BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD

Record 1985/31

RHEOLOGY OF THE LITHOSPHERE
&
AUSTRALIAN EARTHQUAKES

compiled by

B.J. Drummond, M.O. Michael-Leiba, D. Denham and C.D.N. Collins

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PREFACE

This Record is a compilation of the abstracts of papers given at two meetings in Canberra in September, 1985. The meetings were jointly sponsored by the Specialist Group on Solid-Earth Geophysics of the Geological Society of Australia, the Bureau of Mineral Resources and the Research School of Earth Sciences, Australian National University. Each meeting lasted two days. The first was a workshop dealing with the Rheology of the Lithosphere. The second was a symposium entitled 'Intraplate and Interplate Earthquakes'. The abstracts of several papers were not provided in time for inclusion in this Record, which - nevertheless - should still be a useful reference to research currently under way in Australia in the fields of earthquake seismology and lithospheric deformation.

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THE BASE OF THE LITHOSPHERE UNDER AUSTRALIA

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The lithosphere has traditionally been defined as the rigid outer part of the earth overlying a more fluid asthenosphere. Many definitions have been given for the base of the lithosphere. In plate tectonic parlance, it is the depth above which the plates move relative to the upper mantle. In petrological terms, it is the depth at which incipient melting of the lithosphere begins. Turcotte & Schubert (1982) define the lower boundary of the lithosphere as the 1600°K isotherm, because above this temperature rocks behave rigidly but below it they are sufficiently hot to deform easily. Such definitions are vague and are usually not very specific. For example, in southeast Australia, various estimates of the geothermal gradients put the 1600°K geotherm anywhere between 80 and 135km depth. Consequently, in this talk the traditional definition based on seismic data - that is, the base of the lithosphere is marked by the onset of a low velocity zone - will be addressed. The seismic definition therefore describes the base of the lithosphere in terms of the Earth's response to a transient stress. It may behave differently to a tectonic stress applied for much longer periods. However, seismic probing is the most accurate and least ambiguous method for studying the Earth, so that the seismic definition therefore places important constraints on geodynamic models.

Under the Australian shield, there is no evidence in the form of low velocity layers to suggest that the base if the lithosphere lies above the Lehmann Discontinuity at a depth of about 200 km. Rather, two separate refraction studies provide strong evidence that the low velocity layer under northern Australia lies below 200 km. It is suggested that this low velocity layer represents the most probable depth at which the central and western part of the Australian continent is decoupled from the underlying mantle. In eastern Australia, there is reasonably strong evidence for a shallower low velocity layer; its location is uncertain but a review of the available data suggests that it begins at a depth of about 120 km. Although there are some inconsistencies between the velocity models from body and surface wave studies in eastern Australia, it is clear that there are significant differences at depths below 100 km between the upper mantle structure under the shield region of central and western Australia compared with the Phanerozoic region of Australia. These results therefore support the theory that the lithosphere is thicker under old regions than under younger, hotter regions.

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A GEOLOGICAL PERSPECTIVE ON THE LITHOSPHERE

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Details concerning the mechanical significance of the lithosphere have not hindered geological research significantly during the last 2 decades, because geologists have been busy describing the actual phenomena which take place. To reach an understanding of the physics of the tectonic process is nevertheless an important goal, and understanding the mechanical significance of the lithosphere is of particular significance. A geological perspective must emphasize the differences due to varying strain-rates of processes such as involved in: (a) rapid release of energy during a seismic event;
(b) deformation of crust and mantle due to drift of the lithospheric plates; or (c) deformation of crust and mantle as the result of adjustments at the boundaries of the moving plates. The last process can include significant orogeny, and it is well to realize that much of the crustal deformation that takes place in an orogenic belt, may be due to secondary motions involving convergence velocities in the order of 1-2 km/M.Yr, while the primary plate motions take place at orders of magnitude larger velocities. Some significant advances in mechanical understanding of the lithosphere have been made, particularly in experimental rock deformation laboratories and concepts have been introduced such as depth-dependent rheology. This leads to a particularly interesting conundrum in the oceanic lithosphere. Proceeding further, depth-dependent rheology leads to the notion of lithospheric stress guides. I postulate that the upper mantle stress guide varies considerably in its mechanical significance under continents, and that there are many tectonic areas where it attains relative insignificance, where for all practical purposes, the lithosphere does not exist. I reintroduce the concept of coupled world wide orogeny, which has been rejected as impossible according to modern plate tectonic theory. In addition mechanical consequences of delamination of the continental lithosphere will be discussed, and the importance of localized deformation of the lithosphere will be re-emphasized. The apparently futile attemps of geologists to influence their geophysical colleagues on this matter will be noted. There are several different mechanisms which explain the phenomenon of strain localization. Unfortunately, owing to the difficult nature of the experiments, geologically significant problems such as this remain largely beyond the reach of the rock deformation laboratory at the present moment.

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LABORATORY MEASUREMENTS OF POLYCRYSTALLINE OLIVINE DUCTILITY AT HIGH TEMPERATURE AND PRESSURE

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One hundred and twenty deformation experiments have been carried out on a variety of natural olivine-rich rocks and synthesised pure olivine specimens. These experiments have been made in a gas-medium deformation apparatus at a constant confining pressure of 300 MPa at temperatures between 1000° and 1400°C.

The results obtained from these studies serve to highlight five factors which have an important bearing on olivine rock ductility. These factors are:

1. The presence of water.
   Specimens deformed in the presence of $\geq$0.05 weight percent water deform upto 100 times faster than those deformed under dry conditions.

2. Changes in deformation mechanism
   A change in deformation mechanism has been observed in a wide range of olivine polycrystals deformed under wet conditions. At lower temperatures and higher stresses, deformation is accomplished predominantly by dislocation creep while at higher temperatures and lower stresses, diffusional creep contributes to an increasing degree.

3. The grain size of the aggregate
   This property has a strong influence on the mechanism of deformation of the aggregate and upon the rate at which this deformation proceeds at a given stress and temperature.

4. Fabric anisotropy in the aggregate
   The orientation of any pre-existing foliation in the aggregate relative to the differential stress direction has a strong influence on the steady state flow stress. For orientations in which shearing along the foliation is favoured, strengths are substantially lowered.

5. The presence of basaltic melt
   The addition of a few volume percent of basaltic melt to a wet olivine polycrystal with an approximately 10μm grain size results in an increase in strain rate at 1300°C by a factor of about 5.

Results illustrating the effect of each of these factors will be presented and discussed.

COMPARISON OF LABORATORY AND REBOUND RHEOLOGIES FOR THE DEEP MANTLE

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Because of the effect of pressure on rheology, the effective viscosity of the Mantle based on laboratory parameters is predicted to increase by several orders of magnitude with depth in the mantle. On the other hand, post-glacial rebound and rotational data have been interpreted in recent years in terms of viscosities which are uniform or increase by less than a factor of 30. There have been several recent discussions of how these findings might be reconciled. Considerable care is required when trying to compare the non-linear rheologies usually found in laboratory studies with the linear rheologies usually assumed in rebound and rotational studies.

The effect of pressure is controlled by the activation volume, V, of the deformation process. For thermally activated, non-linear, steady-state creep, V enters through the activation enthalpy, $H = E + PV$, where E is the activation energy and P is the pressure. This rheology is described by

$$\sigma=\gamma\ (s.e^{H/RT})^{1/n} \qquad (1)$$

where σ is the deviatoric stress, s is the strain rate, R is the gas constant, T is temperature and γ and n are constants. If an effective viscosity is defined as $\eta = \sigma/s$, it can be written in the alternative forms

$$\eta = \gamma\, s^{(1-n)/n} e^{H/nRT} \qquad (2a)$$

$$\eta = \gamma^{n} \sigma^{1-n} e^{H/RT} \qquad (2b)$$

Karato (1981) and Christensen (1983) have noted that the apparent effect of H depends on whether we compare states with the same strain rate or with the same stress: in the former case, the apparent activation enthalpy is H/n rather than H. On the basis of numerical convection models, Christensen has suggested that a convecting system tends to adjust to some intermediate state of stress and strain rate, such that the effective activation enthalpy is between H/2 and H/3 for n = 3.

Because temperature and pressure have opposing effects on the apparent viscosity, a useful concept for discussing the variation of apparent viscosity with depth in the mantle is the isoviscous temperature profile. From (2a) or (2b), this is

$$T_i=T_o(1 + PV/E) \qquad (3)$$

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where T_0 is the zero-pressure temperature corresponding to the constant value, η_σ, of the apparent viscosity. An idea of the strong effect of pressure on mantle rheology can be obtained by assuming V is constant and equal to 11 cm^3/mole. With E = 500 kJ/mole and a pressure at the base of the mantle of 140 GPa, the term PV/E is (3) is 3.1. For T_0 = 1700 K, this gives T_i = 6940 K at the base of the mantle.

For comparison, typical estimates of the adiabatic temperature increase through the mantle amount to less than 1000 K (e.g., Stacey, 1977), i.e., the adiabat starting at 1700 K at the surface would reach less than 2700 K at the bottom of the mantle. At the same pressure and strain rate, this temperature difference translates into 8 orders of magnitude difference in apparent viscosity, from (2a). At the same pressure and stress, the difference is 24 orders of magnitude, from (2b).

O'Connell (1977) and Karato (1981) have noted that the activation volume probably decreases at least as fast as the molar volume under pressure. This considerably moderates the pressure effect, but still leaves 3 to 5 orders of magnitude of variation along an adiabat at constant strain rate when measured activation volumes for olivine and (Mg,Fe)O are used (9-13 cm^3/mole). To reduce the apparent viscosity variation to less than a factor of 10 would require an average activation volume of about 3.2 cm^3/mole, or a zero pressure value of about 5 cm^3/mole or less.

It seems unlikely that the experimental values are in error by such a large factor, and also unlikely that the rebound studies have been done incorrectly, within the limitations of their assumptions. The conclusion seems to be that the rheology assumed in the models is not the one sampled in the experiments. The question remains as to what deformation regimes are operative in the mantle during rebound, rotational variations and convection.

It seems fair at this stage to pose uncomfortable questions for both experimentalists and modellers.

For experimentalists, what is the likelihood that the deformation mechanisms in the relatively low stress mantle are not the ones operating in the experiments, and further, how reliable are estimates of parameters in inaccessible deformation regimes?

For modellers, when are we going to start seriously modelling the more difficult rheologies: temperature-dependent, pressure-dependent, non-linear and possibly transient?

