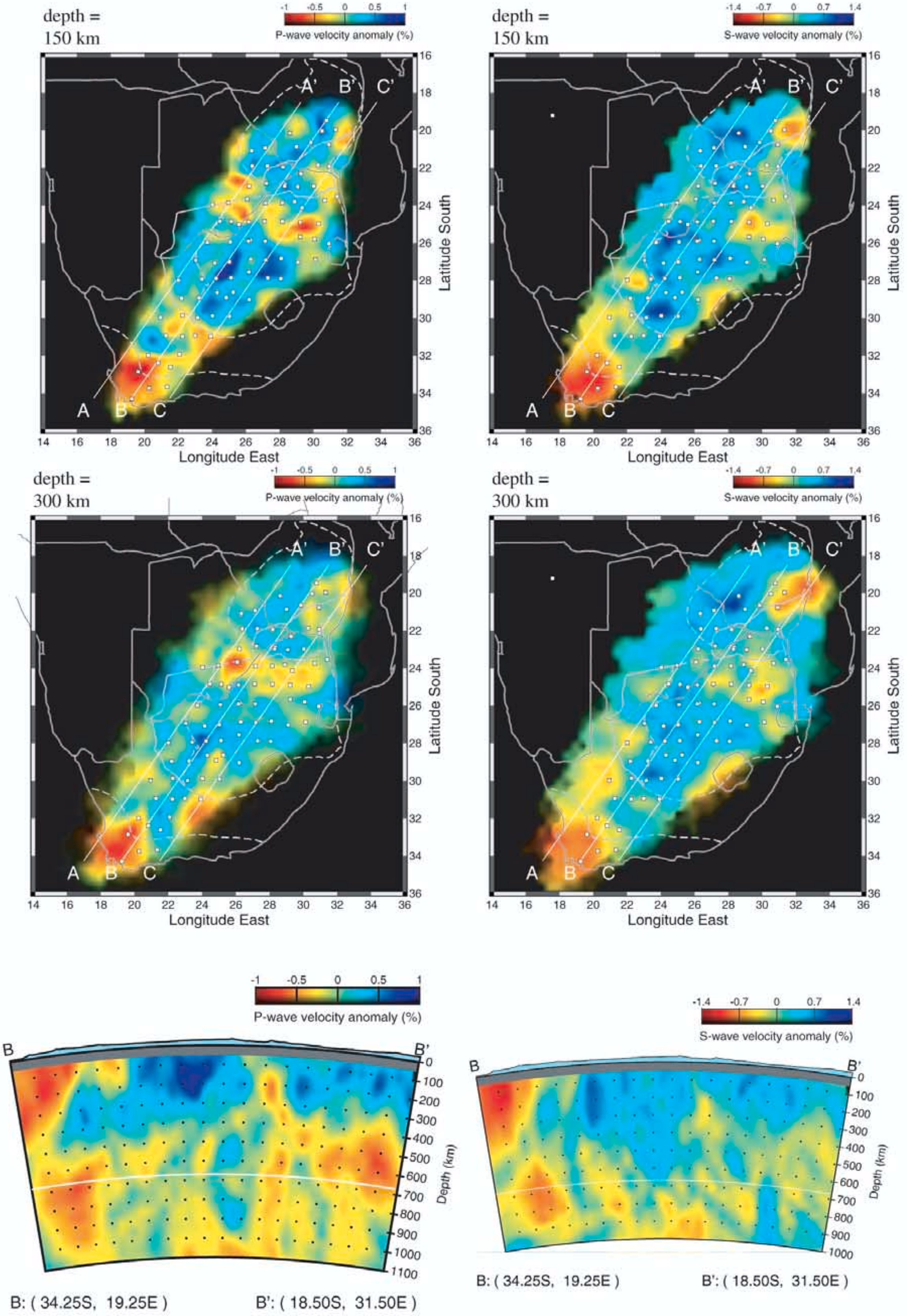

Figure 10. *Horizontal depth sections (map views) through P-wave and S-wave velocity perturbation models at depths of 150 km (top row) and 300 km (middle row), with vertical cross-sections (bottom row) along line B-B′ shown in the horizontal depth sections. Blue = high-velocity anomalies; yellow and red = low-velocity anomalies. The scales fade to black as resolution is lost, with pure black indicating that fewer than 10 rays traversed the grid elements in those regions. The P-wave images are based on about twice the amount of data as the S-wave images and are accordingly considerably sharper. Note particularly the clear outline of the high-velocity (blue) cratonic root both in the 150 km horizontal section and in the vertical cross section. The base of the high-velocity tectospheric keel is not clearly resolved, but probably extends to at least 250 km or more beneath parts of the Kaapvaal craton.*

