Record 1988/21

International Workshop and Symposium

SEISMIC PROBING OF CONTINENTS AND THEIR MARGINS

1 - 8 JULY, 1988, Canberra, Australia.

ABSTRACTS

Edited by J. C. Dooley

Bureau of Mineral Resources, Geology & Geophysics, Canberra, Australia.

This Record contains the abstracts of papers which have been accepted for either oral or poster presentation in the Workshop and Symposium.

Abstracts are in alphabetical order of the first author of the paper; the person making the oral or poster presentation at the Workshop or Symposium is underlined.

CONTENTS

Page

THE DEEP STRUCTURE OF THE CONTINENTAL MARGIN OF EAST OMAN

P.J. Barton, T.R.E. Owen, R.S. White & J.S. Collier

Bullard Laboratories, University of Cambridge,
Madingley Road, Cambridge, England

Late in 1986 a 200 km long wide-angle seismic line was shot from shelf to deep ocean across the continental margin just north of Masirah Island, east Oman. Data were collected using eleven digital OBS and 116 explosive shots varying in size from 25 kg to 200 kg. A multichannel seismic reflection line was collected parallel and close to the wide-angle line, forming part of a grid of regional seismic profiles in the northern Indian Ocean. These regional profiles are used to show that the Owen Fracture Zone is a currently active feature that is connected into the extensional Dalrymple Trough to the north.

We present an initial interpretation of the deep structure of the Masirah margin from the OBS data: shallow control is obtained from the reflection profile. We examine this model in the context of regional right lateral shear, currently taken up by the Owen Fracture Zone. Distributed shear bounded zones in intra-continental settings have been shown to cause rotation and extension of crustal blocks as well as the juxtaposition of diverse terranes. We compare the situation in eastern Oman with other major zones of strike slip motion and discuss whether the ophiolitic rocks of Masirah Island could have been emplaced as a result of this motion.

SEISMIC REFLECTION (GLIMPCE) EVIDENCE OF DEEP CRUSTAL INTRUSIONS AND MAGMATIC UNDERPLATING ASSOCIATED WITH THE MIDCONTINENT RIFT SYSTEM OF NORTH AMERICA

J.C. **Behrendt**[1], D.R. Hutchinson[1], A. Tréhu[1], W. Cannon[1], M.W. Lee[1], C.R. Thornber[1], A. Green[2], B. Milkereit[2], and C. Spencer[2]

1 US Geological Survey
2 Geological Survey of Canada

Reflections recorded in the 1986 GLIMPCE (Great Lakes International Multidisciplinary Program on Crustal Evolution) experiment indicate that crustal extension associated with the ~1100 Ma Midcontinent rift system resulted in rift fill, consisting of 20-30 km (7-10 s) of primarily basalt flows and secondarily synrift volcaniclastic and post-basalt sedimentary rock, and stretching factors of 3-4. These basalt flows deposited in the developing rift basin are technically no longer basalts when buried to 20-30 km depth; they will have been metamorphosed to pyroxenitic granulites or (if wet) amphibolites. Deep crustal and Moho reflections provide evidence for magmatic underplating and intrusions within the lower crust caused by activity associated with the rift. The petrologic nature of this material is likely to depend upon its relation in space and time to rift development. Either asthenospheric or lithospheric mantle melting processes may have predominated, depending upon regional tectonic constraints that governed the rate and extent of rift development. Alternatively, these deep-seated intrusions could result from the shut-down of the Midcontinent rift system. The variability in the strength, times, and character of the deep reflections suggests that extension, underplating, and intrusion were not uniform beneath the rift. Moho reflections recorded in the surrounding Great Lakes indicate about 39-45 km (about 12 s) crustal thickness in contrast to thicknesses as great as 58 km (about 18 s) in areas of the inferred underplating. Scattered subcrustal reflections are apparent in the area of the Midcontinent rift system at 19-20 s times.

The 120-channel data (24- and 30-fold), comprise 20-s records made using a 130-L (7800 in^3) array of about 60 airguns. Large-offset seismic data recorded along the vertical reflection line in the areas of greatest crustal thickness in the Midcontinent rift system are used to constrain the interpretation of deep intrusions and underplating.

CONVERTED WAVES : EXAMPLES FROM THE AUSTRALIAN CRUST AND UPPER MANTLE

G. Bock

Department of Geology & Geophysics, University of New England, Armidale, Australia

The conversion from S to P beneath seismic stations, usually referred to as Sp phases, forms an important class of the many possible mode conversions at seismic discontinuities. Sp phases arrive as precursors to S-waves. It is essential for their study to have data from a three-component seismic station. If correctly identified, Sp phases allow the depth to and velocity contrast across seismic discontinuities to be determined. In addition, they may provide constraints on the sharpness of seismic discontinuities, an important parameter for petrological models of crust and upper mantle, and are thus a useful study object particularly in the depth range which is currently not reached by controlled experiments.

In this paper, observations of Sp phases from the crust-mantle boundary and upper mantle seismic discontinuities under the Australian continent are discussed using earthquake data recorded at the short-period Warramunga Seismic Array (WRA) in central Australia and three long-period seismic stations of the Global Digital Seismograph Network (GDSN) located at Narrogin (NWAO), Charters Towers (CTAO) and Tasmania University (TAU). Sp phases from the crust-mantle boundary ("Moho") were observed at WRA that precede S by about 5.6 s. Synthetic seismograms for a model, in which the "Moho" is approximated by a transition zone from 38 to 41 km depth, are in good agreement with the observations. Sp phases originating in the upper mantle were studied using data from the Australian GDSN stations. Ten earthquakes at epicentral distances between 70^{o} and 91^{o} were selected, of which eight showed precursors to S, SKS and ScS on the long-period vertical-component seismograms. Synthetic seismograms for the PREM model of Dziewonski and Anderson (1981) show good agreement with many details of the data. The main precursor arrivals are compatible with S to P conversions from a seismic discontinuity at 400 km depth. Within the limited resolution of long-period data, there is no indication for strong lateral variations in this discontinuity between various geological provinces of Australia. Sp phases from the "670 km" discontinuity have much smaller amplitudes both in the synthetics and data in the epicentral distance range from 75^{o} to 85^{o}. They are probably best observed at distances beyond 89^{o} which is confirmed by one observation at CTAO and synthetic seismogram modelling. There are indications for the presence of S to P converted phases from a depth near 220 km. Their appearance is variable so that they are difficult to explain by conversions at a seismic discontinuity at this depth

S-WAVE USAGE IN SHALLOW REFRACTION SEISMICS

G. Bock

Department of Geology & Geophysics, University of New England, Armidale, Australia

The study focusses on relatively inexpensive ways of generating and recording S-waves in very shallow seismic refraction work. Possible areas of application are, among others, in civil engineering and groundwater investigations. Theoretical studies as well as the results of field experiments are described.

Synthetic P-SV seismograms were calculated for a two-layer model with a vertical point force applied to the surface simulating the situation in a hammer refraction seismic profile. As is well known, the synthetics are dominated by ground roll. Direct and refracted S-waves have negligible amplitudes. Conversions from P to S at the free surface and the bottom of the upper layer may carry significant energy, and so to become observable as wide-angle primary and multiple reflections under favourable circumstances. An interesting result of the calculations is the fact that wide-angle P reflections stand out more clearly on the horizontal than on the vertical component seismograms.

For the field experiments, the seismic signal was produced by the impact of a 4.5 kg sledgehammer on a steel plate which was firmly embedded in the surface. The source may not be ideal, but it has the advantage of being readily available and repeat shots for signal enhancement are easy to obtain. The angle of impact was vertical and +/-45° normal to the spread direction. A 12-track enhancement seismograph was used together with high-frequency 100-Hz geophones that could be operated either as vertical- or horizontal-component sensors. Forming the difference of the transverse-horizontal recordings obtained for the two inclined shot positions should yield a pure SH record section over flat-layered structures, whereas the sum of the vertical and radial components recorded from the same shots represents P-SV record sections resulting from a vertical single force at the surface. An example is shown from an area which is part of a proposed highway bypass of Armidale. The field site is covered mainly by sedimentary beds of Carboniferous age. Employing the above method, a simulated SH record section could be derived yielding a high value of about 3 for the ratio of apparent P- to SH-wave velocities.

CONTRIBUTION OF DEEP SEISMIC PROFILING TO THE STUDY OF MAJOR GEODYNAMIC PROBLEMS IN FRANCE AND ADJACENT AREAS

C. Bois [1], P. Choukroune, A. Nicolas,
B. Pinet, & M. Cazes

1. Institut Francais du Petrole, Rueil-Malmaison, France

France's geological history consists of (1) the consolidation of the Western European crust during the Paleozoic Variscan orogeny, (2) the formation of Permo-Mesozoic cratonic basins and the opening of the Tethys and Atlantic oceans, and (3) the closure of the Tethys and the building of the Tertiary orogenic ranges (Pyrenees and Alps).

The ECORS deep seismic profiles shot since 1983 are reviewed and compared. In the orogenic belts, the deformation front generally shows an extensive flat above the subducted plate and is rooted within a set of imbricated thrusts in the middle crust. In the Celtic Sea, the Variscan front, however, shows a striking departure from this model. The lower crust and the Moho are deformed and offset beneath the Tertiary ranges, while they are almost flat beneath the Variscan ones, suggesting that their emplacement took place between the two deformation periods. Straight dipping reflectors characterize the deep crust in the Variscan internal zone. They have no definite equivalent in the Tertiary ranges and their interpretation in terms of plate suture is reviewed and discussed.

The Tertiary ranges show large crustal thickening and crust-mantle imbrication. The disappearance of the Paleozoic mountain roots may have resulted from surface erosion and isostatic uplift, or crustal extension and/or creeping, or else deep metamorphism. The present Moho intersects Paleozoic structural features, suggesting that metamorphism played a major part in the late re-equilibration of the crust-mantle transition. The fading of the lower crust reflections in the deepest part of the Tertiary ranges indicates that this process is in progress there.

More precise dating of the emplacement of the Moho and the layering of the lower crust depends on the study of the Permo-Mesozoic basins. This emplacement was certainly prior to the late Jurassic, for these features were involved in crustal attenuation beneath basins of this age (North Sea, Bay of Biscay). A study of the Celtic Sea and English Channel basins suggests this emplacement to be either Permian (crustal equilibration following the Variscan orogeny) or Triassic-Jurassic (Tethys rifting).

From the structure of the Permo-Mesozoic basins and the underlying crust, the simple shear model cannot work and the pure shear one is highly improbable. Thermo-mechanical and/or non-conservative models account for the upper-crust structure better but do not explain the non-attenuated lower crust. The late equilibration of the crust-mantle transition seems to have removed any deep trace of the basins formation. The attenuation however, is clearly observed beneath later basins in the Celtic Sea margin and the Bay of Biscay.

DIRECT COMPARISON OF DYNAMITE AND VIBROSEIS METHODS FOR DEEP CRUSTAL REFLECTION STUDIES IN THE SOUTHWESTERN BASIN AND RANGE

T.M. Brocher and P.E. Hart

US Geological Survey

Exhaustive tests of dynamite versus Vibroseis* (*trademark Conoco, Inc.) methods for deep crustal reflection studies were performed in SW Nevada in January, 1988, in anticipation of a regional deep crustal reflection survey to be conducted as part of a broad geological investigation of a proposed nuclear waste facility. Two sites within the valley floor of Amargosa Desert, located in the Basin and Range Province just to the east of Death Valley, California, were used to investigate the feasibility of obtaining reflections from complex structure using a 480 channel full-word fibre optics recording system. A 60-fold Vibroseis survey along a 33 km long line was recorded using receiver group intervals of 25 m and a symmetric split spread with a maximum source-receiver offset of 6 km. As the receiver spread was rolled along, single 91 kg explosive charges were fired in 76 m deep shotholes to generate a single-fold dynamite section coincident to the Vibroseis section. Despite the high-fold of the Vibroseis data, the low-fold dynamite data provides higher quality images of the lower crust. This result is due primarily to the nearly complete suppression of the air-wave arrival and the partial suppression of the ground roll using buried impulsive sources. Owing to the large-amplitude ground roll and air-wave arrivals produced by the array of 4 massive vibrators (combined peak force in excess of 72,700 kg), 50 m long linear receiver arrays and 70 m long Vibroseis arrays produced records for all travel-times superior to those obtained using point receiver and source arrays. Both the dynamite and Vibroseis sections are coincident with a regional refraction line, permitting comparison of reflection/refraction images of the shallow crust.

The dynamite section clearly shows nearly horizontal, discontinuous reflections within the lower crust below 5 s two-way travel time. Based on limited refraction data the crust is believed to be about 35 km thick. On the newly recorded reflection data the base of the lower crust is ill-defined, with apparent events ringing throughout the record down to 15 s and below. These apparent events are currently thought to represent peg-leg multiple or scattered energy from within near-surface sedimentary basins and/or lower crustal reflectors, and not to correspond to reflections from the upper mantle. The Vibroseis reflection section clearly shows structures within the basins inferred from previous refraction surveys, but the reflectivity within the upper crust is less prominent than within the lower crust. Within the upper crust the Vibroseis records are superior, suggesting that a combined explosive/Vibroseis survey should be undertaken for the regional reflection studies to be conducted in this region in the future.

THE EXPANDING FRONTIERS OF REFLECTION PROFILING: DEEPER, FASTER, OLDER, BRIGHTER, FARTHER

Larry D. Brown

Department of Geological Sciences and Institute for the Study of the Continents, Cornell University, Ithaca, NY 14853

Deep seismic reflection programs the world over have amassed well over 30,000 km of profiling. Significant new insights into crustal structure and evolution have become almost routine from these efforts. To be sure, important questions of technique and interpretation remain to be fully resolved. Yet the robust nature and broad applicability of reflection methods in lithospheric exploration have been well established by a decade of experience. New challenges, and opportunities, for the future abound :

Deeper - Lower crustal/Moho reflections are commonplace; unequivocal mantle reflections are not. Lack of signal penetration is not always the cause; real mantle homogeneity is also involved. Yet the BIRPS discovery of prominent sub-Moho reflectors in northern Britain makes clear that the mantle is a special frontier for future reflection profiling.

Faster - Increasingly sophisticated data processing and a rapidly expanding database add up to massive computational requirements. Supercomputers clearly represent an important resource for deep reflection profiling. Efforts to exploit high performance computers in deep seismic research are just beginning, but the promise is clear: faster processing opens the door to quantitative global syntheses of deep reflection data.

Older - The importance of studying crustal processes "in action" cannot be overstated. Thus recent surveys across young orogens (e.g. the Alps) are especially interesting. New surveys of Proterozoic terranes, in particular, suggest that reflection surveys have a major contribution to make in understanding the accretion of continental crust during this critical period.

Brighter - Although mapping deep structure is the forte of reflection profiling, seismic recordings are also rich with information about physical properties at depth. Consider the "bright spots" that have helped stimulate debate over deep fluids. Attribute analyses (e.g. amplitude, frequency, polarity, interval velocity), together with special auxiliary experiments (e.g. wide-angle, shear wave), will undoubtedly make an increasingly important contribution to understanding of the lithosphere.

Farther - Progress toward global coverage has been impressive, but far from comprehensive and decidedly uneven. Important geologic problems remain unsurveyed even in countries with advanced seismic reflection programs. Most of the world (including the Himalayas/Tibet, Andes, East African Rift, Urals etc) remains terra incognita to crustal reflection profiling. International cooperation to advance deep reflection transects across some of these classic mountain belts represents one of the most exciting opportunities in earth science today.

COCORP SUPERCOMPUTING

L.D. Brown, T.L. Pratt and T.M. Hearn

Institute for the Study of the Continents, Cornell University, Ithaca, NY 14853

The nature of signal enhancement algorithms as well as the organization of multichannel seismic data lend themselves to exploitation of vector and parallel processing. Experience with seismic processing on the IBM 3090-600E of the Cornell National Supercomputer Facility (CNSF) also emphasizes that large memory, massive data storage and interactive graphics are as important as raw computational speed for more effective treatment of seismic recordings.

During the past year, several elements of seismic processing have been implemented on CNSF and related facilities. Basic seismic processing algorithms were ported from VAX routines in the SIOSEIS (univ. California at San Diego) software package. Extensive modifications, especially for I/O routines, were required in this port to take advantage of the IBM capabilities. Large virtual memory, for example, obviated the need for frequent disk access. Among the most useful supercomputer implementations to date has been a velocity estimation routine, in which velocities are interactively picked from previously generated constant velocity stacks.

Advanced imaging algorithms, in the form of a new dip moveout routine (DMO), have also been a goal for supercomputer development. A parallel version of DMO indicates that seismic processing throughput varies almost in direct proportion to the number of available processors (6 on the IBM 3090-600E). Clearly parallel processing is suited to seismic applications.

The computationally intensive software was complemented by a new interactive graphics display package (CISP), originally developed on a microVAX GPX workstation and ported to the 3090 to drive the IBM 5080 workstation. The coupling of high-performance computation to interactive graphics has proven to be a major boon to routine processing.

By moving key processing steps closer to the realm of true interactive turn-around, supercomputers reduce tedium, increase accuracy, and free analyst time for interpretation. This capability becomes increasingly important as the global inventory of deep seismic data mushrooms: simultaneous processing of multiple data-sets is a key requirement for the next generation of quantitative syntheses.

MODELLING REFLECTIONS FROM THE DEEP CRUST IN THREE DIMENSIONS

S.H. Cao & B.L.N. Kennett

Research School of Earth Sciences, Australian National University,
GPO Box 4, Canberra, ACT 2601, Australia

One of the most obvious features of seismic reflection profiles with penetration deep into the crust is that the reflection segments at depth are relatively short, and frequently show a variety of apparent dips. Such features may be interpreted as suggesting segmented reflectors. Some reflectors are relatively large, from several wavelengths up to over a hundred wavelengths of magnitude, which may be considered as separate continuous reflectors. However, some reflectors are fairly small, even down to one tenth wavelength of magnitude, which may be handled as scatterers.

The forward modelling for reflections in three dimensions can be carried out both for scatterers and for a reflective interface. A variety of scatterer and interface configurations can be considered. The seismic wave propagation process may physically be partitioned into three stages. Firstly, seismic energy is directly radiated from the source. Secondly, the interactions of seismic wavefields occur at heterogeneous regions. Thirdly, the primary (direct) wavefield and the secondary wavefield generated from the heterogenous regions are received at seismic sensors. With this partition in mind, we may calculate synthetic seismograms in two steps.

The seismic source is assumed to be a delta function in both space and time. A good representation of the propagation characteristics can then be achieved by using ray-theory approximations for the requisite Green's function, coupled with a wave-theory implementation of the interaction with heterogeneity. To this approximation, the reflected seismic response at a given receiver can be evaluated for each time step by calculating the contribution of an integral over the current isochronal curve. This approach offers considerable computational advantage over methods which require the evaluation of surface integrals.

The seismograms for any particular source and receiver configurations are recovered by convolving the impulse response with a real band-limited wavelet.

CRUSTAL AND UPPER MANTLE STRUCTURE BENEATH LARGE BASALT-COVERED PLATEAUS AND EXTENSIONAL AREAS OF THE NORTHWESTERN UNITED STATES: IMPLICATIONS FOR LITHOSPHERIC EXTENSIONAL PROCESSES

R.D. Catchings

US Geological Survey, 345 Middlefield Rd,MS 977, Menlo Park, CA 94025 USA

The northwestern United States can be subdivided into three separate tectonic provinces, a fore-arc, arc, and back-arc. Although recent seismicity data reveal a subducting Pacific plate, and an active volcanic arc (Cascades) exists, there appears to be little or no present-day extension in the northern half of the back-arc, while there is continued extension in the southern (northern Basin and Range) part of the back-arc. However, recent seismic refraction data and gravity data show that most of the northern back-arc region has experienced considerable extension as well, and when the seismic data are combined with other geophysical data, it is clear that the back-arc area represents a region of major (tens to hundreds of kilometers of) continental growth.

Although a large part of the arc- to back-arc region is covered by mantle-derived basalts, one of the geologic provinces, the Columbia Plateau, is composed of an unusually large volume of basalt, which covers over 200,000 km^2 and represents the third largest basalt-covered continental province on earth. The seismic data show that the Columbia Plateau is underlain by as much as 6 km of basalt, which has accumulated in deep sub-basalt grabens. Most of the other geologic provinces in east-central Oregon and northeastern California are also underlain by deep (2 to 5 km) sub-basalt basins and block faults, indicative of extension and rifting processes. The northwestern Nevada Basin and Range is also underlain by a discrete zone of continental rifting separate from the province-wide Basin and Range surface extension. Throughout the region, upper crustal basement depressions are underlain at depth by a thickened, high-velocity (7.3 to 7.5 km/s) lower crust, which seismically resembles the lower crust observed in most other continental rift zones. This type of lower crust may represent massive igneous underplating which has thickened the crust and counteracted the crustal thinning caused by extension.

The crustal thickness throughout the region (32 minimum to 41 km maximum) is appreciably thicker than previous estimates (20 minimum to 36 km maximum), and the upper mantle velocities are much greater (8.0 minimum to 8.4 km/s maximum) than previous estimates (7.6 minimum to 7.9 km/s maximum). Comparison of the crustal structure of parts of the northwestern US with other continental back-arc regions reveals similarities in crustal thickness (minus the near-surface sediments and volcanics), velocities and heatflow.

THE PYRENEES FROM ECORS SEISMIC DATA - A FINITE MODEL AND ITS EVOLUTION

Choukroune P., Hirn A., Roure F. and ECORS Pyrenees Team

The 250 km long deep seismic survey across Pyrenees, running from Aquitaine basin to Ebro basin, was operated in 1985 and 1986. This operation was sponsored by French and Spanish organisations (CNRS INSU, SNEAP, ESSO REP, CAYCIT IGME, IGN, and REPSOL). This first seismic survey of an entire orogenic belt crosses the deformed boundary between Iberian and European plates, the geometry of which has been greatly debated during the recent past.

The main results can be summarized as follow :

- The entire crust shows well defined reflectors with a general fan shape geometry.
- The Iberian crust seems to be thicker than the European one. Both are limited by a well-defined deep-layered material above the Moho discontinuity.
- Only the Iberian crust was significantly thickened by a southward overtacking of slabs.
- Near the surface in the external domains, reflectors define accurately the geometry of major thrusts and structures affecting the Mesozoic and Cenozoic cover of the Pyrenees.
- The overall geometry of the belt appears to be a flower structure resulting from an alpine shortening of 100 km.

The section of Pyrenees based upon ECORS data can be structurally balanced and the preorogenic configuration implies a Cretaceous crustal thinning of the European margin as a response to the eastward drift of Iberia along the North Pyrenean transform fault zone. This initial vertical boundary is now deformed, as well as the margins of the implied plates.

SEISMIC CHARACTERISTICS OF TWO EXHUMED SECTIONS OF THE CONTINENTAL CRUST; THE KOHISTAN VOLCANIC ARC (N. PAKISTAN) AND THE LOFOTEN ARCHAEAN SUITE (N. NORWAY)

P.N. Chroston

School of Environmental Sciences, University of East Anglia, Norwich, UK

The Kohistan Volcanic Arc is a Cretaceous arc which was sandwiched between the Indian and Asian continental blocks during the Himalayan collision. A 200 km outcrop along the Karakorum highway shows ultramafics, garnet granulites, pyroxene granulites, amphibolites, dioritic-granitic intrusions and metasediments, and is believed to represent a deep section through the original arc. Seismic velocities have been measured at up to 0.7 GPa confining pressure on samples collected from the principal lithologies in order to reconstruct the original velocity structure of the arc. This enables a comparison with the seismic structure of modern volcanic arcs and with older sections of the continental crust. Problems in the analysis include unravelling the metamorphism and present structure and the assumption of pore pressure and thermal gradients, and a range of possible velocity models can be produced. They show a reconstructed "upper crust" with P-wave velocity of 6.2-6.4 km s^{-1}, which comprises the diorite-granite intrusions, volcanics and sediments. The "lower crust" of amphibolite and pyroxene granulites has velocities of 6.4-6.7 km s^{-1}, though the garnet granulites have a high velocity of about 7.8 km s^{-1}. The documented geological history of the arc also allows an estimate of the way the mean velocities change with the arc's development. Reflection co-efficients in the upper part of the arc are up to 0.06, but are much smaller in the lower part. In the present day tectonic setting seismic anisotropy is associated with the major suture which bounds the north of the arc, but the resulting contribution to the reflection co-efficient is relatively small. The overall velocity structure is broadly comparable to those of modern volcanic arcs. The structure is also compared to that deduced from laboratory measurements on samples from an exhumed Archaean suite from Lofoten, N. Norway. Like the Kohistan Arc, the latter may also have tectonic complications, but on the simplest model this much older section of continental crust shows an "upper crust" with P-wave velocities of 5.9-6.2 km s^{-1} and Poisson's ratio c. 0.21, and "lower crust" of velocity c. 6.6 km s^{-1} and Poisson's ratio of 0.27-0.30. The "lower crust" is more varied here and reflection coefficients within it can be 0.04. However, whereas for the Kohistan Arc the change from seismic "upper" to "lower" crust seems to be predominantly due to the loss of granitic intrusions, in Lofoten it is also marked by a change from amphibolite to granulite facies.

LITHOPROBE - A SCIENTIFIC UPDATE: NEW IMAGES OF THE CONTINENTAL CRUST

Ron M. Clowes

Director, Lithoprobe, University of British Columbia
6339 Stores Road, Vancouver, Canada V6T 2B4
(on behalf of Lithoprobe scientists)

LITHOPROBE, a Canadian earth sciences research program which integrates geophysical, geological and geochemical investigations in a collaborative effort among scientists from universities, government and industry to extend and relate surface geology to structures at depth, is up and running. The Lithoprobe Secretariat is established at UBC; the Lithoprobe Seismic Processing Facility (LSPF) is installed at the University of Calgary. The LSPF includes a CDC Cyber 835 with a MAP V array processor and will use the Cogniseis DISCO seismic software. Access by the Canadian research community will be available through remote site connections. All scientific aspects of the program are in operation. This talk will concentrate on some of the spectacular new images of continental crustal structures that have been obtained and their tectonic significance.

Along the eastern portion of the Southern Cordillera Transect, 270 km of crustal reflection data define the westward extent of autochthonous North American basement (truncated by the crustal scale east-dipping Slocan Lake fault zone), the thickening of Purcell Proterozoic supracrustal rocks by folding and thrusting, and a major compressional shear zone underlying the Valhalla gneiss complex. In mid-1988, seismic profiling will be extended westward across the allochthonous terranes and plutonic complexes to the west coast. In our Appalachian transect, Lithoprobe East, more than 3000 km of marine crustal reflection data have been acquired northeast of Newfoundland and in the Gulf of St Lawrence. The miogeocline above the Grenville basement and the Dunnage and Gander tectonostratigraphic terranes all appear to be allochthonous with respect to lower crustal basement. Intracrustal reflectors on the seismic line run across the continental margin northeast of Newfoundland help determine the nature of extensional tectonics and associated sedimentary basin evolution on the rifted margin. In the Gulf, excellent data show the relationships among Grenville basement and the various terranes.

The GLIMPCE Transect has enabled a glimpse of the mid-continent crust by recording marine reflection data in the Great Lakes. The sections from Lake Superior reveal 10 km of sediments overlying a 20 km thick sequence of strongly reflective volcanics and inter-flow sediments, perhaps representing the greatest vertical extent of intra-continental rift deposits on Earth. The original Archean/Early Proterozoic crust is greatly thinned beneath the rift basin. In the Lake Huron/Georgian Bay profile, the Grenville Front is imaged as the westernmost reflection of a spectacular 70 km wide band of southeast dipping reflections that clearly truncates prominent sub-horizontal crustal reflections of the Superior granite-rhyolite terrane on the west.

The Kapuskasing Structure Zone is a sequence of lower crustal rocks that have been thrust upward along the Ivanhoe Lake cataclastic zone and are now exposed at the surface. As part of the Kapuskasing Transect, 340 km of regional deep reflection data and 20 km of 'high resolution' data (20 m station spacing, 40 m source interval, and a higher sweep range) over the cataclastic zone were recorded in 1987-88. The Abitibi sub-province of Ontario and Quebec contains mineralized greenstone belts for which it is famous. As a prelude to the Abitibi-Grenville Transect, a preliminary program consisting of 130 km of regional and 65 km of high resolution seismic profiles also were recorded in 1987-88. These were centred over major fault zones, to which much of the mineralization is related.

THE STRUCTURE AND TECTONIC HISTORY OF THE WESTERN CANADA SUBDUCTION ZONE

R.M. Clowes[1], R.D. Hyndman[2], C.J. Yorath[2] and E.E. Davis[2]

1 Lithoprobe, 6339 Stores Road, University of British Columbia, Vancouver, Canada V6T 2B4

2 Pacific Geoscience Centre, Geological Survey of Canada, P.O. Box 6000, Sidney, BC, Canada V8L 4B2

As part of the Lithoprobe multidisciplinary earth sciences research program, multichannel seismic profiles from the deep ocean to the continental shelf and on Vancouver Island, coupled with a wide range of other geophysical and geological studies, have permitted detailed delineation of the structure and tectonic history of the Juan de Fuca subduction zone in western Canada. The modern continental margin was built against a pre-Tertiary continent consisting of an amalgamation of older terranes, the oldest and westernmost being Wrangellia. No pre-Eocene continental margin record exists and transform fault displacement of margin rocks north to Alaska is inferred. Eocene subduction was interrupted by a seaward jump in the trench axis in latest Eocene, trapping a section of marine volcanics (Crescent Terrane), together with sections of Mesozoic marine sedimentary rocks (Pacific Rim Terrane). These were placed against and under the margin on steeply dipping thrust faults that are well imaged in the seismic reflection data. The terrane positions are also well delineated by magnetic and gravity data. Seaward and underlying the Crescent Terrane is the modern accretionary prism, which is up to 100 km wide. Development of the deformation front at the seaward limit of the prism is clearly shown by landward and seaward verging faults in the sediments overlying the basaltic oceanic crust. SeaMARC II acoustic images illustrate the surficial effects at the deformation front. Beneath the deep ocean, the continental shelf and the western part of Vancouver Island, the top of the downgoing oceanic plate is imaged well by a one or two cycle continuous reflection at depths which are consistent with those determined for the top of the plate from seismic refraction data and Wadati-Benioff zone earthquakes. Above the subducting slab, two broad bands of high reflectivity dip beneath Vancouver Island at angles less than that of the slab. The deeper band coincides with a dipping layer of high conductivity interpreted from a magnetotelluric survey. On the basis of profile heat flow measurements which were converted to isotherms, this layer is isothermal at about 450^{o}. One tectonic model for the origin of the reflective bands suggests that they are thick sections of underplated volcanic and sedimentary material, the lower one of which would be saturated with hot saline fluids. An alternative interpretation, supported particularly by the dipping isotherms, suggests that the lower band is caused by fluids that are driven off the downgoing oceanic plate, and are trapped below an impermeable horizon formed at a metamorphic front.

DEEP SEISMIC REFLECTION STUDIES OF THE CONJUGATE SOUTHEAST AUSTRALIA AND LORD HOWE RISE MARGINS: PRELIMINARY RESULTS

M.F. Coffin, R. Whitworth, S. Kravis, and C. Johnston

Division of Marine Geosciences and Petroleum Geology,
Bureau of Mineral Resources, Geology and Geophysics,
GPO Box 378, Canberra, ACT 2601, Australia

The Gippsland Basin and the Lord Howe Rise are conjugate continental margins separated by the Tasman Basin. Rifting began in the Cretaceous , and the Tasman Basin was created by seafloor spreading between magnetic anomaly 33 (~80 m.y.) and 24 (~52 m.y.) time. In February and March of 1988 the Bureau of Mineral Resources, Geology and Geophysics (Australia) ship R/V RIG SEISMIC acquired the first deep seismic reflection data across the conjugate margins and Tasman Basin. The maximum source array consisted of 20 airguns with a composite volume of 52.4 litres. Maximum receiver length was 4400 metres, and consisted of 88 50-metre channels. Other data acquired include sonobuoy wide-angle reflection and refraction, gravity, magnetics, and bathymetry.

The major objectives of our studies are: 1) to define the structure of the continent-ocean transition in the crust beneath the Lord Howe Rise margin and its conjugate on the Gippsland Basin margin; 2) to determine the rift and breakup history of the crust at the continental margin; 3) to relate continental and oceanic crustal kinematics; 4) to evaluate conceptual, e.g. pure and simple shear, models of margin evolution. We present selected geophysical profiles and our preliminary results and interpretations herewith.

SEISMIC REFLECTION CRUSTAL STRUCTURE IN THE NORTHWESTERN CANADIAN ARCTIC

Frederick A. Cook and Kevin C. Coflin

Department of Geology and Geophysics, University of Calgary, Calgary, Alberta Canada T2N 1N4

Crustal seismic reflection data, acquired through the Geological Survey of Canada Frontier Geoscience Program as well as through petroleum industry operations in the northwestern Canadian arctic, have revealed surprising results bearing on the structure of the northwestern portion of the Canadian shield and adjacent Beaufort Sea margin. Among these are: 1) the discovery of an east-verging compressional orogen of probable middle Proterozoic age situated beneath the Interior Plains between the Beaufort Sea and the exposed portion of the Canadian shield, 2) the discovery of a north-dipping crustal-scale basement ramp structure on the southeast margin of the Beaufort sea that was probably formed during the Proterozoic, but that was reactivated during Upper Devonian (Ellesmerian) compression and again during Mesozoic extension, 3) Ellesmerian compressional structures beneath the southeast margin of the Beaufort Sea that are probably linked to the Ellesmerian orogen in the Arctic Islands, and 4) a highly reflective upper (10-20 km) crust that includes Proterozoic sediments and volcanics. In most areas, the observations record a protracted history of both extensional and compressional features that were reactivated during subsequent deformational periods.

THREE-DIMENSIONAL IMAGING OF CRUSTAL STRUCTURE IN THE NORTHWESTERN CANADIAN ARCTIC

Frederick A. Cook and Kevin C. Coflin

Department of Geology and Geophysics, University of Calgary,
Calgary, Alberta, Canada T2N In4

Areal three-dimensional crustal seismic reflection data acquired near the Mackenzie Delta in northwestern Canada exhibit reflections to about 12.0 s travel time. The data were recorded along a 12.0 km receiver line as Vibroseis (trademark Conoco) units were moved along a 24.0 km perpendicular line. Vibration points were spaced 200 m apart, and receiver stations were spaced 100 m. The resulting data set consists of an area of common depth point coverage that is approximately 6.0 by 12.0 km and includes 14,521 traces. The data quality is very good, with strong dipping reflections visible to about 8.0 s travel time, and horizontal reflections visible at about 12.0 s travel time. Processing of the data has included gathering into 100 m x 200 m bins, 4-fold stacking, and migration. Reflections between the surface and 7.0 s travel time are from Proterozoic strata that rest on basement. Analysis of the three-dimensional geometry shows that the structural deformation of the Proterozoic and Palaeozoic strata is at a significantly different orientation from that of the basement surface, a difference that is most likely due to deformation during the Late Devonian. This geometry is not easily determined from the two perpendicular lines alone, and suggests that such areal surveys may be valuable in furthering our understanding of crustal tectonics elsewhere.

DIGITAL RECORDING AND SEISMIC PROFILES IN BASS STRAIT

J.P. Cull[1], C.D.N. Collins[2], and G.S. Lister[1]

1. Department of Earth Sciences, Monash University, Clayton
2. Bureau of Mineral Resources, Canberra, ACT

Lithosphere stretching has been proposed by McKenzie (1978) to explain the evolution of sedimentary basins characterised by thinning, rifting, and subsidence of the total crustal section. Similar models may be appropriate to the Bass and Gippsland Basins in Australia. However, the diagnostic detachment faults are difficult to recognise using conventional seismic reflection profiles. Interpretations may be improved by generating data in traverses normal to the postulated transfer faults which divide the extending terrane into uniform compartments (Etheridge et al. 1985).

A dual airgun array totalling 3200 cubic inches has been deployed by the Bureau of Mineral Resources to provide longer reflection records than previously available in an attempt to penetrate to the presumed zones of detachment. However the final interpretation can be greatly improved using seismic refraction data for estimates of section velocity. Normally charges exceeding 1 tonne of TNT equivalent are required for this purpose; at least two orders of magnitude greater than the power of the airgun array.

A digital recording system has now been developed to improve airgun data obtained at long range. Novel stacking techniques are essential to compensate for phase migration related to linear changes in ship position during any run. All data are obtained on a portable CPU at 50 samples/s before transfer to disc. Continuous records exceeding 10 minutes duration can be obtained using DMA independant of the ship schedule. New duty cycles can be initiated automatically with dwell times less than 6 s prior to final archive on magnetic tape.

Stacking can proceed only when shot times are accurately established and corrections are required to compensate for any change in ship position. In general a linear correction is considered to be sufficient. Sensitivity has been established directly using quarry blasts for calibration and for comparison with standard analogue instruments. Similar techniques have been employed in Swedish fiords, but noise levels in Bass Strait present a more formidable challenge.

STATIC CORRECTIONS ON CRYSTALLINE ROCK

Trine Dahl-Jensen

University of Uppsala

Static corrections for reflection seismic data shot directly on high-velocity crystalline rock can be calculated directly from the data using an iterative stackpower optimization. The sequence of the parameters (the static corrections) within each iteration is of importance for the result, as the multiple-period nature of the reflections create maxima in the stackpower in a cyclic manner, only slightly smaller than the stackpower of the 'best' stack. By using a random sequence of parameters in the iteration, the ability for a set of parameters and the associated stackpower to move from a local maximum to a larger one is enhanced, thus diminishing the risk of misalignment of traces by using the wrong peak in the multiple period signal. The method is illustrated by a synthetic example, as well as on a data set shot on the granites of Dalarna, Sweden.

FIRST DEEP SEISMIC RESULTS FROM THE SCANDINAVIAN CALEDONIDES

Trine Dahl-Jensen[1], Dan Dyrelius[1], Charles Hurich[2], Yngve Kristoffersen[2], Jonas Lindgren[1], Hans Palm[1]

1. Department of Solid Earth Physics, University of Uppsala, Sweden
2. Seismological Observatory, University of Bergen, Norway

The central Scandinavian Caledonides have been chosen for reflection seismic profiling within the framework of a Central Scandinavian Geotransect. An almost continuous land profile across the Scandinavian mountain belt with a length of at least 100 km is planned for the period 1987-1989. One main purpose of the reflection programme is to investigate the extent of basement activation in the Caledonian Orogen. The Scandinavian Caledonides are suitable for studies of deep structures since the cover is deeply eroded and has escaped post-Caledonian overprints.

In 1987 two profile segments were shot close to the Swedish-Norwegian border. Both the seismic profiles show reflections in a geometrical pattern that resembles a cross section through a stack of thrust sheets. These laterally continuous reflections are seen down to 6 s TWT, indicating a Caledonian activity down to at least 20 km. The reflections occur as discrete zones bounding transparent zones, and those reflectors that project to the surface can be directly associated with outcrops of mylonites along the profiles. We interpret the reflections as tectonic boundaries. By an eastward continuation of the profile in 1988 we attempt to resolve whether the tectonic boundaries are solely within the Precambrian crystalline basement, or include buried basement-metasediment sequences. The plans for 1988 also include a better understanding of the tectonostratigraphy in the central parts of the Caledonian Orogen.