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RHEOLOGICAL PROPERTIES OF THE UPPER MANTLE

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New experimental data are reported for the activation volume and activation energy for creep of peridotite in the pressure range 1.2 to 2.7 GPa and the temperature range 1100°C to 1400°C. The activation volume increases with temperature from 22.5 cm^3mol^{-1} at 1100°C to 27 cm^3mol^{-1} at 1400°C. The activation energy decreases with pressure from ca. 300 KJ mol^{-1} at 1.2 GPa to ca. 150 KJ mol^{-1} at 2.7 GPa. These data agree with those calculated by Karato (1981) from Kohlstedt et al's. (1980) data of ca. 20 cm^3mol^{-1} and ca. 300 KJ mol^{-1} at 500 MPa and 1250°C to 1400°C. The activation volume is larger than has been assumed in previous studies of the rheological behaviour of the upper mantle where a value of 11 cm^3mol^{-1} has been used. The presently determined values are intermediate between those expected for oxygen to be rate controlling (11 cm^3mol^{-1}) and those expected if SiO_4^{-4} is the rate controlling species (37 cm^3mol^{-1}) suggesting that perhaps (SiO_2) is the rate controlling species. High activation volumes mean that the upper mantle is substantially stronger than would otherwise be expected although this effect is offset by the decrease in activation energy with increase in pressure. The aim of this paper is to use these new data to explore the distribution of flow strength within the upper mantle for various postulated geotherms and to comment on the correlations between flow rates and tectonic processes under trenches, back-arc basins, recently deformed areas and ancient Archean Shields.

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EXTRAPOLATION OF LABORATORY RHEOLOGICAL BEHAVIOUR IN TECTONOPHYSICS

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At relatively low temperatures and pressures rocks fail under non-hydrostatic stress by brittle fracture. However, they tend to become ductile as temperature and pressure are raised, although the presence of high pore fluid pressures can greatly extend the brittle field. At lower crustal and upper mantle conditions, ductile behaviour is usually assumed, except where the occurrence of earthquakes points to brittle failure. This note deals only with creep of rocks in the ductile field. Such creep is invoked in considering large scale tectonic processes in the lower crust and upper mantle and therefore the predictions of creep behaviour under natural conditions from laboratory observations would be very useful in constraining tectonophysical models. However, this prediction is hampered by many uncertainties and lack of knowledge, even concerning what are the potentially important variables.

In relating laboratory observations to tectonophysical processes, three types of consideration enter:

(a) The form of the flow criterion for general stress states
(b) The environmental and internal variables that need be considered
(c) The circumstance that different mechanisms may dominate behaviour under different conditions, giving rise to a variety of flow laws for a given rock.

These topics are now discussed in turn.

Almost all laboratory rheological measurements have been made in axial compression under superposed confining pressure, that is, with $\sigma_1 > \sigma_2 = \sigma_3$ where σ_1, σ_2, σ_3 are the principal stresses (compression positive). The quantity $\sigma = \sigma_1 - \sigma_3$ is reported as the "flow stress", determined as a function of the axial strain rate $\dot{\varepsilon}_1 = \dot{\varepsilon}$ (shortening positive) at a given temperature T and confining pressure $\sigma_2 = \sigma_3$. Not much attention has been given to the analysis of transient creep. The test results are usually fitted to a steady state "flow law" of the form

$$\dot{\varepsilon} = A\sigma^n \exp\left(-\frac{Q}{RT}\right) \qquad (1)$$

where A, n and Q are empirical parameters, R is the gas constant and T the absolute temperature. In tectonophysics other types of stress state are involved and so a generalization of this flow law is needed. In engineering creep calculations for general stress states it is often assumed, following Odqvist, that the flow law can be expressed in terms of an "effective stress" σ^* and an "effective strain rate" $\dot{\varepsilon}^*$, in the form (neglecting elastic strains):

$$\sigma^* = (1/\sqrt{2})\{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\}^{\frac{1}{2}}$$

$$\dot{\varepsilon}^* = (\sqrt{2}/3)\{\dot{\varepsilon}_1 - \dot{\varepsilon}_2)^2 + (\dot{\varepsilon}_2 - \dot{\varepsilon}_3) + (\dot{\varepsilon}_3 - \dot{\varepsilon}_1)^2\}^{\frac{1}{2}}$$

In this case it is seen that $\sigma (= \sigma_1 - \sigma_3)$ and $\dot{\varepsilon} (= \dot{\varepsilon}_1)$ in the experiments can be viewed as effective stress and effective strain rate and that it is appropriate to extend (1) to general stress states in terms of σ^* and $\dot{\varepsilon}^*$, remembering, however, that the form (1) is essentially empirical at this point and that other forms might have been used.

Even accepting (1) as the basic form of flow law, $f(\dot{\varepsilon}^*,\sigma^*,T) = 0$, with primary variables $\dot{\varepsilon}^*$, σ^* and T, the flow behaviour in practice can be influenced by the following additional variables:

(a) Pressure or mean stress. The influence of pressure is relatively small in the laboratory range and no precise measurements are available. However, it is thought to be significant in extrapolating to upper mantle conditions, when it can be allowed for by increasing the value of Q.

(b) Grain size. Under some conditions the creep rate can be strongly dependent on grain size. In this case the pre-exponential factor in (1) is rewritten as A/d^p where d is the grain size and p is another empirical constant, usually in the range 0 to 3.

(c) Water activity. Intragranular hydrolytic weakening is an effect of major importance, well known in quartz and olivine and probably occurring in other silicates, although the exact manner in which the dependence on water activity should be incorporated in the flow law has yet to be established. Other thermodynamic variables such as oxygen activity may also prove to be important in particular cases.

(d) Presence of fluid phases. The pore pressure effects that are well known in the brittle field are probably unimportant in the ductile field. However, the presence of fluids in the grain boundary regions can have important rheological effects if conditions are such that diffusive transfer of material through the fluid phase contributes significantly to the strain or if it assists intergranular accommodation. These effects can be expected to introduce some grain size dependence in A and possibly affect the other parameters too.

(e) Preferred crystallographic orientation. This would tend to introduce anisotropy of flow stress, requiring different choice of parameters for different orientations. Little is known about flow laws for anisotropic rock.

The third aspect of flow behaviour to be considered is the variety of deformation mechanisms or rheological regimes. Many mechanisms are known or are conceivable, by means of which rock can flow. The flow law can therefore be expected to vary, in values of parameters and in the variables that need to be incorporated, according to the mechanisms predominating. These mechanisms may include dislocation movement controlled by a variety of factors, displacement of material by diffusion via various paths, and cataclastic processes involving microcracking and granular flow. Correspondingly, laboratory measurements have established different rheological regimes within which different values of the parameters are found when flow law (1) is fitted and different dependences on variables such as grain size appear. Before making any justifiable extrapolation of a laboratory-determined flow law, valid for certain ranges of strain rate, stress, temperature and other variables, to tectonophysical conditions in the Earth it must be established that the same flow mechanism or rheological regime is involved. Microstructural evidence on flow mechanism in laboratory and field is therefore of primary importance in guiding the application of laboratory findings in geology. In the absence of this evidence prediction by extrapolation must be seen as speculative unless the general form of the rheological behaviour within the Earth can be independently established. When the latter is possible, comparison with experiment may permit conclusions about conditions within the Earth, such as temperature and other thermodynamic variables. Otherwise, on present knowledge, only very broad limits can be placed on the rheology of the lower crust and upper mantle by extrapolation from experiments.

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EXTRAPOLATION OF LABORATORY MEASUREMENTS OF OLIVINE DUCTILITY TO THE EARTH - STRENGTHS AND WEAKNESSES

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Laboratory studies of the ductility of olivine-rich rocks cannot at present be easily used to develop a quantitative understanding of natural deformations. This is so both because of limitations inherent in the experimental technique and because of problems in generalising laboratory results on fairly simple systems to the diversity of natural deformations.

Specific issues to be discussed include: the dichotomy in strain rates between laboratory and natural deformations, the relatively high stresses used in most laboratory experiments, the restricted stress geometries used in the laboratory, the much coarser grain sizes and the anisotropy which characterise natural olivine tectonites, the influence of variations in important chemical parameters such as pO_2 and pH_2O in the earth, the likely effect of small amounts of melt, and the important contributions to the overall ductility of ultrabasic rocks arising from the presence of minerals other than olivine.

The importance of these factors will be illustrated by presenting a number of attempted extrapolations and by analysing their relevance and limitations.

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CRUSTAL STRENGTH AND ITS RELATIONSHIP TO WATER FUGACITY

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Recent experimental results show that the defects important in the hydrolytic weakening of quartz are hydrogen and oxygen interstitials. Their concentration depends on the neutrality condition operative during their incorporation into the quartz structure and, when this condition is satisfied by $[H_i^{\bullet}] = 2[O_p^{''}]$ or by $[H_i^{\bullet}] = 4[V_{Si}^{''''}]$, $O_p^{''}$ is the rate controlling defect. This information is inferred from diffusion experiments on single crystals of dry natural quartz at 1.64 GPa confining pressure and 800°C and at controlled thermodynamic conditions providing a range in oxygen fugacity, fO_2, of 28 orders of magnitude and in water fugacity, fH_2O, of 5 orders of magnitude.

Creep experiments conducted under similar experimental conditions and at a differential stress of 435 MPa show further that the strain rate for such quartz crystals loaded in the 1 m orientation varies as $fH_2O^{1/3}$, consistent with the defect analysis from the diffusion experiments. This information may then be incorporated within a flow law for extrapolation to different conditions of P and T using a power law of the form $\dot{\varepsilon} = A.\sigma^n.\exp(-Q/RT)$ in which A may be represented by $A'.(fH_2O)^{1/3}$. A' is now constant for all P and T and can be determined from experiments in which A is calculated. However A and therefore $\dot{\varepsilon}$ are now both pressure as well as temperature dependent through the dependence on fH_2O. For example, using a power law for "wet" quartzite (Koch et al., 1980; Koch, 1983) for which A is 5.05 E-6 ($MPa^{-2.61}.s^{-1}$), n is 2.61 and Q is 145 ($kJ.mol^{-1}$), and using the Ni-NiO solid oxygen buffer for correlation at 1.65 GPa confining pressure and 800°C, A' = 2.65×10^{-7} ($MPa^{-2.94}s^{-1}$). Thus, for a constant differential stress of 100 MPa at 500°C, nd conditions buffered by Ni, or close to the quartz-fayalite-magnetite buffer, quartz will creep at 2.50×10^{-11} s^{-1} at a confining pressure of 100 MPa, or will creep almost 3 times faster, at $6.81 \times 10^{-11} s^{-1}$, at a confining pressure of 1 000 MPa. The aim of this paper is to investigate creep rates for a variety of crustal conditions (including in particular those situations where the crustal fluids are CO_2-rich rather than H_2O-rich) and to examine the implications for deformation mechanism changes within the range covered. It is clear from the above discussion that increases in pressure as well as in temperature will increase the creep rate for a given stress provided H_2O is present. A specific example is provided for a crustal scale water-bearing shear zone in quartz rich rocks where it is shown that incorporation of the water weakening effect into the constitutive law for creep leads to rapid detachment of the shear zone material from the surrounding rocks at amphibolite facies conditions followed by an overall strengthening of the zone at greater depths where granulite facies conditions exist. These changes in strength are expected to be associated with systematic changes in the width of the shear zone with depth;

such changes would be of a different character to those postulated by Sibson (1981).