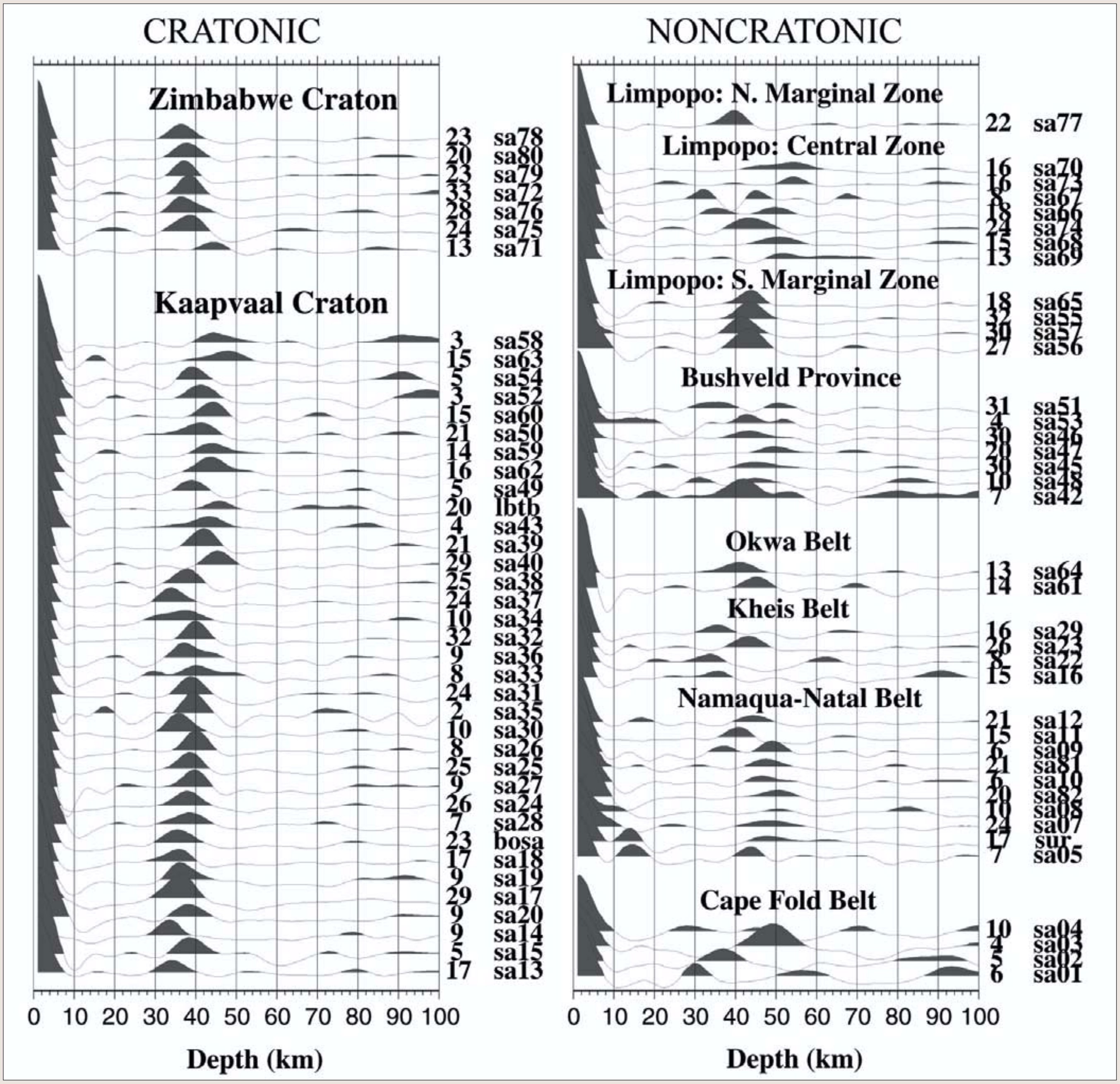

Figure 11. *Receiver function depth images for southern Africa, organized by geologic province. The events included in each stacked trace have been moveout-corrected for ray parameter. The number of events in the stack and the station name for each trace are to the right of the trace. The dominant signal on most of the depth images is the P-to-S conversion (Ps) from the Moho. Relatively thin (35-40 km) crust and sharp, well-defined Ps Moho conversions tend to be associated with undisturbed craton. Ps arrivals associated with disturbed regions of the craton and post-Archean terranes tend to be more diffuse and of smaller amplitude (from Nguuri et al., 2001).*