ECORS EXPERIENCE ON EXPLOSIVE VERSUS VIBRATORS MULTI-OFFSET SEISMIC RECORDING - A FEW EXAMPLES

B. Damotte

IFP ECORS

In the Paris Basin, France, the ECORS program has recorded a deep seismic profile using 2 different sources: vibrators and explosive charges, both of them using the same in-line spread. The explosive source first implemented for refraction surveying, has been, in addition, exploited by recording data for 20 s and by using a very long spread (45 km). The results show that the two techniques are complementary. The vibroseismic 96-fold technique shows a layered lower crust with a good seismic quality on two-thirds of the profile. The explosive seismic, theoretically 3-fold, has been exploited as 3 single sections. More reflections are visible on these explosive sections, especially in the part where the quality of the vibroseismic data is bad. We can explain this difference because, in the latter area, a distorted overthrust formation exists near the surface. Crossing this further, the seismic rays are deformed and the CDP stack is not efficient. Another difference between the results concerns the extension through the lower crust of a fault well known at the surface. The vibroseis image suggests that this fault exists through the crust, whereas the image of the single explosive section does not show the fault. We can conclude that using CDP technique is not always helpful, and that, in this particular case, the use of only a vibroseis source might give an erroneous interpretation.

CRUSTAL SEISMIC MEASUREMENTS ACROSS THE CONVERGENT PLATE BOUNDARY, NORTH ISLAND, NEW ZEALAND

F.J. Davey, T. Stern

Geophysics Division, DSIR, Wellington, New Zealand

Deep seismic reflection measurements, using standard oil industry techniques, have been made across the convergent Australia-Pacific plate boundary through southern North Island, New Zealand. Reflections were recorded to depth of up to 40 km from the top of the subducting Pacific plate under the accretionary wedge and the downwarped back-arc region further east (Wanganui basin). The reflections correspond closely with the top of a zone of high seismicity interpreted as occurring within the upper part of the subducted plate. Layered reflection sequences correspond to the lower crust and Moho of the overlying Australian plate to the east, but are discontinuous spatially with few deeper reflections occurring in the vicinity of major faults through this area. The Moho of this part of the Australian plate dips to the east, towards the back-arc (Wanganui) basin, but appears to shoal markedly (faulted?) along the line of the Taranaki fault zone which forms the western margin of the back-arc basin.

MANTLE UPWELLING, LITHOSPHERIC THINNING AND RIFTING

Geoffrey F. Davies

Research School of Earth Sciences, Australian National University
GPO Box 4, Canberra, ACT 2601, Australia

Recent developments in understanding mantle convection suggest that there are two distinct modes of mantle upwelling. Narrow upwelling mantle plumes are clearly implied by the swells surrounding oceanic hotspots. These swells are about 1 km high and 1000 km across and the plume itself is probably less than 100 km in diameter. Such plumes almost certainly arise from instabilities in a hot boundary layer at the base of the mantle flow.

There are also larger areas, like the southeast Pacific, Africa and possibly the western Pacific, which seem to be several hundred meters higher than expected. Small variations in mantle temperature away from the thermal boundary layers are an inevitable part of mantle convection, and models show that they can cause surface topography with such amplitudes. Warm, broadly upwelling mantle regions will develop in the absence of subduction, a condition enhanced by the presence of a supercontinent. The resulting surface uplift has been termed a mantle superswell, to distinguish it from a hotspot swell.

Hotspots have clearly been associated with continental breakups, but they seem to be too small in scale to be the obvious cause. Calculations of thermal-mechanical thinning of lithosphere by mantle upwelling show that the lithosphere could be thinned by tens of kilometres in a few million years by a plume, but the rate of thinning is much slower for upwellings of larger horizontal scale. This suggests that both plumes and superswells may be involved in major rifts : plumes may weaken the lithosphere and allow the superswell stresses, which would be of continental extent, to rift it. Plumes are expected to occur in greater numbers in regions of warm mantle, and indeed hotspots are concentrated in the Pacific and Africa where there is strong evidence for warmer mantle at depth.

A combination of plumes and a superswell would imply localised uplifts of kilometre amplitudes superimposed on a continent-scale uplift of hundreds of metres. As breakup proceeded, the new continental margins would slide off the hotspot swells on a time scale of 10 Ma, but would take much longer to slide off the superswell. Thus a relatively rapid phase of subsidence would be followed by a slower subsidence which will be difficult to distinguish from subsidence due to conductive cooling of the lithosphere, which may also be occurring. The best discriminant may be a broader area of emergence during rifting than can be explained by hotspot swells.

TELESEISMIC TOMOGRAPHIC DETERMINATION OF LATERAL VARIATION IN VELOCITY OF THE CRUST AND UPPER MANTLE BENEATH THE EAST AFRICAN AND RIO GRANDE RIFTS

Paul M. Davis[1], Hans-Albert Dahleim[1], Ulrich Achauer[2], H.M. Iyer[3], and Ken H. Olsen[4]

1. Department of Earth and Space Sciences, UCLA, Los Angeles CA 90024, US
2. University of Karlsruhe, Karlsruhe, W. Germany
3. US Geological Survey, Menlo Park CA 94025, US
4. Los Alamos National Laboratory, Los Alamos NM 87545 US

We report on the results from three teleseismic experiments on the Rio Grande rift and an analagous experiment on the East African rift, Kenya.

A line run in 1983 crossed the Rio Grande rift at Santa Fe and extended 500 km either side. A second line in 1985 crossed 150 km north at Alamosa and a third, recently completed in late 1987, ran through the southern rift at Socorro. The combined data gives us an effective array aperture of 600 x 800 km spanning the rift. Tomographic analysis of travel time residuals combined with refraction and reflection data, provides an image of the regional thinning of the crust and lithosphere beneath the rift. The single line we have run in Africa, 600 km long crossing the rift in the vicinity of Nairobi, yields similar results. An extension of this experiment, KRISP 88 (Kenya Rift International Seismic Project), will take place later this year which will involve installation of a multi-national teleseismic array of 100 stations and extensive refraction profiling.

Several lines of evidence indicate partial melt is responsible for the low velocities beneath the thinned lithosphere. The velocity contrast is too large to be explained by sub-solidus thermal effects: the ratio of the density contrast as determined from gravity to the velocity contrast is smaller (1/4) than expected for differing rock types from, for example, the Nafe-Drake relation; spectral analysis of the teleseismic waveforms is consistent with high attenuation beneath the rifts; the region has high electrical conductivity; the presence of volcanism with zenoliths from depths as great as 75 km supports the existence of deep partial melt reservoirs. These results place bounds on the energy budget for the rifting process needed to resolve the controversy as to whether rifting is driven by active or passive processes.

VELOCITY STRUCTURE OF THE CRUST AND UPPER MANTLE BENEATH THE LONG VALLEY CALDERA, CALIFORNIA

P.B. Dawson and H.M. Iyer

US Geological Survey, Menlo Park, California, USA

Long Valley caldera, California, is one of several large volcanic centers which currently show signs of seismic and volcanic activity. Several major seismic swarms and uplift of the central resurgent dome during the past decade have prompted many efforts to delineate the magmatic source beneath the caldera. In one specific experiment the US Geological Survey deployed 61 seismic stations over a 45 x 70 km area to record teleseismic P waves and measure traveltime residuals. We inverted the traveltime residuals using the method of Aki, Christoffersson, and Husebye (1977) to obtain an image of the three-dimensional velocity structure to depths of 70 km beneath the array. Resolution of velocity anomalies using this method is about 5 to 6 km. The direct inversion of these data indicated that the 2 to 3 km thick low-velocity caldera fill was contaminating the signal from any mid-crustal velocity anomalies beneath the caldera. Thus, two methods were used to strip the effects of the upper crust from the traveltime residuals : 1) ray tracing through the upper crustal velocity structure provided by seismic refraction experiments, and 2) a multiple iterative stripping scheme using the inversion itself. Both the methods adequately removed the effects of the upper crustal structures. The resulting "stripped" models show two well resolved mid-crustal low-velocity bodies in the Long Valley region. One of the bodies is centered between 10 and 20 km beneath the Mono Craters volcanic center 10 km north of Long Valley, and has a volume of 200 to 600 km^3. The second body occurs at a similar depth beneath the western portion of the resurgent dome in Long Valley caldera and has a volume of about 200 to 300 km^3. The velocity contrasts in both of these bodies are about 6 to 10%, and the features are interpreted as silicic partial melts. It is apparent that no large coherent magma chamber is now present beneath the Long Valley caldera, and it is possible that the resurgent dome anomaly is the final remnant of the caldera-forming magma chamber. The larger low-velocity body beneath the Mono Craters, which are younger than Long Valley, suggests that the focus of volcanism has shifted north from Long Valley to beneath the Mono Craters.

ANALYSIS OF DEEP SEISMIC REFLECTION DATA IN A 3-D EARTH

Beartrice De Voogd and Catharine Dickie

Survey of Canada, Bedford Institute of Oceanography,
Box 1006, Dartmouth, Nova Scotia, B2Y 4A2, Canada

The Grand Banks of Eastern Canada are dissected by a series of normal and transfer faults, resulting in a complex pattern of eep (up to 22 km) troughs and basement highs. Deep seismic reflection profiles of such structures will undoubtedly be affected by severe velocity pull-down effects and side-swipes (i.e., arrivals from off the plane of section), which are a source of serious interpretational pitfalls. In the absence of crustal scale 3-D profiling and 3-D depth migration, forward modeling is an efficient approach that enables the interpreter to quantitatively evaluate velocity and side-swipe effects. Selected examples of how ray-tracing constrains the interpretation of Lithoprobe-East profiles will be presented. Three-dimensional models were created based on preliminary interpretation of the seismic profiles and available drill-hole information, and synthetic seismic sections were generated for comparison with the data. This three-dimensional ray-tracing was performed with Sierra Geophysics Inc. modeling software. The extensive grid of released conventional industry data existing in the area of study was used to constrain the interpretation in the shallow part of the crust. Perspective views illustrate the three-dimensionality of crustal structures. Ray-tracing helped recognize side-swipes on the seismic sections. Major results include mapping of an intra-basement reflector, better constraints on fault geometry (down to Moho depth), and more accurate knowledge of the geometry of deep structures at the continent-ocean boundary.

INHERITED STRUCTURES, DEEP FAULT GEOMETRY AND BASIN STRUCTURAL STYLES IN EASTERN OFFSHORE CANADA

Beartrice De Voogd, Charlotte Keen, and William Kay,

Geological Survey of Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, B2Y 4A2, Canada

The Mesozoic basins of the Grand Banks of Eastern Canada were a primary focus of two campaigns of deep seismic reflection profiling (1985 and 1987) that straddled the region between the Bonavista platform to the west, and the rifted continental margin to the east. As rifting of the North Atlantic progressed northward, several episodes of extension of differing orientations dissected the pre-Mesozoic basement. Pre-existing structures may also have played a role to produce the present-day mosaic of basins and basement highs. Four of the seismic profiles intersect each other near the western edge of the 22 km deep Jeanne d'Arc basin, thereby giving a three-dimensional picture of basement structures. Reactivation of older structural fabrics would be documented in this region, where the basin-bounding fault which marks the eastern edge of the Bonavista platform appears to follow a pre-existing fault system. The jagged edge of the Bonavista platform may be one expression of transfer faults trending obliquely to the normal faults that bound the basins. A puzzling basement ridge trends north-northeast away from the Bonavista platform. It is a narrow ridge, flanked on either side by a deep Mesozoic sedimentary basin. The South Jeanne d'Arc basin is a half-graben, where fault geometry is constrained all the way to Moho depth (about 30 km). The normal fault along which the half-graben was created has an average dip of about 26^{o} to 30^{o} within most of the crust, and appears to flatten at Moho depth. Lower crustal and Moho reflections are observed on most profiles. Large, moderately dipping normal faults that terminate in the lower crust or at Moho depth appear to be the dominant tectonic elements of this region.

INVERSION OF LOVE AND RAYLEIGH WAVES

Lawrence A. Drake

School of Earth Sciences, Macquarie University, NSW 2109

Ocean bottom seismometers with broadband recording are being operated at continental boundaries and in island arc regions. Amplitude and phase measurements, particularly of Love and Rayleigh waves, have become available, and there is a need for computation of wave propagation across realistic models of continental boundaries and island arc regions, first, because the structure of continental shelves is important economically and, secondly, because inversion of uppermost mantle structure is usually done from Love and Rayleigh waves which have traversed at least one continental boundary or island-arc region. The finite-element method in the frequency domain is appropriate for computation of wave propagation across realistic models of these regions, both because the elements can be fitted to irregular geological structure and because absorption in the ocean, crust and uppermost mantle of the Earth can be readily allowed for.

A study by finite-element modelling of Love and Rayleigh waves of periods from 10 s to 60 s propagating normally to the coast of northern California near the Berkeley seismographic stations has shown that, in general, the mean slownesses of these waves across the continental boundary are slightly less than the means of the slownesses of the Love and Rayleigh waves in the oceanic and continental regions. Because the finite-element model of the continental boundary was of predominantly oceanic structure, it is clear that phase advance depends on the material properties of the region of the boundary and not on its irregular structure. Regarding amplitude calculations, at the shorter periods, Love waves are strongly forward scattered into higher Love modes, whereas at a period of 20 s, 95 percent of the energy of Rayleigh waves is transmitted as the Rayleigh fundamental mode.

Study of the Japan subduction zone ESE of the island of Honshu has shown that Love waves increase in slowness across the region, whereas Rayleigh waves of periods from 35 s to 60 s decrease in slowness. Again the material properties of the predominantly crustal material being subducted slow the Love waves, whereas the Rayleigh waves of periods of from 35 s to 60 s tend to retain their oceanic velocities, which are higher than the velocities of Rayleigh waves of those periods for the island of Honshu. Amplitude calculations have shown similar results to those for the continental boundary of northern California.

Study of the New Zealand subduction zone SE of Lake Taupo on the North Island of New Zealand has shown similar results to those for the Japan subduction zone, except that at periods below 20 s much more energy of the Love and Rayleigh waves is transmitted.

DEEP STRUCTURE OF THE CELTIC SEA AND WESTERN APPROACHES: A DISCUSSION ABOUT THE FORMATION OF BASINS

Jerome Dyment[1], Jean-Claude Sibuet[2] and Bertrand Pinet[3]

1 Institut de Physiqaue du Globe, 67084 Strasbourg, France
2 IFREMER, Centre de Brest, 29273 Brest, France
3 Institut Francais du Petrole, 92506 Rueil-Malmaison, France

The SWAT (South-Western Approaches Traverse) deep seismic reflection profiles, acquired in the Celtic Sea and Western Approaches by BIRPS in cooperation with ECORS, enable examination of the whole crust in this area. Deep Meso-Cenozoic basins are underlain by the transparent upper crust and reflective lower crust. The upper crust or both the upper and lower crusts, are cut across by some dipping reflectors which are related to Variscan thrusts. One of these thrusts, the Variscan Front, has been considered as a detachment fault which could have initiated the North Celtic Sea basin. However, this hypothesis is not consistent with the obliquity of the Front with respect to the orientation of the basin's depocenter and the existence of normal faults which probably cut across the Front and controlled the subsidence history of the basin.

In the absence of refraction data, we used two-dimensional gravimetric modelling (with isostatic equilibrium) to ascertain the depth of the Moho. This modelling shows that the gravimetric Moho is coincident (within 1 km) with the base of the reflective lower crust.

The resulting depth sections display the flatness of the Moho and the relative isopacity of the lower crust. The thinning coefficients of the whole continental crust and the stretching coefficients, obtained by comparison of theoretical and computed (backstripping method) subsidence curves, are significantly different.

We suggest three different hypotheses to explain this large gap:
1. post-extensional crustal underplating,
2. extensional processes on a previously thickened crust,
3. mechanisms not related to lithospheric stretching.

A comparison is made with the deep structure of the nearly passive margins of Goban Spur and Northern Bay of Biscay, where extensive crustal thinning is observed in relation to the opening of the North Atlantic domain during Cretaceous times.

SEISMIC PROBING OF THE EASTERN NEWFOUNDLAND CONTINENTAL MARGIN (EAST COAST CANADA): CONTINENT-OCEAN TRANSITION ZONE

M.E. Enachescu

Husky Oil Operations Ltd., PO Box 6525, Station 'D', Calgary, Alberta, Canada, T2P 3G7

The continent-ocean transition zone is the result of successful rifting between two major plates. When the Grand Banks of Newfoundland and Iberia Shelf separated in the Early Cretaceous, two strips of sediment starved basins formed on the transitional zones of the opposing Atlantic margins. The Newfoundland oceanic basin is now located on the western Atlantic slope and rise. This basin is not only floored by oceanic crust, but also by remnants of continental crust and a transition zone of a mixed nature. Previous investigations ignored the transitional character of most of this ancient break-up zone. Usually, a narrow boundary was defined as the contact between continental and oceanic crust. This boundary is often associated with either the first clear magnetic lineation, the base of the slope, or a landward dipping reflection interpreted as magmatic underplating. This paper suggests that between true continental and oceanic crust must always exist a transitional zone formed by thinned and subsided continental blocks which were intruded, flooded, and partially digested by mantle-derived basaltic material. The width of this conspicuous zone can vary between hundreds of metres to several tens of kilometres. This continental basement, attenuated and masked by volcanics, must be accounted for when plate tectonic paleoreconstructions are made.

SEISMIC PROBING OF THE EASTERN NEWFOUNDLAND CONTINENTAL MARGIN (EAST COAST CANADA): EXTENT OF THE MESOZOIC RIFT SYSTEM

M.E. Enachescu

Husky Oil Operations, Calgary, Alberta, Canada.

The modern seismic data base covering the Atlantic passive margin off Newfoundland consists of over 200,000 km of industry-migrated data of various post-1979 vintages, an 11,000 km, 200 m spaced exploration 3D survey, and four deep seismic reflection profiles totalling over 2600 km. These data suggest that the offshore Mesozoic basins were formed by extension along a major eastward dipping Wernicke type of crustal detachment.

The Newfoundland offshore basins were initiated during the Tethys rifting phase (Late Jurassic-Early Cretaceous) and resubjected to extension during the subsequent North Atlantic (Late Jurassic-Early Cretaceous) and Labrador Sea (Late Cretaceous) rifting episodes. The landward limit of the hydrocarbon prone system of basins is marked by the intersection between the shallower part of the intracrustal detachment plane and the surface of the post-extensional regional Avalon unconformity. The oceanward extent is more elusive, being indicated on the shelf by continental-crust cored outer highs and, on the rise, by the incidence of volcanics associated with the oceanic crust.

THE TECTONIC AND STRUCTURAL FRAMEWORK OF THE EASTERN NEWFOUNDLAND CONTINENTAL MARGIN

M.E. Enachescu

Husky Oil Operations Ltd, PO Box 6525,Station 'D', Calgary, Alberta, Canada, T2P 3G7

The eastern Newfoundland continental margin (East Coast of Canada) is primarily an intracontinental failed rift with a complex Mesozoic extensional history, followed by a structurally mild phase of post-rift Late Cretaceous-Tertiary subsidence. The basement, consisting of Precambrian metamorphic, Paleozoic metasediments and pre-rift igneous rocks, underwent extensive block faulting and erosion during the onset of rifting. The complete basinal sedimentary sequence includes: (1) extensional stage sedimentary rocks, represented by an Upper Triassic-Lower Jurassic syn-rift section, overlain by Lower Jurassic-Lower Cretaceous failed rift deposits; (2) thermal subsidence stage sedimentary rocks, represented by uniform Upper Cretaceous and Tertiary marine deposits. The maximum thickness of sediments, over 20 km, is found in the Jeanne d'Arc Basin, east of the Hibernia oil field.

Development of the extensional terrain off Newfoundland, initially took place on a Late Triassic basement fault, which subsequently became the crustal plate detachment. This down-to-the east detachment fault and its associated listric synthetic and antithetic faults are responsible for the creation of half-grabens and ridges on a regional scale, and folds, reverse drag features, rollovers and tilted blocks on a local scale. The intricate contemporary distribution of the structural provinces and tectonic elements is the result of multiphase lithospheric extension along rotational listric faults, coupled with offsets of crustal blocks across transfer faults. Both phenomena were coeval with various stages of the Atlantic opening and segmentation. The basement and sedimentary infill were subjected to successive extensional episodes associated with: a) the Tethyan rift (Late Triassic-Early Jurassic); b) the North Atlantic rift and separation (Late Jurassic-Early Cretaceous); and c) the Labrador-Greenland rifting (Mid-Late Cretaceous). Additional local structural and depositional complications were triggered by halokinesis and extensional halotectonics.

Several topics resulting from the Newfoundland offshore study which can be related to similar passive margin basinal areas (e.g. southeastern Australia) are still controversial. Among these are: the dipping direction of the crustal detachment, the change in polarity of the bounding fault, the incidence and density of transfer faults and accommodation zones, the nature of intrabasinal highs, the importance of reactivation of older zones of weakness as rift bounding faults, the position of Moho beneath rifted areas, and the location and nature of the continent-ocean transition zone. This poster uses the offshore Newfoundland tectonic and structural framework to illustrate these controversial topics and is intended to stimulate debate.

ACQUISITION AND PROCESSING OF MARINE DEEP SEISMIC REFLECTION DATA COLLECTED OFFSHORE NEWFOUNDLAND, EAST COAST CANADA

M.E. Enachescu[1] and Neil Baker[2]

1. Husky Oil Operations Ltd, PO Box 6525,Station 'D', Calgary, Alberta, Canada, T2P 3G7
2. Geophysical Service Inc., 906 - 12 Avenue SW, Calgary, Alberta, Canada, T2R 1K7

The continental margin surrounding the island of Newfoundland, which developed during several Wilson cycles of accretion and extension, has been recognized as a perfect ground for testing various plate tectonic models. A large geophysical and geological data base from industry has existed in the area, but only in the last few years have deep reflection profiles been added, in order to investigate the evolution in depth of the major tectonic lineaments and structural units.

A 430 km long deep-reflection seismic line crossing the Appalachian Orogen was shot in order to correlate Newfoundland's surface geology with the deep crustal seismic structure. Four other lines, totalling 2200 km, were located over the eastern continental shelf, slope, and rise, to investigate the seismic response of the Mesozoic rift system, the continent-ocean transition zone, and the oceanic basin floored by basalts.

The acquisition of deep marine reflection data differs little from the standard industry method, except for the length of recording (up to 20 s). However, the recorded data require special processing and adequate structural display.

ACTIVE-SOURCE HIGH RESOLUTION THREE-DIMENSIONAL IMAGING OF NEWBERRY AND MEDICINE LAKE VOLCANOES, CASCADE RANGE

John R. Evans and H.M. Iyer

US Geological Survey, Menlo Park, California, USA

We determine compressional-wave velocity structure for the upper crust Newberry Volcano, central Oregon, and Medicine Lake Volcano, northern California, using a high-resolution active-source seismic-tomography method. Both volcanoes are bimodal shields east of the axis of the Cascade Range, have summit calderas, are dominantly mafic, and have Holocene rhyolitic flows in the summit region. Each volcano has been studied with numerous methods, but no structures thought to be magma chambers have been found. Our experiments were designed to test the hypothesis that this kind of volcano is underlain only by magma chambers less than about 5 km across.

We placed 120 and 140 instruments (1.5 km spacing), respectively, over the summit region of each volcano, and detonated a series of chemical-explosive sources 30 to 80 km from the summit. High-frequency (c. 7 Hz) crustal phases travelled to the seismograph arrays upward through target volumes beneath the summits. By using sources well distributed in azimuth around the volcanoes we generated dense homogeneous distributions of rays in these summit target volumes. Travel times of these rays are inverted to obtain velocity structure. In this case we used the "ACH" inversion method. This arrangement yields 1- to 2 km resolution (limited by station spacing) in the upper 5 to 6 km of the crust beneath the volcano's summit caldera.

A small low-velocity anomaly delineated about 3 km below each summit caldera supports the small-chamber hypothesis. Each anomaly is interpreted as a possible magma chamber of a few to a few tens of km^3 in volume. At Newberry, a ring-shaped high-velocity anomaly lies between the magma chamber and the surface, coincident with the inner ring fractures of the caldera. It also coincides with an annular gravity high and the vents of several Holocene silicic flows. Hence we interpret it as largely sub-solidus silicic cone sheets. At Medicine Lake, the low-velocoty anomaly is overlain by a horizontal disk shaped high-velocity feature. The disk is east-west elongate and appears to extend east of the caldera to the youngest silicic vents on the volcano. It also strikes parallel to a linear highland that extends from Medicine Lake Volcano to Mount Shasta. Both the highland and the high-velocity anomaly strike perpendicularly to the normal faulting in this region. Hence, we believe these features are controlled by an upper crustal weakness predating Basin and Range faulting. Medicine Lake's high-velocity anomaly suggests an east-west intrusion path from the magma chamber to nearly coeval Holocene silicic vents just east and west of the caldera.

DEEP SEISMIC TRANSECTS ACROSS THE SHEARED WESTERN BARENTS SEA CONTINENTAL MARGIN

Jan Inge Faleide, Steinar T. Gudlaugsson, Ruth Jackson, Annik M. Myhre and Olav Eldholm

Department of Geology, University of Oslo, Norway

Deep seismic reflection and expanded spread refraction profiles constitute crustal transects across the sheared western continental margin of the Barents Sea, which developed in response to the Cenozoic opening of the Norwegian-Greenland Sea. Regionally, the margin is composed of two large shear zones and a central rifted margin segment associated with volcanism. The continent-ocean crustal transition is clear and occurs in a narrow zone (10-20 km) at the sheared margin segments, but is more obscure and partly masked by volcanics at the rifted margin. The crustal structure varies significantly between the two sheared margin segments. In the north, across the Hornsund Fault Zone, the crustal thickness changes abruptly from a continental crust more than 30 km thick on the 3valbard Platform to an oceanic crust 6-8 km thick in the Greenland Sea. In the south, the crustal thinning occurs over a much wider area landward of the Senja Fracture Zone. Here, the margin bounds a basinal province in which as much as 18-20 km of sediments cover a highly attenuated crystalline crust. These deep basins developed in response to an Early Cretaceous attempt of break-up. Later, extensional tectonics associated with opening along the Senja Fracture Zone formed an early Tertiary basin at the continental margin. We believe the changing width of the transition in the lower crust reflects the pre-opening geological configuration. Prominent positive gravity anomalies seaward of the sheared margin segments are related to high density-velocity oceanic crust just seaward of the continent-ocean boundary.

DEEP REFLECTION SEISMIC TRAVERSES ACROSS THE SWISS ALPS

P. Finckh, E. Kissling & the Swiss Working Group
for Reflection Seismology

Represented by the Institute of Geophysics, ETH Honggerberg,
CH-8093 Zurich, Switzerland

In 1986 and 1987 two seismic reflection surveys of each about 100 km were carried out in the eastern and western parts of Switzerland in order to investigate the crustal structures in the Swiss Alps. The lines were oriented from north to south to cross the Alps from the Helvetic nappes to the Penninic nappes. Explosive shots of usually 100 kg spaced at about 10 km were recorded with a 240 channel system and a geophone station spacing of 80 m, provided energy returns from the lower crust. Vibroseis was used at 40 m intervals in order to obtain high coverage and details of near-surface structures. Comparison of 20 vs. 60 s sweep length showed superiority of the latter source. Field acquisition was characterized by extreme topography and by high noise levels necessitating night work. Thus static corrections and S/N enhancement needed special attention in the data processing. Partial prestack migration was applied owing to steep dips.

Shot gathers from explosions on both traverses show a Moho dipping southward from about 35 to 55 km, with parallel reflections in the lower crust. In both cases the Moho is lost as a reflection underneath the Penninic nappes, and reappears updipping at the southernmost ends of the lines. These results confirm earlier refraction experiments. The Vibroseis results of the eastern traverse reveal reflectors underneath the Helvetic nappes representing the autochthonous Triassic cover of the crystalline basement. The imbrication of these units, which takes up the crustal shortening of the Helvetic deformation, is evident. The Penninic complex shows good reflectivity down to 8 s TWT, probably due to the metamorphosed Mesozoic anhydrites and marbles separating the gneissic nappes. Both traverses depict the onlapping of the Penninic napped complex onto the Hercynian Eurasian continental basement.

CRUSTAL TERRANES EAST OF THE NEBINE RIDGE ACROSS PHANEROZOIC AUSTRALIA

D. M. Finlayson, K. D. Wake-Dyster, J. H. Leven,
H. J. Harrington, & R. J. Korsch

Bureau of Mineral Resources, Geology and Geophysics, Canberra.

In a companion paper Harrington et al. outlined the geological history of Phanerozoic Australia and features which should be seismic targets. We discuss here seismic reflection profiles to 20 s two-way time (TWT) and associated wide-angle reflection and refraction profiles extending from the Nebine Ridge to the coast near Brisbane. These profiles give an insight into structures and processes within the crust under three geological provinces, the Nebine Ridge, Taroom Trough of the Bowen Basin, and the New England Orogen. The seismic reflection character, or "fabric", and the crustal velocity structure in each of the three provinces is quite different.

Across the Nebine Ridge a lower crustal reflective zone shallows from about 7 s TWT further west under the Eromanga Basin to 3-4 s TWT, and the reflectors take on a more complex character. An upper crustal non-reflective zone is thought to correspond to an uplifted and eroded Thomson Orogen; the zone disappears on the eastern side of the ridge at the known eastern limit of the orogen. Devonian(?) rocks on the eastern side of the ridge have a very different seismic character from the Devonian basin sequences to the west, suggesting a different tectonic environment. Reflectors increasing in depth westward from the eastern ridge boundary are interpreted to be associated with a crustal-scale Thomson Orogen boundary.

Under the Permo-Triassic Taroom Trough basement, reflectors are generally weak/flat-lying and associated with rift-sequence volcanics. An Early Permian trans-tensional episode is interpreted for the basin. Mid-Permian compression and uplift on the basin's eastern margin is associated with the formation of the Texas Orocline in the New England Orogen, causing crustal loading and further basin development. Mid-Triassic compression is associated with the "docking" of the Gympie Terrane onto eastern Australia.

The New England Orogen can be divided into a number of terranes based on seismic fabric. The Texas Orocline is identified with a possible detatchment at mid-crustal depths. The Triassic Esk Trough is interpreted as a trans-tensional basin, and the fabric under the Beenleigh Block clearly indentifies a terrane underlying the block to mid-crustal depths.

From the Nebine Ridge to the coast the Moho is characterized by a "package" of seismic reflectors tied to wide-angle reflection and refraction data, and undulates only slightly. If processes during major tectonic events required large changes in crustal thickness, the Moho must have since been re-established to its present morphology.

SEISMIC REFLECTION IMAGES OF THE LOWER CRUST OF THE NORTHERN PART OF THE CHUGACH TERRANE, ALASKA; PRELIMINARY RESULTS OF A SURVEY FOR THE TRANS-ALASKA CRUSTAL TRANSECT (TACT)

Michael A. Fisher, Thomas M. Brocher, Warren J. Nokleberg, George Plafker and Gregory L. Smith

US Geological Survey, Menlo Park, CA, 94025, USA

Deep crustal seismic reflection data acquired in early 1986 by the US Geological Survey show strong reflections from the middle and lower crust of the convergent continental margin near the eastern end of the Aleutian trench. These data were collected across the Border Ranges Fault, a major suture zone that separates the Peninsular and Chugach tectonostratigraphic terranes. Surface exposures of the Chugach terrane include metamorphosed, strongly deformed flysch, yet highly reflective rocks lie at depth within or beneath this terrane. On the shallow part of the seismic section (0-5 s) reflections undulate and are interwoven indicating that some events are from outside the plane of the seismic section. Other shallow undulating events could reveal early Cenozoic granitic plutons or antiformal stacks of rock imbricated along thrust faults. In contrast to this shallow reflection pattern, three reflection bands contain most of the events on the middle part of the seismic section (5-12 s). The top of the rocks that return the distinctive reflection bands lies at a depth of 12-15 km. We believe that divergent reflections within part of this band indicate numerous thrust faults, perhaps revealing a major midcrustal decollement that marks the base of the Chugach terrane and the top of underplated rocks. Within parts of the upper two bands, subparallel reflections truncated at the band boundaries may image bedding, a metamorphic foliation, or thrust faults. If the truncated reflections represent thrust faults, then the reflection geometry suggests that subparallel roof and floor thrust faults bound imbricated rocks, forming duplexes. Reflection and seismicity data indicate that the deepest band of subparallel reflections, stemming from rocks 30-35 km deep, does not represent Moho but instead correlates closely in depth with the top of the Wadati-Benioff zone associated with the underthrusting Pacific plate. The reflections probably stem from the decollement that separates lithospheric plates within the subduction zone. This reflection band increases abruptly in thickness, possibly indicating structural thickening of the reflective section along a thrust fault of local underplating of subducting rocks. Neither the Border Ranges Fault, the suture between the Chugach and Peninsular terranes, nor deep crustal layers of the Peninsular terrane, are evident in seismic reflection data.

PIGGY-BACK RECORDING OF VIBROSEIS SIGNALS DURING THE BELCORP/DEKORP SURVEY THROUGH THE RHENISH MASSIF

Ernst R. Fluh, E. Bittner, D. Klaschen, & R. Meissner

Institut fur Geophysik, Olhausenstrasse 40, D-2300 Kiel 1, West Germany.

When the BELCORP/DEKORP 1A and DEKORP 1B Profiles were observed in 1987 additional piggyback recording was performed. At a fixed secondary 96-channel receiving array all signals were recorded. Further, at the intersection of the lines from a fixed point, vibroseis-signals were transmitted into the production array. Up to 50 sweeps were made and recorded to a maximum distance of 93 km. The data provide additional constraints on the velocities in the middle and lower crust. The velocities in the upper crust are partly rather high, reaching 6.6 km/s at a depth of 10 km. There is a good correspondence between the wide-angle reflections and major horizons seen on the near-vertical reflection profile. This allows modelling of the interval velocities and helps to better determination of the true depth.

CRUSTAL STRUCTURE ALONG THE POLAR PROFILE IN NORTHERN FINLAND

Ernst R. Fluh[1] , Ch. Walther[1] , & U. Luosto[2]

1. Institut fur Geophysik, Olhausenstrasse 40, D-2300 Kiel 1, West Germany.
2. Ylakartanonkj 3 D 28, 02360 Espoo, Finland.

Seismic refraction measurements were carried out along the 440 km long POLAR Profile in 1985. Explosions were fired at 9 shot points, and observed with an average station spacing of 2 km. The profile extends from the Karelian Province in the southwest across the Lapland Granulite Belt, onto the Kola Peninsula and Varanger Peninsula Provinces in the northeast. The crustal thickness varies between 40 and 47 km, being thin underneath the Lapland Granulite Belt. Here, the lower crust is rather thin and has lower average velocities compared to the northeast and southwest. This "anomalous" lower crust can be interpreted as the remnants of an Early Proterozoic back-arc basin, that was active prior to the 2.0 to 1.9 Ga plate convergence, during which the Lapland Granulite Belt was thrust onto the Archaean Basement of the Karelian Province. In the Karelian Province a low-velocity zone was found at a depth between 8 and 14 km from the P-wave velocity analysis. However, this zone does not show up as a low-velocity zone for the S-waves.

CONTROLS OF UNDERPLATING AND METAMORPHISM IN EXTENSIONAL TERRAINS

David M. Fountain

Department of Geology and Geophysics, University of Wyoming, Laramie, Wyoming 82070

The parameters of extension rate, amount of extension (B) and the temperature of the underlying asthenosphere exert a strong control of the evolution of the continental lower crust in extended terrains. The extreme case is represented by regions characterized by high extension rates, large B and high asthenospheric temperatures. In this case, upwelling of asthenosphere causes accretion of mafic magmas to the base of the crust (magmatic underplating) thereby raising temperatures to values high enough to drive granulite facies metamorphism, anatexis, migmatization, and to increase also the ductility of the lower crust during extension. The mafic magmas crystallize in the pyroxene granulite and/or garnet granulite facies. The resultant rocks are characterized by high compressional wave velocities similar to those observed in lower crust in continental rift zones and passive continental margins. The Ivrea-Verbano zone in northern Italy, an exposed granulite facies terrain, may represent an example of this type of lower crust. There will be little growth or modification of the continental lower crust for low extension rates, small B or low asthenosphere temperatures. Extended lower crust will exhibit a high degree of diversity, reflecting the relative importance of these parameters.

SEISMIC PROPERTIES OF LOWER CONTINENTAL CRUST BASED ON LABORATORY MEASUREMENTS : THE KAPUSKASING UPLIFT EXAMPLE

David M. Fountain

Department of Geology and Geophysics, University of Wyoming, Laramie, Wyoming 82070

Significant lateral and vertical variations in seismic properties of continental crust of shield areas are suggested by laboratory measurements from the Michipicoten Belt (MB), Wawa gneiss terrane (WGT) and Kapuskasing structural zone (KSZ) in Ontario. These data consist of compressional wave velocity (V_p) measurements at confining pressures <600 MPa for representative rock samples from these terranes. A seismic velocity model of the Superior province crust can be constructed using these data in conjunction with the crustal cross section by Percival and Card (1985). Uppermost crustal levels are characterized by low-V_p tonalite-granodiorite gneisses (6.1 km/s, 100 MPa) that surround metavolcanic (6 km/s, 100 MPa) and metasedimentary (5.9 km/s, 100 MPa) rocks of the MB. Deeper levels in the MB greenstone terrane are composed of higher V_p metavolcanic rocks (6.7-7.2 km/s, 300 MPa), mid-range epidote-bearing granitic plutons (6.5 km/s, 300 MPa), and low V_p metasedimentary rocks (6.3 km/s, 300 MPa). Low V_p tonalitic gneisses (6.2 km/s, 300 MPa) surround the other rock types. Significant lateral velocity changes are therefore expected at this crustal level. Gneisses constituting the deeper mid-crustal WGT exhibit relatively uniform V_p (6.3-6.5 km/s, 300 MPa). Deeper crustal levels (KSZ) are represented by a matrix of mid-range-V_p tonalitic rocks (6.3-6.5 km/s, 600 MPa) and paragneisses (6.4 km/s, 600 MPa) that surround horizontal bodies of high V_p mafic granulite gneisses (7-7.4 km/s, 600 MPa) and anorthosites (7.2 km/s, 600 MPa). Acoustic impedances, coupled with geometrical aspects of these rock units, are sufficient to generate deep reflections from the KSZ. Based on volumetric abundances, KSZ rocks have an average V_p of 6.8 to 6.9 km/s, an increase of 0.3 to 0.4 km/s relative to the mean for the overlying gneisses. The V_p increase corresponds to mid-crustal increases observed in the Canadian shield.

REGIONAL CRUSTAL EXTENSION IN THE SOUTHWESTERN UNITED STATES; SEISMIC GEOMETRIES OF CORE COMPLEXES, EXTENSIONAL BASINS, AND DETACHMENT FAULTS

Eric G. Frost[1] and David A. Okaya[2]

1. Calcrust, Department of Geological Sciences, San Diego State University, San Diego, CA 92182.

2. Calcrust, Department of Geological Sciences, University of Southern California, Los Angeles, CA 90089

Combined geological and geophysical studies of the southern California-western Arizona region of crustal extension have shown that seismic reflections related to mid-Tertiary extensional deformation can be traced downward to middle crustal levels and extrapolated over large regions covered by numerous, but still discrete, seismic data sets. The most prominent of these reflections are those produced by mylonitic rocks of Tertiary age, which represent the middle crustal ductile products of crustal extension. The relatively sharp upper strain boundary of this ductile deformation, or mylonitic front, is especially valuable in tracing the ductile deformation through the crust, because of the major change it produces between the non-reflective upper crust above it and the highly reflective crust below it. Disruption and tilting of the regionally developed mylonitic zone during progressive deformation exposed portions of these ductile rocks against upper-crustal rocks, producing the ranges termed metamorphic core complexes.

Brittle deformation originally above, but also disrupting the mylonitic zone, was along both high- and low-angle normal faults. Widespread faults of moderate dip that originally cut downward to middle crustal level have flattened during multiple generations of faulting to produce low-angle normal faults that continue across most of Arizona and California, far past the core-complex region. Reflections from such faults descend to middle crustal level and then become sub-horizontal; they do not appear to cut through the crust, but feed into the regional zone of distributed ductile shear.