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ANISOTROPY; ITS EFFECT ON PREDICTING DEFORMATIONS

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In order to be able to predict deformations a relation between applied load and consequent deformation must be defined. This is readily done if the assumptions of infinitesimal deformation, isotropy, homogeneity, and elasticity are made. If, however, any one of these criteria is not satisfied the predictive process is suspect. Homogeneity can generally be accounted for by zoning, while elasticity is treated as a monotonic linear relation. Infinitesimal elasticity can be satisfied in the initial stages of the loading process as valid; that is, it is the starting point of the deformational process. This leaves the assumption of anisotropy. Here, because of the advent of computers, a more thorough definition of anisotropy is required. This definition should incorporate all the deformational mechanisms related to the resultant deformation. By considering a combination of some simple deformational models the anisotropy definitions are examined and their effect on the deformational process considered.

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PRECISE GEODETIC MEASUREMENT OF CRUSTAL DEFORMATION

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Direct geodetic measurement of present-day crustal strain rates will provide real-earth data to test geodynamic models proposed during rheological studies.

Three techniques have the precision necessary to measure inter-plate deformations; all involve measurements to extra-terrestrial bodies and are at the leading edge of space technology. The three techniques are Very Long Baseline Radio Interferometry (VLBI), Laser Ranging including both Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR), and presice use of the Global Positioning System (GPS).

VLBI, SLR and LLR have been successfully used to determine the Earth's pole position, length of day and geodetic baselines, and the variations in each of these which have implications for rheological research. Accuracies already obtained are 2 milliaresec (6 cm on the ground) for pole position, 0.1 millisecond for length of day and a few centimetres down to a few millimetres for baselines of thousands down to hundreds of kilometres in length. GPS already has the capability of giving centimetric accuracy for relative station positions using lightweight mobile equipment. Development of GPS to millimetric accuracy can be safely forecast.

Australia is only partly in a position to take advantage of these new techniques. Major investments have established multi-purpose observatories which can provide the base station data needed for the first two techniques. Mobile VLBI and SLR receivers could be obtained at substantial cost and used to measure inter-plate and primary intra-plate baselines. These two techniques are quite independent and provide a realistic check on measurement accuracy. Base stations for GPS measurements could be set up at existing facilities at a lower but still substantial, cost. There is no doubt that GPS will be very widely used by surveyors and by thematic mappers, including the oil and mineral exploration industry. The proposed base stations would benefit that community as well as enabling the higher precision needed for geodetic and geophysical research. Some mobile GPS receivers are already in use for navigation and surveying in Australia, and some are of the types which give the signal data needed for high precision positioning. Several centres are well advanced in development of software to reduce, analyse and apply GPS measurements. Many more GPS receivers will be acquired as the present high cost/receiver reduces dramatically over the next few years.

A report 'Geodetic measurements of crustal deformation in the Australian region' prepared for the Australian Academy of Science has been forwarded to ASTEC and relevant Ministers and opposition spokesmen. It is hoped that at least some of the report's recommendations will be accepted and funded by government.

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GEOMORPHIC CONSTRAINTS ON TECTONIC HYPOPOTHESES

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The effects of tectonic activity are often directly observable at the ground surface, but this primary information is too often subservient to secondary information (gravity, heat flow, seismic data), and even to ruling theory (subduction, compression). Several examples will be used to illustrate the application of geomorphology in tectonics.

1. Geomorphology of passive margins. Elementary plate tectonics suggests that mountains are associated with uplift caused by subduction. But many mountains (Eastern Highlands of Australia, Western Ghats, Drakensberg, etc.) are on passive margins. Many special-case explanations have been offered for these (response to glacial loading, migration over hot spots, basalt intrusion, earlier subduction), but world-wide similarities in major geomorphic features (high plateaus, Great Escarpments) as well as the common tectonic setting suggests that a single mechanism may be responsible for uplift.

2. Erosional tectonics. Some tectonic effects result from gravitational response to erosion, not endogenic forces. Failure to understand this can lead to the invoking of phantom tectonic forces. Examples include folded thrust faults in the Himalayas, and folding in the Dolomites of Italy.

3. Major features of the earth's drainage are old, often pre-dating major tectonic movements (including continental drift). Interpretation of drainage patterns can sometimes afford insight into tectonic processes, and assist in choice between alternative tectonic hypotheses. Examples include the drainage of Lake Victoria and the rift valleys of East Africa, and the drainage of the Zagros mountains of Iran.

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MICROEARTHQUAKES AND THE RHEOLOGY OF THE LITHOSPHERE UNDER NEW ZEALAND

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The tectonic styles of New Zealand range from subduction to continental collision and the continental and oceanic lithospheres are deformed in a variety of ways. Micro-earthquakes are being used to study the state of stress and the rheology of various regions, though the interpretation may not be unique.

Note firstly that microearthquakes appear to be brittle, frictional phenomena, where elastic energy stored in the stressed rock is released suddenly by rapid movement along a fault or faults, For earthquakes to occur then, two features must be present - the absence of ductility so that the elastic energy may be accummulated for friction-failure release and a deviatoric stress field of sufficient magnitude. The absence of microearthquakes implies that one or both of these two features is not present.

Over the last few years accurate hypocentre data has been obtained from a number of permanent and temporary arrays of seismometers in New Zealand. A precise three dimensional picture of the microseismicity of the region is beginning to emerge in place of the previous hazy picture, caused by lack of resolution of the networks and station spacings previously used.

We are now interpreting the pattern of the observed microseismicity in the light of recent work by Chen and Molnar (1983) and Sibson (1983). In continental areas the micro-earthquakes principally occur in the upper crust and occasionally just below the Moho - indicating that the lower crust and lower lithosphere is ductile or quasi-plastic. In some areas however the micro-earthquake activity occurs within the lower crust indicating perhaps lower than usual temperatures at these depths and hence a depression of the boundary between frictional and quasi-plastic behaviour (e.g., Ansell, Aspinall, King and Westaway, 1985). Not all of the deep activity may be explained in this way however and further explanations are being sought. There is also an indication that micro-seismicity in the upper mantle may be correlated with higher P_n values and lower attenuation (high Q).

The microseismicity within the subducting oceanic lithosphere similarly may be interpeted in terms of its rheology and state of stress. The "elastic" thickness of the plate, which is about 100 myr old, appears to be between 50 and 75km. The

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compressional stress due to the bending of the plate seems to be matched by the down dip tension caused by the "pull" of the previously subducted slab.

The interpretation of the microseismicity in terms of rheology and stress leads to an interesting picture, but a number of ambiguities remain unresolved.

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THERMO-MECHANICAL MODELLING OF THE EARTH'S CRUST

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Most published work aimed at modelling the history of P and T in the crust (so called P-T-t paths) are one dimensional and are based on analytical solutions to classical heat flow equations. In order to introduce a little more geological reality into such modelling we are examining two dimensional situations in which the history of P and T is tracked during geologically realistic loading and heating sequences. A particularly important geological situation, common in metamorphic terrains is being modelled in which a thrust block containing hot mafic granulites rapidly over-rides amphibolite and greenschist facies rocks. The analysis allows the tracking through time of pressure and temperature distributions at specific sites within the crust.

The modelling is being carried out using the finite element codes ADINA and ADINAT. The program ADINA enables a gravity loaded crust to be subjected to geologically realistic non-hydrostatic stresses and to be modelled as an elastic material, as an elastic-plastic material or as an elasto-viscous material in which creep is important. Large strains are possible with a number of yield criteria available including Mohr-Couloub, von Mises and Drucker-Prager. ADINAT couples with ADINA and enables a thermal history to be programmed or followed with prescribed distributions of thermal conductivities (including anisotropic), boundary heat sources and sinks and internal heat generation sources. In addition, "birth" and "death" options are available for individual elements in both codes so that we can model erosion of elevated rock masses in a relatively simple manner. We are examining situations where the relative rates of crustal thickening, erosion, isostatic adjustment, and stress relaxation due to creep vary within geologically realistic limits so as to arrive at (i) a range of possible
P-T-t paths and (ii) the ways in which these P-T-t paths are both spatially and chronologically superimposed and related. This modelling enables a far wider range of metamorphic conditions to be simulated than those arrived at by one dimensional analytical solutions. In particular some surprising situations are revealed such as the presence of broad domes in isobars deep in the crust due to thrusting of relatively dense mafic granulites over less dense granitic gneisses and sediments. The precise location and nature of these pressure gradients would not have been suspected without computer modelling, for instance, the steepest pressure gradients tend to be in the overthrust block - a situation which would not have been suspected a priori.

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TILTED BLOCK BASINS OF THE UNITED STATES ROCKY MOUNTAINS FORELAND

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The foreland region of the American Rocky Mountains was deformed during the Laramide Orogeny to produce a number of basement uplifts and sedimentary basins. One well-studied example is the Wind River Mountains and Wind River Basin of southwestern Wyoming. The uplifts and basins are thought to result from the tilting of large, fault-bounded blocks, but there is disagreement as to whether tilting is driven by vertical forces or horizontal compressive forces. The intracratonic position and general features of these basins are similar to those of central Australia and the model presented for their formation may also be applicable to their Australian counterparts.

An elastic plate, representing the upper, strong part of the lithosphere, is cut by one or more planar faults. Fixed horizontal displacements are applied to the ends of the plate causing tilting and flexure of the model blocks. Buoyancy effects of the underlying ductile lithosphere and loading effects of sediment erosion are included.

Conclusions are: 1) Horizontal stresses of 100-200 MPa available from plate tectonics are sufficient to produce the observed basins and uplifts; 2) Fault dips do not significantly affect the geometry of the basins and uplifts but do affect the required driving stresses; 3) A combination of low dip 30°-40° thrust faults and high angle reverse faults, >45°, offers the best explanation of the observations; 4) Gravity anomalies suggest no major offset of the Moho; 5) The tilting was probably preceded by the development of large-scale anticlines and synclines, suggesting that the faults propagated from depth to the surface and that they either die out in the ductile zone at depth or are splays from detachment horizons.

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ON THE DEPTH-DEPENDENT RHEOLOGY OF THE CONTINENTAL LITHOSPHERE

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It has recently become popular to derive specific depth-dependent rheological models for the crust and upper mantle, and to use them to interpret such features as the depth distribution of seismicity and the mechanical response of oceanic and continental lithosphere. These models are generally derived from laboratory rheological data on rocks and minerals in both the brittle and ductile fields.

In our view, all of the models to date are open to criticism, and may substantially misrepresent the rheology of continental lithosphere in particular. The fault of the models lies primarily in uncritical use of the laboratory data, particularly in the ductile regime. We will review the body of laboratory data on quartz to illustrate the primitive state of our understanding of the rheology of crustal materials in the simplest mechanism field, that of crystal plasticity. The rheology of the quartz-poor lower crust is particularly poorly understood. Further, microstructural studies of deformed rocks in a range of crustal environments demonstrate that ductile flow mechanisms much more complex than crystal plasticity may be deformation rate controlling. Virtually nothing is known of the rheological consequences of such mechansims.