extended as far north as the Zimbabwe craton, is characterized by velocity perturbations uniformly lower than those observed beneath the craton. The lower velocities are in keeping with the observation that the off-craton Proterozoic mantle tends to be somewhat more fertile (higher Fe) than that of the adjacent craton. Patches of higher velocity material are seen in the 200-400 km depth range beneath the belt, however, and these higher velocities typically exhibit continuity with the high velocity material beneath the adjacent Kaapvaal craton. It has been speculated that the high velocity regions are the remnants of Proterozoic slabs.

Moho imaging. Single station receiver function analysis of P- to S-wave (Ps) conversions of near-vertical incidence waves at the Moho can be used to obtain crustal thickness beneath each station of the Africa array. The receiver function is a means of isolating relatively small amplitude Ps conversions that are produced at discontinuities beneath the station from the very much larger amplitude direct P-wave arrivals that dominate the same early portion of the record. To compute the receiver function, we deconvolve the vertical component signal (which contains only P-wave energy) from the radial component (which contains both P- and S-wave energy) to produce a so-called "source equalized" radial seismogram. Under ideal conditions, the source equalized (deconvolved) trace consists of a large amplitude initial spike (containing all the P-wave energy present on the original radial component) and a following spike train of smaller signals that are the Ps conversions and converted reflections from discontinuities beneath the station (see companion article in this issue by Pavlis for a more detailed dis-

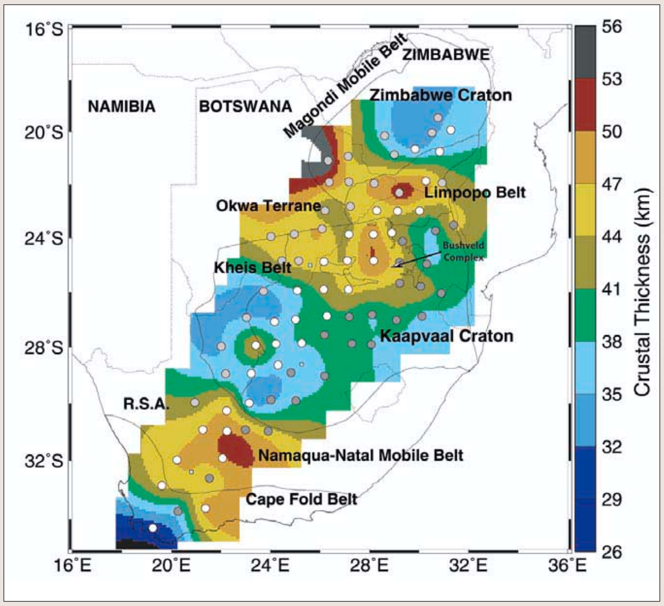

Figure 12. Color-coded contour map of depth to Moho beneath the southern Africa array based on receiver function depth images in Figure 12 (from Nguuri et al., 2001). Crustal thickness color scale is on right. Thin crust tends to be associated with undisturbed areas of the craton, particularly in the southern and western parts of the Kaapvaal craton and in the Zimbabwe craton. Results from the Kimberley array confirm that the crust around Kimberley is flat, sharp, and only about 35 km thick, despite a regional elevation above 1100 m (3500 ft).

cussion of receiver functions and seismic imaging). We have concentrated our crustal studies on the Moho Ps conversion, which for the Kaapvaal and Zimbabwe cratons is the only significant crustal or uppermost mantle discontinuity observed. The receiver function depth images obtained by Nguuri et al. (2001) in Figure 11 are arranged by geologic province as in Figure 2. Only one consistent Ps signal occurs, and it is readily associated with the M-discontinuity. A composite summary of these receiver function results is presented as a color-coded map of crustal thickness reproduced in Figure 12.