Basins form as passive products above the tilted upper-crustal blocks that have moved in response to the underlying distributed simple shear. Addition to the crust by underplating of basaltic magmas during extensional deformation has produced a regionally subhorizontal Moho, elevated the former Moho (paleoMoho) to shallower crustal depths, maintained the regional topographic level during extension, and produced a highly reflective Moho and lower crust. The crustal-scale extension is thought to be produced by motion of the underlying mantle in the wedge below the North American crust and above the subducting Farallon Plate. Rotation of the upper crust about a vertical axis, as shown by paleomagnetic data, may also have occurred above the ductile middle and lower crust as a response to changing plate motions during the later stages of crustal extension. Heating, produced by disruption and exposure of the middle crust and large-scale magmatic addition to the lower crust, needs to be taken into account when studying the thermal and deformational histories of the basins and surrounding ranges.

ANISOTROPY IN CRUST AND UPPER MANTLE - OBSERVATIONS AND MODELS

Fuchs, K., Sandmeier, K.-J., and Nolte, B.,

Geophysical Institute, University of Karisruhs, Hurtrstressw 16,
D-7500 Karlsruhe, F.R. Germany

A new fast program for the calculation of synthetic seismograms implemented on a CDC CYBER 205, has been applied to two models of anisotropy in the lithosphere.

The model of an anisotropic upper mantle in southern Germany is the base for numerical experiments in wave propagation, in a medium with depth variation of horizontal alignment of olivine and basalt depletion. A comparison of observed and synthetic seismograms reveals the matching of azimuthal variations of mantle P-wave amplitudes and phase velocities. The S-wave field, calculated for the same model, shows amplitudes and azimuthal variations comparable to the P-waves, together with clear evidence for birefringence. This is not compatible with the observations, where no S-wave energy from the upper mantle is recorded on any profile in any direction. The observed discrepancy is taken as a powerful constraint on the rates of depth variation of anisotropy and composition during an improved modelling.

Conventional models explain the laminated reflections from the lower continental crust by the reflectivity of isotropic heterogeneous compositional layering. A test is presented of the hypothesis that the laminated reflection pattern might be generated by a stratification of alternating orientations of anisotropic elasticity tensors and almost homogeneous composition throughout the entire lower crust. It is shown that the calculated amplitude patterns match qualitatively the observations. The difference between the results of conventional modelling and the present study is mainly in the S-wave part and the various components.

The presence of a contribution from an "orientationally" layered medium deserves serious consideration, and requires further three-component surveys of P- and S-reflections.

CMP STACKED IMAGES OF RANDOMLY HETEROGENEOUS TARGETS

Bruce S. Gibson and Alan R. Levander

Department of Geology and Geophysics, Rice University
PO Box 1892, Houston, Texas 77251

Layered models for the lower crust and Moho transition are suggested by the numerous subhorizontal to gently-dipping segments that characterize the reflectivity of deep-penetration seismic images. The CMP data acquisition geometry and processing sequence, however, tend to produce stacked images that have more lateral continuity than the geologic structures being surveyed. Here we illustrate two mechanisms that may significantly bias interpretations at all crustal levels toward layered models: dip filtering in the CMP stacking process, and an inherent horizontal bias associated with any surface-recorded data.

These mechanisms are illustrated with finite-difference acoustic-wave synthetic data collected over a target zone having isotropic random velocity variations. The model studied has a background velocity of 6 km/s and a randon zone that extends from 4 to 12 km depth. Velocity variations in the random zone have a standard deviation of 0.5%, a scale length of 100 m, and no preferred spatial orientation,. Data generated for 25 shots (40 Hz maximum frequency, 400 m shot interval, 50 m group interval) were sorted to CMP trace gathers having a maximum fold of 13, and stacked.

The process of conventional CMP stacking acts as a dip filter because of the dip dependence of stacking velocity. For these synthetic data, the attenuation of steeply dipping energy causes the image of the random zone to have increased horizontal continuity. The stacking dip filter can be described in frequency-wavenumber (w-k) space; spatial correlation becomes greater at early reflection times and in cases where long-offset traces are included in the stack. Thus, zones of isotropic random velocity variation can appear to be layered unless care is taken to correct the stacking dip filter through processes such as migration before stack or dip-moveout (DMO) correction.

A second source of bias in images of the subsurface is seen in an "ideal" seismic section, composed of 1-D seismograms calculated for each column of the finite-difference grid. The ideal section shows events with a tendency toward horizontal correlation because the reflectivity of the subsurface depends vertically on the derivative of velocity, but horizontally it depends on the velocity variation directly. The different treatment of the vertical and horizontal directions for these isotropic velocity variations can also be expressed as a dip filter in w-k space. This source of bias is inherent in surface-recorded seismic data, which predominantly senses the vertical derivative of deep targets. The effect can be compensated with a simple integration along the time axis.

SEISMIC REFLECTIONS FROM RANDOMLY HETEROGENEOUS TARGETS AND THE INTERPRETATION OF WIDE-ANGLE COMMON-SHOT GATHERS

Bruce S. Gibson and Alan R. Levander

Department of Geology and Geophysics, Rice University
P.O. Box 1892, Houston, Texas 77251

Interpretations of both common-midpoint (CMP) and wide-angle seismic data suggest that the lower crust and the Moho transition have a generally layered structure. Layered models are based on the numerous subhorizontal reflection segments seen at late times on CMP stacks, and the strong, reverberatory lower crustal response seen in wide-angle common-shot gathers. In contrast, studies of earthquake travel-time anomalies and codas are based on models where velocity variations have no preferred orientation (i.e., they are isotropically random).

Various studies with synthetic data suggest that the reflection response of a randomly heterogeneous target zone will have substantially greater lateral continuity than the actual velocity variations within the zone. For common-shot gathers, a receiver at long offset relative to the depth of the random zone will see energy scattered from the zone arriving with a restricted range of apparent slowness, because the receiver is asymmetrically located with respect to scatterers in the zone. The restricted range of slowness acts as a dip filter that introduces spatial correlation in the recorded wavefield.

We demonstrate the effect with finite-difference acoustic-wave synthetic data generated for a model with a background velocity of 6 km/s and a random zone that extends from 4 to 12 km depth. Velocity variations in the zone have a standard deviationa of 0.5% and a scale length of 100 m. The grid dimension of 25 m allows a maximum source frequency of 40 Hz and data were generated to a maximum offset of 25 km. Near zero offset, the response of the random zone is a complex collection of events that have lateral coherencies similar to the scale of the velocity heterogeneity in the zone. At offsets greater than 12 km, scattered events are laterally continuous over distances as great as 5 km, and the events appear to come from a layered target. The dip-filtering effect predicted by simple traveltime analysis agrees with frequency-wavenumber spectra computed for various portions of the shot gather.

Data were also generated for a crustal velocity model based on the interpretation of field data. In this model, an isotropically random zone was located between 14 and 22.5 km depth, velocity variations had a standard deviation of 3% and a scale length of 200 m, and traces were calculated for offsets up to 90 km. The lower crustal and Moho reflections in these synthetic data match corresponding field records that have also been interpreted in terms of a model with high- and low-velocity lamellae. We conclude that the lateral continuity introduced by the geometry of wide-angle seismic experiments allows another general class of velocity structures to be considered in interpretations of the deep crust and upper mantle.

METHODS FOR IMPROVING THE RESOLUTION OF DEEP SEISMIC REFLECTIONS

Bruce R. Goleby[1&2] & Brian L.N. Kennett[2]

1 Bureau of Mineral Resources, GPO Box 378, Canberra ACT 2601, Australia

2 Research School of Earth Sciences, Australian National University, GPO Box 4, Canberra ACT 2601, Australia

The data quality of the deep seismic reflection data recorded over the Precambrian Arunta Block, Central Australia is good, though individual reflections are generally short in extent. Typically reflector segments are continuous over 10-30 traces (400-1200 m) from the deeper crust which makes correlation difficult. Two different approaches have been tried to improve both the resolution and continuity of the deep seismic reflectors. The first involved using different stacking techniques to improve resolution and continuity,and the second was to apply simple image-processing techniques to selected sections of the stacked data to enhance continuity. The stacking techniques used include single fold display, median stack, coherency stack, and Nth root stack, as well as the standard CMP stack, and extended shot and array simulation techniques. The relatively high level of reflected energy from depth suggested the development of an energy stack. The energy stack is similar to 'reflection strength displays', but instead of modulating the stack with the envelope of the energy density, the energy within a specified time gate is displayed. The energy stack has a number of advantages as it allows the interpreter to look at packets of energy rather than the normal amplitude display, and is not affected by signal polarity. It also enables an easier correlation of events, as they stand out more clearly over the generally noisy background on the seismic sections. Each technique tried showed some advantage over the conventional CMP stack, and, when used in conjunction aided in deep crustal interpretation, by assisting in identifying particular events.

The second approach uses simple sun-illumination image processing routines on the seismic data, treating the seismic data as an image rather than a section. By highlighting, at the correct angle, the peaks, the deep reflectors should be enhanced and their continuity increased. Initial results from this approach applied to the dipping events are not as good as expected. Some trace mixing is required to increase further the continuity of the events prior to illumination.

RESULTS FROM DEEP SEISMIC REFLECTION PROFILING IN THE PRECAMBRIAN ARUNTA BLOCK OF CENTRAL AUSTRALIA

Bruce R. Goleby[1&2], Brian L.N. Kennett[2], Russell D. Shaw[1&2], Cedric Wright[1] & Kurt Lambeck[2]

1 Bureau of Mineral Resources, GPO Box 378, Canberra ACT 2601.
2 Research School of Earth Sciences, Australian National University.

Deep seismic reflection data from the Precambrian Arunta Block, Central Australia, are of very good quality, and have provided an excellent resolution of the crustal structure of this region. The dominant feature seen on these seismic data is a series of moderately dipping faults that appear to penetrate the crust to depths in excess of 35 km. This type of crustal structure indicates 'thick-skinned' tectonic processes were active; processes that involved deformation of the entire crust. This Central Australian region has a series of spectacular gravity anomalies (<1.4 mm s^{-2}), indicating a non-isostatic regime in a region without significant orogeny since 300 Ma.

Approximately 500 km of deep seismic reflection profile (Traverse 1) were recorded by the Bureau of Mineral Resources in 1985, in an attempt to understand the cause of the anomalous gravity field, and to resolve the crustal structure and hence the tectonic evolution of the Arunta Block. The Arunta Block is a region of exposed Precambrian crust, that has been interpreted as a major ensialic mobile belt. It has been divided into three tectonic provinces (Northern, Central and Southern Arunta Tectonic Provinces), which have each undergone separate histories of deformation and metamorphism. The Southern Arunta Province is separated from the Central Arunta Province by the Redbank Deformed Zone, a 7-10 km wide easterly-trending zone of anastomosing mylonites. This zone is regarded as a major Proterozoic crustal suture zone that has been re-activated during the Alice Springs Orogeny (300-400 Ma).

The deep seismic reflection data indicates a series of dipping 'blocks', each having a similar seismic character and bounded by moderately dipping faults. Within each block, the thickness of the granitic crust can be inferred from the depth extent of the region of lower reflectivity. Sub-horizontal reflections at the base of the granitic zone have been used to indicate the present attitude of the original crustal layering. Within some blocks these sub-horizontal events are truncated against the dipping faults, implying that the deformation of the crust occurred by movement along the faults, with little or no rotation of the blocks. In addition, the seismic character of the Southern Arunta Province is different from that observed in the Central and Northern Arunta Provinces. This difference is believed to reflect fundamental differences between the composition of these two regions.

Current tectonic models for the region include a 'thin-skinned' crustal compression model, a mechanical folding and thrusting model,and a 'thick-skinned' faulted block model. The deep seismic reflection data support a hybrid version of the 'thick-skinned' model, whereas the 'thin-skinned' model is discounted because there is no seismic evidence for the mid-crustal ramp structures implicit in the model.

THE CENTRAL AUSTRALIAN DEEP SEISMIC TRANSECT

Bruce R. Goleby[1,2], Cedric Wright[2] and Brian L.N. Kennett[1]
Russell D. Shaw[1,2], and Kurt Lambeck[1]

1 Research School of Earth Sciences, Australian National University, GPO Box 4, Canberra ACT 2601, Australia

2 Bureau of Mineral Resources, GPO Box 378, Canberra City, ACT 2601, Australia.

During the latter half of 1985, the Bureau of Mineral Resources recorded some 500 km of near-vertical incidence (NVI) seismic reflection profiling across the Ngalia Basin, Amadeus Basin and the Arunta Block in central Australia. The Amadeus and Ngalia Basins are two late Proterozoic to Palaeozoic intracratonic basins enclosed within an exposed Precambrian Block, the Arunta Block. The data were collected as part of BMR's Central Australian Research Program. The principal objectives of the survey were to provide geophysical constraints on models of the evolution of the central Australian region. The seismic traverses were positioned so as to cross both the main structural trends of the region as well as the major eat-west trending gravity anomalies that have been observed in the region.

The seismic survey consisted of a main N-S regional line, plus several short cross lines, three expanding spreads, a tomographic experiment and a large offset experiment. Gravity and airborne magnetic readings were recorded along all the seismic lines. The seismic data were collected using a DFS-IV 48 channel seismic acquisition system. The energy source used was the explosive, Anzite Blue, detonated in holes nominally 40 m deep. The data were recorded to 20 s (or 24 s over the basins) at a 2 msec sample rate. The group interval used was 83.3 m; with the nominal fold of coverage in excess of 6 fold, though in places it reaches 12 fold.

Large weathering variations occured along the traverse (in places 30ms variation over 60 m distance), and were the main problem encountered in processing. This required special techniques to be developed to resolve this problem. Problems were also encountered in estimating accurate velocities within the hard-rock terrane of the Arunta Block.

The deep seismic data have been successfully used to discriminate between the various basin and basement evolution models put forward, and support a 'thick-skinned' style of deformation and crustal evolution.

PIGGYBACK SEISMIC REFLECTION DATA FROM THE BASIN AND RANGE - COLORADO PLATEAU TRANSITION ZONE, WESTERN USA.

Erik Goodwin[1], David Okaya[2] and George Thompson[1]

1. Dept of Geophysics, Stanford Uni, Stanford, CA 94305.
2. CALCRUST, Geology Dept, Uni of South California.

The transition zone between the Colorado Plateau and the Basin and Range Province of the western United States represents the boundary between stable and extended continental crust. Within this zone, the crust thins at least 10 km from over 40 km beneath the Colorado Plateau to ~30 km beneath the Basin and Range. Until recently there was no satisfactory, high-resolution seismic image of this deep transition, only hints from refraction surveys that the crust may thin across steep, east-dipping faults. In 1986 COCORP collected deep seismic reflection data across the transition zone in west-central Arizona which revealed - and raised important new questions about - the structure of the crust across the transition zone. Among other things, these data confirmed a regional pattern of strong reflections in the upper crust and showed apparent faulting of the Moho.

A piggyback reflection experiment, to the 1987 US Geological Survey Pacific to Arizona Crustal Experiment (PAACE) across west-central Arizona, provides new data on this critical region of the transition zone. The piggyback data, which are in part coincident with the COCORP data, were acquired using three reflection spreads placed end-to-end that recorded the USGS refraction explosive sources. Several of the field acquisition parameters illustrate the unique nature of the reflection piggyback data: (1) the station spacing was 50 m for much of the profile so that the data have an unusually high spatial resolution; (2) the aperture of the reflection spread was ~25 km, which is larger than standard reflection surveys; (3) the data set includes 40 stations of 3-component data which successfully recorded S-wave arrivals from the crust; (4) the data contain both near-vertical and wide-angle reflections (offsets 0-170 km), including data through the P_n critical point; and (5) two of the shots are fan profiles that provide 3-D control on the Moho.

A common midpoint record processed from the piggyback data shows strong parallel reflections in the shallow- to mid-crust, a seismically transparent zone between 5 and 7 s, and a strongly reflective crust beginning at ~ 7 s. The shallowest events correspond to COCORP's "Bagdad Reflection Sequence", which is recognized throughout the transition zone of west-central Arizona. The event at 7 s varies in two-way travel time by almost 2 s and marks the top of a seismically complex, reflective lower crust. This complicated boundary shows an en echelon reflection pattern on the CMP record with apparent overlap of distinct events at 6, 7.5, and 7 s; depth migrations are only partially successful in unraveling the complicated time section. At present we are investigating alternative models for this structure. One model interprets the en echelon reflections as separate boundaries which underlie one another and a second model interprets the reflections as the same boundary that has been downfaulted. Deeper in the record is the reflection Moho at ~ 10 s, which while visible, is much more diffuse than in the adjacent Basin and Range Province.

ORIGIN OF DEEP CRUSTAL REFLECTIONS : RESULTS FROM SEISMIC PROFILING ACROSS HIGH GRADE METAMORPHIC TERRANES IN CANADA

A. Green[1], A. Davidson[1], J. Percival[1], B. Milkereit[1],
R. Parrish[1], F. Cook[2], W. Cannon[3], D. Hutchinson[3],
G. West[4], and R. Clowes[5]

1. Geological Survey of Canada, Ottawa, Ontario, K1A 0Y3
2. University of Calgary, Calgary, Alberta, T2N 1N4
3. United States Geological Survey, Reston, Virginia, 22092
4. University of Toronto, Toronto, Ontario, M5S 1A7
5. University of British Columbia, Vancouver, BC V6T 1W5

Since the first deep seismic reflection surveys in the 1950's and 1960's the origin of layered reflections in the middle and lower crust has been the subject of considerable speculation and controversy. In an attempt to resolve some aspects of this problem the Canadian LITHOPROBE program has sponsored or co-sponsored seismic reflection surveys across three high-grade metamorphic terranes. The westernmost line of the 1985 Canadian Cordillera transect crossed the Valhalla Dome, a metamorphic core complex that was buried by easterly transported exotic terranes in Jurassic-Cretaceous times and brought to shallow depths during an extensional event in the Tertiary. A profile recorded in Lake Huron by GLIMPCE in 1986 crossed the enigmatic Grenville Front and part of the Grenville Orogen, structures that were buried and exhumed during various phases of middle Proterozoic thrust tectonism. Finally, several profiles recorded in 1987/88 crossed the Kapuskasing Structure, which exposes middle to lower crustal rocks affected by widespread extension in the Archean and a major intra-crustal thrust event sometime ian the early to middle Proterozoic. In all three data sets layered reflections have a variety of origins, but are most often associated with velocity discontinuities at highly strained contacts between gneissic rocks of varying lithologies. Particularly strong reflections originate from zones of mylonite and cataclasis. Rocks are so deformed in these three diverse plastic flow yields seismic images resembling well-stratified sedimentary units. We suggest that certain types of gneissic rock may be a common source of layered reflections from the deep crust, with reflections originating from lithological boundaries and mylonite zones within the gneisses.

A PC BASED, PORTABLE, CONTINUOUS SEISMIC RECORDING SYSTEM

Green, R.W.E., J. Borcher & W. Theron

University of Witswatersrand, Witz 2050, South Africa

Observations of teleseismic events at remote sites necessitated the development of a portable digital recorder that is capable of continuously recording the output of a three component set of long-period transducers. To facilitate the data handling procedure a PC is used as a file management facility with the PC operated in intermittent or "sleeper" mode. Each of the three components are digitized and stored in separate, intelligent A to D cards. When 28K samples have been generated, a trigger is initiated. On the transition of the next real-time second after the trigger the real time is latched and power is applied to the PC. The sample count between the trigger and the latched acknowledgement of the trigger provides for absolute time correlation. After the PC has powered up the data is down-loaded from the 3 acquisition cards to the hard disc/tape streamer. The PC then down-loads the latched time, the sleeper system is reset, and the PC power is removed. Sampling at 17 samples per s/component, the PC is switched on every 27.5 minutes. The settling and down-loading of the 84K of data takes about 80 s, and thus the mean power consumption of the PC is about 6.0 W. The associated long period transducers (Guralp CMG3) consume about 3.6 W and the data acquisition and control about 2.0 W. The electronics are housed in a sealed steel box and the system uses two 45 W solar panels charging two 130 AH batteries for power. Data transfer to the 60 M tape streamer necessitates a visit to the station every 13 to 14 days.

TAU-P TRIAXIAL POLARISATION ANALYSIS OF DEEP SEISMIC REFLECTION/REFRACTION DATA

S.A. Greenhalgh[1], I.M. Mason[2], and C.C. Mosher[3]

1. School of Earth Sciences, Flinders University, Bedford Park, SA 5042
2. Dept of Engineering Science, University of Oxford, Oxford OX1 3PJ England
3. ARCO Oil & Gas Company, Plano, Texas 75074, USA

This paper presents a modified form of polarisation position correlation operator which can be used to separate P and S waves in multi-component deep seismic reflection profile. The essence of the method (in seeking S wave extinction) is to form a dot product between the signal vector and the slowness vector during projection of the seismic section into tau-p space. The dot product (in effect) is a linear controlled direction reception filter (CDR Type I) which selectively passes only P arrivals.

There are two simple modifications to the operation which can enhance the final P-wave time section. The first is to apply a weighting during the Radon transform, in accordance with the mean distance between adjacent traces, in order to compensate for non-uniform spatial sampling of the wavefield. The second is to use the converse rotation operator during the forward transform - to compute both the P-wave w-p "pass plane" and the orthogonal P wave "extinction plane". The two together are needed in order to preserve a measure of the total energy falling within any w-p pixcel in the original time sections. The extinction plane on its own gives a measure of the success achieved by the CDR I filter in isolating P wave energy in a pixel on the pass plane. The best measure of this success is given by performing a cross-spectral analysis of the w-p planes on a pixel-by-pixel basis (summing over a window dw x dp). The ratio of the eigenvalues yields the rectalinearity of polarisation. A two-dimensional gain function based on rectilinearity may be used as a nonlinear boost function in order to enhance strongly polarised P-wave pixels in the w-p pass plane, prior to inverse Radon transformation. Slowness filters and/or windows can also be applied whilst in the w-p or t-p domain, to eliminate multiples and other unwanted modes.

The above procedure falls into the class of CDR II operators discussed by Gal'perin. There have been many attempts to use CDR II filters in the past. These have been frustrated by their restriction to one dimension. The CDR I approach appears to offer a change to effect the arrival separation which is required if non-linear polarisation filters are to work. The fact that CDR II operators are non-linear does not detract from the final seismic sections. The codes have been successfully tried on synthetic data, but they require exhaustive testing on real data in order to exploit the CDR II advance.

CRUSTAL STRUCTURE AND TECTONICS OF THE WESTERN BARENTS SEA - RESULTS FROM DEEP SEISMIC REFLECTION AND REFRACTION EXPERIMENTS

Steinar T. Gudlaugsson[1], Jan Inge Faleide[1], Stein Fanavoll[2], Knut G. Rossland[3] and Bard Johansen[4]

1 Department of Geology, University of Oslo, Norway
2 IKU/SINTEF, Trondheim, Norway
3 Esso Norge, Stavanger, Norway
4 Norwegian Petroleum Directorate, Harstad, Norway

Crustal transects across the western Barents Sea based on deep seismic reflection and refraction data form the basis of structural and tectonic models for the area. The epicontinental Barents Sea, which is underlain by a thick succession of Paleozoic-Cenozoic sedimentary rocks, is bounded on the west by a Tertiary shear margin. Crustal thickness ranges from 20 to 35 km with a systematic thinning towards the margin. Prominent structural differences between the northern and southern parts of the shelf result from a long history of tectonism. The Caledonian consolidation of the Barents Shelf in the Early Paleozoic was followed by a period of strike-slip movements and compression along the western shelf in the Devonian. The tectonic regime then changed to become mainly extensional, and three major rifting phases are documented: Carboniferous, Late Jurassic/Early Cretaceous, and Eocene. The data reveal a systematic pattern in the tectonic evolution through time. In the Carboniferous an attempt at break-up between Norway and Greenland was accompanied by extensive rifting in a NE direction into the southern Barents Sea. Later phases of extension were characterized by a general westward retreat of the rifting activity accompanied by the emergence of a belt of NNW-striking continental transform faults in the area of the present margin. In the Early Cretaceous the attempt at rifting into the southern Barents Sea was finally abandoned when deep rift basins, linked to the continental transforms and cross-cutting older trends, were formed in the southwest. This event effectively decoupled the Barents Sea from NE Greenland. In the final phase, in the Eocene, a transform plate boundary was established which since developed as a passive shear margin. Important aspects of the structural and tectonic models include the Iapetus suture and the transition between Caledonian and older basement, Devonian basins and associated deep crustal fault zones, the deep structure of the Carboniferous rifts and Cretaceous basins, extensional and compressional fabric deep in the crust, and landward dipping reflectors east of the ocean-continent boundary and their relation to volcanism.

REFLECTION SURVEY ON HOBSON'S CHOICE ICE ISLAND, ARCTIC OCEAN

Hajnal[1], Z., I. Kesmarky[1],& Overton, A.

1. Department of Geological Sciences, University of Saskatchewan, Saskatoon, Saskatchewan, S7N OWO;

2. Geological Survey of Canada, 601 Booth Street, Ottawa, KIA OE8

A permanently installed 120-channel seismic reflection system on the Hobson's Choice Ice Island at the northern tip of Axel Heiberg Island in the Arctic ocean, recorded close to 2000 field records in the summers of 1985 aand 1986 while the ice platform drifted irregularly in a north-westerly direction. The acoustically highly contrasting surface ice, ocean water and solid continental margin floor generated extremely strong reverberating waves which resulted in complex contaminated field records. With the implementation of several specially developed noise suppression algorithms, the dramatically improved signal levels permitted the assembly of 13 spatially distributed multifold seismic section segments along the 160 km travel path of the island,. Both first-arrival signal analysis, and velocity spectral computations based on large-scale vertical stacking, indicate that the ocean floor of the continental margin is formed by competent sedimentary rock sequences. The upper approximate 1000 m of rock sequences, with interval velocity of 3700 m/s, are interpreted as younger Tertiary-Cretaceous strata. According to the projected onshore geological trends the underlying 4 to 5 km thick zone, which has interval velocities ranging between 4800 and 5800 m/s is composed of deformed Lower Paleozoic rocks. Preliminary estimates show that the reflection signals successfully imaged the aunderlying strata to a depth somewhat over 6000 m. The lowest seismically recognizable interval, with velocities around 6 km/s, is interpreted as the crystalline basement. Five reflecting horizons were recognized. Two of these, which indicate gentle westerly dip, were easily traceable through the entire survey area. The others were localized, revealing a rather complete subsurface environment along the northern segment of the Canadian Arctic Continental Margin.

DEEP CRUSTAL FABRICS AND DEFORMATION STYLES FROM REFLECTION PROFILES OF THE APPALACHIAN/CALEDONIDE SYSTEM

Jeremy Hall[1], Garry Quinlan[1], Francois Marillier[2] and Charlotte Keen[2]

1. Centre for Earth Resources Research, Department of Earth Sciences, Memorial University of Newfoundlannd, St John's Newfoundland, Canada
2. Atlantic Geoscience Centre, Geological Survey of Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada

Comparisons of deep reflection profiles from the Atlantic edges of the once-continuous Appalachian and Caledonide mobile belts reveal a diversity of structure with a few common elements. Some surface terranes may be correlated with characteristic deep crustal styles, and the latter may be used to map the terranes offshore. One implication of this and of the evidence for compressional tectonism in the deep crust is that the latter preserves some elements of structure imposed in the Paleozoic. Variation in structural style along strike may reflect different degrees of reactivation of earlier structure. This is exemplified in the Paleozoic use of 'Grenville' shear zones, and in post-orogenic extension along older, once-compressional structures. Dipping reflectors appear to cut through the base of the crust especially in the vicinity of the old Grenville passive margin: elsewhere, dipping reflectors cannot be shown to do so, and are assumed to detach in the lower crust. It is suggested that crustal underplating during passive margin development will result in a more mafic, and therefore less ductile, lower crust, through which later shears may cut.

CONTINENTAL MARGINS AND MULTIPLE REFLECTIONS

Robert J.J. Hardy

Bullard Laboratories, Dept. of Earth Sciences, Cambridge University, Madingley Road, Cambridge CB3 0EZ, U.K.

Continental margins provide a particularly severe environment in which to acquire deep seismic reflection data because the water depth and hard sea bottom cause high-amplitude long-period multiple reflections which mask primary events, particularly those from the lower crust and MOHO. The typical continental-margin profile provides three main areas of difficulty in multiple removal; the relatively flat continental shelf under 750 m deep water, the dipping continental slope under about 1500 m of water, and the oceanic deeps under 4500 m of water. This paper investigates the effectiveness of multiple removal and multiple identification in these circumstances using examples from real data augmented by synthetic sections from simple models. Conventional deconvolution and stacking attenuate most of the reverberations in shallow water data (less than 500 m deep) but perform badly in the above conditions. Much effort has been directed at improving them or devising new methods to remove multiple reflections. It is concluded that most of these improved methods fail because they are only optimum at attenuating one type of multiple in one pass; they work well in removing simple water bottom multiples. Filtering in the frequency-wavenumber domain is considered in detail because of the ability to remove water layer and peg-leg multiples simultaneously. Primary enhancement can also be performed. All removal methods, including those based on the scalar wave equation, leave some remnant multiple energy. This causes particular ambiguity in interpretaiton of deep seismic data, and so the approach of labelling seismic energy by differential normal moveout is preferred.

SEISMIC EVENT LABELLING

Robert J.J. Hardy, Richard W. Hobbs and Michael R. Warner

Bullard Laboratories, Dept. of Earth Sciences, University of Cambridge, Madingley Road, Cambridge CB3 0EZ, U.K.

We have found that all methods for multiple removal leave some remnant multiple energy which causes ambiguity during interpretation, particularly in deep seismic data. Seismic event labelling discriminates between primary and multiple energy on a stacked section using differential normal moveout. It can be used to identify multiples before a removal method is tried or can lead to an unambiguous final interpretation or assessment of the removal technique used. Seismic event labelling works by returning the offset information from CDP gathers to the stacked section by producing three overlapping partial gathers which are colour coded after stacking. Superimposing the coloured partial stacks produces an event with combined NMO and stack information. If NMO is incorrectly applied then the partial gathers do not exactly overlap resulting in coloured 'fringing' of the events; the order of colours indicates whether the event is undercorrected or overcorrected for normal moveout. Seismic event labelling was developed as a method to label rather than remove multiple reflections but is useful in any application which requires normal moveout analysis, e.g. stacking velocity analysis both for routine processing and producing pilot traces for use in residual statics calculations. This display illustrates the implementation and use of seismic event labelling using real and synthetic data.

EASTERN AUSTRALIA - GEOLOGICAL INTRODUCTION TO STUDIES BY THE EXPLOSION SEISMIC GROUP

H.J. Harrington, D.M. Finlayson, K.D. Wake-Dyster, J.H. Leven & R.J. Korsch

Bureau of Mineral Resource, Geology & Geophysics, Canberra, Australia

This is the first of a block of three consecutive papers (see Program) discussing seismic work by BMR in eastern Australia, and it is accompanied by a poster paper by K.D. Wake-Dyster. A traverse eastwards from (1) the Precambrian craton of central Australia crosses (2) the Eromanga Basin, (3) the Nebine Ridge, (4) the Surat Basin overlying the Sydney-Bowen foreland basin, (5) the New England-Yarrol Orogen and (6) the Tasman Sea. Analogous traverses would be from the Scandinavian craton to the Mediterranean, or from interior North America to the Atlantic.

A seismic reflection profile has been recorded to 20s TWT for over 1000 km inland from the Tasman Sea and have been accompanied by refraction and wide-angle profiles. The seismic fabric or 'character' differs in each of the main geological provinces.

The New England-Yarrol Orogen contains major bends (oroclines) that could form only above a major detachment surface which may be recognisable seismically at depths of about 20 km. Above the detachment the orogen is divided into a number of terranes with distinct seismic fabrics.

Under the Sydney-Bowen Basin in its deep eastern part, next to the orogen, there are rift volcanics which form weak flat-lying basement reflectors. Further west, the Eromanga Basin is the largest portion of the Great Artesian Basin, a gently-deformed sheet of Jurassic and Cretaceous sediments. It is underlain by a stack of older basins which have been studied closely because of their oil and gas fields and enormous coal deposits. Prominent dipping reflectors in the lower crust are associated with basement highs and with the formation of overlying basins by ramping in the lower crust.

Beneath the basins the postulated Thomson Foldbelt is strangely transparent and non-reflective to 8s TWT. The transparent zone has been followed eastwards with its base shallowing to 4s TWT under the Nebine Ridge, and then ending on the eastern side of the Ridge. This is apparently the eastern limit of the supposed Thomson Orogen. Under it there is a reflective lower crust at 8-13s TWT, and it is interpreted as highly stretched Precambrian basement. If that interpretation is correct the Thomson Orogen is thin and was deposited on a craton and not on an oceanic floor.

The Moho is everywhere characterised by a transition at 11-13s TWT from the reflective lower crust to non-reflective upper mantle. West of the Nebine Ridge the Moho is irregular in places, possibly reflecting major mid-Carboniferous tectonism of Devonian basins that overlie the Thomson Orogen. East of the Nebine Ridge the Moho is the base of a well-defined 'package' of seismic reflectors and undulates only slightly even though major deformation occurred in the mid-Triassic, and as late as Cretaceous near the coast.

REFLECTION MOHO AT 50 KM (16 S) BENEATH THE COLORADO PLATEAU ON COCORP DEEP REFLECTION DATA

E.C. Hauser,

Institute for the Study of the Continents,
Snee Hall, Cornell University, Ithaca, NY 14853.

COCORP deep-reflection data on the Colorado Plateau (CP) reveal reflections to about 16 s two-way travel time (50+ km), beyond which coherent reflections are absent. Elsewhere in some deep-reflection surveys, such a boundary has been interpreted as corresponding to the Moho as defined by nearby refraction experiments; however, a Moho depth of 40-43 km and a P_n velocity of 7.8 km/s have been previously interpreted for the CP from limited refraction data. Not only is the reflection boundary at 16 s clearly deeper than that previously suggested for the Moho there, but an 8.1 km/s Pn velocity is indicated from recent two-station analysis of hundreds of earthquakes received on the CP (Beghoul and Barazangi, 1987). A re-evaluation of the sparse refraction data set on the CP reveals that these data are of poor quality and have a wide station spacing. Recognizing these limitations, together with the new observations described above, a model with a Moho at 50 km (16 s) having a P_n velocity of 8.1 km/s can largely reconcile both the reflection and refraction data sets.

The lack of prominent, laterally extensive reflections at or near the Moho on these COCORP data further suggests that the crust/mantle boundary is a transition (not a velocity step function). A petrologically complex lower-crust and upper-mantle is also suggested from studies of xenoliths from diatremes on the CP. This petrologic variety is consistent with a complexly reflective transition, and supports the choice of the reflection boundary as the seismic Moho, below which the mantle may be dominantly peridotite and relatively non-reflective. As a result, the Moho defined by refraction and reflection data may not necessarily correspond to a petrologic crust-mantle boundary. This suggestion re-emphasizes that the thickness of a petrologic crust should not be assumed to correlate with the depth of a seismically defined Moho.

P & S WAVE VELOCITY STRUCTURE OF THE CRUST BENEATH THE NORTHWESTERN BASIN & RANGE, USA ; 1-D and 2-D INVERSION OF WIDE-ANGLE TRAVEL-TIME DATA FROM THE 1986 NEVADA PASSCAL EXPERIMENT

R.B. Hawman[1], D.A. Walker[1], R. Carbonell[1], R.H. Colburn[1], S.C. Key[1], S.B. Smithson[1], R.A. Johnson[2], W.D. Mooney[3], R.B. Smith[4], & G.A. Thompson[5]

1. Program for Crustal Studies, Dept. of Geology and Geophysics, University of Wyoming, Laramie, WY 82071,
2. Dept. of Geosciences, University of Arizona, Tucson, AZ 85721,
3. USGS, 345 Middlefield Rd., MS 77, Menlo Park, CA, 94025,
4. Dept. of Geology & Geophysics, University of Utah, Salt Lake City, UT, 84112,
5. Dept. of Geophysics, Stanford University, Stanford, CA, 94305, USA

We have inverted P and S wave travel times from explosions recorded with dense arrays (receiver spacing 50 - 100 m) using several different approaches based on generalized least squares. As a rough measure of lateral variation in the crust, we have carried out a series of 1-D analyses of different groupings of the data from the north-south and east-west trending reflection spreads. Tau(p) and X(p) data were extracted from slant stacks of shot gathers covering offsets (with gaps) from 2 - 170 km. An event detection technique based on covariance gives improved resolution of overlapping events in the critical offset ranges compared with more conventional measures of coherence such as semblance. The models are parameterized as stacks of homogeneous layers, and the tau(p) and X(p) data are inverted using both the Backus-Gilbert and generalized least squares methods. We invert for the compressional and shear-wave velocity structure independently; in general the shear arrivals are characterized by poorer coherence and lower S/N, resulting in larger standard errors and broader resolving kernels for the shear-wave model parameters. The averaged, 1-D models are used as starting models in an iterative inversion of T(p) data for 2-D velocity structure beneath the two profiles. Data consist of arrivals from both the unreversed wide angle reflection spreads and the reversed refraction spreads, and are inverted using a variation of generalized least squares based on the method of Tarontola. The results are similar to velocity models derived from refraction data using ray tracing; models for the compressional wave velocity structure show crustal thicknesses between 30 and 33 km with average velocities between 6.1 and 6.2 km/sec. Both P and S velocity models show an abrupt, fairly well resolved increase in velocity in the bottom 5-7 km of the crust. Velocities increase from about 6.45 to 7.50 km/s for P waves, and from 3.75 to 4.15 km/s for S waves. The corresponding increase in Poisson's ratio from about .25 to .28 is consistent with a transition from quartz-rich to plagioclase-rich rock. The latter value is in agreement with laboratory measurements for pyroxene and garnet granulites.

NETWORK COMPUTING CONCEPTS IN SEISMIC DATA ANALYSIS

S.J. Hearn

University of Queensland
Brisbane Australia

The term 'Network Computing' implies the interconnection of a number of discrete computers via high speed links (e.g. ethernet, token ring), the ability to transparently access files and peripherals across these links and, most significantly, the ability to transparently distribute computational tasks.

Seismic data analysis incorporates a number of 'computing disciplines' including parameter input, graphical output, data management, computation proper, and increasingly leading-edge disciplines such as artificial intelligence. Conventional seismic computing systems imply compromises between these disciplines.

A more perfectly integrated solution is potentially available with the advent of network computing technology. Here, 'distribution by discipline' would be achieved utilising a network of specialised database, computation, and A.I. servers. The graphics workstation would provide a stable, transparent, user interface to such diverse and variable resources.

A more specialised application of network computing is in the area of 'loosely-coupled' parallel computation. Here, a single computational task is shared between a number of CPUs on the network. An investigation of optimal distribution algorithms for seismic data processing is being carried out utilising a protocol known as Network Computing System (NCS). Early results indicate that the concept of 'task package size' is important in assessing network overhead. On a token-ring network of MC68020 based workstations, near-ideal distribution can be achieved with packages whose 'data dimension' is of the order of one seismic trace, and whose 'computation dimension' is of the order of 10 * FFTs.

PRELIMINARY CRUSTAL STRUCTURE OF THE WESTERN MOJAVE DESERT, TEHACHAPI MOUNTAINS AND SOUTHERN SAN JOAQUIN VALLEY, CALIFORNIA (CALCRUST REFLECTION PROFILING CORRIDOR III)

T.L. Henyey[1], B. Ambos[1], R. Lawson[1], M. Spongberg[1], P.E. Malin[2], E. Goodman[2], J. Crowell[2], & L. Silver[3].

1. University of Southern California, Los Angeles, CA 90089
2. University of California, Santa Barbara, Santa Barbara, CA 93106
3. California Institute of Technology, Pasadena, CA 91125

CALCRUST Corridor III is anchored to the western Mojave desert near the junction of the San Andreas and Garlock faults. Seismic profiles in this corridor are intended to explore:

1) The nature of the deep crustal transition from the miogeosynclinal Great Valley to the uplifted Mojave block;
2) The change, in late Miocene time, from extensional to compressional tectonics in the southern Great Valley, in response to inception of the modern San Andreas fault;
3) The deep structure of the Tehachapi Mountains, which may have rotated as much as 90 degrees since the Late Cretaceous, and the deformation accompanying that rotation,
4) The nature of deformation in the crustal wedge between the Garlock and San Andreas faults; and
5) The extent to which the Rand schist, a subduction-related complex, is found in the lower crust throughout the Mojave region, and the nature of the deformational processes which have later exhumed the schist.