Finally we will suggest what can be inferred about the depth-dependent rheology of the continental lithosphere from a combination of laboratory data and studies of naturally deformed rocks. Smaller contrasts in strength are predicted between the lower crust and upper mantle, and the depth and stress level of the brittle-ductile transition are strongly dependent on pore fluid behaviour in the deformation zone. These concepts are applied to depth distribution of seismicity.

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CONSTRAINTS ON LITHOSPHERIC RHEOLOGY FROM THE DEVELOPMENT OF BASINS, ARCHES AND DOMES IN THE EASTERN INTERIOR OF NORTH AMERICA

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The broad arches and domes separating the Michigan and Illinois basins from the Appalachian basin are the result of the superposition of the flexurally induced peripheral bulges of these basins. During the Paleozoic Taconian, Acadian, and Alleghanian orogenies overthrusts in the Appalachian orogen depressed the adjacent Appalachian basin and drove its peripheral bulge to the west. During quiescent periods between the orogenies the peripheral bulge migrated back to the east to the present position of the arches and domes. This behaviour is recorded in the stratigraphy of the region.

A comparison of elastic, uniform viscoelastic, and thermally activated viscoelestic models of lithospheric flexure shows that the stratigraphy of the region is best reproduced by a model that allows limited stress relaxation. The observations require the effective elastic thickness of the lithosphere to be 200 km when first loaded but to decrease to 60 km after 200 Ma. The thermally activated viscoelastic model can reproduce this behaviour by the combination of a reasonable continental geotherm with an effective activation energy for creep of 240 ± 25 kJ/mol.

Constraints on the depth-averaged rheology of the continental lithosphere obtained from numerical modelling of continental collision.

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On a sufficiently large horizontal length scale (200 km more or less) the heterogeneities of the upper crust can be ignored and the lithosphere seems to behave approximately as a thin viscous sheet (England and McKenzie, 1983). In this approximation each column of the lithosphere is considered to translate coherently and to undergo thickening or thinning; the strain rate components vary in the horizontal directions, but are independent of depth, while the stresses are considered to be averages over the thickness of the lithosphere.

Because the lithosphere is clearly stratified with respect to temperature, and with respect to composition (the Moho being the most important compositional boundary), most rheological models of the lithosphere show a strongly stratified stress profile also. Because the various deformation mechanisms depend strongly on temperature and/or pressure, typical rheological models show that deviatoric stresses are supported mainly by one or two strong sub-layers within the lithosphere - usually the upper crust and/or the upper mantle (e.g. Brace and Kohlstedt, 1980).

The continental collision models described here provide constraints on the effective vertically - averaged lithosphere rheology under rather general conditions of horizontal compression. These constraints are consistent with a rheological stratification in which most of the horizontal deviatoric stress is supported partly by a brittle upper crustal layer and partly by a deeper ductile layer with non-linear rheology (e.g. olivine upper mantle).

The model consists of a thin viscous sheet within rectangular borders on which the velocity is defined. On most of the boundaries the velocity is zero, but one segment of the boundary is indented at a constant rate. Everywhere within the viscous sheet the deviatoric stress, τ_{ij}, is related to the strain rate, $\dot{\varepsilon}_{ij}$, by:

$$\tau_{ij} = B\,\dot{E}^{(1/n-1)}\,\dot{\varepsilon}_{ij}$$

where B is a constant which incorporates the vertical stratification and the temperature dependence of the lithosphere rheology, and $\dot{E}$ is the second invariant of the strain rate tensor. Laboratory measurements show that the power-law index, n, is approximately 3 for dislocation creep in olivine, but it is treated as an unknown in this work.

The force balance equations are solved using the finite element method to obtain the strain rate distribution everywhere in the region, and hence the rate of crustal thickening or thinning:

$$\frac{1}{S}\frac{\partial S}{\partial t} = -(\dot{\varepsilon}_{xx} + \dot{\varepsilon}_{yy})$$

As the solution evolves with time, the resulting gradients of crustal thickness cause internal body forces which resist continued thickening or thinning. The relative importance of the body forces is determined by a dimensionless number known as the Argand number, Ar, which is the ratio of the gravitational body force resulting from a crustal thickness contrast of order L, to the viscous stresses necessary to produced strain rates of order U_o/L, where

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U_0 is the indenter velocity.

The deformation fields (crustal thickness, strain rate, rotation etc.) have been calculated for different values of n and Ar, for comparison with observations in Central Asia. Acceptable agreement with the present day observations of crustal thickness and strain-rate distributions is obtained for n in the range 3 to 10. For n = 3, Ar is in the range 1 to 3 and for n = 10, Ar is in the range 3 to 10. In fact excellent agreement with the observed structural elements of Central Asia is obtained by the inclusion in the model of a lithospheric strength heterogeneity representing an unusually strong Tarim Basin block (England and Houseman, 1985) and the addition of an arcuate indenter which rotates anticlockwise as it moves northward. However the basic length scale of the deformation is determined by the parameters n and Ar and the width of the indenter (England, Houseman and Sonder, 1985).

A power-law exponent of 3 would be consistent with most of the lithospheric stress being supported by a ductile layer such as the predominantly olivine upper mantle. However, a higher exponent would be expected if a significant proportion of the stress is supported by a layer in which the deformation mechanism is low temperature plasticity or brittle failure. Values of n = 10 or greater could be explained in this way.

The constraints on Ar provide a scale factor which give an estimate of the depth-averaged deviatoric stress for a given strain rate. The maximum vertically averaged deviatoric stress (which occurs in the Tarim Basin) in the most realistic models is of the order of 100 to 150 MPa. The peak deviatoric stresses are probably several times larger.

Although strain rates in a rigid block such as the Tarim Basin may be negligible if the constant B is significantly greater within the block (a factor of 2 to 10 is sufficient) the depth averaged deviatoric stresses are only slightly greater than in the absence of the heterogeneity, because of the strong non-linearity of the rheology.

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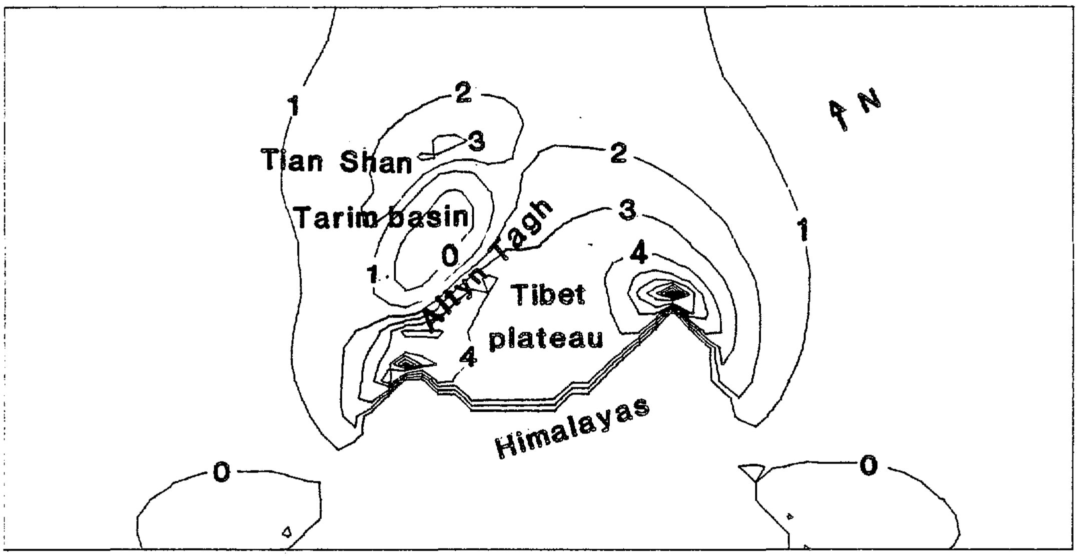

Topographic elevation contours (in km) in Central Asia predicted by the model with n = 3 and Ar = 3. Initial crustal thickness was a uniform 35 km and the indenter has rotated 15° as it moved in at an average rate of 5 cm/yr for 40 Ma.

A RHEOLOGICAL MODEL OF THE NORTHERN CANNING BASIN

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The aim of the paper is to corroborate observed rheological parameters with geological and geophysical basin analysis. The geometry of Devonian to permian sediments in the northern Canning Basin suggests that the lithosphere behaved as an elastic plate during deposition. The following values of rheological parameters were obtained by modelling the basin geometry:

a) <u>DEVONIAN - LOWER CARBONIFEROUS</u>

flexural parameter	=	31.8 km
elastic thickness	=	11.4 km
flexural rigidity	=	7.9×10^{28} dyne cm

b) <u>LATE CARBONIFEROUS - PERMIAN</u>

flexural parameter	=	64 km
elastic thickness	=	29 km
flexural rigidity	=	1.3×10^{30} dyne cm

The Laurel seismic relector (approximately 340 Ma) was used to model Devonian - Lower Carboniferous geometry. The top Grant seismic reflector (approximately 280 Ma) was used to model the Late Carboniferous - Permian geometry.

The Devonian and Lower Carboniferous data are similar to the Basin and Range Province (Walcott, 1970) and young oceanic crust (Watts & Ribe, 1984) data. The Late Carboniferous and Permian data are more consistent with flexure of intracratonic basins during formation. The Devonian and Lower Carboniferous data indicate an anomalously thin lithosphere. The anomaly may result from either (i) an abnormally hot lithosphere or (ii) the assumption of an incorrect rheological model.

Basin analysis suggests that (i) the elastic plate model appears to be valid, and (ii) the lithosphere during the Devonian and Lower Carboniferous was subject to heating. Results of the basin analysis are listed below.

a) Seismic reflection data suggest a flexured hinge line between the Lennard Shelf and Fitzroy Trough with growth faulting of the basin sediments;

b) Structures with large magnetic and gravity anomalies in the axis of the Fitzroy Trough show syndepositional growth during the Devonian and Lower Carboniferous;

c) The large gravity and magnetic anomaly near Grant Range is interpreted as due to a mafic igneous body with a radius of about 10 km, extending from 10 km depth to 25 km depth.

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d) The Grant Range magnetic anomaly appears to have significant remanent magnetism - the direction and magnitude of the remanent magnetism (modelled assuming a magnetic susceptibility of 0.012 SI units) gives a palaeolatitude of 11°S; this palaeolatitude coincided with the Kimberley Region of W.A. during the Devonian and Early Carboniferous;

e) There are strong similarities in tectonic evolution between the Northern Canning Basin and the Benue Trough (Adighije, 1981), a west African aulacogen; the similarities include (i) axial gabbroic intrusions, (ii) basin dimensions (length, width and thickness of sedimentary fill), (iii) early doming of the lithosphere and (iv) lead-zinc mineralization.