Stations located within regions of the Kaapvaal or Zimbabwe cratons that have remained largely undisturbed since Archean time typically exhibit sharp, large amplitude Moho images with Ps-P lapse times indicative of relatively thin crust. Interestingly, there is no evidence for mid-crustal discontinuities anywhere in the craton. Moho depths for the Zimbabwe craton are with one exception less than 40 km; those for the Kaapvaal craton average about 38 km and range from about 34-47 km. Uncertainty in Moho depth is difficult to determine, but we estimate it to be less than about ±3 km based on forward modeling using varying velocity structures. Post-Archean and modified cratonic regions characteristically exhibit smaller amplitude Ps converted phases, and the crust is commonly thicker than that beneath undisturbed craton. A significant result is evidence for pervasive Proterozoic (about ~2 billion years ago) modification of Archean crust across a huge east-west zone at the latitude of the Bushveld complex, consistent with what we see in the tomography. Moho Ps conversions for stations in this region of disrupted craton tend to be low in amplitude and in some cases ambiguous, suggesting that the Moho may be a weak and/or broad transitional (i.e. > 3-5 km) boundary. Both crustal thickness and the Moho signature observed in the region of modified Archean crust are similar to those observed at stations in the Proterozoic Namaqua-Natal belt.

Depth images for the northern and southern marginal zones of the intercratonic Limpopo Belt exhibit a characteristic cratonic signature in both Ps and in crustal thickness. These results are consistent with geologic interpretations of these marginal zones as overthrust belts atop cratonic crust. The Central Zone, on the other hand, displays thickened crust (up to 50 km or more) and poorly developed Moho Ps conversions, a likely product of pervasive shortening and crustal thickening during the collision of the Kaapvaal and Zimbabwe cratons in the Archean.

Kimberley Array. The Kimberley region of the southern Kaapvaal craton is one of classic cratonic crust and was an obvious target for the high-resolution Kimberley broadband array installed as part of the larger seismic experiment. The results have not disappointed. The analysis of both teleseismic and local events recorded on the Kimberley broadband array reveals a remarkably uniform crustal structure beneath the array. From the analysis of the broadband array data we can conclude: (1) The cratonic crust is thin (about 35 km thick), it has a low Poisson's ratio (~0.25, $V_P/V_S \approx 1.73$) suggesting felsic to intermediate composition even in its lowermost section, and it is uniform over thousands of km^2; (2) The Moho is a sharp discontinuity, with a remarkably thin crust-mantle transition less than 0.5 km beneath the array. (3) The Moho is almost perfectly flat, with less than 1 km of relief within the aperture of the array (Niu and James, 2002).

Implications of crustal composition. The low Poisson's ratio of 0.25 ($V_P/V_S = 1.73$) for the crustal average and an inferred density of 2.86 gm/cc for lowermost crustal rocks (see Niu and James) provide compelling evidence that the lower crust beneath the Kaapvaal craton is dominated by rocks of intermediate to felsic composition. (Note: The discussion here loosely follows the International Union of Geological