Data being analyzed come from five principal sources, including a 34 km CALCRUST deep crustal line; several tens of km of COCORP line from their 1982 Mojave survey, several hundred kms of "5 s" industry data from both the Mojave Desert and San Joaquin Valley which have been extended, correlated, and reprocessed; a 115 km refraction profile across the Tehachapi Mountains; and geologic mapping in the Mojave and Tehachapi blocks. Selected seismic profiles and geological cross-sections from the San Joaquin Valley and Mojave Desert, together with crossings of the Tehachapi Mountains, will be shown.

VSP AND CDP PROFILES OF THE UPPER CRUST FROM THE CAJON PASS DEEP SCIENTIFIC BOREHOLE SITE - A JOINT DOSECC/CALCRUST EXPERIMENT

T.L. Henyey[1], P.C. Leary[1] and T.V. McEvilly[2]

1 University of Southern California, Los Angeles, CA 90089
2 University of California, Berkeley, Berkeley, CA 90720

The second phase of scientific drilling (6000 ft - 12,000 ft) has just been completed at Cajon Pass, California, in an experiment to study the state of stress along the San Andreas Fault. In addition to this primary objective, the hole is also providing an opportunity to study the nature of seismic wave-field propagation and reflectivity in the nearby crystalline crust, using a combination of VSP and CDP profiling. To date, two short walk-through CDP profiles and a pilot VSP study between the surface and 6000 ft in the borehole have been carried out. A comprehensive VSP program to 12,000 ft is planned for next year (1989).

The two walk-through CDP profiles utilized fixed 120 and 240 channels spreads with 15 m group spacing. The CDP fold ranged from 1 at the ends to 30 at the center. The VSP experiment utilized a four element downhole tool (four sondes at 10 m intervals); each sonde contained three orthogonal 15 Hz geophones and was clamped to the borehole wall. During a run, the tool was lowered to the bottom of the hole and raised at 30 m intervals to provide a 10 m group spacing over the entire length of the hole. Six P-wave and one S-wave vibrator shot points were occupied on the surface in the vicinity of the hole.

The local geology at Cajon Pass consists of a small intermontane basin with steeply dipping terrestrial sedimentary rocks overlying crystalline basement along a highly irregular contact. Faults and fracture zones are common in the basement. The hole is about 3.5 km from the San Andreas fault. The CDP profiles suffer from the low fold at the ends and are highly contaminated by scattered wave energy originating in the basin. The sediment/basement contact and two basement reflectors appear with low resolution in the upper two seconds on these profiles. In contrast, the VSP data, with the exception of a major correlation ghost, are relatively clean, and provide a high-resolution look at the basement both within the logged interval (0-6000ft) and the interval presently being drilled (6000-12,000). Thus the VSP served as a "look-ahead" for the second phase of drilling, and future VSP work in the hole should provide information well into the upper crust.

Numerous fracture zones were encountered by the drill hole. These zones are characterized by high P-wave reflectivity, strong attenuation of downgoing energy, and rich P to S mode conversion. The most coherent events observed on the CDP sections appear to correlate with the highest reflectivities in the VSP data. These events are associated with well developed fracture or, more probably, fault zones in the crystalline basement. The fracture zones and a nearby 300 m step (fault?) in the basement combine to produce strong amplitude anomalies in the downgoing wavefield. Shear waves produced by P to S mode conversion in the upper part of the hole show approximately a 10% (3.0 vs 3.3 km/s) birefringence or splitting, consistent with a crack density on the order of a few percent. It is hoped that analysis of VSP wave-fields at Cajon Pass will provide an improved understanding of the influence of the first few km of the crust - particularly the fracture zones - on the quality and character of deep crustal reflection data.

EVIDENCE FOR MESOZOIC SUBDUCTION IN SOUTHWESTERN U.S. FROM SEISMIC REFLECTION PROFILING AND REGIONAL GEOLOGIC SYNTHESIS

T.L. Henyey[1] & P.E. Malin[2].

1. University of Southern California, Los Angeles, CA 90089
2. University of California, Santa Barbara, Santa Barbara, CA 93106

Prior to Miocene time, a convergent margin existed in southwestern U.S. In addition to a number of other relict island-arc features, evidence for pre-Miocene subduction is provided by about a dozen outcroppings of Pelona-Orocopia-Rand schist throughout southern California and western Arizona. These schists are believed to represent ocean-floor protoliths which were subducted to depths of 10-20 km and later exhumed by uplift and erosion, primarily along major strike-slip fault zones. They are everywhere overthrust by older plutonic and metamorphic rocks; however their base is never observed in outcrop. Their subsurface extent within the crystalline terrane of southern California is not known. For example, it is not known whether they represent small pieces of the downgoing seafloor which were tectonically detached and accreted to the continental crust, or whether they are parts of a regionally continuous slab which did not sink into the mantle, but rather became attached to the base of the continental crust beneath much of southwestern U.S. The picture is further clouded by the fact that at least some of the schist bodies are found in large blocks of the continental crust which appear to have been accreted to the margin of western North America in early Tertiary time.

A 1982 reflection survey of the western Mojave desert by COCORP was able to extend one of the overthrusts - the Rand thrust which overlies the Rand schist - to a depth of several km into the crust along a line extending approximately 30 km southwest of the surface trace of the fault. More recent seismic reflection data collected by CALCRUST and donated by industry to CALCRUST (some of it reprocessed) together with an alternate interpretation of the COCORP Mojave data suggest that the schist may be regionally ubiquitous in the lower crust throughout much of southern California. Under this hypothesis, prominent mid and lower crustal reflectors appearing variously on a number of lines may be delineating both the upper (overthrust) and lower extent of the schist. The "base" of the schist might represent either a transition to more mafic oceanic protolith or obduction of accreted coastal terranes onto western North America. Further work would be necessary to distinguish between these alternative models if the hypothesis that the schist is widespread ifn the lower crust is correct. The presence of a relict slab beneath the continent would have important implications for plate-tectonic forces in subduction zones.

CRUSTAL THICKENING IN MOUNTAIN RANGES: WIDE-ANGLE AND VERTICAL SEISMICS THROUGH THE ALPS AND PYRENEES

A. Hirn

Institute de Physique du Globe, Paris, France.

ECORS, in joint efforts with ECORS Spain and CROP Italy, traversed recently the two orogenic belts of the Pyrenees and Alps. Refraction and wide-angle seismic data and detailed gravity data were available or acquired as part of an accompanying project to the main data set, vertical reflection lines several hundreds kilometres long and respectively 25 and 40 s TWT deep.

Localized crustal thickening, lateral change in the internal structure of the crust, and interpenetration of crust and mantle material may be reasonably documented, but only through the combination of the different approaches. The spatial repartition of high frequency reflectivity from vertical reflection provides most evidence for determining units, and their tectonic limits in the crust and in some examples in the mantle. Wide-angle seismics identify the depth to the upper mantle and gravity allows estimation of the balance of allochthonous materials.

DETERMINING THE PHYSICAL PROPERTIES OF THE CRUST

R.W. Hobbs & BIRPS Group

Bullard Laboratories, Madingley Road, Cambridge CB3 OEZ, UK

The reflection seismic technique has been used with great success to image the lower crust and upper mantle. The SWAT and WAM surveys show examples of complex patterns of highly reflective lower crust, while the NEC profile shows examples of simpler reflectivity where the reflectors seen on the seismic section are used to constrain the geological interpretation. It should be possible to extract more information from the seismic data. In particular for a given reflection it should be possible to determine how the acoustic energy is being absorbed and scattered by its transmission through the crust, i.e. the effective Q.

Two techniques can be used to determine the effective Q: time-domain modelling, and comparing frequency spectra at different time slices down the profile.

For isolated reflectors the transmission path can be modelled in the time domain. This technique has the added advantage of allowing the determination of the polarity in good signal-to-noise ratio data. Starting with a synthetic far-field source wavelet and with a detailed knowledge of the geometry and impulse response of the recording equipment,it is possible to synthesize the wavelet that would be recorded from a simple far-field reflector given an ideal transmission path, i.e. infinite Q. This wavelet can then be degraded by the application of realistic earth filters and convolved with the near-surface peg-leg and water-multiple series to generate a range of possible wavetrains that would be recorded during the survey. These can then be compared with the raw shot record data to determine the best fit model.

The second method is used for areas of complex reflectivity as seen on the SWAT and WAM profiles where it is difficult to identify individual reflectors in the lower crust. In order to extract the information it is necessary to understand how the water multiples modify the spectra. A typical value for effective Q for the lower crust, as determined from the WAM survey, is 400 +/-200.

HOW NEAR-SURFACE GEOLOGY AFFECTS THE IMAGING OF THE LOWER CRUST

R.W. Hobbs, D. Scheirer & BIRPS Group

Bullard Laboratories, Madingley Road, Cambridge CB3 OEZ, UK

BIRPS has collected over 12000 km of marine seismic reflection profile, recorded to at least 15 s TWTT, from around Britain. The survey lines cross a wide range of different near-surface geology, from sedimentary basins such as the North Sea to exposed metamorphic basement off the west coast of Scotland. Examples taken from this wide-ranging data set can be used to demonstrate how the near surface geology affects the imaging of the lower crust.

Data from different surveys shot with different source arrays, in different prevailing weather conditions, cannot be compared directly. However, it is possible to select individual profiles, from within a given survey, that do cross several different geological regions. For example, one profile from the NSDP-84 survey starts on the Shetland platform and as the profile proceeds eastwards towards the centre of the Viking Graben the thickness of the lower effective Q sedimentary section increases. This absorbs more of the seismic energy hence the imaging of the lower crust becomes poorer. The reverse effect can be seen in the SWAT survey when crossing granite bodies intruded into the upper crust. The apparent strength of the received reflected energy from the lower crust increases by about a factor of 10. The phase attribute of the data shows that reflectors in the lower crust beneath the granite can be traced over 10 km away from the intrusion. Assuming that the reflectivity of the lower crust is constant, the enhanced imaging must be due to the effect of the granite acting as a high Q 'window' compared to the surrounding upper crust.

COMBINED WIDE-ANGLE AND NEAR-VERTICAL INCIDENCE SEISMIC PROFILING OF THE LITHOSPHERE IN THE NORTHWESTERN BASIN AND RANGE PROVINCE, NEVADA, USA

W. Steven Holbrook[1], Rufus D. Catchings[2], Walter D. Mooney[2], Craig M. Jarchow[1], and George A. Thompson[1].

1 Dept. of Geophysics, Stanford University, CA 94305.
2 US Geological Survey, Menlo Park, CA.

The Basin and Range Province (BRP) of western North America is one of the world's largest continental rift zones. In order to understand better the role of the lower crust and uppermost mantle in the rifting process, and to shed new light on existing seismic reflection data in the province, a combined wide-angle and near-vertical incidence seismic survey was conducted in 1986 in the northwestern BRP of Nevada. In this paper we present data and modeling results from the experiment.

The backbone of the experiment consisted of two perpendicular refraction profiles : a 200-km-long line oriented parallel to basin-range structure (NE-SW), and a 280 km long line perpendicular to basin-range structure (NW-SE). One hundred forty instruments were stationed in three deployments, yielding an average station spacing of 1.5 km on the NE-SW profile and 0.9-1.4 km on the NW-SE profile. Chemical explosions were detonated in five shotpoints along the NE-SW provile and eleven shotpoints on the NW-SE profile. Models of the two profiles derived from two-dimensional raytracing show: (1) basins filled with up to 2 km of sediments (2.0-3.0 km/s) and volcaniclastics (4.0-4.5 km/s); (2) mountain ranges with bedrock velocities of 4.0-5.5 km/s; (3) crystalline basement of velocity 5.4-5.9 km/s; (4) a relatively uniform upper crust with velocities of 6.0-6.2 km/s; and (5) a distinct mid-crustal boundary at 18-22 km depth, below which velocities increase to 6.6-6.7 km/s in the lower crust. We are pursuing two alternative models of the crust/mantle transition, based on two differing correlations of seismic phases. In Model A, the Moho is a 3 km thick gradient zone at about 30 km depth, across which velocities increase from 6.7 to 7.6 km/s. The upper mantle has a velocity of 7.8-7.9 km/s, and there is a low-velocity zone (~ 7.5 km/s) within the upper mantle at about 40 km depth. In Model B, an 8 km thick rift pillow (7.4 km/s) overlies an upper mantle of velocity 8.2 km/s. The crustal thickness in both models is greater than in previous crustal models of the BRP, and Moho two-way traveltimes agree with those observed on the COCORP 40° N transect, which is approximately coincident with our NW-SE profile.

The "piggyback" reflection data recorded during the refraction survey consisted of a 20 km spread along the NE-SW profile, and a 65 km spread along the NW-SE profile, with group intervals of 67-100 m. At 4 s two-way traveltime on the near-vertical incidence shot gathers in the center of the survey, an abrupt transition occurs from a remarkably transparent zone to a deeper, highly reflective zone. This transition may coincide with the base of a localized mid-crustal low-velocity zone in the refraction velocity models. Bright, laminated reflections at the Moho on the reflection gathers probably represent the crust-mantle transition zone, which we have modeled alternatively as a gradient zone or a discrete rift pillow.

DEEP STRUCTURE OF THE SOUTHERN NORWEGIAN CALEDONIDES; A POSSIBLE LINK BETWEEN THE SCANDINAVIAN AND BRITISH CALEDONIDES

C.A. Hurich, S.J. Deemer and Y. Kristoffersen

Seismological Observatory, University of Bergen,
Allegaten 41 5007, Bergen, Norway

Seismic reflection profiling along the southwest coast of Norway indicates considerable basement involvement during development of the Scandinavian Caledonides. A prominent zone of northwest dipping reflections near the mouth of Hardangerfjord is interpreted as a crustal-scale shear zone that correlates with well developed fabrics in basement rocks and extends to lower crustal depths. The reflection data and coincident wide-angle data independently document a crustal thickening of 4 to 5 km southward across the shear zone. We interpret the shear zone to represent southeast thrusting of an at least semi-independent basement block during Caledonide deformation. The Hardangerfjord shear zone may represent an even more fundamental crustal feature that may provide a critical link between the Scandinavian and British Caledonides. Seismic profiling along the northeast coast of Great Britain (BIRPS NEC profile) reveals a north dipping zone of reflections similar to those at Hardangerfjord. Eastward projection of the strike of the Hardangerfjord shear zone suggests a possible correlation between the two zones of reflections. Projection of the Hardangerfjord shear zone also correlates with a major change in structural trend marking the boundaries between the Central and Viking grabens in the North Sea, suggesting the presence of a fundamental crustal structure. The seismic data also indicate that the Hardangerfjord shear zone was reactivated as a normal fault with as much as 8 km of normal offset, either during Late-Caledonide extension or Mesozoic extension in the North Sea.

DEEP SEISMIC REFLECTION PROFILING IN NORWAY

C.A. Hurich & Norwegian Lithosphere Project

Seismological Observatory, University of Bergen,
Allegaten 41 5007, Bergen, Norway

8000 km of marine seismic reflection data recorded to 15 or 16 s TWT form the basis of a major nation-wide effort toward understanding crustal and lithospheric processes. Data sets span a large range of geologic and tectonic environments supporting studies of extensional and compressional tectonics, continental margin development, the continent-ocean transition and development of spreading ridges. The Norwegian Lithosphere Project has also initiated a new program of deep seismic profiling on land. Land seismic work is presently concentrated in the central Scandinavian Caledonides in a joint Norwegian-Swedish effort within the framework of the Global Geotransects Program. We present data illustrating specific results of importance to a broad range of the geological/geophysical community.

LABORATORY WAVE VELOCITY MEASUREMENTS AND THE CONSTITUTION OF THE CONTINENTAL LITHOSPHERE

I. Jackson[1], R.L. Rudnick[2], S.Y. O'Reilly[3] and C. Bezant[3]

1. Research School of Earth Sciences, Australian National University.
2. Abteilung Geochemie, Max Planck Institut fur Chemie, Mainz.
3. School of Earth Sciences, Macquarie University.

Compressional wave velocities have been measured as functions of pressure (generally to 1 GPa), on jacketed specimens cored from a variety of mafic and ultramafic xenoliths derived from the lower crust and upper mantle beneath Eastern Australia. Three broadly representative suites have been studied: (i) mafic, pyroxene-rich, garnet granulites and eclogites from the Calcutteroo kimberlite pipe in South Australia (Jackson and Arculus, 1984); (ii) mafic, plagioclase-rich garnet granulites from the Chudleigh volcanic province of North Queensland; (iii) ultramafic rocks (spinel lherzolites, an olivine websterite, and a garnet pyroxenite) from the adjacent Bullenmerri and Gnotuk Maars and from Mt Porndon in Victoria. For each of these rocks, compressional- and shear-wave velocities have also been calculated for the modal mineralogy from appropriate single-crystal elasticity data via the theory of Hashin and Shtrikman.

Comparison of measured and calculated velocities provides a framework within which the reliability of the measured velocities may be assessed. The general consistency between measured and calculated velocities for the freshest xenoliths demonstrates the adequacy of this approach; any discrepancies are diagnostic of departures of the mineralogy of the measured core from the modal mineralogy determined on a separate sample of the same xenolith. Such departures may be caused by mineralogical heterogeneity, neglect of low-temperature alteration products or by unwanted epoxy impregnation during specimen preparation.

For the Calcutteroo suite, the measured (400 MPa) compressional wave velocities for nominally fresh garnet granulites and eclogites range from 7.5 to 8.0 $km.s^{-1}$. The lower end of this range corresponds to calculated velocities for assemblages of clinopyroxene and garnet with 25-30% quartz+plagioclase, whereas the upper end is identified with calculated velocities for plagioclase-free assemblages (eclogites). For three of the six rocks, the measured and calculated velocities are consistent within 1%; elsewhere the measured velocities are either low (alteration?) or high (mineralogical heterogeneity?) by as much as 0.5 km/s.

For the more aluminous granulites of the Chudleigh suite, measured velocities are consistently lower than calculated, even after allowance is made for the transformation of garnet to kelyphite (a fine-grained mixture of anorthite, orthopyroxene, clinopyroxene and spinel). This discrepancy is tentatively attributed to low-temperature alteration. The calculated velocities for this essentially isochemical suite increase with increasing metamorphic grade from ~7.4 km/s for an olivine-bearing plagioclase-rich representative (60% plagioclase) to ~8.0 km/s for the most garnet-rich (45%) member of the suite.

For the ultramafic suite, measured (1 GPa) velocities for the two olivine-rich (~70%) spinel lherzolites are within 1% of the value 8.27 km/s calculated from single-crystal elasticity data. On the other hand, measured compressional wave velocities for an olivine websterite (37% olivine) and for a garnet clinopyroxenite (20% garnet) are lower than calculated by 3-4% as a result of alteration and/or epoxy impregnation problems. The sensitivity of V_p to the variation of the relative proportions of olivine and pyroxenes in ultramafic rocks is therefore best estimated from the calculated velocities. A decrease of 0.09 km/s for a 20% reduction in modal olivine is indicated. Calculated velocities for the garnet pyroxenite, and for a garnet lherzolite (60% olivine, 20% orthopyroxene, 20% garnet) are respectively 8.04 km/s and 8.35 km/s. All of these calculated velocities pertain to conditions of one atmosphere pressure and 25°C, and must be adjusted for the higher temperatures and pressures prevailing in situ. The necessary pressure and temperature derivatives are fortunately not strongly dependent upon composition or mineralogy: $dV_p/dP \sim 0.1$ km/s.GPa andd $V_p/dT \sim -5x10^{-4}$ km/s.K being representative for a wide range of lithologies.

The covariation of temperature and pressure along the palaeogeotherm of O'Reilly and Griffin (1985) for S.E. Australia is such that the calculated velocity for any given assemblage is essentially independent of depth between 30 km (850°C) and 70 km (1160°C) - and approximately 0.35 km/s lower than the corresponding 1 atmosphere, 25°C datum. This geotherm has contemporary relevance only for regions of widespread recent volcanism and high present-day heat flow. Elsewhere, sufficient higher velocities (by ~0.05/km/s per 100°C) to prevail.

Calculated velocity-depth models will be compared with those of seismological origin for Eastern Australia in order to derive firmer constraints on the lithological character of the lower crust and uppermost mantle.

References:

Jackson, I. and R.J. Arculus. Tectonophys. 101,185-197, (1984)

O'Reilly, S.Y. and W.L. Griffin. Tectonophys. 111, 41-63 (1985)

INTERPRETATION OF THE REFLECTIONS IN THE SILJAN RING AREA BASED ON THE RESULTS FROM THE GRAVBERG-1 BOREHOLE

Christopher Juhlin,

University of Uppsala and Vattenfall

During 1985 a total of approximately 75 km of surface seismic reflection data was collected in the Siljan Ring area in central Sweden. The geology of the area consists mainly of granitic and gneissic rock ranging in age from 1400-2000 million years. The Siljan Ring refers to remnants of Palaeozoic sedimentary rocks that form a circular ring about 40 km in diameter, which have not been eroded, owing to downfaulting after a meteorite impact about 360 Ma. Several dolerite dikes are also present in the area ranging in age from 900-1200 million years. The seismics were shot over the meteorite impact structure and revealed several high amplitude sub-horizontal reflections in the northern part of the structure. The presence of the high-amplitude reflections and possible low-velocity zones below the third and fourth reflectors were contributing factors in choosing the site for the Gravberg-1 Deep Earth Gas test well, in the sense that it would penetrate at least 3 of these reflectors. Upon drilling the well and using vertical seismic profiling (VSP) to verify their existence and determine their depths, it was found that the reflectors were closely associated with dolerite sills which had intruded into the surrounding granite. These sills range in thickness from a few meters up to 60 m, and must have had a pre-impact areal extent of at least 800 square kms. An attempt to characterize the reflectors by looking at amplitude and frequency versus offset (AFVO) has been made using data from the borehole and the surface seismics. Results from a one-dimensional synthetic model, based on observed densities and velocities in the borehole, show that for the thicker dolerites a simple granite-dolerite-granite layering produces reflections whose amplitude and frequency increase with offset. Analyses of the surface seismic data in the vicinity of the borehole show increases in amplitude with offset while the peak frequency remains fairly constant.

RESULTS FROM SURFACE AND BOREHOLE INVESTIGATIONS DURING THE DEEP GAS DRILLING PROJECT IN THE SILJAN IMPACT STRUCTURE

Christopher Juhlin[1], Goran Rissler-Akesson[2], Laust Borsting-Pedersen[1] & Dan Dyrelius[1]

1. University of Uppsala and Vattenfall
2. Microline Consulting

Results from pre-drilling geophysical surveys are displayed. Seismic data revealing the high-amplitude sub-horizontal reflections in crystalline rock are presented along with a geological map that shows where the lines were shot and the location of the borehole. Results from other geophysical investigations, including gravity, magnetics, VLF and magnetotellurics, are also displayed. By using vertical seismic profiling (VSP), the depth in the borehole can be related directly to traveltimes on the seismics and ensure that the reflections are real. All of the surface investigations indicate the Siljan Ring area to be a geophysically anomalous region. A composite log, which includes the standard logs run in most boreholes, shows gradual as well as abrupt changes in the amount of natural gamma activity, sonic velocity and resistivity of the rock. The discrepancy between the maximum caliper reading and the minimum caliper reading on the four-arm caliper log gives a clear indication of the anisotropic horizontal stress conditions present in the rock. The resulting elliptical and rugose hole caused several complications both in the data acquisition and processing. The micro-electric scanner-tool (FMS) display shows the configuration of the individual fractures within the fracture zones.

DEEP SEISMIC SOUNDINGS IN THE GODAVARI RIFT VALLEY, INDIA

K.L. Kaila, P.R.K. Murty, V.K. Rao and N. Venkateswarlu
National Geophysical Research Institute, Hyderabad 500007, India

Deep Seismic Sounding (DSS) investigations have been carried out in the Pranahita-Godavari rift valley and the Krishna-Godavari (coastal) basin in Andhra Pradesh, along the Kallur-Polavaram (K-P) 100 km long west-east profile and the Paloncha-Narsapur (P-N) 170 km long NW-SE profile. DSS data were recorded along these two profiles from 30 shot points at interval of about 11-12 km, up to a maximum distance of 155 km, with 200 m geophone spacing. Basement configuration along these profiles was mapped initially using first-arrival travel-time data, and subsequently confirmed by 2-D velocity modelling by generating synthetic travel times and matching the same with the observations.

Along the K-P profile, in the central part of the rift, the first layer has a maximum thickness of 0.65 km (velocity 2.5 km/s) corresponding to Kamthi sandstones, second layer has a thickness of 2.4 km (velocity 3.5 km/s). Both these layers may correspond to the Lower Gondwanas. The basement velocity is found to vary between 5.3 and 5.6 km/s along this profile. Below the basement a high velocity layer (velocity 6.3 to 6.4 km/s), in the form of a domal upwarp at a depth of about 3.5 km lying immediately below the central part of the rift, is also mapped.

Along the Paloncha-Narsapur profile, which runs along the axis of the rift valley, two layers have been mapped, the first layer with maximum thickness of 1.2 km (velocity 2.5 km/s) and the second layer with maximum thickness of 2.2 km (velocity 3.5 km/s). Towards the coastal part along this profile, three layers have been mapped first layer, recent Alluvium, 1.2 km thick (velocity 1.8 km/s), second layer 2.5 km thick (velocity 4.0 km/s), followed by granitic basement (velocity 5.5-6.2 km/s). Along this axial profile between SP 6 and SP 12 a broad basement ridge is revealed about 60 km wide, that lies in the region of Eastern Ghats, which are almost perpendicular to the Godavari rift. This basement ridge may be an imprint of the Eastern Ghats orogeny. Towards the coastal part another small basement high has been mapped between SP 2 and SP 4 which lies at a depth of 2.6 km.

The deeper crustal sections along the two profiles were prepared by inverting wide-angle reflection travel-time data from intermediate layers and the Moho boundary. One-dimensional velocity modelling was also done for various shot points and based on that the Moho configuration was mapped. This was taken as an initial model for two-dimensional forward modelling using Cerveny's ray-tracing program, and final Moho configuration was obtained by matching the synthetic travel times with observations from various shot points. Along both the profiles, the Moho discontinuity is found at a depth varying between 40 and 42 km, almost showing a flat picture, the velocity below the Moho being 8.1 km/s.

THE COCORP TRANSECTS

S. Kaufman and the COCORP Staff

Institute for the Study of the Continents
Cornell University, Ithaca, N.Y. 14853

Many of COCORP's 9500 km of deep reflection data lie along regional geotectonic traverses. Compilation of the reflection imagery along these transects in a standard format provides a truly crustal-scale perspective on lithospheric structural variations. Highlights of these transects include:

Northwest Cordillera to Archean Craton: Prominent intracrustal layered complexes of variable dip and depth appear to be "truncated" by a relatively narrow band of flat Moho reflections beneath the Cordilleran interior. The adjacent Archean craton is also complexly reflective throughout, although Moho reflections *per se* are relatively rare until the transect passes into the Williston intracratonic basin. The changes in Moho character suggest that subcrustal magma emplacement has a role in Moho generation.

North Central Basin and Range to Colorado Plateau (40°N): A remarkably flat set of Moho reflections beneath, and a set of low-angle normal faults at the eastern margin of, the Basin and Range are the dominant features of this transect. The apparent re-equilibration of Moho geometry is clearly one of the most important observations from regional deep seismic profiles. A bimodal reflection character (i.e. transparent upper crust, laminated lower crust) is indicated on at least parts of this transect of an extensional province.

S.W. Basin and Range to Colorado Plateau: COCORP surveys in Arizona delineate a massive layered complex in the upper basement in the transition zone between extended Basin and Range crust and the relatively undeformed Colorado Plateau. Faulting of the Moho is also indicated.

Northern Appalachians: COCORP's transect of New England delineates a deeply penetrating reflection zone that marks a crustal-scale thrust ramp carrying the Taconic suture. Lack of reflections from the high-grade basement rocks exposed in the Adirondacks is an important constraint on speculations concerning the origin of crustal reflections elsewhere.

Southern Appalachians to Mississippi Embayment: New profiling has extended COCORP's Southern Applachian surveys northwestward across the adjacent Grenville craton and Reelfoot rift (Mississippi Embayment). Among the surprises: lack of strong lower crustal lamination, a possible intramantle reflection beneath the rift, and a crustal penetrating, west-dipping reflection zone that may coincide with the presumed, albeit poorly constrained, location of the Grenville front.

Midcontinent: The most recent of COCORP's transects reveals a thick layered sequence beneath the Paleozoic veneer of the east-central U.S. that may be part of an extensive Proterozoic volcanic outpouring or sedimentary sequence. In addition, a zone of east-dipping reflections marks the Grenville Front in Ohio; correlation with similar GLIMPCE reflections from the Great Lakes to the north is inescapable. West-dipping reflections located east of the Grenville Front are speculated to correlate with those on the Southern Appalachians transect, perhaps marking a new continental scale fault system.

THE MODERN CONTINENTAL MARGIN OF EASTERN CANADA; DEEP SEISMIC REFLECTION PROFILING

Kay, W.A., Keen, C.E., DeVoogd, B., and Dickie, K.,

Geological Survey of Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, B2Y 4A2, Canada

The modern continental margin of eastern Canada is diverse in tectonic character. Recent deep reflection profiling has produced five outstanding crossings of three distinctly different margins. Southeast of Newfoundland, Jurassic to Early Cretaceous separation of Africa and North America resulted in transform motion along the margin. Deep reflection data show a highly reflective lower continental crust, thinning across the margin. Reflection Moho is observed to shallow, and remains visible to within 15 km of its shallower oceanic counterpart.

To the north on the eastern Grand Banks, a rifted margin resulted from the Early-Middle Cretaceous separation of Iberia and North America. Again the deep continental crust is characterized by high reflectivity and rapid crustal thinning near the margin. Unlike the transform margin to the south however, the transition from continental crust to oceanic crust is more gradual.

East of Newfoundland Late Cretaceous rifting of northwest Europe and North America produced the Northeast Newfoundland margin. A broad basin (400 km wide) lies landward of the margin, the apparent result of a prolonged period (50 Ma) of rifting and thinning of the continental material, followed by rapid subsidence in the Eocene. A prominent series of reflectors within the crust appears to define a decollement between the upper (brittle) and lower (more ductile) crust.

Common to the southern and eastern margins are a series of Mesozoic basins ranging in depth from less than 4 km to more than 12 km.

Prominent landward dipping reflectors (LDR) are observed on both the margin east of Newfoundland and the eastern Grand Banks margin, at the continent-ocean transition.

DEEP STRUCTURE AND EVOLUTION OF A TRANSFORM MARGIN DETERMINED FROM DEEP SEISMIC REFLECTION DATA

Keen, C.E.[1], Kay, W.A.[1] & Todd, B.J.[2]

1. Atlantic Geoscience Centre, Geological Survey of Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada, B2Y 4A2;
2. Department of Geology, Dalhousie University, Halifax, Nova Scotia, Canada, B3H 3J5.

The continental margin southwest of the Grand Banks of Newfoundland, offshore eastern Canada, was formed by transform motion between the African and North American plates in Jurassic to Early Cretaceous time, and now offsets the rift marine segments by about 400 km. A deep seismic reflection profile was obtained across this margin, as part of a regional study of the seismic structure of the Grand Banks region. Observations along this profile have been combined with seismic refraction measurements to produce a detailed cross-section of the ocean-continent transition.

Beginning at the continental end of the cross-section, it shows a zone, about 45 km wide, of gradual crustal thinning, from a "normal" continental thickness of 38 km to about 23 km. Seaward of this zone there is a region of more rapid crustal thinning, about 20 km wide, resulting in continental crustal thicknesses of about 8 km at the ocean continent transition. The oceanic crust seaward of the transition exhibits a normal (8 km) thickness, but a peculiar velocity structure. The continental reflection Moho can be traced to within 15 km of oceanic crust without a major break. This suggests that the transform fault of shear zone lies within 15 km of the ocean-continent transition. The geometry of crustal thinning, and the sedimentary stratigraphy will be discussed in relation to the predictions of a thermal model of the transform margin, which involves the motion of a hot mid-ocean ridge along a relatively cool continental block, and the conductive transfer of heat to the continent.

THREE-DIMENSIONAL GEOMETRY OF THE CANADIAN APPALACHIANS FROM DEEP SEISMIC REFLECTION DATA

Keen, C.E., Marillier, F., & the LITHOPROBE EAST Working Group,

Atlantic Geoscience Centre, Geological Survey of Canada,
Bedford Institute of Oceanography, Dartmouth, Nova Scotia,
Canada, B2Y 4A2

In 1984 and 1986 a total of 1620 km of deep marine seismic reflection data were recorded across the Appalachian orogen, off the east coast of Canada. The seismic lines cross all five Paleozoic tectonostratigraphic zones of the Canadian Appalachians, as well as the Precambrian Grenville foreland to the west. The lines are situated so that seismic characteristics of the deep crust can be compared over a distance of approximately 600 km, along strike of the orogen. Three seismically distinct deep crustal blocks have been identified which appear to have similar characteristics over hundreds of kilometres along strike. The western block probably consists of crust associated with the Grenville foreland. The crust in this block was part of the ancient rifted margin which was overridden in the early Paleozoic by collisional events which created the Appalachians. The central block may represent the continental edge which once opposed this Grenville passive margin, and was separated from it by an ocean basin. The eastern block represents the easternmost of the suspect terranes off Newfoundland. The top of the western block is an east-dipping, low-angle detachment surface over which allochthonous terranes have been thrust. There is a possible suture between the central and western block deep within the crust, although its geometry is unclear. The central-eastern boundary is a near-vertical strike slip.

The most surprising result of our studies so far is the apparent along-strike continuity in the seismic character of the lower crust and Moho. This allows us to examine the three-dimensional crustal geometry of the northern Appalachians and relate it to the near-surface tectonostratigraphic terranes. This, in turn, can be used to constrain the plate-tectonic history of the region during Paleozoic time.

DEEP SEISMIC REFLECTION LINES FROM THE CANADIAN APPALACHIANS

Keen, C.E., Marillier, F., Durling, P., Kay, W.A.

Atlantic Geoscience Centre, Geological Survey of Canada,
Bedford Institute of Oceanography, Dartmouth, Nova Scotia,
Canada, B2Y 4A2

Marine seismic reflection data crossing the Appalachian orogen in eastern Canada reveals the deep structure corresponding to a number of major near-surface tectonic features. In the west the ancient passive margin of the Grenville Precambrian craton, which was overridden during orogenesis, is observed. The crust of this margin thins toward the east, suggesting that structural telescoping during the creation of the Appalachians did not restore or overthicken the crust to thicknesses typical of the craton to the west. The eastern boundary of this margin dips gently to the east, and can be traced to Moho depths. It is overridden by allochthonous terranes of the Appalachians, and exhibits a complex contact with the adjacent crustal block to the east. The latter, known as the central block, may represent the margin which was conjugate to the Grenville margin, before the intervening ocean basin was destroyed. The third, easternmost crustal block, the Avalon block, is associated with one of the eastern suspect terranes. It is separated from the central block by a near-vertical, strike-slip boundary.

Each of these deep crustal blocks exhibits a characteristic seismic signature. The reflection Moho is particularly interesting in the variety of appearances it assumes, from diffuse to sharp, and from bright to weak. The crust cannot be divided into transparent upper and reflective lower regions, and reflectivity is, in general, uniformly distributed throughout the crust. Offsets in the lower crust and variations in Moho depth suggest that at least some of the crustal effects of Paleozoic tectonics have persisted to the present.

THREE-DIMENSIONAL CRUSTAL STRUCTURE IN YELLOWSTONE, WYOMING, BY INVERSION OF LOCAL EARTHQUAKE DATA

E. Kissling

Institute of Geophysics, ETH Hoenggerberg, CH-8093 Zurich, Switzerland

The Yellowstone area is part of the Intermountain Seismic Belt. Over 10,000 events that were recorded in the time period 1973 to 1985, at about 40 permanent and over 200 temporary stations, provide the means to illuminate the three-dimensional structure of the crust and the uppermost mantle beneath the Yellowstone hot spot. This 3D-structure is obtained by use of a method of damped least-squares linear inversion applied to local earthquake data. The resolution of the data set for Yellowstone, and the effects of this specific numerical method, are displayed by the resulting velocity fields that were obtained from inversions of realistic artificial data. The exciting result of this inversion is the image of a large body of very low P-velocity in the mid-crust beneath the caldera. In correlation with various other geophysical data, this body of laterally low velocity can be interpreted as a magma chamber at middle and upper crustal level overlying a less disturbed lower crust.

SIX PARALLEL CROSSINGS OF THE IAPETUS SUTURE : PALAEOZOIC LOWER CRUSTAL REFLECTORS TRACED FOR 900 KM ALONG STRIKE

Simon Klemperer and the BIRPS Group,

British Institutions' Reflection Profiling Syndicate,
Bullard Laboratories, University of Cambridge, Madingley Rise,
Cambridge CB3 OEZ, UK

BIRPS profiles have been used to trace the Iapetus suture, the site of final closure of a large Lower Palaeozoic ocean, for 900 km from the Atlantic margin to the Central Graben of the North Sea.

Six long north-south profiles to study the British Caledonides have been recorded over the last six years. Each profile begins on crust known to be part of the pre-Caledonian North American continent and ends on crust known to be part of the pre-Caledonian European/Baltic continent, based on the evidence of faunal assemblages in Lower Palaeozoic outcrops, and therefore must cross the Iapetus suture. Four profiles have been recorded in the North Sea between Britain and the Mesozoic North Sea rift (NEC, NSDP and MOBIL programs), one profile between Britain and Ireland (WINCH), and one profile west of Ireland along the Atlantic continental shelf (WIRELINES).

On all six profiles, prominent north-dipping reflections are observed beneath the Solway Line - Shannon Estuary, the geologist's traditional location of the Iapetus suture. These north-dipping reflections and diffractions can be traced as shallow as 4 s and as deep as 18 s, though after migration they lie entirely above the reflection Moho, and dip at about 40^{o} . The gross similarity of these dipping reflections, in the same geological position with Caledonian strike on all six profiles, strongly suggests that they correspond to a single mega-tectonic feature of Lower Palaeozoic age.

We interpret these north-dipping reflectors to be the frontal thrusts and shear zones of the Iapetus suture zone, which are either truncated at 10 s by a younger (Mesozoic?) reflection Moho, or which rotate into horizontal shears and run along or near the present-day Moho to the north before eventually diving into the mantle. On three profiles in the North Sea, about 50 km north of the dipping reflectors, the reflection Moho deepens by 2 s travel-time for andacross-strike distance of only about 15 km, suggestive of the remnant of a crustal root zone and possibly marking the northern limit of a Caledonian shear zone at the present-day Moho.

Work in progress aims to establish how far this and other reflective features can be traced along-strike across Britain and Ireland, and hence to determine the uniformity or non-uniformity of the collision process along a substantial segment of the orogen.

REFLECTION SIGNATURES OF PALAEOZOIC TERRANE ACCRETION ON BIRPS DATA

Simon Klemperer, Brett Freeman and the BIRPS Group,

British Institutions' Reflection Profiling Syndicate,
Bullard Laboratories, University of Cambridge, Madingley Rise,
Cambridge CB3 OEZ, UK

Comparison of parallel deep reflection profiles recorded across the strike of Lower Palaeozoic accreted terranes suggests that it is possible to recognise different lower crustal reflection signatures from different crustal terranes.