Rheological data, at present, appears to indicate that the lithosphere of the northern Canning Basin was thickening during the Late Palaeozoic after a failed rifting event in the Silurian - Devonian.

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CRUSTAL AND UPPER-MANTLE LATERAL HETEROGENEITY: THEORETICAL AND OBSERVATIONAL ASPECTS

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Although the use of horizontally stratified models has provided a convenient framework for the understanding of many seismic wave phenomena, further development is needed for studying the laterally heterogeneous Earth. We can retain the convenience of physical interpretation provided by working with the reflection and transmission properties of the medium, but include the effect of lateral variations by introducing mixing of wavenumber components. A wide variety of phenomena can be simulated by varying the size and character of the cross-coupling between different wavenumber components as needed to describe the nature of different types of heterogeneity.

Such an approach allows a quantitative study of the degradation of the major seismic phases, as compared to the predictions for stratified models, and also the characterisation of the codas of these phases. The effects of crustal and upper mantle heterogeneity are most apparent in short period recordings at regional ranges, and are clearly seen in the complex records of events from Indonesia and New Guinea at stations in Central Australia. Comparison of the observations with synthetic seismograms, including the effects of heterogeneity, allows us to begin to estimate the scales and size of the lateral variations in seismic properties.

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SEISMIC REFLECTION TOMOGRAPHY

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Tomographic methods show considerable promise for the delineation of seismic velocity distributions in regions where there is good data coverage. In this application, the travel times of waves reflected from a buried surface are inverted to attempt to recover the velocity distribution in the region above the reflector and the shape of the surface. In the case of a fixed shape of surface a non-linear approach based on a modified steepest descent algorithm gives good results in a reasonable number of iterations. If the velocity field is known similarly good results can be found for the shape of the surface. However the joint inverse problems of finding both the velocity distribution and the shape of the surface presents much greater difficulties, at the very least more dense data coverage is required and some a priori assumptions as to the class of possible solutions may be needed to regularise the solution.

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DETERMINATION OF EARTHQUAKE FOCAL MECHANISMS AND CRUSTAL STRUCTURE IN EASTERN AUSTRALIA USING SURFACE WAVES

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Surface waves from the 1966 Mt Hotham and 1982 Wonnangatta earthquakes were examined to determine average S-wave crustal structure for the region and the focal mechanisms of the two earthquakes. The S-wave models were determined from an analysis of the group velocities of the Rayleigh waves. For all paths a two- layer crust overlying a Moho at about 40 km was required to fit the observations. In the upper layer, down to about 25 km, the velocity gradients are very small and the S-wave velocities are in the range 3.4-3.6 km/s.

In the lower crust the S-wave velocities increase gradually to about 4.6 km/s at the Moho where the velocity gradients are again very small. The region where the S-wave velocities increase significantly with depth corresponds to the region of the lower crust which generates strong seismic reflections (Mathur, 1983). The thin crust postulated beneath Bass Strait and Tasmania by Johnson, (1973) is not substantiated by these data and a crustal thickness of about 40 km is also required for this region. For the longer profiles (~1800 km) to the north and northwest of the earthquakes, the velocity step at the Moho is smaller than for the shorter profiles (~ 700 km). However, because the surface waves are less dispersed for the shorter profiles the resolution is poorer and the models less reliable. For the 1982 Wonnangatta earthquake the surface-wave synthetics from a focal mechanism similar to that obtained by Denham et al. (1985) fit the observations at five regional stations very well, and confirm the northwest-southeast compressive stress regime found by other workers.

However, for the 1966 Mt Hotham earthquake the surface wave synthetics generated from the normal faulting solution, which was obtained from an analysis of P-wave first motions (Denham et al., 1985), do not agree with the Rayleigh wave-trains observed at Australian stations. Rather, the surface wave observations support a thrust fault type mechanism with the pressure axis having a similar direction to that obtained from the 1982 Wonnangatta earthquake and other earthquakes in the region.

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THE LITHOSPHERE IN VICTORIA AS OBTAINED FROM INVERSION OF EARTHQUAKE BODY WAVES

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Relatively simple models of the lithosphere in Victoria are required by the Seismology Research Centre at Phillip Institute of Technology for the location of earthquakes within the state. A secondary use of such models is to determine the properties of the lithosphere. Models with only a few layers (i.e. two to ten) with constant P and S seismic velocities are used and discontinuous velocity-depth functions are adequate for this purpose.

A review of previous seismic models for the area shows their development. In the 1950's the first local models were developed containing one layer over a half-space. It was not until the 1970's that more complex models were developed. These contained a few layers over a half-space and some had layers with velocity gradients.

Most models were developed using recordings from large blasts at quarries or construction sites. These were recorded by a number of seismographs at various distances. In some cases large explosions have been detonated specifically for this purpose. The disadvantages of using blast data are that blast locations are not well distributed across the area to be modelled, are all at the surface, and most are not large enough to be well recorded over long distances. To overcome these limitations, data from naturally occurring earthquakes were added to that from blasts. Earthquakes occur at various depths, can be selected uniformly over the area, and are often larger than blasts. The disadvantage is that the precise location of the earthquake is not known, so additional parameters must be added to the model. Only events which have been recorded on a nearby seismograph should be used.

The modelling was performed using a non-linear least squares method of joint hypocentre and model determination. In 1980 a four layer model, VIC4A, was developed using this technique and has been used since then for locating all Victorian earthquakes. Recently a five layer, constant velocity, horizontal interface model VIC5A was developed. This used about 450 arrival times from seismographs in Victoria, New South Wales, the A.C.T. and Tasmania from 20 events. Most of the arrivals used, at least initially, were first P or first S phases since these are the least ambiguous. The inversion program written is quite efficient and each iteration of such a model, which has about 100 parameters, takes around 15 seconds CPU time on a VAX 11/780.

The VIC5a model has a number of interesting features which are an extension of those found in VIC4A. It has very low lower crustal velocities and relatively low upper mantle velocities. The Poisson (and Vp/Vs) ratios increase with depth, from 0.20 in the surface sedimentary layer to 0.26 in the upper mantle.

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STRUCTURE OF THE UPPER MANTLE BENEATH THE CORAL AND TASMAN SEAS, AS OBTAINED FROM GROUP AND PHASE VELOCITIES OF RAYLEIGH WAVES

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Group and phase velocities for Rayleigh waves, in the period range 15-100s, were analysed for paths crossing the Coral and Tasman Seas. We used data from 14 earthquakes recorded at the six WWSSSs, CTA, HNR, PMG, RIV, TAU and WEL. By fixing the S-wave velocities at 4.65 km/s from 220 to 400 km and at 5.0 km/s for greater depths (from the PREM), we modelled the upper 220 km. As previous workers have found for oceanic regions, it was necessary to incorporate a significant low velocity layer (LVL), usually centered at about 150 km, in all models. Typically the lid above the LVL has an S-wave velocity of 4.5 km/s, the LVL a velocity of 4.25 km/s and the velocities were determined to a precision of ±0.05 km/s.

Although the resolution of the models obtained precludes the determination of detailed earth structure, the observations suggest that the thickness of the lid varies significantly between the 'oceanic' and 'plateaux' regions of Coral and Tasman Seas. It was found to be significantly thicker beneath the Norfolk Ridge (90 km) and the Lord Howe Rise (85 km) than it is beneath the New Caledonia Basin (45 km), the Coral Sea (60 km), and the Tasman Basin (65 km). The lid/LVL boundary is determined to within ±10 km.

THE STABILITY OF FRICTIONAL SLIDING AND EARTHQUAKE MECHANISMS

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Classical views of the mechanisms of shallow earthquakes involve the shear failure of asperities on the sliding surface and/or the decrease in shear stress associated with a change from a "static" to a "dynamic" coefficient of friction. In this paper such mechanisms are viewed as one end of a spectrum of possible combinations of mechanisms. The other end of the spectrum encompasses the inherent instability that exists in the sliding of multiple spring-block systems. The first part of this paper involves an analysis of such instabilities using constitutive laws for sliding developed by Dieterich and Ruina modified by recent experimental data on the time and velocity dependence of the coefficient of friction. Inherent in such constitutive laws are length scales which govern the response of shear stress to changes in velocity and in normal stress. A basic problem in the past has been to scale these characteristic lengths from laboratory size experiments up to those sizes associated with earthquake events. Recent experiments by us on large natural joint surfaces combined with a consideration of the fractal geometry of natural joints and faults enables scaling of the characteristic lengths involved in the constitutive laws so that instabilities with the character of natural earthquake events can be modelled. The second part of this paper involves the modelling of realistic fault geometries using a hybrid distinct-element, boundary element code. Detailed fault geometries may be taken into account including dilational jogs and asperities. Realistic constitutive laws may also be incorporated including the elastic properties of the crust, Mohr-Coulomb behaviour of individual surfaces, the normal and shear stiffnesses of joints and faults and velocity dependent constitutive frictional laws. Such models are used to show the ways in which earthquake instabilities develop and to discuss the fractal "geometry" of such instabilities in shear-stress, velocity, displacement space. The fractal geometry of such plots enables precise statements about the recurrent times of earthquake events to be made and indicates the way in which a systematic search for precursor events may be made.

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THE TASMAN SEA EARTHQUAKE OF 25 NOVEMBER 1983 AND STRESS IN THE AUSTRALIAN PLATE

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The Tasman Sea earthquake of 25 November 1983 was large enough ($M_0 \approx 1.1 \times 10^{18}$ Nm) to be recorded world-wide and provide information on the state of intraplate stress in the lithosphere beneath the Tasman Sea. The earthquake occurred under the abyssal plain at a depth of about 25 km and was associated with almost pure dip-slip faulting. The direction of the pressure axis of the focal mechanism is similar (139 degrees E of N) to those obtained from earthquakes occurring in the nearby Australian continent and from breakout directions in boreholes drilled in the Gippsland Basin. Hence both the oceanic Tasman Sea and continental Australia appear to be part of the same stress regime. However, the direction of stress in this part of the Australian plate does not coincide with the north-south direction of motion of the plate and therefore forces other than the ridge push must be invoked to generate the stresses observed.

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HISTORICAL OVERVIEW OF THE SEISMICITY OF THE SOUTHWEST SEISMIC ZONE

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The Southwest Seismic Zone is a zone of seismic activity cutting across the south-west corner of Western Australia. The main zone of activity is approximately 650 km long by 160 km wide, covering an area of 100,000 sq km. The zone traverses the south-west corner of the Precambrian shield. Its long axis runs north-northwest, parallel to the general structural trend of the southwest province of the Yilgarn Block.

There is evidence from research carried out by Everingham and Tilbury (1972) that the southwest seismic zone has been active from at least early in the history of settlement of Western Australia. Newspaper reports from as early as 1849 indicate activity in the zone.

The discovery of old fault scarps at Lort River to the south, Hyden to the east and Mt Narryer to the north point to a longer history of significant activity. These fault scarps are similar in character to the recent scarps produced at Meckering (1968), Calingiri (1970) and Cadoux (1979).