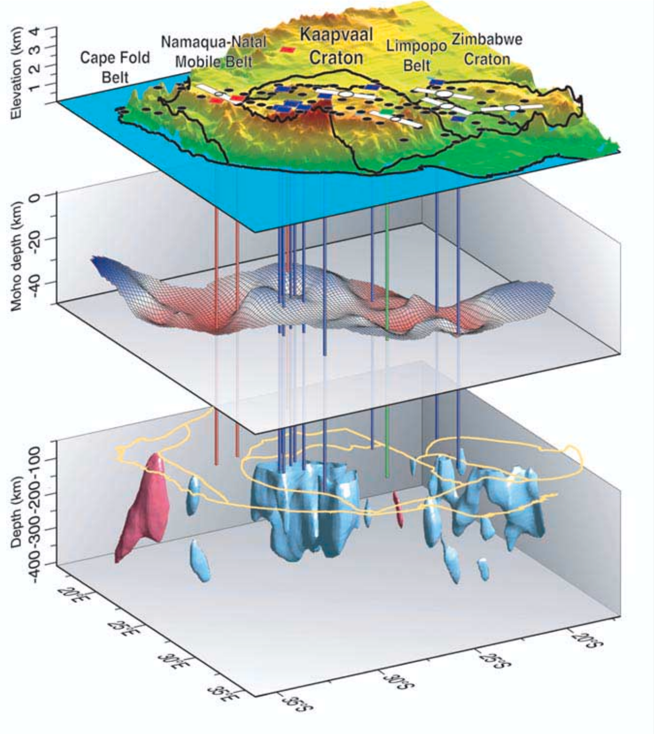

Figure 13. *Three-dimensional illustration summarizing results from the Kaapvaal Project of southern Africa. Top panel = three-dimensional perspective of topography on which are outlined the principal geologic provinces (heavy black lines), locations of portable broadband seismic stations of the southern Africa seismic experiment (black dots), and fast polarization directions from shear wave splitting (white circles with elongated white bars). Major kimberlite localities are filled diamonds, color coded to Re/Os model ages determined from mantle xenoliths (blue > 2.5 billion years ago; green = 2.0-2.5 billion years ago; red < 2.0 billion years). The kimberlite pipes are extended schematically downward to the top of third panel to show their relationship with crustal and mantle seismic structure. Middle panel = three-dimensional surface of the Moho. Blues denote thin crust; reds denote thick crust. Bottom panel = three-dimensional image of P-wave velocity perturbations in the upper mantle. Blue shading encloses positive velocity anomaly surfaces, red shading encloses negative velocity anomaly surfaces. The major structures outlined in blue define the tectospheric roots beneath the Archean Kaapvaal and Zimbabwe cratons. A map view of geologic boundaries is superimposed in yellow on the bottom panel. (Image from cover of GRL, 2001, created by M. Fouch and D. James.)*

Sciences igneous rock categories: mafic rocks have < 52% SiO_2, intermediate rocks have 52-63% SiO_2, and felsic rocks have > 63% SiO_2. These compositions are sufficiently distinct as to have relevance in terms of quantifiable seismic wave velocities and rock densities.) The absence of a mafic signature in the seismic results is consistent with the fact that mafic granulite xenoliths from the lower Kaapvaal crust are rare. These observations highlight one of the great dilemmas of Archean crustal composition: If the continental crust was derived from a hotter mantle in the Archean, why is the crust not basaltic or even picritic in composition? Instead, not even the lowermost crust beneath the Kimberley area is significantly mafic in composition. The crust beneath the Kaapvaal appears to be less mafic than that beneath adjacent Proterozoic mobile belts, where mafic granulite xenoliths from the lower crust are common. Niu and James (2002) suggested that the present composition of the Kaapvaal crust is most plausibly explained as the result of extensive melting of the lower crust during ultrahigh-temperature metamorphism associated with the Ventersdorp tectonomagmatic event around 2.7 billion years ago (Schmitz and Bowring, in press). Temperatures in excess of 1000° C in the lowermost crust, coupled with widespread crustal melting during the Ventersdorp event, imply significant degrees of partial melting, magmatic differentiation, and ductile flow in the lower crust beneath Kimberley. Layering associated with the crystallization of melt in the lowermost crust is one possible means for producing both a flat and sharp Moho as well as the evolved rock compositions that we infer from the seismic data.

Implications of Moho structure. Models of the assembly history of the Kaapvaal craton typically involve extensive collisional accretion of island arcs and microcontinental blocks to form nuclear continental masses. Such accretionary processes may be expected to produce a complicated mosaic of varying Moho structures and diverse crustal lithology. We observe just such structures in the Limpopo Belt, a late Archean collisional zone sandwiched between the Zimbabwe and Kaapvaal cratons that exhibits many traits of tectonic deformation seen in modern continent-continent collision, including extensive crustal thickening and a highly complex Moho. Such structures are notably absent beneath the undisturbed Kaapvaal craton, where around Kimberley the Moho is remarkably sharp and flat.

Lack of Moho relief in regions where we expect Moho topography is surprisingly common. That fact has been attributed to postformation modification of the lower crust through magmatic reworking and ductile flow. The relatively flat Moho in extensional provinces such as the Basin and Range in the western United States, for example, is commonly interpreted to be due to reforming of the Moho by igneous and ductile deformation in the deep crust (e.g. Klemperer et al., 1986). Such igneous reworking implies that the lowermost crust and the crust-mantle transition are effectively the "youngest" layers within the continental crust. It follows that extensive remelting and ductile flow in the lower Kaapvaal crust are probable consequences of the profound thermal perturbation resulting from the Ventersdorp intracratonic event, which involved flood basalt magmatism, crustal extension, and widespread anatexis.