The BIRPS-NEC deep reflection profile crosses the Lower Palaeozoic Caledonian collisional belt of northern Britain, which comprises elements of older continental crust, arc-related crust, and a subduction complex at least in part oceanic. The profile images north-dipping reflections interpreted to represent the Iapetus suture zone, and shows that the reflectivity characteristics of the lower crust and reflection Moho vary considerably across the orogen, potentially offering clues to the different crustal types present at depth. In order to test the hypothesis that the variable crustal reflectivity and north-dipping reflectors mark Palaeozoic collision- or accretion-related features, two additional parallel profiles were recorded up to 60 km distant along Palaeozoic strike as part of the BIRPS-MOBIL survey.

Brute stacks of the new profiles available at the time of writing confirm that the most significant lower crustal reflectivity variations observed on NEC are also visible 60 km distant on the MOBIL data. In particular, a change from highly reflective and diffractive lower crust of the presumed Iapetus suture zone, to a conspicuously unreflective lower crust south of the Iapetus suture, is clearly seen on all three profiles. The unreflective lower crustal block is underlain by an exceptionally bright reflection Moho, demonstrating that the lack of lower crustal reflectivity is not due to upper-crustal or mid-crustal absorption. These profiles were recorded as strike-lines to the Mesozoic North Sea rift, and run over a very uniform sedimentary section, so that the observed reflectivity variations may be assumed to be dependent only on variations in the crystalline basement, which is last known to have been metamorphosed in the Caledonian orogeny.

Thus, the present-day reflectivity pattern is apparently controlled by Caledonian geology. Whether the reflectors themselves would yield Caledonian geologic ages if drilled (though they lie at >20 km so this is not feasible), or whether they represent post-Caledonian utilisation or reactivation by magmatism, metamorphism or tectonism of older structures, is inevitably unresolved.

If these hypotheses are correct, then we can begin to use deep reflection profiles to map ancient collisional structures and different basement types, even in areas where the upper crustal geology is less well known.

THE TECTONICS OF CENTRAL AUSTRALIA: THE 1985 BMR SEISMIC EXPERIMENT

R.J. Korsch

Bureau of Mineral Resources, GPO Box 378, Canberra, Australia

Central Australia consists of highly deformed, east-west trending, Proterozoic high-grade metamorphic-plutonic complexes (Arunta and Musgrave Blocks) separated by moderately deformed sedimentary basins of Late Proterozoic to Late Palaeozoic age (Ngalia and Amadeus basins). Also in central Australia are some of the largest gravity anomalies known from the Earth's continental regions. Several crustal models have been proposed to explain these anomalies, but the early models were not related to tectonic processes.

Earlier seismic profiling by the BMR (1967-1969) over the NW margin of the Ngalia Basin imaged the Waite Creek Thrust, and showed Arunta basement being thrust over the basin sequence on a low angle, north-dipping fault.

The Arunta Block has been subjected to six cycles of crustal extension and compression between pre-1800 Ma and the Alice Springs Orogeny (400-350 Ma), and has been divided into three provinces with separate deformational and metamorphic histories, separated by major north-dipping ductile shear zones.

The Amadeus and Ngalia basins contain sedimentary sequences up to 14 km thick that have been deformed by thrusting and large-scale folding during the Alice Springs Orogeny. One thermomechanical model proposes that the basins evolved during a protracted period of crustal compression, during which the crust buckled to form the depocentres and basement highs. Another model proposes that the basins were initiated during an extensional event c.900 Ma, and underwent another extensional event at about the Proterozoic-Cambrian boundary (c.600 Ma). Foreland basins then formed along the northern margins of both basins during the Alice Springs Orogeny.

Tectonic models for the evolution of the basement, involving either a thin-skinned style of thrusting, above a low-angle detachment or thick-skinned (crustal scale) thrusting have been proposed recently, and there is also debate about whether the thrusting was predominantly during the Alice Springs Orogeny, or whether this event simply reactivated earlier structures.

Thus the 1985 BMR seismic experiment was designed to test the various models that have been proposed for the tectonic evolution of the basement and intracratonic basins in central Australia. The seismic results have allowed discrimination between the thin-skinned and thick-skinned models for the final compressional event, the Alice Springs Orogeny.

DEEP SEISMIC STUDIES OF THE TASMAN SEA BASIN - TECHNICAL ASPECTS

S.P. Kravis, M.F. Coffin and R. Whitworth

Division of Marine Geosciences and Petroleum Geology, Bureau of Mineral Resources, PO Box 378, Canberra City, ACT 2601, Australia

Deep reflections, appearing at two-way times of 6 to 20 s, are characterised by a low signal-to-noise ratio and a low-frequency content (5-30 Hz). Optimising the visibility of these reflections requires that

1) The source energy be concentrated in this band.
2) The receiver should be as long as practically possible.
3) The shot spacing should be as small as possible.
4) Receiver noise should be minimised.

An airgun array simulation program was used to investigate the effect of operating a 10-gun array at different depths. It was found that the source energy could be enhanced at low frequencies by running the gun array at depths of up to 25 m, and that this would improve the signal-to-noise ratio for deep reflectors by a factor of 2, at the cost of some loss of temporal resolution.

The receiver length was limited to 4.4 km by the number of cable sections available and the maximum tension allowable in the cable. It was configured as 88 channels of 50 m length. In order to reduce the shot spacing, minimise the tow noise, and reduce tension in the cable, the ship speed was reduced to 3.5 knots. In order to reduce sea-state noise and keep the receiver ghost notch frequency outside the frequency band of interest,a cable depth of 20 m was aimed for. These measures gave tow-noise levels of 1-2 microbars under normal operating conditions.

A variety of problems was encountered in the field. Fish bites holed 50% of the total cable inventory, and the loss rate was so high over the Lord Howe Rise that the cable had to be retrieved every day or so. Leakage of ballast oil made cable-depth stabilisation difficult, and depth sensors and controllers sustained damage as cable sections sank below their maximum rated depth.

Despite these problems, useful data were obtained over the Lord Howe Rise, Dampier Ridge, and deep abyssal plain. The concept of using an airgun array tuned for maximum energy was demonstrated.

TRANSTENSIONAL EVOLUTION OF THE OTWAY AND SORELL BASINS OFF SOUTHEASTERN AUSTRALIA

C.S. Lee, N.F. Exon and J.B. Willcox

Bureau of Mineral Resources, GPO Box 378, Canberra, ACT 2601

Regional seismic data across the Otway and Sorell Basins indicate that they have the characteristics of extensional basins which probably have been affected by two periods of strike-slip movements, creating 'transtensional' and 'transpressional' structures. Seaward-dipping normal faults, probably detaching on Palaeozoic basement, indicate less than 5% extension beneath the continental shelf and upper slope, and about 30% extension beneath the middle and lower slope. These areas of different extension are separated by a sub-branch of the detachment, with associated landward-dipping faults in places.

The basins were possibly initiated by left-lateral strike-slip movements (along a northwest to southeast trend) in the pre-Middle Jurassic, but developed as transtensional basins in the Early Cretaceous. A continuing strike-slip sense of movement appears to have created uplift of tilt-blocks below the lower slope in the Late Cretaceous, and extensively faulted anticlines and 'squeezed blocks' below the upper slope in the Eocene and Early Oligocene. There is evidence that Tertiary structuring is associated with reactivation of the heads of sub-branches of the detachment.

Most of the margin separated from Antarctica in the Late Cretaceous, but Tasmania cleared the adjacent landmass (Antarctica or South Tasman Rise) in the Early Tertiary. The 1987 R/V Rig Seismic geological cruise results show that continental basement and Early-Late Cretaceous detrital sedimentary rocks crop out on the lowermost continental slope. The mid-slope is characterized by Early Tertiary detrital sediment, and the upper slope by Late Tertiary carbonates. Recovery of Eocene peaty sediments in deep water throughout the basin suggests rapid subsidence since the Eocene. High heatflow values in the upper slope further support substantial post-breakup activity. Geological sampling and heatflow data will be related to the tectonic evolution of the SE Australian continental margin.

CONTROLS ON EPISODIC BASIN DEVELOPMENT IN THE NORTH PERTH BASIN WESTERN AUSTRALIA

C.S. Lee, J.F. Marshall and D.C. Ramsay

Bureau of Mineral Resources, G.P.O. Box 378
Canberra, ACT 2601

In July 1986, BMR collected 2400 km of 48-channel seismic reflection data and occupied some 70 dredging, coring and heatflow stations on the transform margin that forms the offshore extension of the North Perth Basin. Cruise results, coupled with released petroleum company seismic and well data, suggest a fairly broad diversity of structural styles and fault patterns, which are probably representative of at least 3 tectonic episodes that developed within the basin prior to breakup in the Neocomian.

The earliest identified (Carboniferous?) extension, dominated by landward-dipping rotational faults, is present beneath the Edel Platform to the northeast. Within the adjacent Abrolhos Sub-basin, possibly separated from the former by a strike-slip fault, another style of extension during the Late Permian resulted in tilted fault blocks, forming a series of half-grabens with concomitant rift fill. During the Triassic and Jurassic, marine sedimentation, but becoming progressively more continental in character, originally onlapped the half-grabens and then blanketed the relatively rapidly subsiding basin. Prior to breakup, there was reactivation of the possible Permian tilted fault blocks, while further to the west there developed a series of seaward-dipping normal faults beneath the continental slope. It is believed that the composite fault pattern associated with the reactivation of tilted blocks may have been produced by oblique extension of the basin.

Controls on episodic basin development (i.e. the structural styles, the fault patterns, and the distribution of possible transfer zones) suggest a similarity to other regions that exhibit a substantial component of strike-slip motion and its associated oblique extension at present-time (e.g. the San Andreas Fault system). Particularly, analysis of the fault patterns indicates that most of the extensional normal faults can account for only about 15% basin extension. This implies that the basin may have undergone more an oblique-slip motion than the more usual extensional normal displacement at different phases of the pre-Neocomian break-up history. We believe that NNW trending boundary fault, the onshore Darling Fault, may be the surface boundary fault, the onshore Darling Fault, may be the surface manifestation of the major detachment fault along the rifted basin of southwestern Australian continental margin.

WIDE-ANGLE AND VERTICAL INCIDENCE SEISMIC DATA IN THE CENTRAL CALIFORNIA MARGIN

Alan R. Levander and Anne S. Meltzer

Department of Geology and Geophysics, Rice University,
PO Box 1892, Houston, Texas 77251

Rice participated in a multi-institution seismic survey in the central California transform margin in late 1986. We acquired 115 km of onshore-offshore wide-angle seismic data, and, with the Houston Area Research Center, 425 km of marine reflection data. The reflection data extend from the coast across the shelf and slope, and into the deep ocean basin. Sixteen seconds of 45-fold CMP data were recorded with a 180-channel streamer (25 m group interval, 4.7 km maximum offset) using a 6000 cu. in. airgun array (50 m shot interval).

The reflection data images the top of Pacific oceanic crust: a bright reflection at 6 km depth near the continental rise dips 6.5^{o} landward for 50 km to a depth of 14 km beneath the Santa Lucia High (SLH). We interpret this as a decollement separating the Pacific plate from the overriding North American plate. Discontinuous reflection segments appear at the same depth beneath the Santa Maria Basin (SMB). Moho reflections are at 18 to 20 km beneath the SLH. Shallow strike-slip and high-angle faults show evidence for Neogene extension followed by compression. These faults die out with depth in the Franciscan accretionary basement, demonstrating that the 12 km of accreted sediment separates the shallow structures from the deep decollement.

The wide-angle experiment recorded 406 marine airgun pops and three land explosions at a 50 km land array (154 recorders, 350 m group interval, 115 km maximum offset). The array extended northeast from Morro Bay across the allochthonous Sur-Obispo and Salinian terranes. A seismic vessel fired a 10,280 cu. in. airgun array every 155 m in line with the receiver array. This experiment has been interpreted as a long-offset CMP survey, as a reversed shot-gather land refraction profile, and as an unreversed onshore-offshore receiver-gather refraction profile.

The velocity model from the refraction interpretations is consistent with the onshore geology, the wide-angle CMP stack, and the marine reflection data. With the combined reflection and refraction profiles, the Pacific oceanic crust can be followed from the abyssal plane landward beneath the coast. Wide-angle reflections from the base of the oceanic crustal layer show that it dips abruptly, and is twice the thickness of normal oceanic crust near the coast. This suggests that the Pacific plate is either imbricated, or underthrusts relict oceanic crust in the area immediately offshore.

MID-CRUSTAL DYNAMICS CONTROLLING BASIN FORMATION: EXAMPLES FROM THE DEVONIAN SUB-BASINS IN WESTERN QUEENSLAND

J.H. Leven and D.M. Finlayson

Bureau of Mineral Resources, Geology and Geophysics
Canberra, Australia

The Devonian Quilpie Trough in the southern Adavale Basin displays the characteristics of a ramp basin, and overlies a ramp structure in the boundary between the upper non-reflective and lower reflective crust. It is interpreted to have formed by the relative movement of the early Palaeozoic upper crust (uppermost 20-25 km) over this mid-crustal ramp.

Symmetric ramp basins are formed by simple vertical shear within an upper plate during movement over a ramp structure, provided the ramp does not deform during this event. The significant asymmetry of the Quilpie Trough is interpreted to indicate that the lower crustal ramp was extended during (or by?) the translation of the upper crust.

Assuming simple vertical shear in the upper plate, a triangular shaped ramp basin can form only if the distance the upper plate moves corresponds to the horizontal distance between the upper and lower hinges, or to the width of the underlying ramp. This constrains the westward diplacement of the non-reflective Thomson Fold Belt to be equal to this horizontal dimension of the observed mid-crustal ramp (~20 km). However, the westward translation of the upper crust was not uniform over the region, as evidenced by the Pleasant Creek Arch. This arch was formed by both upper and mid-crustal thrusting, which accommodated or absorbed the westward displacement of the Thomson Fold Belt to the north of the Quilpie Trough.

The formation of other Devonian sub-basins in the vicinity of the Quilpie Trough is interpreted in terms of the Carboniferous relative movement of the upper crustal Thomson Fold Belt over the lower crust, with amount of relative movement and the topography of this upper/lower crustal interface controlling the geometry of these ramp basins.

The BMR deep seismic reflection data from the Central Eromanga Basin indicate that relative movements can occur between the upper and lower crust, and illustrates the importance of such mid-crustal processes in understanding the surface geology.

A DEEP SEISMIC SURVEY ACROSS THE TUMUT TROUGH, SOUTHEASTERN AUSTRALIA

Jim Leven[1], Peter Stuart-Smith[1], Mike Rickard[2] and Keith Crook[2].

1. Bureau of Mineral Resources, Geology and Geophysics, Canberra,
2. Geology Department, Australian National University, Canberra.

The Tumut Trough is an Early Paleozoic tectonic and paleogeographic feature striking NNW-SSE within the Lachlan Fold Belt. It is bounded to the east by the Mooney Mooney Fault System, and to the west by the Gilmore Fault, both of which have been interpreted as terrane boundaries. Interest in the Tumut Trough stems from the occurrence there of ultramafic rocks and Silurian flysch in association, not found elsewhere in the Lachlan Fold Belt. Ultramafics along the bounding faults of the trough indicate deep penetration and involvement of mantle material. Within the trough a basement anticline of amphibolitic schists of possible Ordovician age is flanked by basaltic and dacitic volcanics. The trough is bordered to the east and west by the dominantly granitic rocks of the Lachlan Fold Belt: to the east - the Late Silurian Young Granodiorite; and to the west - the Ordovician Wagga Metamorphic Belt.

The association with felsic volcanics of ultramafics, gabbros, pillow basalts, cherts, and turbidites, has led to a variety of scenarios for the formation of the trough - marginal sea, continental rift, trans-tensive pull-apart basin - and for its closure by transpression or eastward-directed subduction of the trough floor. To investigate which of these models best represent the development of this trough, it is necessary to understand its underlying crustal structure. For this purpose, a deep seismic survey was conducted as a joint project by the Bureau of Mineral Resources and the Geology Department, Australian National University, in May, 1987.

The target of this survey was the bounding faults which were thought to dip to the east and have a listric form. The occurrence of serpentinite along these major faults was expected to provide a marked seismic impedance contrast with the surrounding rocks, and produce relatively strong reflection signals. However, the stacked section of the Tumut Trough seismic data shows no indication of these listric bounding faults, even though strong reflectors at 7.2 s two-way time (TWT) indicate the penetration of seismic energy to depths of 20 km. This suggests that the bounding faults do not have a listric form and are probably nearly vertical.

Beneath the Young Granodiorite there is a non-reflective zone to 3 s TWT, interpreted to be the batholith extending to a depth of around 9 km. Beneath this zone reflections extend down to a strong sub-horizontal reflector at 7.2 s TWT. Within the Tumut Trough there are two regions which display coherent reflections. The mapped fold structure of the Bullawyarra Schist is reflected in short segments of coherent energy east of Brungle. Near Minjary, a set of strong sub-horizontal reflectors at 1 s TWT is interpreted to be either structural basement or the Gocup Granite contact. The deeper seismic data shows no coherent energy beneath 10 s TWT, but the depth of the Moho is undetermined. Between 3 and 9 s TWT, sub- coherent reflections dip eastward, suggesting imbricate structures beneath the trough.

THE RAY-MATRIX METHOD OF SYNTHETIC SEISMOGRAMS FOR DIFFERENT SOURCE AND RECEIVER STRUCTURES

Liu Qiyuan, Fan Huiji
Institute of Geology, State Seismological Bureau, Beijing, China

A new method of computing synthetic seismograms of teleseismic body waves is described, in which the generalized ray theory and matrix method are combined together in order to include multiple reflections of thin layers automatically. The Earth's model is separated into three different parts: the source area, the mantle area and the receiver area. The layered model of the Q value is used in this method. The new-ray code method reduces the input data greatly. The comparison of this algorithm with the reflectivity method (Kind, 1985) shows the main phases are consistent. And our method is more convenient to use for the interpretation of the phases.

A PROCEDURE OF DETERMINING THE VELOCITY STRUCTURE OF THE LITHOSPHERE FROM BROADBAND TELESEISMIC P WAVEFORMS

Liu Qiyuan, Lu Yumei

Institute of Geology, State Seismological Bureau, Beijing, China

A procedure for determining the velocity structure of the lithosphere from a suite of broadband teleseismic P waveforms of deep-focus events, or nuclear explosions recorded at the same station, has been described in this paper. The identification of the multiple reflections and conversions in the P waveforms is emphasized in this procedure. The following steps are included: 1) the coordinate system is rotated to the ray direction; 2) correlation and deconvolution are performed; 3) then the frequency range is extended by a recursive application of a unit-step prediction operator determined by Burg's algorithm, in order to increase the resolution in the time domain; 4) this prediction algorithm is also used for improving the determination of the source wavelet to remove the effects of the structure near the surface under the receiver; 5) the phase identification and waveform inversion are performed in terms of the ray-matrix method of synthetic seismograms for different source and receiver arrangements (Liu & Fan, 1987). This processing procedure is used for interpretation of the data of the GRF broadband seismic array.

SHEAR-WAVE EXPLORATION OF THE CRUST BENEATH THE BLACK FOREST, SOUTHWEST GERMANY

Luschen, E., Hubral P. and Fuchs K.

Geophysical Institute, University of Karlsruhe, Hertzstrasse 16, D-7500 Karlsruhe 21

A new crustal exploration tool, shear-wave-Vibroseis, has been tested and successfully applied for investigations of the lower crust.

An experiment using a horizontal vibrator as a controlled shear-wave source has been conducted in the Black Forest region in SW Germany in November 1987. These Vibroseis data have been complemented by recordings of a three-hole shot. First results from three near-vertical reflection lines will be reported, which were tied to P-wave reflection lines of the 1984 KTB (Continental Deep Drilling) - reconnaissance program.

These experiments were done in the same region where the previous reflection experiments detected the lamination of the lower crust for P-waves. Wide-angle experiments corroborated these findings in P but provided strong evidence that the lamination is not present in the shear-wave velocity. Surprisingly, the present shear-wave near-vertical experiments produced evidence for reflected shear energy out of the lower crust.

This discrepancy will be discussed with regard to constraints on the physical and chemical composition of the lower crust.

CRUSTAL STRUCTURE OF THE BASIN AND RANGE PROVINCE AND ADJACENT TRANSITION ZONE IN CENTRAL ARIZONA, USA, FROM SEISMIC REFRACTION AND WIDE-ANGLE REFLECTION PROFILING: IMPLICATIONS FOR CONTINENTAL EXTENSION

J. McCarthy, S.P. Larkin, G.S. Fuis

US Geological Survey, MS 977, 345 Middlefield Rd., Menlo Park, C.A. 94025, USA)

In 1987, the US Geological Survey collected 180 km of deep-crustal seismic refraction/wide-angle reflection data across the transition zone between the Basin and Range Province and the Colorado Plateau in Arizona. The experiment consisted of 27 shots, 19 shot points, and 240 receiver stations with an average spacing of 750 m.

Preliminary results indicate that the crust thickens from approximately 28 km under the Basin and Range Province to more than 33 km under the transition zone. P_n velocity is 7.9-8.0 km/s, typical for an upper mantle velocity. The character of PmP arrivals, especially at wide angles, suggests complexities in the lower crust and possibly the upper mantle. In addition, a major change in PmP character is observed for receivers located in the transition zone. Shots arriving from the northeastern edge of the Basin and Range Province yield a high-amplitude PmP reflection with pre-critical arrivals observed as close as 40 km from the shot. PmP arrivals from a shotpoint located on the southwestern edge of the Colorado Plateau, however, are much lower in amplitude and are observed within 70 km of the shot. Moho depth does not change significantly enough to account for this amplitude change, suggesting a physical change in Moho character in this region.

A prominent mid-crustal reflection is present on record sections covering the southwestern half of the profile. Detailed modeling of this reflector from 8 shots reveals a mid-crustal layer whose top is dome-shaped with a relief of 11 km and whose base is flat at approximately 20 km depth. The approximate velocity of this structure is 6.3 km/s. The apex of this domed layer is centered roughly beneath the Buckskin Mountains metamorphic core complex, and corresponds well with the region of major tectonic denudation and uplift (of ~ 10 km) defined by surface geologic mapping. Despite the presence of a thickened mid-crustal layer, the lower crust maintains a uniform thickness across the study area. Furthermore, the average crustal velocities (~ 6.3 km/s) are low, indicating that if gabbroic underplating has occurred contemporaneously with extension, it has not significantly raised the velocity or the thickness of the lower crust in this region. Instead, the processes that control continental extension, such as magmatism and ductile flow, appear to have been concentrated in the middle crust.

THE CRUSTAL EVOLUTION OF THE SOUTHERN SAN JOAQUIN/TEJON EMBAYMENT FROM CALCRUST SEISMIC REFLECTION AND REFRACTION PROFILING

P.E. Malin[1], E.D. Goodman[1], T.L. Henyey[2], E.L. Ambos[2], D.A. Okaya[3] and T.V. McEvilly[3].

1. Institute for Crustal Studies, University of California, Santa Barbara, Santa Barbara, CA 93106
2. Department of Geological Sciences, University of Southern California, Los Angeles, CA 90089
3. Center for Computational Seismology, Lawrence Berkeley Laboratory Berkeley, CA 94720

The deep sedimentary sub-basins of the southern San Joaquin Valley present a number of geologic questions. Paleomagnetic evidence suggests that the basement rocks bordering the basins may have rotated as much as 90 degrees clockwise since the Late Cretaceous, yet the basins in front of this rotated block show little evidence of folding. Instead, surface and subsurface geologic maps show normal, reverse, and strike-slip faults in close proximity to each other. The ages of these features can be related to the plate-tectonic reorganizations that have taken place along the southern California continental margin. Travel-time residuals from earthquake sources suggest that the lower crust has a regionally continuous character, but the upper crust is broken into grossly different blocks. Evidently, the structures responsible for opening and rotating the upper crust either do not extend into the lower crust, or are not apparent from subsurface geophysical data.

CALCRUST is working to answer these questions with the aid of well data, industry CMP data, deep seismic reflection data, and regional refraction profiles. These data have allowed us to understand the timing and magnitude of the faulting. The fault-related opening and deepening of the basins took place, respectively, before and after the passage of the Mendocino triple junction, thereby constraining the range of tectonic regimes in which they have evolved. The refraction and reflection data suggest that fault zones, such as the segmented and multi-stranded White Wolf thrust, originated as extensional features and served as the framework for opening the basins.

The deep seismic reflection data contain large, dipping structures which may represent fundamental boundaries in the crust and account for the observed lateral differences in earthquake travel times. In one suggested model, the paleomagnetic rotations are accommodated by slip on these structures, with associated upper crustal warping taking place north and south of the southernmost San Joaquin. This model would require that any resulting large vertical deformations at the bottom of the crust would subsequently have been reorganized to produce a geophysically uniform layer. In our presentation, we discuss these and other interpretations of the available data.

SIGNAL SEPARATION BY COHERENCE ESTIMATION: APPLICATION TO THE ECORS DATA

J.M. Marthelot and M. Bano

EOPGS, Univ. Louis Pasteur, Strasbourg, France

We have implemented sveral techniques to complement the industrial processing of the ECORS deep seismic reflection data, in order to help to constrain their interpretation. Discontinuous segments of reflectors are automatically extracted from stacked sections by amplitude filtering of traces transformed by local slant stack in a moving window. The filter threshold varies laterally as the variance of the distribution of transformed noise. Segments of reflectors with a given slope can also be isolated by multiplying the traces with a coherency-weighted slowness filter.

We have tried to discriminate true dipping reflectors from gently dipping diffraction hyperbolas in two ways. Hyperbolas can be extracted from the section by a process of repeated f-k migration, followed by amplitude filtering and diffraction. Synthetic diffraction hyperbolas can also be constructed by diffracting the segments of sub-horizontal reflectors present on the section. In addition, we have implemented a migration program that includes a coherency-weighted slowness filter.

We will show how the application of these techniques permits a detailed analysis of zones of complex reflection pattern, particularly within the lower crust of the ECORS North of France Profile.

12,000 KM OF BIRPS: HIGHLIGHTS AND PLANS

D.H. Matthews & BIRPS Group

Bullard Laboratories, Madingley Road, Cambridge CB3 OEZ, UK

BIRPS has acquired and processed 4000 km more deep seismic reflection profile to add to the 8000 km that were presented at the Cambridge meeting in 1986. The British Isles are now ringed with exploratory lines, and we have shot several experiments to check ideas or extend techniques. Twelve thousand km of data in an area equal to the Basin & Range make this the best known patch of the lithosphere. The total cost since 1981 is about 3 millon pounds, including salaries, postage, and travel; about 250 pounds per kilometre.

Six perpendicular crossings, from west of Ireland to the central North Sea, trace the Iapetus suture over 900 km. All have significant points in common. The conclusion that different terranes cannot be distinguished on BIRPS data is not yet unanimous, even within BIRPS. Structures in the mantle have been mapped in 3-D by a grid of lines north of Scotland and by several crossing lines north of Ireland. Profiling in the North Sea, combined with computer studies of the effects of normal faulting, has reconciled the conflicting estimates of extension in the northern North Sea made from observations of normal faulting in the sediments on the one hand, and from subsidence and crustal thinning on the other. Lithospheric simple shear is less able to explain the observations than uniform stretching. Lower crust and mantle reflectors have reflection co-efficients of about 0.1. Controversy still surrounds the physics of their origin : there are BIRPS who are sure that deep reflections must represent basalt underplating after widespread extension; others still hanker after fluids. Amplitude-offset relations observed north of Scotland may provide crucial data.

We have successfully used our small computer to migrate the better deep data using industry algorithms, and have evaluated polarity and Q. Multiples from deep water sites can now be labelled and eliminated. Noise reduction is the key to deep reflections, and so we have concentrated on noise analyses. Improvements in industrial techniques are beyond our capacity, but we have just completed an innovative dynamite survey on land, generating S-waves, and hoping to measure Poisson's ratio in the lower crust. We have not yet been allowed to work in areas beyond the British Isles and plans after 1989 are in doubt.

DEKORP'S NEW LINES: ASPECTS OF VARISCAN TECTONICS

R. Meissner, T. Wever and the DEKORP Research Group

Institut fur Geophysik, Kiel University, D-2300 Kiel and
Bundesanstalt fur Geowissenschaft (BGR) Hannover, West Germany

Pattern recognition of reflectivity along reflection profiles in West Germany reveals the character and sometimes the history of the latest tectonic events in the Variscides. Lower crustal lamellae prefer zones of young and warm crusts where some post-orogenic extension took place. Flake and "crocodile" tectonics are observed in and along the older massifs, concentrating in the upper and middle crust and preserving a certain memory of old collisional belts.

AN EFFICIENT METHOD FOR SENDING A LARGE SEISMIC SECTION FROM A MAINFRAME COMPUTER TO A DOT-MATRIX PRINTER LOCATED AT A REMOTE SITE

R.F. Mereu, B. Dunn and J. Brunet

Department of Geophysics, University of Western Ontario, London, Ontario, N6A 5B7

The processing of seismic reflection data sets is usually done on large computers which have both vector processing and large memory capabilities. Many researchers in university, government and industry laboratories have access to these machines via remote terminals and small work stations. Jobs can therefore be conveniently run, however a major problem occurs when one would like to see the results within a few minutes so that appropriate changes may be made. Although seismic centres have professional electrostatic plotters, it may not always be convenient to wait for the plots via courier services. Many university computing centres are equipped with only pen plotters. These are not practical to use for large seismic sections with shaded traces.

An efficient method of sending the data set from the mainframe computer to a small PC computer with a modem and a dot matrix printer is described in this paper. The method works primarily with two FORTRAN programs. The first is resident on the mainframe computer. This program strips the data set of all its non-essential bits, partially rasterizes the set, and converts it into a simple ASCII character set sequence. The second program resides on the PC computer. It obtains the condensed data file from the mainframe, and completes the rasterizing process by creating the bit map for the printer. Any reasonable size data set can be sent down the line as the method does not require the use of a hard disk on the PC. Screen dumps from a graphics terminal are not carried out. Instead there is a steady flow of data from the main frame disk, through the PC and then to the printer.

In a test example, a 500 trace data set containing 8.4 megabytes of data on a CYBER 180 mainframe was condensed down to 1.2 megabytes and sent down a 9600 baud serial line to the PC. The PC generated a bit map consisting of 32 million bits . This was plotted by a 180 dot per inch printer on a 6 ft by 14 in plot. The total time required to transmit and plot the data was 25 minutes. This represents a rate of approximately 3 s for each 2250 point trade.

Pg SHINGLES: RESULTS FROM THE GLIMPCE ON-SHORE REFRACTION DATA

R.F. Mereu and D. Epili

Department of Geophysics, University of Western Ontario, London, Ontario, Canada, N6A 5B7

During the summer of 1986, the University of Western Ontario participated with other research groups in the Great Lakes Multidisciplinary Program for Crustal Evolution (GLIMPCE). The experiment was a major on-ship on-shore combined seismic reflection and refraction survey of the structure of the crust beneath the Great Lakes. The sources of energy came from a large air gun fired at closely spaced intervals (60-100 m) over several 150-340 km long lines which crossed the Keweenawan rift zone in Lake Superior and the Grenville front in Lake Huron. The University of Western Ontario collected data at 5 separate land stations using portable seismic refraction instruments. Over 20,000 seismic traces were recorded over a 200 hour continuous recording period.

Observations of all the in-line profiles show that the character of the direct crustal phase is not simple, but appears to have a "shingle-like" pattern, which may be caused by wide-angle reflection effects from numerous short reflectors within the upper portions of the crust. Near-surface velocities were found to increase from 5.6 km/s in the upper layers to 6.5 km/s in the mid-crust. A major difference in the record sections between those obtained from Georgean Bay and those from Lake Superior, was the large variations in the amplitudes of the observed S waves. Observations of data obtained on the Bruce Peninsula for the profile running to the west indicate the presence of the Grenville front by a distinct interruption in the pattern of Pg refraction arrivals. PmP appeared as a very complex pattern of reflectors on all the profiles. Data from a fan profile in Lake Superior supported earlier studies, which showed that the crust under the rift is 50 to 60 km thick.

In all sections there was excellent trace-to-trace correlation of the various "shingle-like" arrivals. To interpret these signals, an automatic data adaptive method was developed which measures the apparent velocities of all correlatable signals along the whole trace. This information, along with data from the near-vertical reflection data, was used as input data to an inverse method which models laterally heterogeneous structures using a triangular block method.

PRE- AND POST-STACK MIGRATION AND IMAGE ENCHANCEMENT TECHNIQUES: APPLICATION TO GLIMPCE REFLECTION DATA

M. Milkereit[1], A.G. Green[1], M.W. Lee[2], W.F. Agena[2] and C. Spencer[1]

1 Geological Survey of Canada, 1 Observatory Cr., Ottawa, K1A OY3
2 U.S. Geological Survey, Denver Federal Center, Denver, Co 80225

GLIMPCE deep seismic reflection profiles across the Midcontinent Rift System beneath Lake Superior reveal a central asymmetric rift with an enormous thickness of volcanic and sedimentary rocks. Imaging of high-angle normal faults, later converted to reverse faults, provide key structural information essential for understanding the evolution of the rift system.

To improve images of steeply dipping faults, unconformities, and other discontinuities in deep seismic data we describe the performance and results of conventional and true-amplitude CMP processing, post-stack and pre-stack depth migration, post-migration image enhancement techniques, and forward modeling. Our results indicate that structural interpretation of complex deep reflection records, such as those recorded by GLIMPCE, should always be based on migrated data. Migration provides a useful starting model for forward modeling. We also demonstrate that application of pre-stack migration results in improved seismic images of steeply dipping reflections (faults?).

Display and interpretation of deep seismic data are closely interwoven. We use image enhancement techniques to display residual amplitude variations of true-amplitude processed data, to highlight variably dipping components, and to improve signal-to-noise ratio of stacked sections.

IMAGING FLUIDS ON SEISMIC PROFILES ACROSS THE MAKRAN ACCRETIONARY PRISM

T.A. Minshull and R.S. White

Bullard Laboratories, Dept. of Earth Sciences, Madingley Road, Cambridge CB3 OEZ, U.K.

The presence of fluids in the crust exerts a prominent role in geological processes, ranging from their influence on diagenetic through metamorphic reactions to controlling small and large-scale tectonic processes. The presence of water and the rate and means by which sediments are dewatered in the accretionary sediment prisms above subduction zones are crucial in controlling their tectonic development.

Using recently acquired multichannel seismic profiles across the Makran accretionary prism in the Gulf of Oman, NW Indian Ocean, we discuss methods of investigating and modelling the presence of fluids from the seismic data. In common with other continental margin settings, there is abundant gas present in the sediments which is trapped beneath a gas hydrate zone. This generates a prominent "bottom simulating reflector" 500 to 800 m below the seafloor and localised thick accumulations of free gas. We show how amplitude versus offset analysis of the hydrate free-gas reflector, together with normal-incidence polarity and amplitude measurements and synthetic seismogram modelling, enable up to identify and map the presence of free gas. Geologically, the gas can then be used as a marker to help interpret the tectonic processes in the accretionary wedge. For example, the shape and position of thrust faults can be imaged by acoustically transparent zones probably generated by gas exsolved from pore waters migrating forwards and upwards from deep in the sediment pile along permeable fault zones. The hydrate reflector shallows in the region of some faults, suggesting a temperature anomaly caused by advected heat in warm upwards moving pore waters.

De-watering processes can be mapped indirectly by measuring seismic velocity changes in the sediments. This has been done using velocity analyses of common mid-point gathers and also wide-angle sonobuoy data. There is a dramatic increase in velocities at the toe of the accretionary prism as the porosity decreases, then a gradual increase in velocities across the remainder of the sediment prism. The application of wedge dynamics to the Makran suggests that pore fluid pressure must be high, at least in the region of the basal decollement, in order to explain the low surface and decollement dips. A low permeability is required to maintain this high pore pressure. Hence two stages of sediment compaction are implied: an initial rapid reduction in porosity (seen as an increase in seismic velocity) as fluids are expelled through relatively permeable sediment, followed by a build-up of pore pressure as the permeability decreases and fluid migration is restricted to fault zones.

THE GLOBAL GEOSCIENCE TRANSECTS PROJECT: A PROGRESS REPORT

J.W.H. Monger

Geological Survey of Canada, Vancouver

The objective of the Global Geoscience Transect project (GGT) is the preparation of cross-sections (or transects) that extend down at least to the base of the Earth's crust, and deeper where data permit. To do this, relevant geological, geophysical and geochemical data along a transect corridor 100 km wide and up to a few thousand kilometers long are compiled and integrated in an interpretative cross-section, which ideally shows distribution of protoliths of major lithological components of the crust, metamorphism and intrustion. Such cross-sections are, in effect, vertical tectonic maps of the Earth's lithosphere, and ideally show how the lithosphere along the line of the transect evolved.

Following inception of GGT by the Inter-Union Commission on the Lithosphere in August 1985, requests for detailed transect proposals were distributed, and by December 1987, 110 detailed transect proposals and 25 proposals on sketch maps had been received.

GGT guidelines, established in August 1987, ask scientists to prepare transects in a common format so that comparisons can be made readily between the lithosphere in different parts of the Earth. GGT transect displays typically have a scale of $1:10^6$, and use colours denoting age of rock units modified from those recommended by the Commission for the Geological Map of the World. Displays include a geological strip map and cross-section that shows geology, DSS or multichannel seismic reflection line drawings, gravity and magnetic maps, geophysical interpretations such as velocity-density diagrams, a diagram showing stratigraphic, structural, magmatic and metamorphic events in time/space coordinates, and the interpretative cross-section with units coloured according to inferred tectonic settings at the time of their formation. Profiles and cross-sections are drawn on bases with curved lines, whose curvature corresponds to a scaled Earth radius of 6371 km. A brief accompanying pamphlet gives the bases for construction of the transect and a full biblography. First displays of GGT transects from all parts of the world will be at the International Geological Contress in July 1989.

EVOLUTION OF CORDILLERAN CRUST IN WESTERN CANADA

J.W.H. Monger[1] & R.M. Clowes[2].

1. Geological Survey of Canada, Vancouver,
2. Dept. of Geophysics and Astronomy, University of British Columbia, Vancouver

The Canadian Cordillera has features of both collisional and subduction-related orogens. It records one way in which oceanic and transitional crust evolves into continental crust, as three-quarters of its width consists of ensimatic material accreted to the ancient cratonic margin. It has an unusually long history for an orogenic belt of at least 700 Ma, an interval conveniently divided into the following five stages:

1) Proterozoic and early Paleozoic (ca. 700-360 Ma) extensional episodes are recorded by rocks of the eastern Cordillera, where a mainly passive margin existed on the boundary of the North American craton between mid-Proterozoic and Late Jurassic time.

2) Late Paleozoic - earliest Mesozoic (350-230 Ma) plate convergence is recorded by calc-alkaline magmatism and thrusts in western terranes whose paleogeographic positions relative to the cratonic margin are uncertain; convergence in this interval locally and temporarily reversed sedimentation patterns along the passive cratonic margin.

3) Specifically Cordilleran Crust appears to have been created mainly in Mesozoic and earliest Tertiary times (230-55 Ma) by accretion of ensimatic material to the ancient cratonic margin, emplacement of subduction-related and anatectic granites, and crustal thickening during convergence between various Pacific plates and the North American plate, which has been on a northwestward then westward trajectory for the past 200 Ma.

With the exception of Precambrian structures in cratonic crust beneath the eastern Cordillera, the primary Cordilleran crustal structure appears to consist of east- and west-dipping stacks of thrust sheets, with thrusts that decrease in age from top to bottom of the stacks and towards the margins of the orogen. The extensive, coherent accreted terranes are embedded within the thrust stacks as enormous "flakes", as shown by LITHOPROBE studies on Vancouver Island, where the lower crust and mantle of the Paleozoic through Jurassic terrane called Wrangellia was completely removed, and replaced by underplated late Mesozoic, Tertiary and Recent material. Four east-dipping thrust stacks in the western Cordillera of early Mesozoic, Late Mesozoic, Eocene and the late Cenozoic to Recent ages, involve subduction of oceanic crust. A major, west-dipping Middle Jurassic to Eocene thrust stack in the eastern Cordillera incorporates rocks that formed along and on the ancient continental margin and, in its later stages at least, involved subduction of continental crust. In the Cretaceous and early Tertiary the thrust stacks formed during oblique convergence, and in places were disrupted by dextral transcurrent faults.