Instrumental recording of earthquakes commenced at the Perth Observatory in 1904 and continued through to 1960. All but a few of the Milne seismograms for the period 1904 to 1922 are missing. Everingham and Tilbury (1972) examined Milne Shaw seismograms from 1923-1960. Using recent experience they were able to locate sixteen earthquakes in the zone between the period 1940-1960. A vertical component Willmore seismograph was operated at Watheroo from 31 March 1958 to 12 January 1959. Eighteen earthquakes were recorded from the zone during that period. Although instrumentation was limited it seems unlikely that any earthquakes of magnitude ML > 4.5 that had occurred in the zone would have gone undetected.

The installation of a 3-component short-period Benioff seismograph at Mundaring in July 1959 heralded the era of improved instrumentation of the zone. A second station was installed at Narrogin in May 1976. The early 1980's saw an expansion in station coverage with seismographs being installed at Kellerberrin (1981), Ballidu (1982), Rocky Gully (1983) and Morawa (1984).

It is now possible to locate magnitude ML = 2 earthquakes over 90% of the zone. Magnitude ML = 1 earthquakes can be detected over 90% of the zone. The extreme south-eastern corner of the zone is the area of deficiency in both cases.

Prior to the 1968 Meckering earthquake there were only 12 earthquakes of magnitude ML > 4.5 located in the zone. In the 17 years since 1968 there have been 18, including major earthquakes located at Meckering (1968), ML = 7; Calingiri (1970), ML = 6; and Cadoux (1979), ML = 6.2. This represents a significant increase in the level of seismic activity.

Since the establishment of the Mundaring Observatory nearly 2000 earthquakes have been located in the zone. Currently in excess of 500 earthquakes of magnitude ML > 1 are being detected annually.

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CRUSTAL STRUCTURE IN THE SOUTHWEST SEISMIC ZONE, WESTERN AUSTRALIA

by

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The Bureau of Mineral Resources, the Western Australian Institute of Technology and the Geological Survey of Western Australia undertook a seismic refraction survey of the southwest part of the Yilgarn Craton late in 1983. The aims of the survey were to develop crustal models of the region as an aid to the accurate location of the earthquakes which occur throughout the region, and to further studies of Archaean crustal evolution. Two seismic refraction profiles were recorded. One trended northwest/southeast, approximately parallel and adjacent to the boundary between the Western Gneiss Belt and the Southern Cross Provinces. This line also transected the region where most of the recent seismic activity has occurred. It was bisected by the second line which trended northeast/ southwest and was oriented approximately at right angles to the regional geological strike.

The results reveal that the crust over the southern part of the block is two-layered and is typical of most Archaean terranes. Velocities, and therefore rock densities, in the near-surface rocks increase abruptly towards the southwest. Gravity data were used to map the strike of the abrupt density change. It trends NNW and lies along the western edge of the Southwest Seismic Zone. We propose a tectonic model for the region in which the southwest corner of the Yilgarn Block has been uplifted recently. The uplift is consistent with erosion patterns in the river valleys and the exposure of granulite facies rocks in the area.

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VERTICAL GROUND MOVEMENT FROM REPEAT LEVELLING AND GRAVITY MEASUREMENTS, SOUTHWEST SEISMIC ZONE, WESTERN AUSTRALIA

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A program of repeat levelling and repeat gravity measurement has been carried out in the Southwest Seismic Zone. There are several objectives to the program: first, to confirm that there is a correlation between the areas of small earthquakes, and areas of greater ground movement - as an independant check of the areas with the greatest risk of large earthquakes; secondly to investigate the pattern of ground movement at the time of larger earthquakes, in order to investigate the large earthquake's cause and mechanism: thirdly to localize areas of greatest ground movement so that continuous recording instrumentation could be installed.

Levelling observations in the earthquake zone have been made during four time periods: 1) 1958 to the time of the Meckering Earthquake of 1968. 2) levelling mainly after the Meckering Earthquake, 3) 1977 levelling in a small area near Meckering Earthquake Fault, and 4) 1981-1983 second order levelling. Differences between the levelling measurements of the four periods can be calculated. The differences can be attributed to a combination of levelling measurement errors, geological ground movement affecting several bench marks, and movement of an individual bench mark relative to the immediate ground surface. Areas of geological ground movement can be identified either by analysis of the changes in height difference between adjacent bench marks, or by least squares adjustment of each epoch of levelling and then mapping the apparent height changes. Identified areas of ground movement characteristically have an amplitude of 100 mm or more and a wavelength of 50 km. Only some of these areas are associated with known seismic activity. Further levelling work is being carried out by the Australian Survey Office in order to more accurately locate areas of ground movement, and check whether movement is continuing. Analysis of available levelling measurements is being refined, and geological interpretation of known movements continues.

Within the earthquake zone deep bench marks have been established at 10 km intervals along the levelling traverses. Gravity observations have been made at these and adjacent bench marks at two epochs: 1980-1981 and 1983. The measurements were made with three LaCoste & Romberg gravity meters. The gravity observations were reduced by solving by least squares for gravity meter drift rates and calibration, as well as gravity values at the observation points. Assuming the mean gravity value has not changed between surveys, then the gravity change at bench marks is found to be as high as 0.6 um s-2, with an uncertainty of 0.24 um s-2 at the 95% confidence level. These gravity changes are higher than the more reliable levelling indicates, so the apparent gravity changes are likely to be measurement errors.

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INTRAPLATE STRESS AND THE 1979 CADOUX EARTHQUAKE

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The 1979 Cadoux earthquake was associated with right-lateral strike-slip displacement along a near vertical fault dipping to the east. The fault length was approximately 15 km and the maximum displacement close to one metre. The seismic moment was estimated to be $0.8 \pm 0.2 \times 10^{18}$ Nm and the earthquake was, like the 1968 Meckering earthquake, caused by east-west compressive stress in the crust.

The aftershocks of the Cadoux earthquake are still continuing at the northern and southern ends of the area affected by the main earthquake, and strain-release studies indicate that a significant strain is still to be released in the region.

Hydrofracturing and overcoring measurements confirm high stresses in the crust and indicate results consistent with those obtained from the earthquake focal mechanisms.

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TEMPORAL VARIATION IN SEISMICITY OF THE SOUTHWEST SEISMIC ZONE, WESTERN AUSTRALIA: IMPLICATIONS FOR EARTHQUAKE RISK ASSESSMENT

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In the area, 30-33°S, 116-118°E, of the Southwest Seismic Zone of Western Australia, $ML \geq 4.0$ earthquakes during the period 1960-1983 do not fit a Poisson model. However, when foreshocks and aftershocks are excluded, the hypothesis of a Poisson distribution cannot be rejected for the resulting series of main shocks.

A similar result holds for the subset of $ML \gtrsim 5.0$ events during the period 1949-1983.

Consequently, when assessing earthquake risk using methods which assume a Poisson distribution, foreshocks and aftershocks should be excluded. However, the consequent apparent reduction of risk caused by removing these potentially damaging earthquake should be pointed out.

Although records of seismicity are probably incomplete for the early part of this century, there appears to have been an increase in numbers of $ML \geq 4.0$ events starting around 1949. However, the data are too few and uncertain to test this statistically. If the apparent increase is real and not an artefact of the Poisson process, it will need to be taken into account in the interpretation of earthquake risk calculations.

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PROBABILISTIC EARTHQUAKE RISK MAPS
OF SOUTHWEST WESTERN AUSTRALIA

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New earthquake risk maps of southwest Western Australia including continental margins have been prepared. The risk is depicted as contours of peak ground velocity, acceleration and ground intensity with a 10 percent probability of being exceeded in 50 years.

These maps have been based on the "Cornell-McGuire" methodology.

Ten earthquake source zones were thus defined and corresponding recurrence relations derived. The relation obtained, using a maximum-likelihood fit, for the primary zone to the east of Perth, was, log N = 3.66-0.90 ML, where N is the number of events greater than or equal to the Richter magnitude, ML.

For the first time local attenuation constants have been derived and used in the procedure. In the expression $Y = ae^{(bML)}/R^c$, where Y is the estimated peak ground velocity (in mms^{-1}) or acceleration (in ms^{-2}) at a hypocentral distance, Rkm, from an earthquake of magnitude ML, the adopted values for corresponding constants a, b and c were 3.30, 1.04, 0.96 and 0.025, 1.10, 1.03 respectively.

The contour expressing the greatest risk in the area of interest was that of a peak ground velocity of 160 mms^{-1} and it enclosed an area of about 6000 km^2 centred on the primary source zone. The contour for Perth was 50 mms^{-1}.

Increasing (i) the maximum magnitude from ML7.5 to ML8.5; (ii) the depth of earthquake foci from 5 to 15 km; (iii) the b value from 0.90 to 0.94; and (iv) the attenuation constants to their estimated maximum value, in the primary source zone, gave rise to changing the Perth velocity contour from 50 mms^{-1} to 58 mms^{-1}, 50 mms^{-1}, 44 mms^{-1} and 60 mms^{-1} respectively. The omission of a suspected seismic gap 100 km east of Perth, from the primary source zone had the effect of changing the velocity contour from 50 mms^{-1} to 48 mms^{-1}.

We recommend a microzonation study of Perth and installation of more strong motion instruments to improve our risk estimates which should be updated in 5-10 years.

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AN AUSTRALIAN CENTRE FOR MONITORING NUCLEAR EXPLOSIONS

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Adequate and acceptable means of verification are the cornerstones of any treaty and the Conference on Disarmament has promoted the view that seismology can play a key role in the verification of a comprehensive (nuclear) test ban treaty (CTBT).

The Australian Government, as a leading proponent of that view, introduced a new program in August 1984 aimed at providing a national monitoring capability, and at contributing to international co-operative monitoring measures. The Bureau of Mineral Resources has been given the task of establishing and operating facilities to carry out this program; over the last year a new group dedicated to nuclear monitoring has begun the task - the new facility will be known as the National Seismological Monitoring Centre. While its primary function is to provide rapid information on underground nuclear explosions, the Centre will work closely with BMR's earthquake seismology section, and clearly the new resources will provide a significant increase in seismological research facilities.

In the first stage the NSMC will acquire and process signals from the array at the Joint Geological and Geophysical Research Station (JGGRS), Alice Springs which is operated by BMR and the US Air Force. The array will be upgraded and enlarged early in 1986 and the digital signals from all 22 seismometers will be sent to Canberra by a Telecom digital data service. It is intended that the signal processing will allow for automatic event-detection and waveform segmentation, beam-forming, rotation of horizontal components, and multi-channel filtering. A project to provide these capabilities is underway with the US Air Force and the Defence Advanced Research Projects Agency.

In later stages it is planned to access signals from quiet sites such as Charters Towers (Queensland), Tennant Creek (NT) and in central Western Australia. Such a network is expected to provide a very powerful monitoring capability with a detection threshold below 10 kilotons. But that is a few years into the future.