In terms of geologically plausible scenarios, thermal reactivation and large volume melting of the cratonic crust in late Archean time is the most viable hypothesis for flattening and sharpening of the Moho and for the absence of mafic layering in the lowermost crust. Other explanations are possible, however, and one is particularly interesting in the current context. Moho and lower crustal structure imaged as part of Lithoprobe seismic reflection profiling across the Phanerozoic accreted terranes of southwestern Canada suggest that a relatively flat Moho is not necessarily inconsistent with accretionary tectonics or with large-scale crustal structures that are geometrically discordant with a flat Moho (Cook, 1995). As evidenced from the Lithoprobe data, upper crustal structures appear to flatten into the deep crust and Moho, tending to converge into what Cook interprets to be zones of regional detachment. This mechanism also implies some degree of ductile flow, given the clear geometrical relationship between Moho and deep crustal reflections with higher angle fault structures in the shallower crust. While the Canadian model is not necessarily applicable to the Kaapvaal craton, regional detachment at the Moho may be a viable means by which to produce primary Moho structures that are relatively flat during the processes of crustal aggregation. In that hypothetical circumstance, the Ventersdorp thermal remobilization of the lower crust and the ductile stretching resulting from crustal rifting would act to enhance flattening of the Moho and to sharpen the crust-mantle transition zone even further. Such a combination of primary and late stage tectonothermal processes may suffice to explain both lowermost crustal compositions and the remarkable Moho structures observed beneath the Kaapvaal craton.

Concluding remarks. Figure 13 is a three-dimensional composite both of the results discussed above and of a few results not discussed (see caption). P and S wave tomography shows that a mantle keel extends beneath both the Kaapvaal and Zimbabwe cratons to depths of at least 200 km and locally to 250-300 km. High-velocity mantle roots are confined to regions of Archean craton. The cratonic keel is not uniform, however, and the seismic images suggest the remarkable result that a large volume of the mantle beneath the Kaapvaal craton may have been significantly modified by the Bushveld event about 2.05 billion years ago, as evidenced by significantly lower mantle velocities. These seismic results are buttressed by results from isotope analyses showing that mantle ages in the region were reset by the Bushveld event. The strong distinction between mantle signatures of craton versus off-craton and disturbed cratonic regions is mirrored in receiver function analysis of crustal structure. Undisturbed cratonic crust is characterized by a sharp and large velocity contrast Moho. In contrast, regions that are off-craton or in modified or disturbed craton, notably the Bushveld and the Limpopo belts, exhibit a more complex and poorly defined Moho. Cratonic crust is also unexpectedly thin (35-40 km), given the higher elevations associated with the cratons, whereas noncratonic regions are typically characterized by crustal sections 45 km thick or more. The crust beneath the undisturbed southern Kaapvaal craton around Kimberley exhibits a remarkably flat and very sharp Moho and appears to lack a significant mafic component even in its deeper sections. Both the Moho structure and the crustal composition are consistent with massive remelting and reworking of the crust in latest Archean time and suggest remarkable stability since that time.

Suggested reading. "Structure and formation of the continental tectosphere" by Jordan (*Journal of Petrology, Special Lithosphere Issue*, 1988); all eight papers comprising the special Kaapvaal Project section of *Geophysical Research Letters*, 2001; "Formation and evolution of Archean cratons: Insights from southern Africa" by James and Fouch (in *The Early Earth: Physical, Chemical and Biological Development*, 2002); "Continental growth, preservation and modification in southern Africa" by Carlson et al. (*GSA Today*, 2000); "Fine structure of the lowermost crust beneath the Kaapvaal craton and its implications for crustal formation and evolution" by Niu and James (*EPSL*, 2002); "Diamond genesis, seismic structure, and evolution of the Kaapvaal-Zimbabwe craton" by Shirey et al. (*Science*, 2002). TLE

Acknowledgments: The Kaapvaal Project has been an adventure that involved the efforts of more than 100 people affiliated with about 30 institutions. Details of participants and a project summary can be found on the Kaapvaal Web site www.ciw.edu/kaapvaal. *I give special thanks to each and every one of those who were part of the monumental effort to make this experiment a success. A special note of thanks, however, goes to Rod Green of Green's Geophysics who laid out so much of the logistical groundwork for the experiment and to whom the southern Africa seismic experiment owes a particular debt. The Kaapvaal Project is funded by grants to Carnegie and MIT from the National Science Foundation Continental Dynamics Program (EAR-9526840) and by several public and private sources in southern Africa. Map figures were produced with GMT developed by Wessel and Smith (EOS, 1991).*

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