4) In Paleogene (55-40 Ma) time, transtension and extension, in places with normal faults penetrating the entire crust, disrupted older contractional structures; extension may result from gravitational collapse of over-thickened crust and/or changes of plate motion.

5) In later Tertiary and Recent time (40-0 Ma) subduction of the small Juan de Fuca plate between latitudes 40^{o} and 51^{o}N is accompanied by arc volcanism to the east; north of 51^{o}N the continental margin is bounded by a transform fault.

PASSCAL BASIN AND RANGE LITHOSPHERIC SEISMIC EXPERIMENT NORTHWESTERN NEVADA, USA

W.D. Mooney[1], K.F. Priestly[2], G.A. Thompson[3], R.B. Smith[4]
and the PASSCAL Basin and Range Working Group.

1 US Geological Survey, Menlo Park, California, USA
2 Seismological Laboratory, Univ. of Nevada, Reno, USA
3 Depart. of Geophysics, Stanford University,USA
4 Geology & Geophysics, Univ. of Utah, Salt Lake City, USA.

The 1986 PASSCAL (Program for Array Seismic Studies of the Continental Lithosphere) Basin amd Range Lithospheric Seismic Experiment utilized methodologies from reflection, refraction/ wide-angle reflection, and earthquake seismology, to investigate one of the world's largest continental rift zones: the Basin and Range Province of the western US. Seventeen institutions participated in the fieldwork, and data analysis has been undertaken by a large number of individuals and research groups. The results have provided a dramatically improved understanding of the lithospheric structure of the northwestern Basin and Range of Nevada.

(1) Seismic reflection data were collected using a 400-channel array. In this experiment, chemical explosion data are superior to vibroseis data; the reflection Moho and "X" (supra-Moho) events are laminated, laterally variable, and locally have extremely high amplitudes (about 15 db above "background" events). Below about 4 s TWT there is in general an abrupt transition from a distinctly transparent upper crust to a highly reflective lower crust. Strong shear-wave energy is observed on most gathers.

(2) Refraction/wide-angle reflection data were recorded on two profiles with a total of twenty-eight shots. The P-wave velocity structure has been interpreted variously by different investigators, but the transparent upper crust shows generally low velocities (4.1-6.2 km/s) and the reflective lower crust shows generally high velocities (6.5 km/s and higher for depths greater than about 18 km). We are exploring two possible models of the crust/mantle transition zone: a 2 km thick gradient zone, and a "rift pillow-type" layer with average velocity of 7.5 km/s. Crustal thickness calculations depend greatly on the lower crustal velocity model, but typically give 27-35 km, and the uppermost mantle velocity (P_n) is about 7.9 km +/-0.1 km/s. Previously reported thin crust is not found in NW Nevada, nor is an anomalously low (7.6-7.7 km/s) P_n velocity. The crustal thickness correlates well with the reflection Moho seen on COCORP reflection data where the two surveys coincide.

(3) S-wave wide-angle reflections from the Moho (SmS) were recorded, but no other unequivocal S-wave phases were recorded, indicating either weak S-wave generation or high S-wave attenuation and scattering. Comparisons of PmP and SmS traveltimes indicate a mean crustal Poisson's ratio of 0.26 to 0.27, somewhat higher than the value of 0.25 commonly found for crustal rocks. Correlation with high heatflow in the Basin and Range suggests that high temperatures (or melting) explain the high Poisson's ratio.

(4) High temperatures in the lower crust and uppermost mantle may also explain the anomalously strong (localized) attenuation of the P_n phase on the east-west profile.

SEISMIC, GRAVITY, AND MAGNETIC PROFILES OVER THE HATTON BANK (NORTHWEST U.K.) PASSIVE MARGIN: THE IMPORTANCE OF ACQUIRING A LARGE AND DIVERSE GEOPHYSICAL DATASET

J.V. Morgan[1], P.J. Barton[1], C.N. Prescott[3],
G.D. Spence[1*], S.R. Fowler[1+], R.S. White[1],
G.K. Westbrook[2], A.N. Bowen[3++], and M.H.P. Bott[3]

1 Bullard Labs; Dept. of Earth Sciences, Cambridge, U.K.
2 Dept. of Geological Sciences, Birmingham, U.K.
3 Dept. of Geological Sciences, Durham, U.K.
* Now at Pacific Geoscience Center, Canada
\+ Now with B.P., Aberdeen
++ Now with Marconi, Cambridge

In May 1985, the Universities of Cambridge, Durham, and Birmingham acquired an extensive geophysical dataset over the Hatton Bank continental margin. The data included nine expanding spread profiles (ESP's) parallel to the margin, an OBS and multichannel wide-angle seismic refraction line that was shot perpendicular to the margin and through the centre of the ESP's, and multichannel seismic, gravity, magnetic, and bathymetry profiles. This paper summarizes the results to date, and presents new results from the recently completed modelling of the seismic refraction and gravity data.

In the original interpretation of the ESP's, the lower crust beneath the margin was modelled as 10-15 km of material with a seismic velocity of 7.3-7.4 km/s. The high seismic velocity (and density) of this material suggested that it was dominantly igneous. It has been proposed that the particularly thick volcanic sequences found at North Atlantic margins are related to large amounts of partial melt generated by: 1) the high asthenospheric temperatures in the vicinity of the Icelandic hot spot, or 2) small-scale convection cells initiated by abrupt rifting of the continental lithosphere.

In the forward modelling of the refraction data, the ESP-derived model was used as a starting point. The final velocity model does not have such a thick, uniform, high-velocity lower crust. The refraction data, together with the seismic reflection and gravity data, outlines a high velocity (~ 7.2 km/s at base) and high-density volcanic pile in the upper crust midway up the continental slope. The pile appears to be a late-stage igneous feature, as it overlies the dipping reflector sequences known to be associated with rifting. Below the pile, there is a velocity inversion to ~ 6.7 km/s, and then the velocity increases gradually to ~ 7.3/7.4 km/s at the Moho. The differences between the ESP and refraction velocity-depth models across the margin can be explained by the three-dimensional nature of the volcanic pile; the ESP's were interpreted assuming the velocity structure below basement was one-dimensional. The final model over the mid-slope volcanic pile shows high velocities and densities in both the upper and lower crust, confirming the igneous nature of the margin. The velocity model alone does not unequivocally distinguish between the two mechanisms of igneous accretion proposed above.

These results over the Hatton Bank margin demonstrate the value of collecting a variety of geophysical datasets, including different types of seismic data.

RECENT STUDIES FOR UPPER CRUSTAL STRUCTURE AS DERIVED FROM EXPLOSION SEISMIC OBSERVATIONS IN JAPAN

Takeo Moriya,

Department of Geophysics Faculty of Science, Hokkaido University, Sapporo

Under the fourth and fifth Earthquake Prediction Projects of Japan starting from 1979, the Research Group for Explosion Seismology conducted a series of explosion seismic experiments to reveal detailed structure of the shallow crust. In this paper, results from three experiments executed in 1984, 1985 and 1986 are shown. Each measurement line crossed over a large-scale fracture zone. The profile of 1984 took place across the southern part of the Kamuikotan metamorphic belt, Hokkaido Island, where Urakawa-Oki earthquake (M:7.0) occurred in 1982. The profile of 1985 was chosen to cross Fossa-Magna in central Honshu. Tanakura fracture zone, northern Honshu arc, was crossed by the profile of 1986. On each measurement line extending 50-60 km long, 5-7 shots were detonated and 60-70 stations were arranged. FM and PCM data recorders and seismic sensors with natural frequency of 2 Hz were used for the experiments. The FM data were analyzed mainly by a ray-trace method, and very complicated upper crustal structures down to about 5 km were inferred. Beneath the Kamikotan Belt, structure in which high-velocity material thrusts over low-velocity material that may consist of crushed rocks or sedimentary layers, were revealed. Beneath Fossa-Magna, it was found that low-velocity material, 10 km wide and more than 6 km deep, was inserted; and in the eastern part of the Itoigawa-Shizuoka tectonic line, thick sedimentary layers were developed. But beneath Tanakura Fracture Zone where shallow earthquakes seldom occur, no velocity anomaly was found in the deep part, though thick low-velocity sediments were deposited. The Tanakura Fracture zone seems to have ceased tectonic movement already.

LITHOSPHERIC STRUCTURE AND DEEP-REACHING PROCESSES BENEATH THE ALPS

St. Mueller

Institute of Geophysics, Swiss Federal Institute of Technology, ETH-Honggerberg, CH-8093 Zurich, Switzerland

The Alps are a deep-reaching crust-mantle structure in Europe situated at the northernmost tip of the Adriatic promontory of the African plate. In that region the contact against the Eurasian plate is presently characterized by a NW-SE oriented compressional stress regime. A detailed regional analysis of seismic surface-wave dispersion and of P-wave travel time residuals ("acoustic tomography"), as well as long-range seismic refraction measurements and the interpretation of "stripped" residual gravity anomalies, have revealed a rather anomalous structure within the uppermost mantle under the Alpine arc. As a result of the massive continent-continent collision, parts of the lithosphere have been delaminated - a process which has led to "flaking" in the upper crust, combined with a thickening of the entire crust and the formation of a pronounced relatively cold, dense, and slowly subsiding "lithospheric root" beneath the mountain chain. In this still ongoing plate collision the lower parts of the lithosphere apparently have penetrated into the asthenosphere to a depth of 130 to 200 km in a steep zone of "subfluence" ("Verschluckung"). On this scale the continuing uplift of the Alpine chain (by about 0.1 cm per year) is a secondary effect due to isostatic rebound of less dense crustal masses which previously had been forced to greater depths. A configuration of this type generates regionally compressive dynamics of its own on which - within a wider framework - rotational processes may be superimposed.

DEEP SEISMIC REFLECTION IMAGING OF CONTINENTAL MARGINS DEVELOPED FROM WIDE-APERTURE CDP PROFILING

John C. Mutter and Peter Buhl

Lamont-Doherty Geological Observatory of Columbia University, New York, NY 10964-0190

During the last decade two-ship seismic reflection and refraction techniques have become the focus of several experiments designed to investigate the deep structure of passive continental margins at several locations in the world's oceans, as well as at convergent plate boundaries and the oceanic crust of deep ocean basins. We were drawn to the development of these techniques as a way of obtaining the large source-receiver offsets needed to discriminate against interbed multiples that frequently pervade the lower continental crust, and increase the multiplicity of the stack needed to improve the signal-to-noise ratio to resolve deep, weak events adequately.

The technique involves two vessels steaming in line, each with energy sources and hydrophone arrays, their separation being equal to twice that of the maximum source-receiver offset of the lead ship. Cyclic shooting and receiving on both vessels achieves full coverage, though the nominal CDP fold for any source-receiver pair is usually quite low.

In our early attempts to apply the technique, for example the LASE profile off the US East Coast, substantial improvements were obtained primarily through detailed velocity analyses which resulted in stacking enhancements for most of the sections. The source limitations and mismatched source-receiver combinations within the complete configuration limited further improvements. The North Atlantic Transect (NAT) experiment, conducted shortly after LASE, was better able to achieve improved images of the lower oceanic crust, largely owing to better source-receiver matching. This enabled us to combine successfully the 0-6 km offset source-receiver pairs and achieve the desired signal enhancement.

Results from experiments off Norway and East Greenland in 1983, and off NW Australia in 1986, have achieved the best results thus far. In the latter we used R/V CONRAD'S 10-gun tuned source array firing 6000 cu. in. of air. In the Norwegian-Greenland experiments, S/V PROSPEKTA's 30-gun array provided the principal source. Both experiments emphasized the critical importance of a strong, impulsive source in obtaining deep crustal reflections.

The data can be processed by fairly standard techniques, either by combining all offset combinations into a single wide aperture gather and stacking, or stacking the gathers appropriate for each offset combination, then summing the results. Simple stacks of gathers from offsets greater than 4 km often show considerable attenuation of interbed multiples. The application of F-K filtering techniques, or false moveout-based velocity filtering of these gathers, has also proved successful in enhancing the images. The larger offsets also allow us to select particular plane wave components to enhance images of dipping interfaces.

MECHANISMS OF LITHOSPHERIC DEFORMATION AND MAGMATISM DURING RIFTING; A DEEP SEISMIC STUDY OF THE N.W. AUSTRALIAN MARGIN

John C. Mutter[1], Roger L. Larson[2], and David A. Falvey[3]

1. Lamont-Doherty Geological Observatory of Columbia University, New York, NY 10964-0190
2. Graduate School of Oceanography, University of Rhode Island, Narragansett, R.I. 02882-1197
3. Bureau of Mineral Resources, Geology and Geophysics, Canberra City, A.C.T. 2601, Australia

Many models of intra-continental extension invoke uniform, in situ, irrotational coaxial deformation of the crust and lithosphere; that is, a pure shear deformational mechanism. These models have also been applied to passive margin evolution and are successful in predicting aspects of their structure, uplift and subsidence history, and geophysical signature. Recently, however, interpretations of some geological and geophysical studies in the Basin and Range Province of the western USA have led to the suggestion that detachment faulting may be evidence of lithospheric-scale simple shear processes. This has inspired a re-evaluation of extensional structures observed in the crust of intra-continental rifts and passive margins world wide, which has grown to include observations of highly reflective lower continental crust, 7.2 km/s layers beneath extended crust of some passive margins, and unusually voluminous basaltic magmatism associated with extension. It is now clear that no single style of deformation wholly characterizes extensional terranes, and that the mantle's response to rifting may provide valuable insight into whole-lithosphere extensional mechanisms.

Results from a two-ship seismic reflection and refraction experiment carried out jointly by Lamont-Doherty Geological Observatory, the Graduate School of Oceanography at the University of Rhode Island, and the Australian Bureau of Mineral Resources show that the outer Exmouth Plateau is dominated by large, rotated blocks bounded by deeply penetrating normal faults, some of which include large intrusions. Magmatic underplating, evidenced by a deep layer having velocity >7.0 km/s, accompanied this extension, but is absent in the central region where a set of prominent mid-crustal, subhorizontal reflecting arrivals are interpreted to be detachment surfaces. The detachment underlies the central Exmouth Plateau over an area of at least 600 km^2 with the large block faults flanking the plateau. Results of extensive exploration-seismic coverage, drilling and sampling suggests that the extensional deformation of the outer plateau margin post-dates that in the central plateau.

We therefore propose that the initial response to tensional forces on the Exmouth Plateau of the NW Australia passive margin involved a largely amagmatic simple shear mechanism with large-scale detachment faulting. This developed in space and time into a magmatically attended, dominantly pure shear system focused at the nascent continent-ocean boundary.

PROTEROZOIC STRATIFIED SEQUENCES OF THE SOUTHERN NORTH AMERICAN CONTINENT

D. Nelson, T. Pratt, L. Brown, R. Culotta, M. Giguere, E. Hauser, S. Kaufman, J. Oliver and J. Zhang

Institute for the Study of the Continents, Cornell University, Ithaca, NY 14853.

Perhaps the most dramatic result of recent COCORP efforts in the US midcontinent is the observation that the upper several seconds of the basement beneath southern Illinois and Indiana shows distinct stratification, reminiscent of a layered sedimentary assemblage. Prominent in this comparison is the existence of half graben-like features within the lower portion of the sequence. This extensive layered unit occurs within the 1.48 +/-0.3 Ga. "Eastern Granite Rhyolite Province" defined on the basis of scattered basement penetrations, and is considerably thicker than the overlying Phanerozoic fill of the Illinois basin. Previous COCORP surveys in southern Oklahoma, northern Texas, and arguably central Arizona, have likewise imaged prominent stratified sequences comprising the upper crust within the somewhat younger "Western Granite-Rhyolite Province", leading to the suggestion that much of the Proterozoic granite-rhyolite terrane of southern North America is composed of stratified rocks, the area in question being on the order of 10^6 km^2. Exposure of >8 km of silicic volcanic rocks in the St Francois Mts, the only significant outcrop, implies that all of this layered material could be volcanic in origin. However, we are skeptical of taking this comparison too literally because 1) the St Francois Mts represent an exposed eruptive center, while the seismic sections could be imaging strata deposited well away from such centers, and therefore of a different character; and 2) a COCORP profile extending to the edge of the St. Francois Mts. does not show prominent layering associated with the exposed volcanics. As an alternative, we suggest that much of the southern mid-continent may in fact be underlain by extensive Proterozoic sedimentary assemblages, intruded by scattered high level granites, and capped by a relatively thin veneer (in most places) of cogenetic silicic volcanic material. This hypothesis obviates the need for melting a large fraction of the lower-crust over a wide area to supply such a large volume of silicic volcanics, and likewise obviates the need for adding a comparable volume of basaltic material to the lower crust to drive the melting. As yet evidence for an extensive basaltic underplate, in the form of a prominently reflective Moho and/or laminated lower crust, has not been observed in the southern mid-continent. However, regardless of what interpretation ultimately proves correct, these layered sequences constitute a major new crustal unit within the Precambrian tectonic framework of North America. Determining their continuity, lateral extent, internal structure, and composition, are first-order problems "tailor-made" for continental reflection profiling.

DEEP CRUSTAL IMAGING IN SOUTHWEST U.S. USING INDUSTRY SEISMIC PROFILES

David A. Okaya[1], Thomas L. Henyey[1], & Eric G. Frost[2].

1. Dept. Geological Sciences, University of Southern California, Los Angeles, California, 90089, USA;
2. Dept. Geological Sciences, San Diego State University, San Diego, California 92181, USA

Reprocessing of industrial seismic profiles using extended correlation has revealed significant middle and lower crustal seismic events throughout the southwestern United States. Original field tapes for seismic profiles were obtained from PHILLIPS, EXXON, TEXACO, Seisdata Services Corp., and Western Geophysical, by the CALCRUST research program, in an attempt to increase the lateral coverage of deep crustal seismic profiles. Three-dimensional crustal imaging is provided by sets of intersecting profiles in the southernmost San Joaquin Valley, western Mojave block, Salton trough, and Colorado River region in southern Californiaa. Additional profiles yield crustal information in the transition zone, the metamorphic core complex belt, and the southern Basin and Range province of central to southwestern Arizona. These profiles, often with excellent ties to surface outcrops, provide subsurface and deep crustal structure.

Seismic reprocessing of these profiles is no more complicated than their original processing. Extra steps such as cosine-squared tapering of the uncorrelated data, or time-variable bandpass filtering and deconvolution, are easily implemented. Velocity analysis of the lower crustal portion of such data is simplified by the relatively short source-receiver offsets used in conventional acquisition; normal moveout correction of deep crustal events seen over short offsets is in general insensitive to small changes in stacking velocity.

Eight seismic profiles in the transition zone between the Colorado Plateau and the southern Basin and Range of west-central Arizona indicate an upper to middle crust of distinct, strongly sub-horizontal reflections. These reflections are found in profiles to extend through a region of 3750 km^2, and are also seen in COCORP seismic profiles, USGS-PACE refraction surveys, and a Stanford-USC piggyback experiment. Lowermost crustal reflections are diffusely present; Moho reflections exist at 11 s.

Seismic profiles within and southwest of the metamorphic core complex belt in southeastern California and southwestern Arizona indicate an extremely highly reflective middle and lower crust. Middle crustal reflections are short sub-horizontal, discontinuous events which appear to have surface expressions in Tertiary extensional mylonitic and Mesozoic compressional gneissic fabrics. Lower crustal reflections are slightly different in character and appear to be related to the Tertiary extension associated with metamorphic core complex development. These profiles reveal a consistently flat (9 s) Moho over much of the southwestern Basin and Range.

Late Tertiary and Quaternary sediments are imaged in seismic profiles in the Salton Trough. Deeper reflections are not seen beneath the basin floor; signal-noise studies in the region suggest the lack of reflections is due to the lack of geologic reflectors, and not to surface acquisition conditions or too high noise levels.

Reprocessed seismic profiles in the western Mojave block indicate substantial middle to lower crustal seismic events. These events are correlative with reflectivity seen in COCORP profiles, but are revealed to be widely pervasive as based on the distribution of several reprocessed seismic profiles.

CALCRUST ACQUISITION AND PROCESSING OF DEEP CRUSTAL SEISMIC PROFILES

David A. Okaya[1], Thomas L. Henyey[1], Thomas V. McEvilly[2], Peter E. Malin[3] & Robert W. Clayton[4].

1. Dept. Geol. Sci., University of Southern California, Los Angeles, California, 90089, USA;
2. Dept. Geol. & Geophys. Sci., University of California, Berkeley, California, 94720, USA;
3. Dept. Geol. Sci., University of California, Santa Barbara, California, 93106, USA; and
4. Div. Geol. & Planetary Sci., California Institute of Technology, Pasadena, California, 91125, USA

The California Consortium for Crustal Studies (CALCRUST) research group has collected seismic profiles in four sites in southern California, USA. In addition, CALCRUST has obtained industry profiles in key tectonic regions for reprocessing and analysis. A major focus of CALCRUST's use of seismic reflection data has been to make as strong as possible the connection between surface geological outcrop and the subsurface seismic information.

The CALCRUST technical committee, which has overseen the seismic field acquisition, has emphasized four major points: a full analysis of already existing seismic data before conducting the field acquisition, extensive dialogue with project geologists, field processing capability during the acquisition, and the addition of piggyback experiments. Examination of existing seismic data prior to data acquisition has given staff scientists a better understanding of shooting conditions, affecting the choice of field parameters and preparing the field observers for the expected data quality. Discussion with the project geologists as to scientific objectives and location of useful geologic evidence has further affected the experiment designs. Field processing capability has allowed for quality control examination of daily acquisition and for the construction of field brute stacks. The use of additional piggyback multichannel recorders has given wider-aperture data at little extra expense.

Seismic data processing of the CALCRUST and industry seismic profiles has involved in-depth examination of the data at essentially all processing steps. These data have been processed to allow for in-depth interpretation. Non-conventional processing steps, when used, are applied to enhance the seismic data under the condition that the integrity of the data is preserved.

Pre-Vibroseis correlation steps applied to CALCRUST or industry data have focussed on either preparing the data for extended correlation or removing vibrator-generated correlation artifacts using time-variable frequency filtering. This latter step is performed by decomposing each uncorrelated seismic trace into frequency-time space, where "polygon-slice" filtering is performed. The reconstructed seismic traces are then correlated, without the correlation artifacts present.

Pre-stack routines have been applied to enhance data signal:noise before stacking. For example, reprocessing of a seismic profile collected at the base of the Whipple Mts (SE California) metamorphic core complex, required suppression of strong ground-roll/surface-wave events. The application of linear moveout (reduced travel time) using surface-wave group velocities aligns these events horizontally. Usually spatially aliased, these events can be removed by the use of a horizontal dip-reject spatial filter. Inverse linear moveout restores the (shot) gathers and reveals reflected events. Other data enhancement steps used are pie-slice (x-t) bandpass filtering and the use of spatial dip filters to isolate reflected energy.

A post-stack step applied to the crustal profiles in the Whipple Mts region involved weighted blending of dip-filtered and un-dip-filtered stacks to obtain the benefit of dip-filter enhancement yet lessen the lateral smearing caused by the dip filter. For display, the creation of full-sample line drawings using a lateral continuity algorithm, is possible for data of high spatial resolution. These line drawings preserve the detailed information in the seismic stacks without the presence of lateral smearing as created by coherency filters.

PSEUDO 3-D STUDY USING CROOKED LINES FROM THE SWISS ALPINE PROFILES PNR-20

R. Olivier, J.-J. Wagner, L. Levato, S. Sellami,
L. du Bois & J. Besnard

Gransir, Universite de Lausanne, Chateau de Bassenges,
CH=1024 Ecublens, Switzerland

The Swiss deep geological structures project PNR-20 has acquired vibroseis data of two profiles crossing the Swiss Alps of 110 and 90 km long, in the east and west respectively. The rough topography leads to crooked lines. Where a line has large changes in direction it was decided to apply a pseudo 3-D analysis in an attempt to have seismic information on the dip of geological formations.

GEOVECTEUR (Trade Mark: Compagnie Generale de Geophysique) enables splitting the CDP swath into numerous bins; these are reassembled into several parallel strips and then processed separately in a standard manner. Through an analysis of perpendicular strips, it is possible to study the lateral dips, and by further processing of the general profile to attenuate their effects on the final stack.

THE INTEGRATION OF SEISMIC, MAGNETIC, THERMAL AND PETROLOGIC DATA FOR CRATONIC AND NON-CRATONIC LITHOSPHERE IN AUSTRALIA

Suzanne Y. O'Reilly[1], W.L. Griffin[2], B.D. Johnson[3] and N.J. Pearson[1]

1 School of Earth Sciences, Macquarie University, Sydney, NSW 2109
2 Division of Exploration Geosciences, CSIRO, North Ryde, NSW 2113
3 Bureau of Mineral Resources, Canberra, ACT 2601

XENOLITH DATA, GEOTHERMS AND PALEOGEOTHERMS, AND LITHOSPHERIC MODELS

Basaltic and kimberlitic rocks are widespread in eastern Australia and near the southeastern margin of the Australian craton. Xenoliths in these rocks provide a broad geographic sampling of the lower crust and upper mantle rocks in these regions.

The xenolith data show that the crust-mantle boundary (CMB), defined by the depth at which ultramafic rocks (spinel lherzolites) become volumetrically significant, occurs at depths ranging from 25 to 340 km in different regions of non-cratonic eastern Australia. The lower crust wall rocks are mafic to felsic granulites. There is a zone from about 15-40 km depth with abundant mafic lens-like or sill-like intrusions (some re-equilibrated to granulites) which correspond to horizontal reflectors seen on seismic reflection profiles. The CMB lies well within this zone,but the Moho (as defined by seismic refraction data) is commonly located at the base of this zone. Reversed seismic profiles in southeastern Australia demonstrate that the refraction Moho lies at about 55 km. Petrologic and P/T data show that this does not coincide with the CMB (i.e. the change from granulite to spinel lherzolite wall-rocks) but probably represents the spinel to garnet-lherzolite transition within the mantle.

Appropriate mineral assemblages from xenoliths can be used to define vertical temperature profiles for crustal and upper mantle depths. A geotherm has been constructed which represents the present-day temperature profile for western Victoria and east-central Queensland. In other areas of eastern Australia this is the paleogeotherm existing at the time of extrusion of the host basalt or kimberlite. The xenolith assemblages near the eastern craton margin are mineralogically and chemically distinct from those in eastern Australia, and yield a paleogeotherm which is 150-200^{o}C cooler than the eastern Australian geotherm at any given depth .

MAGSAT INTERPRETATIONS AND THE THERMAL AND MAGNETIC STATE OF THE LITHOSPHERE

Inversion techniques have been applied to the MAGSAT data to obtain an equivalent-layer solution comprising a horizontal distribution of average vertical magnetisation for a crustal layer of constant thickness. The MAGSAT data represent the signal from magnetite (and titanomagnetite) domains in crustal rocks down to the Curie isotherm, which in east-Australia lies at 12-15 km. Laboratory measurements, carried out on xenolith rock types from eastern Australia, confirm that eclogites and mantle lherzolites are non-magnetic, but granulites are highly magnetic.

The two contrasting xenolith-derived geotherms described above allow calibration of the MAGSAT-derived magnetization contours to model the Curie isotherm surface. Initial modelling has produced promising results. A maximum depth of magnetization (for cool regions) is located at 35 km and a minimum depth occurs near the surface for the hottest region in oceanic crust south of South Australia). Clearly factors other than heat flow need to be taken into account for a refined model. For example, regions of low magnetization in the Yilgarn probably reflect lower crustal rock types with low magnetic signatures (eg eclogites rather than granulites, or more silicic rocks). This is the first step towards producing a heat-flow model for Australia which can be used to predict temperature at any location and depth.

EFFECT OF GEOTHERMAL PROFILES ON SEISMIC INTERPRETATION

Seismic profiles for southeastern Australia show a gradient in Vp from about 28 to 55 km where Vp ~ 8 km/sec. In contrast, cratonic areas generally show a sharper, shallower Moho. The geothermal gradient is significantly lower in cratonic regions. Xenolith data show that the composition of the lower crust, at least in eastern Australia, is dominantly mafic. The thermal profile is critical in determining whether the equilibrium mineral assemblage for these rocks lies in the eclogite or the granulite facies, and hence in determining the Vp of the lower crust. With successive cooling, mafic assemblages convert from granulites to eclogites at shallower depths. This transition to eclogite results in an increase in Vp of 0.5 to 1.0 km/sec. The decrease in temperature will also raise the V_p of the other rock types.

Lithological interpretation of geophysical data (especially seismic reflection and refraction surveys) requires knowledge of the local geothermal profile and of the effect of temperature on the stability of mineral assemblages at depth. MAGSAT data can assist by providing present-day thermal information for regions which lack relevant xenolith data.

THE CAMBRIDGE DIGITAL SEISMIC SYSTEM FOR LAND AND MARINE USE

T.R.E. Owen and P.J. Barton

Bullard Laboratories, Cambridge University
Cambridge, England

We have developed a simple and compact micro-processor based recorder as the basis for a range of seismic or similar instruments. The system is capable of recording from 1 to 4 channels of data at 4 or 8 ms sampling interval and stores data in digital form on unmodified professional audio cassette recorders. Up to 4 recorders can be installed in an instrument, giving a recording capacity of over 20 million samples.

The ocean bottom seismometers have 4 cassette recorders and can record up to 1000 programmed windows of hydrophone and three-component geophone data, up to a total recording time of 6 hours. The instrument fits in a tube of 150 mm internal diameter and 1100 mm length, including dry batteries for a 30-day deployment.

The standard marine instruments can be used as a land recorder in a suitable housing, but a more compact version has been developed for micro-earthquake studies with a seismic signal channel, a filtered seismic trigger channel, and two auxiliary timing channels. A trigger algorithm is defined in software, and the instrument is capable of recording up to 600 events with a 20 s pre-trigger and 40 s post-trigger window. Event windows extend automatically for as long as the event lasts. A summary of each event is stored in memory giving the trigger time and 1 s values of the signal amplitude; the complete list of summaries can be transferred to a host system and used as a guide to the nature and frequency of events. The micro-earthquake instrument will run for 5 days on internal dry cells, or from any external 12 V source.

These systems are constructed from a set of four printed circuit cards connected by a bus, consisting of C.P.U. card, a recorder formatter and controller card, a Replay card and an analogue to digital converter card. Instrument functions, including gain ranging, triggering, block lengths, pre-trigger times and number of signal channels are software defined either in the EPROM program of the isntrument or as set-up parameters under operator control. The hardware and software is thus very flexible and new instruments for other purposes can be constructed rapidly. We have used the C.P.U. card as a controller in a number of instruments, and the C.P.U. and recorder as the basis for a new induced electro-magnetism recorder.

AMPLITUDE-WITH-OFFSET STUDIES OF THE LOWER CRUST ON BIRPS SYNTHETIC-APERTURE DEEP SEISMIC REFLECTION DATA

Carolyn Peddy,
British Institutions Reflection Profiling Syndicate, Bullard Laboratories, Madingley Road, Cambridge CB3 OEZ

In 1987 BIRPS conducted a two-ship experiment north of Scotland, in the area of previous BIRPS surveys MOIST, WINCH-1, DRUM, and GRID. The two-ship experiment, SLAVE (Synthetic Long Aperture Velocity Experiment), provides a continuous range of source-receiver offsets from near-vertical to 16.0 km. This corresponds to incidence angles of up to about 30^{o} for the Outer Isles Fault reflection and reflections from the middle crust, and angles of about 20-25^{o} for the reflection Moho. Preliminary results obtained from the shot gathers show that the SLAVE data are of high quality, and show clear reflections from the middle to lower crust at all offsets. If substantial changes in Poisson's ratio are present across these reflectors in the middle and lower crust, then changes in amplitude with increasing angle of incidence should be present on the common-depth-point (CDP) gathers.

HOW MUCH DO BACKGROUND NOISE LEVELS AFFECT WHAT WE SEE ON DEEP SEISMIC REFLECTION PROFILES?

C. Peddy and D. Scheirer,

British Institutions Reflection Profiling Syndicate, Bullard Laboratories, Madingley Road, Cambridge CB3 OEZ UK

When interpreting deep seismic reflection data, the possibility that reflectors are present in the crust but not imaged as reflections must be kept in mind. Effects such as high noise levels, high attenuation due to sediments, and insufficient source size, can prevent deep reflectors from appearing on seismic records. This poster addresses the effects of differing ambient noise levels on BIRPS marine deep seismic profiles. BIRPS has collected several coincident reflection profiles using identical sources and receivers. Therefore, any differences in data quality between the two seismic profiles are due to varying ambient noise levels. The coincident profiles are located north of Scotland, west of Ireland, and in the Southwest Approaches, and range from short 20 km long segments in the Southwest Approaches, to the entire 150 km SLAVE profile north of Scotland. The profiles were collected during a large range of ambient noise conditions, with noise levels ranging from just below the maximum allowable by quality control specifications (3-4 microbars) to negligible levels. The coincident data sets collected in each area for the most part contain roughly the same reflection segments, though there are examples where the ambient noise has completely obscured reflections. The greatest effect of ambient noise is a reduction in the detail of the seismic image of deep reflectors. For example, on the SLAVE profile the Flannan Fault reflection is composed of a very bright, continuous segment and a dimmer, more steeply dipping segment on the quiet seismic profile, while only the bright segment is visible on the noisy profile. Quantitative measurments of the reduction in reflection length and continuity are given for a given noise level.

LOWER CRUSTAL HETEROGENEITY BENEATH BRITAIN FROM DEEP SEISMIC REFLECTION DATA

Pharaoh, T.C. and Chadwick, R.A.

Deep Geology Research Group, British Geological Survey, Keyworth, Notts, UK

450 km of deep seismic reflection data have been acquired over the UK land-mass. A qualitative assessment of lower crustal reflectivity (based on the amplitude and coherency of deep crustal events) has been made. In the cratonic area of central England, the lower crust is generally poorly reflective, while in the foldbelt terrains of southern, eastern, and northern England it is more strongly reflective. Beneath the Variscides of southern England an important distinction can be made between poorly reflective 'foreland-type' lower crust lying beneath the Variscan Front thrust, and strongly reflective 'orogenic' lower crust farther south. A brief review is given of hypotheses for the origin of lower crustal reflectivity, and the relationship of the latter to crustal tectonic regime, both in the UK and elsewhere. It is concluded that the types of lower crustal heterogeneity required to produce the observed reflections are most easily generated in orogenic provinces (fold/thrust/metamorphic belts) than in areas which have undergone only low to moderate crustal extension (beneath typical sedimentary basins). The generation of granites by partial melting within the lower crust, and processes of metamorphic differentiation and recrystallisation which accompany orogenic activity, are likely to play a significant role in the development of such heterogeneities. Deep seismic data gathered from regions containing upper crustal granites (and which appear to have undergone negligible Mesozoic extension) support this hypothesis.

COHERENCY TECHNIQUES IN PROCESSING CRUSTAL REFLECTION DATA

Robert A. Phinney, K. Roy-Chowdhury, S.M. Kong, Katherine M. Hansen

Department of Geological and Geophysical Sciences,
Princeton University, Princeton, NJ 08544, USA

J. Leven

Bureau of Mineral Resources, G.P.O. Box 378, Canberra 2601,
Australia

The phase coherency along a given curve on a certain number of neighbouring traces is the criterion commonly used to identify seismic arrivals. Amplitude **per se** is not a very useful parameter, given its sensitivity to near surface conditions and its consequent variability over small distances. We report here on some approaches that we have taken to utilise spatial phase coherency as a seismic signal detector.

Adaptive Stack: Semblance measure evaluated along constant-velocity NMO curves can be used to weight CMP stack traces. Computed for a range of probable velocities, such traces can then be added to yield a stack trace without an exact knowledge of the stacking velocity; indeed, the optimal velocity function is obtained as a by-product. A **generalized mute** can be applied before the final summing, thus preserving shallow reflections and allowing additional undesirable deeper signals to be filtered out. Finally, because of using a range of velocities, the method is especially robust in presence of dipping structures.

Spatial Signal Detector (SSD): The stack section obtained from crustal-seismic data usually has a low signal-to-noise ratio (SNR). We have used the semblace measure extensively to filter out incoherent noise and enhance the SNR in the process. The resulting **automatic line drawings** are objective, and the tunable parameters of the SSD (range of apparent slownesses, width of the spatial window etc) provide the interpreter with tools to obtain different sub-surface images for comparison. The detector can be implemented in either x-t or p-tau domain, and can also be used as a pre-stacking filter.

Sign Filter: The semblance measure, although effective as a signal discriminator, is not robust in terms of its statistical properties. An approach which looks particularly promising in this respect, uses the theory of statistical hypothesis testing. The sign test statistic as evaluated for any segment in x-t is used to accept (or reject) the hypothesis that no signal is present. Tunable parameters provide alternative objective results for comparison. The method is simple and non-parametric. Probabilistic statements can therefore be made about the behaviour of the sign filter without assuming a specific distribution for the noise.

In our opinion, it is important, while applying any of these clean-up filters and displaying the result, not to overdo it and to leave some visible noise. It must also be mentioned that coherency based filters are all non-linear, and hence their effect depends on their location in the processing pipeline.

PROBING INTO EXTENSIONAL SEDIMENTARY BASINS

Bertrand Pinet and Bernard Colletta

Institut Francais du Petrole, 92500 Rueil-Malmaison, France

More and more deep seismic profiling is revealing the complex evolution of the continental crust, which bears the imprints of former plate movements. Previous subduction zones and mountain belts may exist before the formation of intra-cratonic sedimentary basins or passive margins. Therefore the geological setting must always be taken into account in deep reflection studies of such areas. Recent deep seismic profiles in NW Europe and other parts of the world have evidenced this largely heterogenous nature of the continental crust, with strong dipping reflectors within the crust that can always be interpreted as phantoms of inherited thrust planes related to crustal shortening during previous orogenies. Some of these inherited faults have been imaged beneath sedimentary basins of different ages and contrasting styles (half-grabens or symmetrical basins) and their reactivation depends on their direction in comparison with extensional stress field. These pre-existing zones of weakness induce an anisotropy in the upper crust, which will control the asymmetry of future extensional tectonics. When the direction of the inherited faults is perpendicular to the extensional stress field, they may be reactivated as a detachment surface controlling the sedimentary infill. Most of the time, their obliquity induces local changes and segmentation of the rift when they are crossed. In such a case, they correspond to transfer faults, acting as relays between major normal faults, or to "twist zones" where changes occur in the throw of the major blocks, sometimes evolving to an inversion of the polarity in the tilting of the major blocks.

During an extensional regime the top of the lower crust acts as a layer of mechanical decoupling boundary, separating asymmetrical brittle failure within the upper crust and symmetrical ductile creep within the lower crust. Extensional models may explain the great values of crustal thinning observed in both upper and lower crusts beneath rifts and passive margins related to the opening of an oceanic domain. More surprising is the large thinning imaged only within the upper crust of some intracratonic sedimentary basins. This suggests either that the flat laminations postdate the formation of the basin, or that it was created with mechanisms related to a previous tectonic setting and that extensional models do not take into account.

DEEP STRUCTURE AND NUMERICAL MODELLING OF THE VIKING GRABEN, NORTH SEA

Bertrand Pinet and Brigitte Doligez

Institut Francais du Petrole, 92500 Rueil-Malmaison, France

We used coincident deep seismic (GECO-NSDP), expanding spread profiles (IFP and EAN), and a large network of industrial lines and petroleum boreholes, to support a well-constrained 3D interpretation of the Viking Graben. Strong dipping reflectors within the crust are interpreted here as phantoms of inherited thrust planes related to the Caledonian orogeny which will control the asymmetry of future Jurassic extensional tectonics. During the Mesozoic lithospheric stretching, the top of the lower crust acted as a layer of mechanical decoupling boundary separating asymmetrical brittle failure within the upper crust and symmetrical ductile creep within the lower crust. This behaviour may explain the segmentation of the general N-S trend of the graben.