Development of an international data centre is to start in 1987 when the main computers and communications equipment have been commissioned. The prime object of this service will be to allow participation in global monitoring programs irrespective of the ratification of a CTBT. This will involve the operation of computer-computer links with overseas centres, the establishment of comprehensive data bases and associated programs. Once operating, the service will provide first class opportunities for more general research, and in principle will be available to the seismological community.

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DEPTHS AND SOURCE MECHANISMS OF EARTHQUAKES FROM THE EASTERN SUNDA ARC, INDONESIA

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The depths and fault plane solutions of 23 earth quakes from the eastern Sunda Arc (114° to 123°E) have been determined by a formal inversion of long-period P and SH waves. The region encloses the western edge of the collision between the Sunda Arc and the Australian continent. In the backarc, near Bali Island, the fault planes and hypocenters of 7 thrust events delineate a seismic zone that dips 10° to the south to a depth of 20 km. The earthquakes' trend projects northward into the Bali Basin where the sediments are gently folded, probably marking the western end of the Flores Thrust. At the eastern end of this backarc thrust zone (121.4°), two thrust events at depths of 11 and 16 km have nodal planes that dip 30° to the south. Shallow earthquakes beneath the arc itself show strike-slip mechanisms with roughly north trending compressional axes.

Beneath the forearc, shallow events (10-30 km depth) indicate low angle underthrusting and are concentrated near Sumba island. Deeper earthquakes that occur within the subducted slab (60-100 km depth) also show thrust mechanisms but with P axes that trend east-west, perpendicular to the convergent margin. Two of the deeper events occurred directly below both Sumba island and the underthrusting events.

Underthrusting earthquakes in the forearc region east of Java are concentrated near Sumba island, a continental fragment within the forearc. We suggest that the thick crust of Sumba increases the coupling between the plates thus localising seismic energy release beneath the island. The coupling between the downgoing plate and the forearc crust may also cause backarc thrusting by increasing compressive stresses across the arc. Hence the backarc thrusting (as is observed from Bali to Flores) may result from subduction of normal oceanic crust beneath an anomalously thick forearc rather than from continental collision.

DISPERSION OF LOVE WAVES ACROSS SUBDUCTION ZONES

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The phase velocities and scattering of energy into reflected and higher transmitted modes have been calculated by the finite element method for Love waves of the fundamental mode crossing at normal incidence the subduction zones under Japan and the North Island of New Zealand.

Other methods of solving the problem of the passage of Love waves across laterally varying structures were listed by Kazi (1978). Knopoff and Hudson (1964) used Kirchhoff's method to investigate the problem of Love waves past a step change in elevation; their method involved a surface integral over the vertical plane containing the step. Gregersen and Alsop (1976) extended this method to the problem of the oblique incidence of Love waves at a continental boundary. Kazi (1978) supposed the existence of two sets of eigenfunctions in terms of which the displacements on both sides of a vertical discontinuity could be expressed. In addition, he established a continuous spectrum which gave rise to improper eigenfunctions associated with the propagation of SH body waves. In later work, Bukchin and Levshin (1980) used eigenfunctions corresponding to the continuous spectrum of the Love wave operator; in addition, the method of these authors made use of finite difference approximations of displacement derivatives to find stresses on both sides of the vertical plane of discontinuity.

By means of the finite element method, dispersion curves for Love waves across the Japan and New Zealand subduction zones have been calculated for wave periods between 5 and 60 s. Comparison with phase velocity curves for the adjacent ocean and island regions shows that the phase velocity for the subduction zones is, in general, slightly less than the mean of the phase velocities of the adjacent regions. For example, at a period of 30 s the phase velocity in the model of the subduction zone under Japan is 4.309 km/s and the mean of the phase velocities in the regions at the ends of the model is 4.350 km/s; at the same period the phase velocity in the model of the subduction zone under the North Island of New Zealand is 4.124 km/s and the mean of the phase velocities at the ends of the model is 4.253 km/s.

At a period of 10 s, only 5 percent of the energy of the incident fundamental Love mode is transmitted in the fundamental mode across the model of the subduction zone under Japan; at a period of 15 s, 18 percent of the energy of the incident fundamental Love mode is transmitted in the fundamental Love mode across the model of the subduction zone under the North Island of New Zealand. Gregersen and Alsop (1976) and Drake and Bolt (1980) have found similar results for models of boundaries between oceans and continents. Energy scattering is important below periods of approximately 40 s; these periods are well below those considered in the inversion of surface waves with circumglobal paths (e.g. 135 s; Woodhouse and Dziewonski, 1984).

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MICRO-EARTHQUAKE STUDIES OF A SUBDUCTING MARGIN

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Off the east coast of the North Island of New Zealand and the northern South Island, the Pacific plate is subducting under the Indian/Australia plate to the west. This subduction zone has been marked by large historic earthquakes such as the Wellington earthquake M = 8.0 in 1855 and the Napier Earthquake M = 7.8 in 1931. However the detailed structure of the zone has been largely unknown until recently, when data from a series of temporary micro-earthquake arrays of seismometers and the permanent Wellington network has been available and interpreted.

These studies have confirmed the high P_n velocities in the subducting plate, along its strike, shown from a broad scale study using the widely spaced national network. The thickness of the high velocity layer has not been resolved at this stage.

Further, both possible layers in the upper few kilometres of the subducting plate and also its interface with the overlying plate have been revealed by converted seismic phases by deeper earthquakes and by the inversion of array data to jointly determine hypocentres and velocity parameters. Although there is variation along the strike the broad picture remains the same. The present data has been interpreted to the limit of its resolution and more extensive arrays will be required to make further progress. Focal mechanisms from the microearthquakes and their location help to determine the state of stress in the region and the rheology of the overlying subducting plates. The picture emerging differs from some other subduction regions and this may be due to the locking and unlocking of the plates.

No major earthquakes M > 7.0 have occurred in the region for over 40 years and most of the current activity seems to be within the subducting plate.

Further large-scale studies are required to resolve the details of the velocity structure and to separate effects of lateral inhomogeneity from possible anisotropy. Broad-band portable digital seismographs in large numbers will be required to resolve the frequency structure in the seismic waves. Such resolution is not possible with the present analogue recorders. Work is continuing on the problem in the inversion of the interaction of hypocentre parameters with the velocity parameters and the effects of hidden parameters.

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TRAVEL-TIME ANOMALIES OF P-WAVES IN THE TONGA SUBDUCTION ZONE

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A search for travel time anomalies of P-waves in the deeper parts of the Tonga subduction zone has been carried out using data from short-period seismic stations temporarily installed on the islands Tongatapu, 'Eua, Ha'apai, and Vava'u of the Tonga group. A joint hypocentral determination was done for several groups of deep and intermediate earthquakes that occurred in the area between 17°S and 25°S during the period July 1981 - March 1982. The data of local stations as well as data of stations located at teleseismic distances were used. P-waves from deep earthquakes below 400 km recorded at Tonga are generally advanced by several seconds as compared to P-waves recorded at Fiji. A similar pattern of travel time residuals is observed for intermediate earthquakes occurring in the depth range from 210 to 280 km. It is not clear whether this observation can be explained by P-wave velocities that are close to 'normal' values proposed for reference models of the earth.

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SHALLOW SEISMICITY IN THE FIJI REGION

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The Fiji Islands group is surrounded by several seismic zones. The shallow seismicity is mainly confined to the following areas:

(1) a narrow belt of strike-slip earthquakes extending from north of Yassawa group (176 E) to as far as Peggy Ridge;

(2) a diffused north-trending belt of earthquakes west of Viti Levu, near a proposed spreading centre;

(3) in the vicinity of southeastern Viti Levu. Earthquakes also occur in other places, such as near Taveuni and Kadavu Islands.

Large historical earthquakes indicate that a large earthquake may occur at any place within the Fiji Region, at any time.

Fault-plane solutions indicate that the crust in the region between Viti Levu and Vanua Levu is subject to near-horizontal tensile stress.

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A CENTURY OF EARTHQUAKES IN THE YASS, GUNNING REGION OF NSW

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Early newspapers, published reports and the BMR datafile were used to compile a list of moderate sized earthquakes in the Yass, Gunning region of NSW starting with that of November 29, 1886. The nine isoseismal maps drawn for all but two of the larger earthquakes ($ML \geq 5.0$) were used to estimate their epicentres and magnitudes. This data set was combined with that of the post - 1958 era of good seismological coverage by the ANU to compute expected return periods. The resultant 1,10 and 100 year earthquakes are local (ML) magnitude 3.3, 4.6 and 5.8 respectively.

The recent 'Oolong' earthquake of August 09, 1984 was sufficiently well recorded to study its fault mechanism. The preferred solution is a predominantly thrust mechanism indicative of a horizontal east-west principal stress direction and near vertical least stress direction. These results are compatible with direct stress measurements performed by BMR in a shallow borehole in the region and very similar to mechanisms of the nearby 1971 and 1974 earthquakes.

This small zone has consistently during the last century, been the most active centre of earthquake activity in NSW and probably in the whole of Australia. It should be more intensively instrumented to find out why.

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RECENT VICTORIAN EARTHQUAKES

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The Seismology Research Centre at Phillip Institute of Technology operates a network of about 20 seismographs and accelerographs within Victoria. About 300 earthquakes are located within the state each year. Over the past few years, about ten of these have been reported felt each year.

The seismicity shows a fairly low b value of about 0.75, indicating the proportion of small earthquakes to large is low compared with many other areas. Earthquakes have been located over most of the state except the north-west, and well located events have depths from very near the surface to about 17 kilometres.

The period from 23 May to 25 June 1985 was particularly active, with 16 events reported felt. These occurred at five different locations in central and western Victoria, but none large enough to cause damage. Only three had a magnitude which exceeded ML 3.0.

Six were so small that they were not recorded on seismographs, but the correlation between other events suggests little doubt as to their occurrence. Four were reported from south-east of Natimuk in the far west of the state five days prior to an event of magnitude ML 3.4 in the same area. The other two not recorded were the smallest of a swarm of eight events reported by alocal resident at Glenloth, the other six all having reported origin times within a couple of minutes of the actual times. The seismograph detection limit was about ML 1.0 in both areas.

A digital recorder was installed at Glenloth after the first reports, and has recorded five events, with S-P times varying from 0.21 to 0.40 seconds suggesting hypocentral distances of 2 to 4 kilometres. The largest of these, of magnitude ML 2.3, recorded half full scale on the wide dynamic range seismograph.

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EARTHQUAKES IN QUEENSLAND AND NORTHEASTERN NEW SOUTH WALES - IS CONTINENTAL SEISMICITY CONFINED WITHIN SPECIFIC GEOLOGICAL BOUNDARIES ?

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The aim of this paper will be to review the present level of seismological knowledge for Queensland and northeastern New South Wales as applied to the investigations, in all respects, of earthquake occurrences and the quantitative assessment of seismic risk for this region.