A two-dimensional numerical model (called THEMIS) was also used to simulate the evolution of the basin and to evaluate its petroleum potential, accounting for the history of sedimentation, paleotemperatures, paleopressures, fluid dynamics, hydrocarbon formation and migration. Significant excess pressures and preferred areas of accumulation of hydrocarbons have been predicted. They are compared with the oil industry control points.

THE CROP-ECORS WESTERN ALPS SEISMIC GEOTRAVERSE

Ricardo Polino & ECORS-CROP Equipe

The Alps are an example of the contrast in a cross section between the detailed description of the first one or two km where observations are possible and the almost blank representation of the deeper crustal section.

A vertical seismic reflection profile 350 km long recorded from the Massif Central to the Po plain, across the Jura and Alpine belts, aims to bridge this gap.

The 240 km long section presented here transects the main Alpine structure at high angles in a domain where they are comparatively cylindrical. It extends from the European foreland (Barnes Massif) in the north-west to the tilted outcrops of the overriding Apulian (African) continental plate, which exposes deep crustal formations and underlying mantle of the Ivrea Zone, and to the Po Plain hinterland as far as the Monferrato front.

The work was done in the frame of a French (ECORS)-Italian (CROP) joint venture. Multiple-coverage vertical-reflection data have been acquired by track mounted vibrators and by explosive charges. Furthermore a number of large shots were fired into the spreads to obtain deep complementary information.

First results are summarized in a line drawing, and a tentative interpretation of the structure and evolution of the western alpine chain is presented.

DEEP SEISMIC INVESTIGATION OF THE LITHOSPHERE IN HUNGARY

Posgay K., Hegedus C., & Timar Z.

Budapest, Columbus U. 17-23, Hungary

Investigation of the crust and upper mantle by seismic methods has a significant tradition in Hungary. Reflections from the crust-mantle boundary were observed by researchers of the "Eotvos" Institute as early as the late 50's. The technique of reflection seismic deep sounding that is able to penetrate to the depth of the asthenosphere was successfully established in the 70's (Posgay et al., 1984). One of the aims of our Geoscience Transect programme was to examine the possibility of obtaining seismic events from the asthenosphere along a profile traversing the whole central part of the Pannonian Basin - i.e. along a section substantially exceeding in length the earlier experimental profiles. In a part of this programme realized in 1987 we succeeded in determining reflection horizons within the depth range of the asthenosphere. The possibility of studying by seismic means this depth range, which plays a fundamental role in the theory of plate tectonics, opens new prospects.

The authors raise several ideas in this paper that help to analyse the result: they discuss conditions that may prove to be more favourable in Hungary than in other areas where the bulk of seismic lithosphere investigations was performed abroad. Apart from seismogeological conditions, the reduced depth of the asthenosphere (about 60 km) that can be brought into relation with the observed heat flux density of about 100 mW/m^2, may also account for it. We deem that the techniques of seismic lithosphere investigation, as formed in the result of several decades' development, must also have contributed to the feasibility of asthenosphere investigations by reflection seismics.

Posgay K., Albu I., Raner G., Varga G., 1984: Characteristics of the reflecting layers in the Earth's Crust and Upper Mantle in Hungary. AGU Geodynamics Series, Vol. 3. 3.pp.55. 1986.

COCORP PROFILING OF THE EASTERN MID-CONTINENT OF NORTH AMERICA: PROTEROZOIC LAYERED ROCKS AND THE WESTERN GRENVILLE PROVINCE

T.L. Pratt, R. Culotta, E. Hauser, K.D. Nelson, L.D. Brown, J.E. Oliver and S. Kaufman

Institute for the Study of the Continents, Cornell University, Ithaca, New York 14853 USA

A new view of the Proterozoic basement rocks of the eastern midcontinent of North America is emerging from COCORP and other deep seismic reflection traverses. The most recent of these is the 720 km COCORP transect from the St Francois Mountains of southeastern Missouri to the western Grenville Province. Basement rocks along the traverse are entirely covered by a thick (3.6 km) succession of Phanerozoic sedimentary rocks, including parts of the Illinois and Appalachian basins.

Large-scale structures are evident in the Proterozoic basement rocks along this transect. Most prominent is a layered sequence up to 6.5 km in thickness underlying the Paleozoic rocks of the Illinois Basin, where sparse drillhole information suggests that shallow basement rocks are part of an extensive granite-rhyolite terrane. Therefore these reflections may arise from a thick pile of ash-flow tuffs, rhyolite flows, and shallowly intrusive granites like those exposed in the St Francois Mountains, as well as intercalated or underlying sediments or mafic igneous rocks. The layered rocks appear to dwarf the overlying Illinois Basin sedimentary sequence; drillhole and other seismic data suggest that large areas of the mid-continent of North America may be underlain by similar Proterozoic sequences.

East of these layered basement rocks the survey crosses the suspected buried extension of the Grenville Front Tectonic Zone (GFTZ), which in Canada is a band of tectonized rocks marking the western limit of Grenville (950-1200 Ma) deformation. Basement reflectors include a 30 km wide zone of east-dipping events which are similar to those imaged on the GLIMPCE data more than 500 km to the north. Both sets correlate with the GFTZ and are interpreted as ductile deformation zones.

Surprisingly, a much wider (>70 km) region of <u>west</u>-dipping events lies about 100 km east of the GFTZ and may also represent ductile deformation zones. The relationship between these oppositely-dipping zones is speculative at present, but potential field data support a correlation between the west-dipping zone and similarly oriented reflectors evident on a COCORP traverse 650 km to the south. If such correlations prove valid, these deformation zones may delineate crustal blocks that provide a relatively simple structural framework for the eastern midcontinent.

RESULTS OF DEKORP DEEP-SEISMIC REFLECTION INVESTIGATIONS IN THE RHENISH MASSIF

C. Reichert and DEKORP Research Group

Geological Survey of Lower Saxony, Stilleweg 2. D-3000 Hannover 51, Federal Republic of Germany

Amongst other deep-seismic reflection lines within the **"Deutsches Kontinentales Reflexionsseismiches Programm"** (=DEKORP) two lines in the Rhenish Massif were investigated in 1986 and 1987. The Rhenish Massif is part of the Mid-European Variscides, an orogenic belt generated in the Upper Devonian/Carboniferous. Devonian rocks crop out at surface with only very few exceptions. The Rhenish Massif is bordered by two sedimentary troughs: the sub-Variscan Foredeep in the north and the Hessian depression in the south. In the east-west direction it is subdivided by the River Rhine and another depression, the so-called Eifel North-South-Zone.

Line DEKORP 1 is located west of the River Rhine and consists of two parts: (A) A WNW/ESE running branch of about 60 km length crossing the Eifel N-S zone nearly perpendicularly. DEKORP 1 continues 35 km into Belgium as part of the BELCORP project, reaching the Dutch/Belgian border SE of Maastricht. (B) A nearly N/S running branch from the eastern end of branch (A) to the River Moselle.

Line DEKORP 2-North is located east of the River Rhine and consists also of two parts: (A) A NNW/SSE running branch which prolongates an earlier profile, DEKORP 2-South. (B) At its northern end a WSW/ENE running branch in the sub-Variscan Foredeep.

The aim of these surveys was to investigate the crustal structure of the Rhenish Massif and its adjacent areas, with special focus on differences between its western and eastern parts and on the northern and southern border zones, which are characterized by prominent faults. Special care was taken to allow a close connection between the seismic structure of the deeper crust with surface geology. The results indicate the presence of NW-convergent tectonics reaching down to the deep parts of the crust. This finding raises evidence for horizontal compressional tectonics, which argues against the previous hypothesis of an orogeny with merely vertical tectonic style in this part of the Variscides.

MODELLING LOWER CRUSTAL STRUCTURE

Tim Reston

RHB New College, London, now at Cornell University, USA.

The nature of the lower crust reflective zone (LCRZ) is a matter of considerable debate. This paper presents an integrated model for the reflectivity and structure of the lower crust.

Around Britain, the LCRZ is not uniformly reflective, but varies in terms of the characteristics of individual reflections and the way they are distributed thoughout the zone. The character of reflections varies systematically with azimuth - reflections are longer, flatter and more continuous on strike lines. A consideration of 3-D spatial interference effects can explain this observation if lower crust reflecting bodies are shorter in the extension direction than along strike, a result consistent with shear pods and boudins within shear zones.

Moreover, the LCRZ contains both highly reflective bands and poorly reflective ("transparent") lenticular zones. The structure of the lower crust is predicted from lithospheric rheology, slip-line field theory, the deformational style of basement terranes and plastic materials, the kinematics of high-grade shear zones, and the geometry of faults and shear zones observed in the upper crust and mantle. These predict that the plastic lower crust must deform by both bulk pure and simple shear, and that bulk pure shear is itself accommodated by simple shear along low-angle, localised, conjugate shear zones. Forward modelling of the predicted shear zone patterns produces sections that closely match both the characteristics and distribution of reflections, and the appearance of the whole LCRZ, including the presence of transparent and reflective zones.

Although these results imply that the reflectivity is due to shear fabrics, both igneous intrusions and fluids are likely to be preferentially concentrated into shear zones and so may contribute to the reflectivity of the LCRZ. Reflection amplitudes are better explained by the reflection coefficients between acidic and basic igneous rocks than by fluids, but cannot distinguish between sheared and unsheared contacts. This problem is approached by evaluating correlations of reflectivity with electrical conductivity, refraction velocity, heat flow, age and igneous activity, and by considering the likelihood and form of syn-extensional intrusions (from stretching factors and field studies of intrusions emplaced under lower crustal conditions). These all suggest that the reflectivity of the lower crust around Britain is due to the presence of <u>sheared</u> lithological contrasts (perhaps originally intrusions) within zones of simple shear, and not due to igneous intrusion syn- or post-extension.

A CORRELATION BETWEEN SEISMIC REFLECTION, MAGNETIC ANOMALY AND BASEMENT STRUCTURAL PATTERNS IN THE CHAOTIC AREAS OF SPREADING-FORMED BASINS

W.D. Roots

School of Earth Sciences, Macquarie University, North Ryde, 2109, Australia

The MOR structural detail of a mature ocean is the end pattern of an evolution that began at breakup, and typically consists of 50-200 km long spreading segments and RR transform faults that have persisted for most of the ocean's history. The end-pattern is unambiguously revealed by magnetic and seismic profiles. The starting-pattern in this evolution is controlled by rift shape (unrelated to later spreading geometry), and differs from the end-pattern. A mature MOR shape is not a detailed match to the COB, yet COB shape is clearly present in the average MOR shape throughout sea-floor evolution, implying little information loss and tight constraints on spreading throughout the evolution. Given (a) initial COB shape, (b) the final MOR pattern, and (c) the orthogonal MOR/FZ relationship throughout spreading, the evolution of any passive-margined spreading basin can be modelled to give early basement structural evolution, with each unit of basement having a correct relative age. Magnetic anomaly patterns can then be calculated and compared with the actual patterns. The seismic reflection pattern of the marine basement will be controlled by the density of separate structural units in the basement. Large homogeneous areas of mature basement are flat near-horizontal reflecting planes, separated by major steps (FZs). The large numbers of small spreading segments and FZs (that initially form to match COB shape) outline small reflectors that can tilt considerably from horizontal, and collectively will yield a chaotic pattern of uncorrelatable reflections from the many edges, faces and sides of individual structural blocks (many being to the side of the recording-ship's track). Chaotic seismic areas coincide with 'structural' magnetic quiet zones in the sea floor, formed by spreading oblique to COBs and following changes in spreading direction (oblique to ocean-ocean boundaries), both during and outside the Cretaceous Long Normal Period. Thus the correlation between basement structural evolution, spreading geometry, and magnetic anomaly pattern, and seismic reflection signature, permits a better understanding of the most complex areas of oceanic basement, which typically lie along COBs, in marginal seas, and in areas formed following changes in spreading direction.

REPROCESSED SEISMIC SECTIONS: A TOUR THROUGH EASTERN US

K. Roy-Chowdhury and Robert A. Phinney

Department of Geological and Geophysicsl Sciences,
Princeton, NJ 08544, USA)

The Paleozoic Appalachian orogen in the Eastern US was one of the first targets of the deep crustal seismic reflection profiling. Several transects have been completed during the last decade and now provide a considerable volume of data to allow a preliminary synthesis of the results.

From north to south the data quality is highly variable and points to the differences in the composition and structural styles of the constituent units of the crust. The importance of near-surface conditions cannot however be overemphasized, some of the best deep crustal data anywhere in the world being recorded in the offshore setting of the Long-Island Platform. On the other hand the data from parts of the transect across the state of New York and Vermont show hardly any usable arrivals. Recent advances in signal detection techniques motivated us to reprocess the available stack sections. These sections were then migrated except when the signal-to-noise ratio was very low. Finally, suitable display parameters were used to obtain standardized crustal sections. This last step, the choice of display parameters as a filter, is, in our opinion, a non-trivial part of the processing sequence. Further, it is of particular importance that the interpreter is closely associated with these final steps of imaging. The resulting images are automatic (objective) line drawings suitable for direct interpretation.

Certain structural similarities in the sections are apparent. A major east-dipping boundary marks the Alleghanian suture. Further west is a second east-dipping suture (Taconian?), west of which are the thin-skinned Taconic Klippen. Between the two sutures is a highly strained east-dipping package, reaching often to the base of the crust. On sections that show details of the lower crust east of the Alleghanian suture, there are indications of a mid-crustal delamination, possibly a result of the collision.

Many of the sections are characterized by a pronounced transparent zone in the upper crust. Presence of steep dips, produced by tectonics in a regime of brittle deformation, is a likely explanation. On one of the Georgia transects there is some evidence of steeply folded structures near the surface, that change to sub-horizontal in the deeper regions associated with ductile deformation.

CONSEQUENCES OF MULTIPLE SCALES OF LAYERING FOR THE CRUSTAL SEISMIC RESPONSE.

K. Roy-Chowdhury, Robert A. Phinney and J. Pan

Department of Geological and Geophysical Sciences, Princeton University, Princeton, NJ 08544, USA

Crust is known to have layering at different scales. Exposures of deeper crust often show felsic-mafic banding, with the thickness of the units varying from a few cm to a few m. These are caused presumably by compositional differences and tectonic history. Seismic sections of the crust also often show 1-3 km thick strongly reflective zones at mid- to lower- crustal depths. The enigma of hard rocks showing layered structure under illumination by wavelengths of 200-250m prompted us to undertake numerical studies on the seismic response of a package containing unresolvable microstructure.

The model is a stack 2-10 km thick, made up of a sequence of thin layers (~ 10m thick) of bimodal composition. The signal contains frequencies in the range 12-50 Hz, and we consider only the vertical-incidence seismic response of the stack. Starting with a purely felsic model (homogeneous slab), we replace the micro-layers randomly with mafic units of equivalent vertical travel time.

The integrated seismic response of the layered-sequence depends on the properties of its constituent micro-units. Significant seismic energy is seen to be reflected back by such a layered sequence of between 20% and 80% mafic composition, with the seismic response showing a layered appearance. The variation of the impedance contrast, band-width of the source, and presence of anelasticity, all affect the reflectivity. Amplitude reflection coefficients of up to 70% are seen to occur as a result of complex interlayer interference. The reflected energy depends strongly upon the source wave-length; changing the source spectrum from 12-50 Hz to 12-30 Hz decreased the reflected energy by a factor of two. Decreasing the attenuation or increasing the impedance contrast increases the reflected energy.

It may thus be possible to classify different regions of the crust in terms of their composition (<10% vs. >20% mafic) depending upon their seismic transparency or otherwise. The high fraction of seismic energy reflected back by a layered sequence of alternating felsic-mafic composition can also be the reason for the observed blanketing effect of roofs of magma chambers.

The macroscopic response of the layered complex is clearly dependent on its microstructure. By modelling the composition of the micro-layers in the sequence to be a Bernoulli random variable, and associating the composition of the stack with the probability that a particular layer is mafic, one can compute the different scale-lengths present in the model and provide a qualitative explanation for the increase in reflectivity at a given composition.

3-D STRUCTURE OF SOUTHEASTERN AUSTRALIA - A NON-LINEAR INVERSION OF REGIONAL TRAVEL TIMES

M.S. Sambridge, & B.L.N. Kennett

Research School of Earth Sciences, Australian National University, GPO Box 4, Canberra, ACT 2601, Australia

The three-dimensional seismic velocity structure in southeastern Australia has been determined by the inversion of travel times from regional earthquakes, quarry blasts, and controlled sources from seismic refraction surveys. Over 350 well recorded earthquakes, with good spatial location across the region, were selected from the data base of the regional seismic network which has 16 stations throughout the highland region around Canberra. The permanent station recordings of the major quarries in the area were supplemented by in-line and fan refraction profile data.

This large-scale non-linear inverse problem requires simultaneous determination of earthquake hypocentres and seismic velocity structure. The velocity structure is parameterised using a large scale 3D lattice, to which a variable smoothing technique has been applied. As the inversion progresses the 'rigidity' of the model is decreased, allowing the longer wavelengths to be resolved first and the more detailed structure later.

P-wave and S-wave crustal and upper mantle structure has been inverted for, together with parameters representing the depth of the Moho. This multi-parameter type large-scale inverse problem requires careful handling of the different parameter types to avoid the introduction of bias. A new algorithm based on the minimization of a measure of the misfit between observed and computed travel times has been used, which offers considerable computational advantages over methods which require the inversion of large scale matrices. At each iteration a projection is made onto a 'subspace' derived from a few well chosen vectors in model parameter space, related to the properties of the misfit function, and the next model estimate is constructed in this subspace. Here we have determined the subspace vectors by partitioning the gradient of the data misfit into parts associated with each parameter class. In this way we are able to remove 'down-weighting' effects that may occur in single-gradient methods owing to a poor <u>a priori</u> choice of model covariances. In the new method each parameter type is adjusted, at each iteration, in response to its effect on the data misfit without unwarranted influence from other parameter types.

The nonlinear inversion requires fully three-dimensional raypaths to be determined. This has been achieved with the use of an efficient two-point ray tracing program, which allows travel times to be determined to a high degree of accuracy. We are therefore able to treat the problem more realistically and avoid the errors introduced from the use of approximate raypaths. The resulting maps of crustal and upper mantle velocity distribution, and depths to the Mohorovicic discontinuity, show interesting relations to surface geological structure.

CONSTRAINTS ON THE PETROLOGICAL COMPOSITION OF THE LOWER CRUST FROM MODELLING COMPRESSIONAL- AND SHEAR-WAVES

L.J. Sandmeier, F. Wenzel, & K. Fuchs,

Geophysikalisches Institut, Universitat Karlsruhe, Hertzstrasse 16, D-7500 Karlsruhe 21)

The seismic reflection explorations of recent years have clearly shown that the lower crust in many parts of the continents is highly reflective. Nevertheless, only little is known about the nature of the reflecting elements, because P-wave observations do not tightly constrain the lower crustal petrology. In seismic refraction experiments in the Black Forest S-waves of high energy and frequency content have been generated. This suggests a combined P- and S-wave interpretation which allows one to derive additional information on the physical characteristics of the lower crust. As main features we find a strong zonation of P-velocity and Poisson-ratio in the lower crust, whereas S-velocity and density vary only on a much smaller scale. These parameters form the data basis used to define the field of compatible petrological compositions. It turns out that the most reasonable explanation for the lamination of P-velocity and Poisson-ratio is a successive layering of rocks with higher and lower amount of mafic components. Other theories concerning the causes of high reflectivity like fluid inclusions, partial melting or anisotropy are considered. The influence of these assumptions on the elastic properties of the lower crust are examined and the compatibility with our P- and S-wave observations are discussed.

MOBIL SURVEY: SOUTHERN NORTH SEA

R.A. Scott-Robinson & D.J. Blundell, R.H.B.

New College, University of London, United Kingdom

In June 1987 c.1500 km of marine deep seismic lines were shot offshore of the UK for the British Institutions Reflection Profiling Syndicate (BIRPS) by the M/V Mobil Search as a generous gift by Mobil North Sea Limited. About 900 km of these lines were shot in the southern North Sea, crossing the Dowsing Fault Zone four times along its path, and transecting a region of the London Platform where earlier surveys have shown reflective bands in the mid crust (3.5-6 s TWT) dipping to the south-west. These reflections are imaged very strongly on this survey and differ substantially from those normally found in the mid and upper crust on other BIRPS profiles. They flatten out at c.3.5 s TWT, cannot be correlated with known faults at surface and do not have half-graben basins developed in their hanging walls. They follow the NW-SE trend of surrounding structural features (Dowsing Fault Zone, Broad Fourteens Basin), which coincides with the structural 'grain' of late Proterozoic basement rocks exposed in central England. The truncated and cross-cutting nature of the reflections suggests that they are created from a complex interference pattern, and this impression is reinforced by long diffraction tails which make a substantial contribution to the continuity of the events.

The reflectivity of the lower crust on these southern MOBIL lines is greatest beneath the rim of the southern North Sea Basin, and generally diminishes as the Mesozoic and Tertiary sediments thicken. 'Moho' events remain as short reflections beneath the thickening sediments but are laterally discontinuous. It is quite possible that the reduction in reflectivity of the lower crust away from the Basin margin is due to difficulty in achieving seismic penetration through the sediment pile, which extends down to a maximum of over 4 s TWT. However, there is some evidence to suggest that this is not the only reason. If lack of seismic penetration does not offer a full explanation of the diminished reflectivity, another geological cause must be sought. The southern North Sea area has been the seat of regional extension in the late Paleozoic and Mesozoic. If processes related to regional extension are a cause of lower crustal reflectivity, it becomes necessary to consider processes that might serve to reduce the reflectivity created by that extension during the subsequent evolution of the region.

MODELLING OF STEEPLY DIPPING REFLECTIONS AIDS CMP PROCESSING: THE DARLING FAULT, WA

Michael R. Seman, Roger A. Young & Brian J. Evans

Curtin University of Technology, Perth, W.A.

The Darling Fault, Western Australia, is a profound discontinuity between crystalline terrain of the Yilgarn Block and sediments of the Perth Basin. Conventional stacked sections across the fault exhibit several strong modes associated with this steeply dipping boundary. These events are enhanced by NMO correction with very fast stacking velocities.

Diffractions at the fault zone boundary overprint reflections from sedimentary layers adjacent to the fault. Consequently, accurate determination of fault location and dip is difficult using subhorizontal reflections alone. Raytrace modelling of the fault plane reflections themselves provides both an additional constraint on fault location and an assessment of possible reflection raypath trajectories.

A clearcut dipping event at a two-way time of 3.0 to 3.4 s occurs on the Yilgarn Block side of the fault. Continuity is weak but the lateral extent appears to be several kilometres. Possible origins are given for this feature, which resembles reflections from a sedimentary sequence.

THE TECTONIC EVOLUTION AND CRUSTAL STRUCTURE
OF CENTRAL AUSTRALIA

Russell D. Shaw[1,2], Bruce R. Goleby[1,2], Kurt Lambeck[1]
Brian L.N. Kennett[1] and Cedric Wright[2]

1 Research School of Earth Sciences, Australian National University, Canberra, Australia.
2 Bureau of Mineral Resources, Canberra, Australia.

The central Australian Amadeus and Ngalia Basins and the Arunta Block have had a long tectonic history covering more than 1800 Ma. One of the principal tectonic features of this region is a 30-50 km wide 700 km long thrust belt in the southern Arunta Block that developed in an intracratonic environment. Major activation of this thrust occurred in Devonian-Carboniferous time. Geophysical observations (gravity and teleseismic travel time anomalies) indicate that the region is out of local isostatic equilibrium and that major lateral variations in density and seismic velocities must occur throughout the crust and into the upper mantle. Deep reflection seismic data also indicate lateral structure down to the crust-mantle boundary. The examination of geological and isotopic data has led to a tectonic model for the past 1600 Ma whose principal events are summarized in Table 1.

The principal thrust zone is the Redbank Deformed Zone, a 7-10 km wide zone of anastomosing mylonites with an average dip of about 45 degrees. Earlier suturing across the Redbank Deformed Zone is indicated by metamorphic terranes, north and south of the Redbank Deformed Zone, which evolved independently until 1450 Ma. The principal period of thrusting across this zone occurred in the Late Devonian to Carboniferous, and was on a scale that involved the entire crust yet appears to have been mainly concentrated within the Redbank Deformed Zone. Gravity, teleseismic and deep seismic reflection data are consistant with the Redbank Deformed Zone continuing to depths of about 30 km, and displacing the lower crust and possibly the mantle.

South of the Redbank Deformed Zone, there are only a few other thrusts in a 30-50 km wide belt of diffuse crustal shortening and thickening. To the north, deep seismic reflection results suggest that some minor reverse faults, spread over a 100 km wide belt north of the Redbank Deformed Zone may have been reactivated as normal or lag faults in the final stages of movement. Some of these reverse faults may become listric beyond 30 km depth.

Table 1 - Senario for Tectonic Development

1600 Ma	Main tectonic elements established.
1450 Ma	Granulites upthrust on Redbank Deformed Zone to above 20 km.
1100 Ma	Gneisses south of the Redbank Deformed Zone migmatised then uplifted to above 12 km depth.
850-450 Ma	Intracratonic basin formation.
400-340 Ma	Reactivation of the Redbank Deformed Zone.
330 Ma	Uplift on the Ormiston Nappe, Passive back-thrusting at basin margin (AH).
330-270 Ma	Extensional spreading of hinterland north of the Redbank Deformed Zone away from thrust

DIFFERENT SUBDUCTION STRUCTURES IN ACTIVE MARGINS NEAR JAPAN REVEALED BY OBS DETAILED REFRACTION STUDIES

Hideki Shimamura and Takaya Iwasaki

Laboratory for Ocean Bottom Seismology, Hokkaido University, Sapporo 060, Japan

Very detailed velocity structures of crust and upper mantle in two parts of the subduction zones in the north-western Pacific were obtained from refraction profiling in which we made use of many ocean bottom seismographs. The observed data were dense and had good quality, which enabled us to obtain detailed structure of the active margin to a depth of 20-30 km.

One structure was obtained in the southernmost part of the Kuril Trench, south of Hokkaido Island, where Pacific Plate is subducting. The other was in the Ryukyu Trench area, south of Kyushu Island, where the Philippine Sea Plate is subducting. The comparison between the two subduction zones revealed a drastic contrast in the manner of subduction. The two regions are about 1600 km apart.

In the Kuril Trench, a smooth subduction of oceanic layer 2 was found, without forming a wedge structure. The subducted layer 2 forms a relatively low-velocity zone beneath the continental slope. On the other hand, in the Ryukyu Trench, a huge accretionary wedge, with a maximum thickness over 12 km, has been found. The wedge must have been formed by a continent-ocean collision. The wedge extended from 50 to 150 km landward of the deep sea trench. The difference in the manner of subduction of oceanic layer 2 may affect the occurrence of large earthquakes, since many earthquakes with magnitude more than 8 have occurred in the Kuril Trench region, whereas relatively small earthquakes have occurred in the Ryukyyu trench region.

In both regions, the oceanic basin has a typical oceanic crust with a thickness of about 8 km, though the Moho velocity is slightly lower than typical, 7.8 - 8.0 km/s. We have obtained not only velocity structure, but also velocity gradients in each layer. For example, in the oceanic basin near the Kuril Trench, the crust has three layers that are characterized more by contrasts in the velocity gradients than by the velocity contrasts themselves. The velocity gradient is small but not uniform in the oceanic layer 3, and was obtained as 0.08 s^{-1} for its upper part, and 0.1 s^{-1} for the lower part. The upper mantle velocity increases downward with a rather small velocity gradient, about 0.02 s^{-1}.

INSTRUMENTAL DEVELOPMENTS IN JAPANESE OBS (OCEAN BOTTOM SEISMOGRAPH)

Hideki Shimamura[1] and Toshihiko Kanazawa[2]

1 Laboratory for Ocean Bottom Seismology, Hokkaido University, Sapporo 060, Japan
2 Geophysical Institute, University of Tokyo, Tokyo 113, Japan

Various OBS systems in Japan in the past and in the near future are reviewed, and a recent OBS system is introduced in detail.

Our current main OBS is of a pop-up design. It descends to the sea bottom and after observation, it returns to the sea surface. In order to call up the OBS from the sea bottom, an acoustic command is sent from a shipboard transducer to activate the release mechanism of the OBS.

Since the OBS was designed to record both controlled-source signals and natural earthquakes, it has a continuous recording system with a duration of a few weeks, which we believe has an advantage: our OBS will not miss any events throughout the observation period.

The important points of our OBS design are:
a) - good coupling to the ocean bottom.
b) - low noise design (amplifier electrical noise, insulation of vibration of mechanical rotating parts in the tape recorders from geophones, decrease of water-current induced noise).
c) - high reliability.
d) - high quality record to enable digital processing.
e) - small and light-weight design (which enables an increase in the number of OBS in an experiment. We have more than 40 OBS's available. The OBS were sometimes deployed by a helicopter).

The recording period is either 14 or 30 days continuous. The recording frequency range is 1 to 30 Hz when the recording period is 14 days. Each OBS has two tape-recorders are in an OBS which run very slowly (0.1 mm/s speed). The number of recording channels is 6 (signal) + 2 (clock) in total; they can be used either for 3-component signals with different amplifier gains, or 3-component signals each with only one gain, with the tape-recorders running one after the other to double the recording period. The geophones are 4.5 Hz 3-component, mounted on a gimbal mechanism. Low-noise and low-power signal amplifiers with maximum amplification of 96 dB are used.

Each tape-recorder has its own programmable timer, which programs initiation of the recording. The operating depth is up to 6000 m. The OBS transponder system is used both to call up the OBS, and to locate the OBS accurately on the sea bottom. Maximum communication range is up to 15 km, depending on the environmental noise level. Our OBS has a reliable unique release mechanism, which makes use of electrically forced corrosion of a thin stainless-steel plate.

GRID - 3-DIMENSIONAL MAPPING OF CRUST AND MANTLE REFLECTIONS, NORTH OF SCOTLAND

Catherine Smith & BIRPS Group

Bullard Laboratories, Madingley Road, Cambridge CB3 OEZ, UK.

Since 1981 BIRPS has collected 1600 km of deep seismic reflection data on the UK continental shelf to the north of Scotland, in an area 200 km x 120 km. Structures have been imaged across the Caledonian orogen and adjacent foreland. One thousand kilometres of this data were collected in 1986/87 (the GRID survey), with profiles recorded to 15, 24, 30, and 60 s two-way time. Lines were sited using existing seismic data from this area, in order to image in three dimenstions particularly bright reflective structures in the mantle.

With this data set we have imaged the deepest, brightest and most continuous reflections so far seen in the upper mantle on multichannel seismic reflection records worldwide. The high density of profiling in this area allows the mantle reflections to be mapped in three dimensions.

The most spectacular feature is the Flannan Event, a set of reflections dipping towards the east at approximately 30^{o}, reaching from the Moho at 26 km to a depth of 80 km, and seen to be continuing along strike for at least 90 km. The Flannan Event is complex in detail, having an internal reflection structure and relationship with the reflection Moho that varies along strike. In some places it is seen as a thick wedge of reflections that cut across the Moho with no apparent offset. In the north and south of the GRID survey area the reflection structure is simpler, the wedge of reflections is absent, and the Flannan Event seems to terminate at the Moho. There are smaller structures in the mantle between the Moho and the Flannan Event with westerly dip, and also structures deeper in the mantle below the Flannan. The geometry of these separate reflection events and their relationship has been mapped.

Mantle structures imaged on the continental shelf of the UK are often associated with dipping reflections interpreted as large-scale crustal faults. The Flannan Event is no exception, sitting below the Outer Isles Fault, which is thought to be a thrust fault reactivated as a normal fault.

There is no unequivocal explanation for the origin of these mantle reflectors. Studies of reflection characteristics show them to be as bright as reflections from the sediments in the upper crust, and continuous over spectacular distances. The Moho is abruptly terminated by the Flannan reflectors in some areas, indicating the Flannan Event is a younger structure. The proximity of a similar trending fault in the crust above suggests that they were formed by the same tectonic forces.

MANTLE REFLECTIONS MAPPED IN 3-DIMENSIONS

Catherine Smith & BIRPS Group

Bullard Laboratories, Madingley Road, Cambridge CB3 OEZ, UK.

Deep seismic reflection data acquired on the UK continental shelf, to the north and west of Scotland, has recorded high-amplitude reflections from the upper mantle. Although other BIRPS data on the continental shelf also show reflections that appear to originate in the mantle, it is only in the area around Scotland that there is more than one crossing of such features. It can therefore be concluded that the reflections are truly from mantle structures, and their 3-D geometry can be mapped.

North of Scotland BIRPS has acquired a grid of lines spaced approximately every 5 km along strike and every 10 km along dip, totalling 1,600 km. A complex reflection structure dipping eastwards, from Moho (26 km) depth to depths of 80 km, is imaged for 90 km along strike. A thick (1 s) package of reflections crosses the reflection Moho with no apparent offset in the central part of the survey area. To the north and south the reflections appear to terminate against the Moho.

Two hundred and fifty kilometres to the south, in an area to the north of Ireland, reflections from the upper mantle were recorded on the BIRPS-WINCH survey. Three further crossings of this feature have recently been collected - the WIRELINES survey. The reflections in the mantle here have a true dip to the SSE.

Both sets of reflections lie beneath large scale faults in the crust. The reflections north of Scotland are found beneath the Outer Isles Fault, and those to the west of Scotland are beneath the Great Glen (strike-slip) Fault.

Mapping of the crustal reflections, Moho and mantle reflections is used to constrain the age and origins of the mantle reflections. Were they formed by the same tectonic forces that deformed the crust above? In places the Moho is disturbed by the mantle structures, indicating that the mantle reflections are the younger, but how old is the Moho?

Despite the evergrowing volume of deep seismic data from many tectonic settings around the world, bright reflections from the mantle are not widely imaged. The relatively close proximity of these two sets of mantle reflections suggests that they may be related, and perhaps the images obtained are from northern and southern portions of a continuous structure running below the west coast of Scotland.

CONTRASTING CRUSTAL STRUCTURE

S.B. Smithson, R.B. Hawman, R.M. Berg, R.A. Black, J.R. Cozzens, K. Gohl, M.T. May, L.J. Mayrand, M.A. Speece, P.J. Taucher, M.E. Templeton, D.P. Wang, & D. Zhang,

Program for Crustal Studies, Dept. of Geology and Geophysics, University of Wyoming, Laramie, WY 82071, USA.

Combined wide-angle and vertical-incidence recording are used together with specialized processing to determine crustal structure. The resulting models for long- and short-wavelength velocity structure can then be related to lithologies and ultimately to crustal genesis. The best reflections are found in four metamorphic core complexes and are associated with mylonites and crustal extension. Faulting, tuff stratigraphy, intrusions, and possibly a magma chamber, are imaged in the difficult seismic environment of the Long Valley Caldera. Wyoming Proterozoic crust shows reflections from some plutons, and a deep crust and Moho that are reflective at wide angles. Proterozoic crust in Kansas shows complex geologic structure, possible underplating, and no reflective Moho. Reconstituted crust in NE Washington shows thrust stacking, complex geologic structure, and a reflective Moho. The deep crust of the Basin and Range of NE Nevada and the Minnesota Archean represent strongly contrasting tectonic features. The lower crust in the Basin and Range is horizontally layered, probably as a result of extensional ductile flow during the Cenozoic, representing a major metamorphic event. The lower crust is compositionally layered and predominantly mafic, underlain by a more mafic 3 km zone of cumulate or residual material related to magmatic history. The Moho is a sharp compositional boundary marked by strong interlayering of mantle and crustal rocks to produce unusually high reflectivity, and the crustal rocks may be partially molten to explain the reflectivity. About 50% of the crust is mafic material, and probably a maximum of 25% of the crust represents mafic additions and underplating during Cenozoic extension. In the Minnesota-early Archean crust reflections become weaker and less continuous in the lower crust, and absent in the lowermost crust and Moho zone (based on the Moho depth from a single refraction interpretation). Here most of the deep crust seems to have been thickened by stacking of nappes, which are "floating" in small bodies of later anatectic granite. The lowermost Archean crust is a distinctly different tectonic regime, possibly formed by subhorizontal compressional shearing that may have erased larger scale structures, or by later gabbroic underplating that thickened the early Archean crust. The Moho in Minnesota must be strikingly different from that in the Basin and Range. It is either gradational or a relatively small step-function change in chemical composition, such as garnet pyroxene granulite to peridotite; it is probably not layered unless the velocity changes across the layering are very small. If it is gradational, then it is probably formed by the gabbro-eclogite phase change, and the gabbroic zone could have been underplated.

THEORETICAL PREDICTIONS OF THE SEISMIC STRUCTURE FOR THE LOWER CRUST OF DIFFERENT CHEMICAL COMPOSITIONS

Sobolev, S.V., & Babeiko, A. Yu.

Institute of Physics of the Earth, B. Gruzinskaya 10, Moscow
D242

A method of theoretical prediction of seismic structure of the lower crust of the given chemical composition is suggested. It consists of two blocks: 1) Computation of equilibrium mineralogical composition, density and seismic velocities using the Gibb's energy minimization technique. Minerals are considered as multicomponent non-ideal solid solutions. 2) Computation of deviations of real mineralogical composition and seismic parameters from equilibrium state using linear kinetic models for solid state transformations and models of thermal evolution of the crust.

The computations are made for a number of chemical compositions varying from picritic to andesitic basalts. The computed seismic parameters - depth relations are reasonable for tholeiite or more acidic chemical compositions if the kinetics of solid-phase transformations are taken into account. The layered basaltic intrusion as a model of seismic laminae in the lower crust is also considered.

EXTENSION, COMPRESSION, AND THE FORMATION OF THE CENTRAL GREAT AUSTRALIAN BIGHT BASIN

H.M.J. Stagg, J.B. Wilcox & H.L. Davies

Division of Marine Geosciences & Petroleum Geology,
Bureau of Mineral Resources, Canberra, Australia.

Deep seismic data acquired by BMR on the Rig Seismic in late 1986 is leading to a considerable revision of the widely held picture of the southern margin of Australia as a classical Atlantic-type margin, that separated from Antarctica in the Cenomanian, after a period of rifting that commenced in the Jurassic. In particular, a pair of lines extending SE from the Eyre Terrace and SW from the Ceduna Terrace, which intersect on the Continental rise, reveal a number of features of importance to formation of this margin. These features may be summarised as -

(1) A thick continental rise section (up to about 6 km thick) overlying highly extended lower crust. The principal components of the sedimentary section, dated by ties to Jerboa-1 in the Eyre Sub-basin and Potoroo-1 in the Great Australian Bight Basin, are a basal, flat-lying, almost undisturbed, (?heavily indurated) sequence separated by a decollement of probable Neocomian age from an overlying section consisting principally of Lower to Upper Cretaceous sediments that may include volcanics. The post-breakup section is thin, and the rise is almost bereft of Tertiary sediments.

(2) Although basin-forming structures are indistinct beyond the Eyre Terrace, due to the considerable thickness of synrift and post-rift sediments, they suggest a NW-SE extension at least between the Eyre and Ceduna Terraces in the pre-Middle Jurassic.

(3) Beneath the SW flank of the Ceduna Terrace there is a major overthrust sequence lying immediately above the Neocomian decollement. The overthrust 'belt' strikes SE and individual structures take the form of shallow-dipping nappes. It incorporates 2-3 km of section, and may include an incompetent unit such as salt or shale. Although they parallel the SW margin of the Ceduna Terrace, the overthrusts are unlikely to have formed by gravity sliding since they predate the commonly accepted age for thermal subsidence of the margin (ie Cenomonian breakup).

While examination of the Rig Seismic data set is at an early stage, there is mounting evidence for interpretation of the central part of the southern margin as a basically NW-SE extensional regime in which the present SW Ceduna Terrace was underlain by a major transpressional zone. We believe it likely that the faults intersecting the Cenomanian horizon on the Ceduna Terrace, which have been used to infer SSW-oriented extension (as in Gippsland and Bass Basins), may be post-breakup overprinting due to subsidence of the margin in the Late Cretaceous. Although it is generally assumed that margin rifting commenced in the Jurassic, we do not discount the possibility that the pre-Neocomian basal section beneath the continental rise may be a relic of an intracratonic basin formed in an earlier tectonic episode.

BASEMENT CONTROL UPON THE STRUCTURAL STYLES OF SEDIMENTARY BASINS, NW SCOTLAND, UK

A.M. Stein & D.J. Blundell,

R.H.B. New College, University of London, United Kingdom

The NW Scottish continental shelf has become a classic locality for the study of reactivated basement structures. Since 1981 the BIRPS Syndicate has collected over 1,500 km of deep seismic data in this area (MOIST, 1981; WINCH, 1982; DRUM, 1984; and GRID,1986. An integrated basin analysis has been completed using these profiles in conjunction with 1,100 km of commercial deep seismic profiles, over 10,000 km of standard oil industry seismic profiles, thematically mapped Landsat images and most importantly, studies of surface geology in NW Scotland.

The key to success in this area has been the widespread exposure on-shore of crystalline basement (the Lewisian) in close proximity to the offshore seismic data base. The basement structure has been analysed using Landsat images in conjunction with field studies and reference to published data. Results indicate that the principal basin bounding fault, identified on the seismic data for over 200 km along strike, is the partially reactivated Outer Isles Fault, which outcrops along the eastern coast of the Outer Hebrides. Previous workers have assumed that this fault is a reactivated Caledonian thrust, but the field data clearly demonstrates that it developed in the early Proterozoic (c. 2200 Ma.) as part of a set of inclined NE-SW mid-crustal shear zones linked by steeper NW-SE structures.

Maps generated from the seismic data show that a compartmentalised hanging-wall basin has developed above the planar Outer Isles Fault. The compartmentalisation occurs principally where he Outer Isles Fault is intersected by one of the NW-SE shear zones. It can be demonstrated that it is the three-dimensional shape of the Outer Isles Fault which controls the internal geometry and overall shape of the sedimentary basin. Similar basins have developed above other shear zones of the same trend that occur to the west of the Hebrides. Basins which have not developed in the hanging walls of these structures have fundamentally different geometries and are bounded by presumably newly formed listric faults. The in-depth knowledge of the basement controls in this area has given us a better understanding of the spatial and temporal distribution of the sedimentary sequences within the basin and has led to the recognition of a thick Carboniferous sequence in some of the basins which had hitherto only been inferred. This sequence has been proved by us to contain mature hydrocarbon source rocks and fundamentally changes the economic prospectivity of these basins.

LITHOSPHERIC FLEXURE AS SEE IN SEISMIC REFLECTION DATA; EXAMPLES FROM PLATE BOUNDARIES WITHIN NEW ZEALAND AND ANTARCTICA

T.A. Stern & F.J. Davey

Geophysics Division, DSIR, PO Box 1320, Wellington, New Zealand

Lithospheric flexure has traditionally been studied in the oceans using gravity and bathymetric data. Flexure, and the related issue of lithospheric strength, within the structurally complex continents is a more difficult problem to study. This is particularly so using just gravity and topographical data. Induced flexure should, nevertheless, be seen right through the lithosphere including at the crust-mantle boundary. Thus crustal seismic reflection data can, in some cases, be used indirectly to study flexure and hence lithospheric rigidity.

Behind the southern portion of the Hikurangi subduction zone of New Zealand is a broad crustal downwarp - the Wanganui Basin. A 220 km long multichannel seismic reflection profile reveals that the reflection Moho of the Australian Plate is flexed down beneath the basin. The driving force for this flexure appears to be a shear coupling between the overriding Australian Plate and the subducted Pacific Plate. An approximate 200 km flexural wavelength can be measured, which closely matches that seen on the shallower basement-sediment interface. A flexural rigidity of about 8×10^{22} N.m is estimated for the edge of the Australian Plate.

Flexure can also been seen expressed in seismic stratigraphy. Within the Ross Embayment of Antarctica seismic reflection data can be used to map a shallow unconformity, interpreted to be due to flexure induced by the young volcanic load of Ross Island. Here the stretched and thinned continental lithosphere of the Ross Embayment has an estimated flexural rigidity of about 1×10^{23} N.m.

TOMOGRAPHIC RECONSTRUCTION OF UPPER CRUSTAL VELOCITY VARIATIONS IN THE ARUNTA BLOCK, CENTRAL AUSTRALIA

S. Sugiharto[1], S.A. Greenhalgh[1], & C. Wright[2].

1. School of Earth Sciences, Flinders University of South Australia, Bedford Park, S.A. 5042
2. Bureau of Mineral Resources, GPO Box 378, Canberra, ACT 2601

A seismic refraction/reflection programme of crustal/upper mantle investigations was recently undertaken by the Bureau of Mineral Resources within the Central Province of the Arunta Block, central Australia. One experiment involved the successive deployment of sixteen portable seismic recorders on two approximately orthogonal, intersecting traverses. Twenty shots at 2 km intervals were fired along one profile, and recorded by the 16 instruments placed at 2 km intervals along the other traverse. The geometry was then reversed and a further 19 shots were fired into the orthogonal profile. Shot-receiver distance varied from 1 to 39 km. Data were digitised into 579 traces and then processed in a variety of ways.

One such process was OCSIRT (overlapping cell simultaneous iterative reconstruction tomography), whereby first-arrival travel times were converted into a map of upper crustal velocity inhomogeneity. Colour velocity tomograms were obtained for various combinations of shot-receiver offset, grid interval, cell radius and number of iterations. Synthetic examples, using the same shooting geometry, were computed and studied as an aid to interpretation. The final tomograms, which exhibit a velocity variation from 5.4 to 6.0 km/s, can be related to the broad structural fabric of the area. For example, the velocity decrease to the south-east of the area is interpreted as due to the presence of a younger sub-thrust layer. However, poor ray sampling in some areas complicates the detailed geological interpretation of the data.

The first arrival times show a dependence on shot-receiver orientation, implying possible anisotropy. The maximum velocity occurs at azimuths of N60° - and 240°. The minima are displaced by 90° from the maximum values. The observed velocity variation of 500 km/s corresponds to an anisotropy factor of 9%, which is in the range of anisotropy observations reported from previous studies of the upper crust. The minimum velocity axis is aligned sub-parallel to the direction of maximum compression, which has deformed the Arunta region into a series of east-west folds over the last 1000 million years.

Various non-linear multichannel filters were applied to the shot-gather seismograms in order to detect and identify (if present) reflections from the mid to lower crust, which were not visible on the raw record sections. No coherent late-arrival signals were extracted, despite an intensive search. Static errors are a likely source of contamination which would destroy phase alignment. Further analyses of the data is underway.

DIFFERENTIAL STATICS: THEIR APPLICATION TO REFLECTION TRAVERSES OVER BASEMENT

F.J. Taylor, B.R. Goleby & J.H. Leven
Bureau of Mineral Resources
Canberra, Australia

Static corrections for seismic reflection processing are usually calculated in the case of explosion surveys by the use of uphole time and shot depths, or in the case of non-explosive surveys, by separate uphole surveys. Short wavelength static corrections are then accommodated by autostatic routines. However, these autostatic routines are notorious for producing worse results when the signal to noise ratio is poor. This is a particular problem for seismic surveys across basement regions where there are usually no strong reflectors on which to key the cross correlation of the autostatics.

The use of first break arrival times to calculate static corrections has attracted more attention in recent times. These first break analyses are commonly based on the reciprocal, plus/minus or GRM methods, and generally enable the determination of both the short and long wavelength static variations. A more straight-forward utilization of the first break data which provides station statics directly is the differential statics method. This technique makes maximum use of the redundancy of the first break data.

The differential static method calculates the first difference between neighbouring stations of the sum of first break times from shots on either side of these stations. The method is independent of variations in the sub-weathering velocity. At any station, the median differential static is selected, and with the available data redundancy, errors associated with cycle skips and first break mispicks are eliminated. Integrating the differential statics and tying this time correction curve to the reliable uphole time data provides excellent station corrections for both long and short wavelength statics.

Examples of the application of this differential static technique from the 1985 BMR Central Australia survey and the 1987 Tumut Trough survey illustrate the improvement in the quality of the stack section.

SEISMOLOGICAL STUDY ON THE STRUCTURE OF THE LITHOSPHERE ALONG THE CONTINENTAL MARGINAL BELT IN THE NORTH PART OF CHINA

Teng Jiweng (J.W. Teng)

Institute of Geophysics, Academia Sinica, Beijing, China.

The North and continental margin of China is a place where tectonic movements are complex and seismic activities are strong; also it has rich mineral and energy resources. This tectonic zone is under the influence of the Western Pacific Ocean, which it faces. All these factors show that the tectonics and lithospheric structure have a special background at depth.

In this paper typical sections are presented for crustal structure of 30 profiles of deep seismic sounding (DSS): Yuanshi-Jinan profile, Lianyungang-Laocheng profile, Lingbi-Fengzian profile of Yangtze region, Haixin-Fengning profile, Leting-Changping profile, Baigezhuang-Fenging profile, and the structure of the Upper Mantle in regions of Hebei and Shandong provinces, direction of Beijing-Shkhalin, Beinjing Qinghai, Beijing-Sichuan, Beijing-Taiwan and its vicinity. In these areas the structure of layers, distribution of velocity, their regional characteristics and transverse imhomogeneity, are studied by the use of explosion seismology and natural earthquakes.

These results indicated that the studies can play a very important role in exploration for the occurrence and prediction of earthquakes, the distribution of oil and gas basins, and the dynamics of the lithosphere.

STRATOTECTONIC PALEOSTRESS ANALYSIS OF SPITSBERGEN CENTRAL BASIN: IMPLICATIONS FOR BASIN DEVELOPMENT AND RELATIVE PLATE MOTION

Teyssier, C., Pershing, I.C. and Kleinspehn, K.L.,

Department of Geology and Geophysics, University of Minnesota, 310 Pillsbury Drive, SE, Minneapolis, MN 55455

We propose a new technique, "stratotectonic paleostress analysis", based on the orientation of microtectonic features such as minor faults, tension cracks and stylolites in the strata of a sedimentary basin. These structures are interpreted to be the response of the sedimentary rock to the local or regional stress fields associated with tectonism. Analysis of these structures requires a means of separating the various deformation events that are recorded within a single stratigraphic unit. A method developed by Etchecopar et al. (1984) is used which allows multiple stress tensors to be extracted from a fault population. By carefully extracting the latest stress tensor from the upper part of a stratigraphic sequence, and by imposing that same tensor on the underlying rocks, one can ideally isolate all associated faults. One can then move to the next unit down and apply the same extracting-imposing principle until the fault data are exhausted. Reiterations of this technique separate all successive paleostress tensors.

Important limitations of this "stratotectonic paleostress analysis" are (1) the impossibility of separating two stress tensors with similar orientations and relative magnitudes even if the tensors represent two completely separate events in time; (2) the difficulty associated with the variation in the mechanical responses of different rock types in the sequence, potentially leading to the definition of several tensors for the same tectonic event.

This stratotectonic paleostress analysis has been applied to the relatively undeformed foreland Tertiary Central Basin of Spitsbergen and its underlying Cretaceous strata. Over 1000 fault striation orientations were measured in six stratotectonic units defining five major paleostress tensors.

Successive stress orientations interpreted with respect to the present NW-SE axis of the fold-thrust belt along the West Spitsbergen margin suggests that a Late Cretaceous dextral strike-slip regime was probably responsible for the major pre-Tertiary unconformity and possibly initiated the development of the Central Basin. During subsequent sedimentation in the basin, movement along the deformed belt reversed, yielding a sinistral sense of shear. A normal composite compressional event followed, which we interpret as being coeval with the culimination of deformation in the fold-thrust belt west of the study area. The upper part of the Central Basin sequence records a dominantly extensional event that we correlate with the separation of Svalbard from Greenland during the opening of the Norwegian-Greenland Sea.

Our results compare favorably with the earlier work, based on both magnetic seafloor anomalies (Talwani and Eldholm, 1977; Muller and Scotees, 1987) and sedimentologic analysis (Steel et al., 1985) with the notable addition in this study of a sinistral transgressive event in the early history of the orogeny. Whereas this episode might be a reflection of a local variation in stress due to block rotation in the field area, it might instead indicate a reversal in the sense of relative motion of the American and European plates during the early stages of the opening of the Norwegian-Greenland Sea.

DEEP REFLECTION TRAVERSES IN THE WEST CARPATHIANS (CZECHOSLOVAKIA)

Tomek, C.[1], Korab, T.[2], Ibrmajer, I.,[2] Biely, A.[2], Lexa, J.,[2], & Dvorakova, L[1]

1 Geofyzika Brno, P.O. Box 62, 612 46 Brno, Czechoslovakia
2 Geological Institute of Dionyz Stur, Mlynska dolina 1, 817 04 Bratislava, Czechoslovakia.

A multichannel seismic reflection survey, conducted along two profiles more than 150 km long in the Czechoslovak part of the West Carpathians, has recently been completed by Geoifyzika Brno and Geological Institute of Dionyz Stur Bratislava. Seismic events were recorded to 14-16 s using both dynamite and vibroseis technology.

The data obtained along both traverses are of excellent quality. In the migrated sections striking reflections are interpreted as corresponding to the upper surface of the downgoing European plate and to thrust faults of various ages and positions within the upper Carpatho-Pannonian plate. In the migrated section of the western Traverse 8HR, a westward dipping package of strong reflections is clearly related to the Variscan collision tectonics of the Bohemian Massif.

The most notable feature in the southern part of the migrated section of the eastern Traverse 2T, is the southward dipping package of reflections which corresponds to the total crustal thickness. The reflections are probably from thrust faults and mylonite zones of the Tatraveporic and Gemeric Upper Cretaceous continental collision. This gigantic collision probably took place during the Alpine - West Cartpathian realm, but corresponding features cannot be recognized in the Alps because of the consequent Tertiary continental collision. Other prominent northward dipping reflections occurring in the northern part of the section of Traverse 21 probably originate from Upper Oligocene transgressional events along the Pienniny Klippen belt.

Southeast-dipping prominent high-amplitude reflections characterize the accretionary wedge of the Zdanice flysch in the section of Traverse 8HR . Both borehole and seismic results document a progressive accretion of trench deposits during the Miocene subduction. Farther to the southeast, the pull-apart Vienna Basin, with the underlying older Eocene Magura accretionary wedge, is obvious in the seismic section.

The lower plate thrust under the West Carpathians is formed by the Precambrian and Variscan Paleozoic continental crust and the Upper Jurassic passive margin. This plate is manifested by arcward dipping events in the lower crust in both sections. These reflections can be interpreted as due to a bend of the lower-plate surface. We interpret these packages from the lower crust as a subduction bend of the lower plate. They terminate above subhorizontal reflections defining the Moho. This implies that the Moho is a relatively young feature that postdates the Lower Miocene subduction. The lower crust beneath the West Carpathians is mostly transparent. Some dipping events in the lower crust that might indicate thrusting episodes are an exception.

DETERMINING LOWER CRUSTAL SEISMIC VELOCITIES FROM LONG-OFFSET REFLECTION DATA

Ian Totterdell & Mike Warner

BIRPS, Bullard Laboratories, Madingley Road, Cambridge CB3 OEZ, UK.

In order to obtain accurate velocities from the lower crust, the British Institutions Reflection Profiling Syndicate (BIRPS) ran a Synthetic Large-Aperture Velocity Experiment (SLAVE) off the north coast of Scotland during 1987. In this experiment two ships, each recording and shooting, sailed the line twice at different spacing, to synthesise a recording cable of up to 16 km length. However in the processing of the data collected, conventional velocity analysis cannot be applied: the ray-paths cannot be taken as being straight, and there may be significant lateral variation of the velocity structure of the length-scale of the largest offsets. These effects lead to move-out with offset curves in CDP gathers which are not hyperbolae.

In the method described in this paper, the non-hyperbolic shape of the curves at each depth is taken account of by fast and accurate ray-tracing through the previously-determined velocity structure above that depth. The CDP gather is corrected for move-out according to the appropriate curve and its semblance calculated. The peaks of semblance give the velocity just above the event, and its dip. The velocities thus determined are smoothed and used as input for ray-tracing to the next depth.

Examples of this method applied to both real and synthetic data are shown, and it is demonstrated by synthetic examples that the method can resolve an accurate model of the velocity structure at depth. The method can also be used as an aid to producing improved stacked sections.

PHYSICAL PROPERTIES OF THE DEEP ALPINE CRUST

J.-J. Wagner, F. Barblan, R. Chessex, S. Sellami & A. Zingg

Lab. of Petrophysics, Department of Mineralogy,
University of Geneva, CH-1211 Geneva 4, Switzerland

To make an interpretation of the deep crust it is necessary to have some information about its physical properties. For this purpose we study in our laboratory, under different conditions of temperature and pressure, rocks from deep facies. The samples are from the Serre Massif in Calabria and from the Ivrea zone. Velocity of P and S waves to 400 Mpa, density, and magnetic susceptibility are made, together with petrographic analysis.

A CRUSTAL TRANSECT ACROSS PHANEROZOIC EASTERN AUSTRALIA IN SOUTHERN QUEENSLAND

K. D. Wake-Dyster, D. M. Finlayson, J. H. Leven,
H. J. Harrington, & D. W. Johnstone.

Bureau of Mineral Resources, Geology and Geophysics, Canberra.

In southern Queensland, Australia, seismic reflection profiles to 20 s two-way time (TWT) and associated wide-angle reflection and refraction profiles extend for about 1100 km from the central Eromanga Basin to the coast near Brisbane. These profiles give an insight into structures and processes within the crust under four geological provinces, which, west to east, are the central Eromanga Basin, the Nebine Ridge, the Taroom Trough of the Bowen Basin, and the New England Fold Belt.

The seismic character or "fabric" in these four provinces is quite different. Under the central Eromanga Basin there is a non-reflective basement to 8 s TWT, and a reflective lower crust at 8-13 s TWT. Some prominent dipping reflectors in the lower crust are interpreted to be associated with basement highs and/or lower crustal ramping. Under the Nebine Ridge the base of the non-reflective zone shallows to about 4 s TWT, and the Moho becomes more clearly defined at 12-13 s. The extinction of the non-reflective zone occurs on the eastern side of the ridge at the eastern limit of the Thomson Orogen. Westward-dipping structures on the mid-crustal boundary are observed, and movement of the Thomson Fold Belt over these structures is interpreted to explain major northeast basement trends, the Nebine Ridge and the Pleasant Creek Arch trends.

Basement reflectors under the Permo-Triassic Taroom Trough are generally weak and flat lying, and are associated with rift-sequence volcanics. East of the Kumbarilla Ridge, the New England Orogen can be separated into a number of terranes based on seismic fabric. Multiple reflectors throughout the crust characterize the Texas Orocline in the west, and in the east there are features associated with the Carboniferous deformation of the orogen and the formation of Triassic basins.

Along the entire length of the transect the Moho is characterized by the transition from reflective lower crust to non-reflective upper mantle at 11-13 s TWT. Under the Thomson Orogen the Moho is irregular in places, possibly the result of Carboniferous tectonism which severely deformed the Devonian basins. East of the Nebine Ridge, the Moho is the base of a well-defined "package" of seismic reflectors and undulates only slightly.

ABSOLUTE REFLECTION COEFFICIENTS FROM DEEP REFLECTORS

Mike Warner

BIRPS, Bullard Laboratories, Madingley Road, Cambridge CB3 OEZ, UK

Obtaining accurate reflection coefficients from deep seismic data is difficult, and requires accurate absolute calibration of the acquisition system. There are several ways this may be a attempted. One of the most accurate is to use sea-floor reflections and sea-floor - surface - floor multiples to calibrate the system by directly determining the reflection coefficient of the sea floor. In deep water (about 4 km) with good data the method is accurate to a few per cent.

Having calibrated the system, reflection coefficients from the lower crust and upper mantle can be determined if the velocity structure and attenuation due to scattering and anelastic absorbtion are known. In practice it is most useful to choose values for these parameters that determine minimum possible reflection coefficients. The change in spectral content of the reflections must also be taken into account. Although interference due to multi-cyclic layering of the reflectors is often suggested as a plausible mechanism for increasing reflection amplitudes, this is generally not the case. For the finite bandwidth, short duration signals typically used in marine profiling, increases in amplitude of more than a few tens of percent are not generally possible.

Many of the bright reflections observed in the lower crust, Moho, and upper mantle have reflection coefficients in excess of 0.1, that is an acoustic impedance contrast of 20%. Several of the explanations currently suggested for deep reflections have difficulty in explaining such large contrasts.

BASALTS, WATER OR SHEAR ZONES IN THE LOWER CRUST?

Mike Warner

BIRPS, Bullard Laboratories, Madingley Road, Cambridge CB3 OEZ, UK.

Bright, sub-horizontal, laterally extensive, multi-cyclic layered reflections have now been recorded in the lower continental crust from many areas. In contrast, this reflection signature is rare in the continental upper crystalline crust and upper mantle, and in the oceanic lithosphere. With the present state of knowledge it is sensible to seek a single quantitative explanation for all such layering.

Qualitative explanations for lower crustal layering abound and can be broadly divided into: igneous, metamorphic, structural, or fluid related. Measurements of reflection coefficients from the lower crust place strong quantitative constraints on possible explanations. Structurally induced anisotropy, metamorphic layering, or free fluids cannot realistically produce sufficiently bright reflections. Igneous layering or mineralogically distinct shear zones can produce strong reflections.

Results from crustal xenoliths, helium isotope ratios, palaeo-geothermal gradients, and chemistry of flood basalts, together with numerical modelling of lithospheric extension and asthenospheric melting, suggest that underplating and intrusion of the lower crust with mantle derived mafic igneous rocks is common. The apparent spatial relationship between lower crustal layering and continental extension, the strength and continuity of the reflections, the apparent mobility of the Moho, and the lack of a close match between the brittle-ductile transition and the top of the layering, suggest that underplating, related to extension and/or elevated mantle temperatures, is the explanation for lower crustal layering.

THE NATURE OF EXTENSION IN THE NORTH SEA

Nicky White

BIRPS, Bullard Laboratories, Madingley Rd, Cambridge CB3 OEZ UK

There is considerable debate concerning the relative importance of pure and simple shear during lithospheric extension. Much of the argument has focussed on the North Sea Basin, where both the uniform stretching model and the lithospheric simple shear model have recently been applied.

A simple numerical model is used to investigate the geometrical and thermal consequences of lithospheric simple shear. Approximately symmetrical crustal thinning is predicted by the model. In addition, the axes of initial subsidence, thermal subsidence, and crustal thinning are coincident. The magnitude of post-rift thermal subsidence varies considerably across the basin, being smallest where the detachment reaches the surface.

These results have been applied to 5,000 km of shallow and 1,500 km of deep seismic reflection data from the northern North Sea to determine the nature of extension. The data were calibrated with 150 well logs. Steeply dipping faults can be inferred in the upper crust. In the lower crust and upper mantle, the presence or absence of a low-angle lithospheric 'detachment' cannot be proven from the seismic reflection data alone. Although crustal thinning and subsidence are grossly symmetrical and coincident with each other, such observations cannot discriminate between uniform stretchikng and lithospheric simple shear. It is argued here that only the geometry of the post-rift thermal subsidence can satisfactorily distinguish the two models. The observed geometry is not compatible with the lithospheric simple shear model in its simplest form.

EXTENSION AND SUBSIDENCE OF THE CONTINENTAL LITHOSPHERE USING REGIONAL SEISMIC REFLECTION PROFILES FROM THE NORTH SEA

Nicky White & BIRPS Group

Bullard Laboratories, Madingley Road, Cambridge CB3 OEZ, UK.

Basin structure has been investigated in the North Sea using a network of deep seismic reflection profiles shot to 15 s TWTT (NSDP-84 and NSDP-85 surveys). When combined with shallow industrial profiles, these data can be used to address a number of important issues.

Perhaps the most important of these is the widely recognised discrepancy between the amount of extension measured on faulting in the brittle upper crust, and that calculated from subsidence analysis and crustal thinning. Crustal thinning can be estimated from the shallowing of the reflection Moho, and gives maximum stretching factors for Mesozoic extension of about 2. Backstripped subsidence data from the deepest part of the graben give similar values. On the Shetland Terrace, where normal faulting can be unambiguously interpreted, the amounts of stretching calculated from subsidence analysis and from faulting agree well and are consistent with crustal thinning.

Post-rift stratigraphic onlap is an important observation which cannot be explained by the uniform stretching model: the displayed data clearly show the resultant 'steer's head' cross-sectional geometry. Current explanations for the 'steer's head' geometry include global sea-level rise and increasing flexural rigidity of the continental lithosphere after rifting. There are important problems associated with both of these mechanisms. Here, an alternative model based on two-layer lithospheric stretching is presented. The predicted pattern of onlap agrees well with that observed, provided the lithospheric mantle is stretched over a fractionally wider region than is the crust. This is important as it means that the conclusions concerning the extension discrepancy are not affected.

MAGMATISM AT CONTINENTAL RIFTS AND MARGINS

R.S. White

Bullard Laboratories, Madingley Road, Cambridge, U.K.

When continental lithosphere is stretched, the rifting is sometimes accompanied by extensive magmatism, but sometimes is volcanically quiescent. This is true both of sedimentary basins and of continental margins, where the rifting has continued to the formation of a new oceanic basin.

New work on the Rockall continental margin off Britain shows that on volcanic margins there is not only a considerable quantity of extruded volcanic rock, but that this is accompanied by massive addition of igneous rock to the lower crust, either by intrusion or by underplating. The igneous lower crust is characterised by high seismic velocities of 7.2-7.4 km/s.

The production of massive quantities of igneous rock in rifting areas can be explained very simply by partial melting resulting from decompression of asthenospheric mantle as it wells up passively beneath the thinned lithosphere. Using parameterisations of the amount of melt and its composition developed by McKenzie and Bickle from laboratory data, it is apparent that the volume of melt generated is very sensitive to the asthenospheric temperature. An increase in the asthenospheric temperature of 150°C above normal trebles to over 10 km the thickness of igneous rock produced on a rifted continental margin. Anomalous upper-mantle temperatures of 100-200°C above normal are produced across 2000 km broad regions around hot spots such as Iceland and Hawaii. The production of massive outbursts of magmatism in rifted regions can thus be explained readily by passive upwelling if the rift passes across the thermal anomaly surrounding a hot-spot plume.

This model can easily be tested. Most obviously, all volcanic margins should be associated with a hot-spot plume at the time of rifting. Further, the timing of the volcanism, its duration, the occurrence of igneous underplating, the geochemistry of the volcanics, and the subsidence history of the margin, are all diagnostics which can be used to test this model.

From a global review of magmatism in rifted areas and the association with nearby hot-spot plumes, I show that this simple model of melt production by adiabatic decompression can explain all the occurrences of extensive magmatism at continental rifts and margins. It also explains the production of voluminous continental flood basalts.

CRUSTAL STRUCTURE AND FORMATION OF A MAGNETIC QUIET ZONE - AUSTRALIAN SOUTHERN MARGIN

Paul E. Williamson, Clive D.N. Collins, and David A. Falvey

Bureau of Mineral Resources, PO Box 378, Canberra, ACT 2601, Australia

The crustal structure of the "magnetic quiet zone" outboard of the Otway Basin of the Australian Southern Margin has been interpreted for the whole crustal section, using fully processed multichannel seismic reflection data, seismic refraction data, and dredge data collected by the BMR vessel Rig Seismic, and extrapolation of well control. The crust of the quiet zone is interpreted to consist of relatively thin (10 km), faulted and extended continental crust. The upper and lower crust are shown to be extended by around 40 percent, separately by different, respectively listric and sub-planar fault regimes during a final (secondary) extensional phase prior to seafloor spreading. A discrepancy occurs between observed crustal thickness and that implied by fault geometry, since the interpreted basement and lower crustal thickness is 7 km, and the observed faulting would not thin the crust to less than 25 km thickness from an initial continental crustal thickness of around 35 km. Subsidence calculations are, however, consistent with the interpreted crustal thicknesses. This requires crustal thinning other than by the observed secondary faulting, and argues for two distinct phases in the formation of the continental margin and quiet zone. A model is presented for the Early Cretaceous formation of the continental margin quiet zone of the Australian southern margin by secondary rifting of an older onshore rift. In this model the 'lower plate' of a primary onshore rift produced by simple and/or pure shear, is subjected to subsidence and overlying sedimentation, followed by secondary rifting involving separate upper and lower crustal extension and thinning, by the interpreted extensional faults during the formation and thermal subsidence of the 'lower plate' continental passive margin and continental magnetic quiet zone. A ridge at the southern end of the transect corresponds to a free-air gravity high, and the beginning of long wavelength magnetic anomalies with amplitudes of approximately 100 nT, and corresponds to the continent/ocean boundary. The model, if valid, may have implications for other magnetic quiet zones and continental margins, particularly those with 'lower plate' origins.

CRUSTAL STRUCTURE OF THE EXMOUTH PLATEAU REGION

P.E. Williamson[1], S. Kravis[1], D.A. Falvey[1]
and the N.W. Australia Study Group[1,2,3]

1 BMR, Canberra, Australia
2 Lamont-Doherty Geological Observatory, USA
3 University of Rhode Island, USA

Two-ship Wide Aperture CDP (WACDP) and Expanding Spread Profile (ESP) data were collected for the Exmouth Plateau Region by R/V Conrad of Lamont-Doherty Geological Observatory (LDGO) and R/V Rig Seismic of the Australian Bureau of Mineral Resources (BMR). Twenty ESP profiles, each with offsets of up to 100 km on three transects - the Exmouth, Cape Range, and Cuvier transects - were obtained, as well as three WACDP profiles totalling 1450 km tying the centres of the ESPs.

The Exmouth and Cuvier transects allow the crustal structure of a marginal plateau to be compared and contrasted with that of the adjacent normal passive continental margin. Post-Paleozoic upper crustal sediments are 10 km thick over the Exmouth Plateau but less than 4 km over the Cuvier transect. The Exmouth Plateau shows a lower crust (greater than 6 km/s) with relatively constant thickness of 10 km over approximately 300 km of the Exmouth transect, but thinned to around 8 km beneath the Kangaroo Syncline, before thickening shoreward to 20 km beneath the Rankin Trend. The Cuvier transect exhibits a more progressive thinning of the lower crust, from 22 km on the continental shelf to 10 km adjacent to the abyssal plain. Crustal thinning on the Cuvier transect is shown to occur over a distance of approximately 200 km, with increased thinning of the lower crust approximately corresponding to the break in the continental slope.

Low levels of extension within the sedimentary upper crust of the Exmouth Plateau are associated with normal faults which dip seaward on the outer plateauand landward on the inner plateau. This low level extension, where it occurs, is associated with detachment zones in the deepest sedimentary sections above basement. A well-developed landward dipping detachment affecting basement and lower crust is associated with the western margin of the Kangaroo Syncline and another seaward dipping major detachment is associated with its eastern margin. The structural regimes of the Cuvier and Exmouth transects are separated by the southern transform margin of the plateau. The edges of the continental plates on both transects thin rapidly and exhibit strong igneous activity.

The upper and lower plate separations which formed the basic basement and cover crustal architecture of the Exmouth and Cuvier margins were pre-Mesozoic and likely pre-Permian in age. The gross extent and rate of thinning of the Paleozoic basement and lower crust on the outer Cuvier Transect is similar to that landward of the Kangaroo Syncline on the Exmouth Transect. The Exmouth Plateau margin has, however, an additional 150 km of uniformly thin basement and lower crust. That thinning by pure and/or simple shear results in a basement and lower crust approximately half its thickness on the continental slope. The presense of > 7 km/s lower crustal velocities on the Exmouth transect and their absence on the Cuvier transect argues for respectively lower plate and upper plate origins separated by the southern Exmouth Plateau transform margin; if the > 7 km/s velocities represent retension of the lowest crust of the Pilbara Archean Craton and not a later underplating episode.

THE INTERPRETATION OF EXPANDING SPREAD REFLECTION PROFILES: EXAMPLES FROM CENTRAL AND EASTERN AUSTRALIA

C. Wright, T. Barton, A. Spence, B. Goleby & D. Pfister

Bureau of Mineral Resources, GPO Box 378, Canberra, ACT 2601, Australia

The Australian Bureau of Mineral Resources has recorded expanding reflection spreads coincident with regional deep seismic reflection profiles on land, both in sedimentary basins and in areas of exposed basement rocks. The purposes of these expanding spreads were to obtain localised velocity estimates throughout the crust, and to examine changes in reflection character as a function of angle of incidence. For each expanding spread, arrival times of refracted and reflected arrivals were measured, and a preliminary velocity model was fitted to the data by using ray tracing for the reflected arrivals, and a Hergoltz-Weichert inversion for refracted signals. Significant lateral variations in seismic velocity in both sedimentary and basement rocks, and apparent inconsistencies between near-vertical incidence and moderate to wide-angle reflection data frequently occur. One expanding spread recorded above the Nebine Ridge in southern Queensland shows P to SV and SV to P converted reflections from a bright spot in the near-vertical incidence section at a depth of 17 km. Another expanding spread recorded in the Amadeus Basin has provided a detailed seismic velocity distribution throughout the 9 km thick sedimentary sequence,that is assisting in understanding the evolution of the basin by enabling more reliable formation thicknesses to be determined. The quality and complexity of the seismic information varies considerably between expanding spreads, so that different approaches to processing and interpretation are required for each geological situation. Although the resolution of shallow velocity variation is good, the absence of persistent continuous deep reflectors, and the presence of peg-leg multiples within sedimentary basins, have resulted in poor resolution of deep crustal velocities.

DEEP SEISMIC PROFILING IN CENTRAL AUSTRALIA

C. Wright, B.R. Goleby, C.D.N. Collins & T. Barton

Bureau of Mineral Resources, GPO Box 378, Canberra, ACT 2601
Australia

In 1985, the Australian Bureau of Mineral Resources recorded more than 500 km of deep seismic reflection data across the Arunta Block and the Ngalia and Amadeus Basins, as part of a multidisciplinary program to study the tectonic evolution of the central Australian region. The seismic sections within the Arunta Block show many northerly dipping events that are interpreted as reflections from faults, many of which are evident in surface geological mapping. In particular, the Redbank Deformed Zone, a major thrust feature, has been imaged to depths of at least 30 km. The nature of the deep reflectors differs on either side of the Redbank Zone, the persistent steep northerly dipping character of seismic energy being absent below the Southern Arunta Province and the Amadeus Basin. Sub-horizontal bands of reflectors below the Southern Arunta Province and the southern platform region of the Amadeus Basin occur at depths between 18 and 30 km, with small apparent dips to the north and south respectively. The character of the reflectors supports a thick-skinned model for the evolution of the Arunta Block and northern Amadeus Basin.

Complicated variations in overburden and weathering thickness throughout the central Australian region have led to the development of alternative refraction methods of computing static corrections and of imaging unweathered bedrock. The results of the refraction modelling provide constraints on lithological variations which assist in interpreting faint events in the seismic sections, which may be reflections from dipping faults. Expanding reflection spreads and three-dimensional refraction data provide evidence of anisotropy and complicated lithological variations in the vicinity of the Redbank Zone. A seismic refraction survey recorded within the Arunta Block suggests a crust at least 50 km thick within much of the Central Arunta Province, although the reflection records do not enable a clear crust-mantle boundary to be identified. An expanding reflection spread recorded in the northern part of the Amadeus Basin has enabled complicated vertical and lateral velocity changes to be resolved within the 10 km thick sedimentary section. These results assist studies of the evolution of the basin.

ANOMALOUS CRUSTAL STRUCTURE FROM DEEP SEISMIC PROFILING IN THE KAROO BASIN, BOTSWANA

James A. Wright and Jeremy Hall

Centre for Earth Resources Research, Department of Earth Sciences, Memorial University of Newfoundland, St. John's, Canada A1B 3X7

During 1987, PetroCanada International Assistance Corporation (PCIAC) conducted a reconnaissance seismic survey on behalf of the Government of Botswana. About 700 km of 12-fold data were obtained along profiles in two sub-basins in the Karoo of western Botswana. It was recognised that fundamental questions relating to the formation of this intracratonic basin could be addressed if the data record length was adequate. PCIAC agreed to collect 15 s data throughout the survey area. The stacked sections exhibit good reflections throughout the whole record length, but this paper emphasises results from those reflections deeper than about 5s - the inferred depth to the sedimentary basement. The preliminary seismic data confirm previous interpretations, based on aeromagnetic data, that there is up to 15 km of sediment infill. Good reflections below this continue to the base of the record section, but are particularly frequent in three sub-horizontal bands between 5 s and 10 s. The uppermost band may relate to Precambrian assemblages onto which later sediments appear to overlap as the basin margin is approached to the north. The base of the crust is not readily estimated because there is no one abrupt base to the reflectivity. However, a broad thinning of the section containing the three reflective bands occurs below one of the sub-basins, suggesting an extensional origin for the early basin that involved pure shear in the lower crust.

DEEP SEISMIC AND GEOCHEMICAL EVIDENCE FOR RIFT-INDUCED MAGMATISM DURING BREAKUP OF THE N. ATLANTIC

Carolyn M. Zehnder and John C. Mutter

Lamont-Doherty Geological Observatory of Columbia University, New York, NY 10964-0190

The application of two-ship multichannel seismic techniques has greatly increased our ability to determine deep crustal structures and thereby determine processes of lithospheric extension. It has become increasingly apparent that magmatism plays an important yet varied role during lithospheric extension, resulting in passive margins that are underplated by mafic melts as well as those that have experienced a short-lived but prolific stage of volcanic activity.

We have recently suggested that the variation in magmatism may be related to the rate and regional extent of lithospheric thinning. Areas that have undergone extension over a broad region and for a long period of time, such as the Bay of Biscay, appear to be devoid of magmatism. In contrast, the relatively abrupt cleaving of the lithosphere that occurred during the formation of the Norwegian-Greenland Sea, was accompanied by a short-lived but voluminous magmatic episode, resulting in the emplacement of unusually thick oceanic crust. The basalt flow of this crust forms conjugate seaward dipping units on the Norwegian and East Greenland margins. Margins with seaward dipping reflectors have also been recognized off SW Rockall, NW Africa, NW Australia, and Wilkes Land, Antarctica, as well as several other locations worldwide.

As rifting thins the continental lithosphere, passive mantle upwelling fills the void. The resulting thermal gradients cause density instabilities that can induce small-scale convection in the upper mantle beneath the extended lithosphere. This rift-induced circulation can derive a greater amount of mantle material into the pressure-temperature field where partial melting begins, than would occur through passive upwelling alone. That is, for a particular potential temperature of the mantle, the rift-induced circulation causes a greater volume of mantle to be melted, though the extent of partial melting of the mantle remains comparable to that of passive upwelling. Crustal thickness would be expected to diminish as this secondary convection slows, but the degree of partial melting of the source should not change dramatically. Thick crust formed by this process should notably differ in geochemistry from thick crust resulting from high mantle potential temperatures, since in the latter case the higher temperature leads to greater extents of melting. For example, the thick crust formed as a result of convective partial melting processes would be relatively enriched in incompatible elements such as sodium, compared with crust of the same thickness resulting exclusively from high mantle potential temperatures.

We interpret the results of seismic and geochemical studies from the Voring Plateau and Rockall Margin as evidence that rift-induced, small-scale convection in the mantle is an important component of lithospheric thinning and the initiation of seafloor spreading. The convective partial melting process can result in the emplacement of thick igneous crust early in the seafloor spreading history without appealing to short-lived mantle temperature perturbations. The abundance of seaward dipping reflections in margins worldwide may well attest to the widespread occurrence of this rift-induced process.