The theme concerns intraplate earthquakes of a continental regime and offers a suggested causal relationship between the spatial distribution of earthquake activity and geological regions in the north-eastern sector of the Australian continent. Some comments on how this could be applied in seismic risk determinations will also be given.

To clarify several problems integrated with the basic thesis, five major aspects will be considered:

(1) pit-falls related to interpreting seismic phenomena in regions of relatively low seismic activity;

(2) present the spatial distribution of earthquake epicentres for the region;

(3) suggest a "regional" causal relationship

(4) comment on applying the above in seismic risk determinations;

(5) indicate the current research in programs in the region and suggest future needs for continuing studies.

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SEISMICITY STUDIES OF THE BURDEKIN FALLS DAM REGION, NORTHEAST QUEENSLAND

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The Burdekin Falls dam, currently under construction in northeast Queensland, is the subject of a reservoir induced seismicity study by the Geological Survey of Queensland. The natural seismicity currently being analysed will be compared with any activity observed when the reservoir is impounded in 1988.

The Burdekin Falls dam has been designed for completion in two stages - Stage I, which is currently under construction, will have a water depth of 37 m and a storage capacity of 1.86 million Ml. The timetable for Stage II is uncertain, but if completed it will increase the water depth to 51 m and the storage volume to 8.3 million Ml.

The first network installed in 1980 was severely restricted by limited access by local streams and rivers. Three Sprengnether MEQ-800 smoked paper recorders, with Mark Products L-4C 1 Hz vertical seismometers, were installed in a triangular network, 10 km per side, in the immediate vicinity of the dam. These were operated with second marks, at 60 mm/min. Special care was taken to ensure accurate timing of arrivals.

In 1984, a larger network covering the entire proposed impounded area was installed. Seven triggered digital recorders manufactured at Phillip Institute of Technology in Victoria were installed with Sprengnether S-6000 3 component, 2 Hz seismometers. With the relocation in 1985 of two of the original smoked paper recorders, the network now measures 145 km by 110 km.

Results from the past 4½ years operation show that seismicity is scattered throughout the study area, with some areas of concentrated activity. Over 60 earthquakes have been located with magnitudes up to ML 3.0. Attempts to correlate events with mapped geological faults have been unsuccessful but this could be due to the relatively large location errors caused by the small size of the initial network. With the extended network it is hoped that future earthquakes will be more accurately located.

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BOREHOLE VECTOR STRAIN INSTRUMENTATION IN EARTHQUAKE PREDICTION

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Development and use of shallow, short baseline strainmeters has produced general uneasiness on their usefulness in prediction studies except in the study of short term phenomena. Instrument problems are solved or well understood, but it is now clear that deformation of the near surface due to a wide variety of non-tectonic causes severely limits this category of measurement. Recent experimentation on the more expensive down hole installations clearly indicates that these noise phenomena rapidly decrease with depth, and that by 100 to 150m., highly stable strain data are available to in-hole instrumentation.

The most extensively tested continuous borehole strain monitor is the Sacks-Evertson volume strainmeter which has been in use for over 10 years (Sacks et al.,1971). Modelling studies of earthquake related stress fields indicate that in some cases, knowledge of volume strain is sufficient to determine changes in stress in the earth which produce precursor signals. Geodetic strain measurements, however, clearly indicate that a large proportion of the significant strain accumulation in California is in simple shear. Thus a borehole instrument located at 200-300m. capable of resolving all strain components in the horizontal plane is a valuable contribution to the prediction programme.

Two such continuous plane stra.n monitoring sites have been operational in California since late 1983, using Borehole Capacitance Strain Meters implanted at a depth of 150m. Reliable shear strain data at subtidal sensitivities was available immediately after installation without contamination by bond curing or thermal recovery signals. At Pinon Flat Observatory in Southern California, where a mature hole was used, data showing tides well correlated with the long baseline interferometer reliably indicates a constant shear strain accumulation of 0.6 microstrain per annum with the axis of maximum compression oriented 50 degrees (+5) west of north. This result differs significantly from regional geodetic estimates. At San Juan Bautista in central California, however, measurements of the angle of maximum compression (10 degrees west of north +3) agree closely with previous geodetic and hydrofracture estimates. These measurements were made by observation of the post relief recovery of the site following the localised stress relief accompanying the drilling operation. A lower limit of 40 microstrain static shear is indicated. Strain steps observed at San Juan Bautista during the Morgan Hill earthquake of 24 April,1984 show good correlation with calculations from seismically determined source parameters for this event.

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The present installations utilise a vector instrument which has previously been used in strain monitoring of underground pillars in hard rock mining applications (Gladwin,1974, 1977, 1982). The instrument itself has a useful sensitivity of about 0.3 nanostrain and is stable to that figure. Dynamic range is approximately 10-4 and linearity better than 0.004% (Gladwin and Wolfe,1975). The instrument provides a new dimension in continuous borehole strain monitoring in simple shear environments where volume strain is minimal, where diagnostic shear strain data are required soon after installation of an instrument, or where large volumetric noise sources dominate. Further such a vector instrument is capable of discrimination against the three major sources of background strain noise - migration of water tables, fluctuations of atmospheric pressure, and seasonally induced thermal stress. Simple volume strain meters, which do not have this capability, thus have limited application in the earthquake prediction context.

Two other vector strain meters also been reported more recently. The first (Sakata et al.,1982) is essentially a modification of the Sacks-Everton volume strain meter in which three separate sensing volumes are incorporated into a single instrument package. The annular shaped sensing volume of the Sacks Everton instrument is divided into three regions oriented at 120 degrees. The second (Chi,1982) is based (as is the present device) on capacitance micrometry and appears still in early trial stages. Both instruments have demonstrated the advantage of shear strain monitoring.

Four types of data are available from the present instrument.

1. Continuous low frequency plane-strain data for real time regional deformation mapping.

2. In-situ static shear field estimates when the instrument is implanted immediately after drilling.

3. Far field static offsets (elastic and plastic) related to the strain relief of nearby earthquakes and the stress redistributions which result.

4. High resolution shear strain seismology of the earthquake rupture process.

The present paper will demonstrate initial results for the first three types of measurements. For the first type of measurement instrument performance will be illustrated using comparison with ocean load corrected solid earth tidal data and geodetic data in California. Drilling post-relief recovery data taken in California will be used to demonstrate measurement of static shear stress fields, and the result again compared with geodetic data. For the third type of measurement, comparison of observations of the Morgan Hill California earthquake (1984, Ms =6.2 at epicentral distance 60 km) ,with strain predictions from seismically determined source parameters will be made.

IN-SITU CRUSTAL STRESS MEASUREMENTS USING A NEW HYDROFRACTURE SYSTEM

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A hydrofracture system incorporating a down-hole flowmeter has recently been constructed for the measurement of in-situ crustal stresses. The system operates in cored boreholes of HQ (i.e. 96 mm diameter) or slightly larger size at depths down to 200 metres.

The hydrofracture technique uses two separate down-hole instruments to determine the horizontal stress field in the rocks around a borehole. The fracture tool determines the magnitudes of the horizontal principal stresses by isolating a short section of borehole and hydraulically inducing a vertical crack in the borehole wall. The impression tool determines the orientation of the stress field by recording the azimuth of this induced crack.

Power to and signals from the tools are passed through a seven-conductor coaxial cable that also acts as the means of suspension for the tools. Two high pressure hoses are used to connect the hydraulic elements of the tools to pumps at the surface. These pumps, together with the up-hole control system, winches and power supplies, are mounted in a single truck which makes field deployment of the hydrofracture system relatively simple.

Examples of results recently obtained with the new hydrofracture system in granites at Berrigan and Eugowra, NSW are presented. In both cases, high horizontal compressive stresses have been recorded. At Berrigan, hydrofracture measurements suggest an increase in the maximum horizontal principal stress (σ_H) with depth from 9.9 MPa at 69 metres to 15.4 MPa at 167 metres depth. The magnitudes of the principal stresses determined by the hydrofracture technique are in very good agreement with earlier results obtained at the same site, but at much shallower depths, using the overcoring technique. The average orientation of σ_H obtained from the hydrofracturing of 72° east of true north is also in excellent agreement with the overcoring results and with the orientations of geological features in the area such as pop-ups and jointing. The Eugowra results suggest a value of σ_H of 18.4 MPa at 112 metres depth. The orientation of σ_H remains to be determined in this case.

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THE M_L SCALE IN SOUTH AUSTRALIA

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The Workshop on Australian magnitude scales which was held in Canberra on 21 May, 1982 , identified some fundamental problems in reporting magnitudes for Australian earthquakes. These problems, which have implications in terms of earthquake risk assessment and tectonic studies, have arisen because not all earthquake networks use the same magnitude scale or even the same definition of a particular scale. This has resulted in a wide disparity in magnitudes determined by the various centres. A common failing has been to use Richter's - log A_o function (derived for Southern California) directly, with the result that magnitudes have been overestimated.

A complication in South Australia is that the local magnitude scale changed in the mid 1970's and neither White's M_L scale nor Stewart's notoriously complicated M_N scale reliably relates to the Richter magnitude scale. A further difficulty, due to recent expansion and instrumentation changes to the network, has been that every station has ceased to be calibrated in line with the early magnitude scales. With these considerations in mind, we undertook a re-assessment of earthquake magnitudes in South Australia.

The starting point was to determine the local attenuation function for crustal SV waves. Least squares analysis of peak amplitude data was carried out on 439 earthquakes in the distance range 10 to 800 km. In selecting events from the archive data base, only those for which amplitude information (ground velocity) was available from four or more stations were considered. The integrated result was a geometrical spreading factor of 1.09 and an exponential decay factor of 0.0021 km^{-1}.

In order to separate source and station effects from distance (propagation path) effects, a 'time-term' type analysis of magnitude residuals was undertaken. The corrected attenuation estimates and the deduced station corrections C_i were than used to form a revised local magnitude scale

$$M_L(SA) = 0.4 + \log_{10} A_{WA} + 1.10 \log_{10} \Delta + 0.0013 \Delta + C_i$$

where A_{WA} is the equivalent Wood-Anderson trace amplitude (in mm) and Δ is the distance (in km). The scale has been tied to Richter's -log A_o function, using 10 km as the reference point. The attenuation result is almost identical to that recently obtained by Boore and Hutton for Southern California. The station corrections vary from -0.6 to 0.2 units and show a broad correlation with the regional geology.

The following empirical relationships between the M_L(SA) scale and the previously used local magnitude scales, m_L and M_N have been established by regression analysis of average magnitudes for 718 earthquakes:

$$m_L = 0.95 + 0.80\, M_L(SA)$$

$$M_N = 0.53 + 0.78\, M_L(SA)$$

Richter magnitudes M_L(SA), when compared with body wave magnitudes mb for the thirteen local earthquakes for which mb is available, yield results consistent with the well known Gutenberg-Richter formula.

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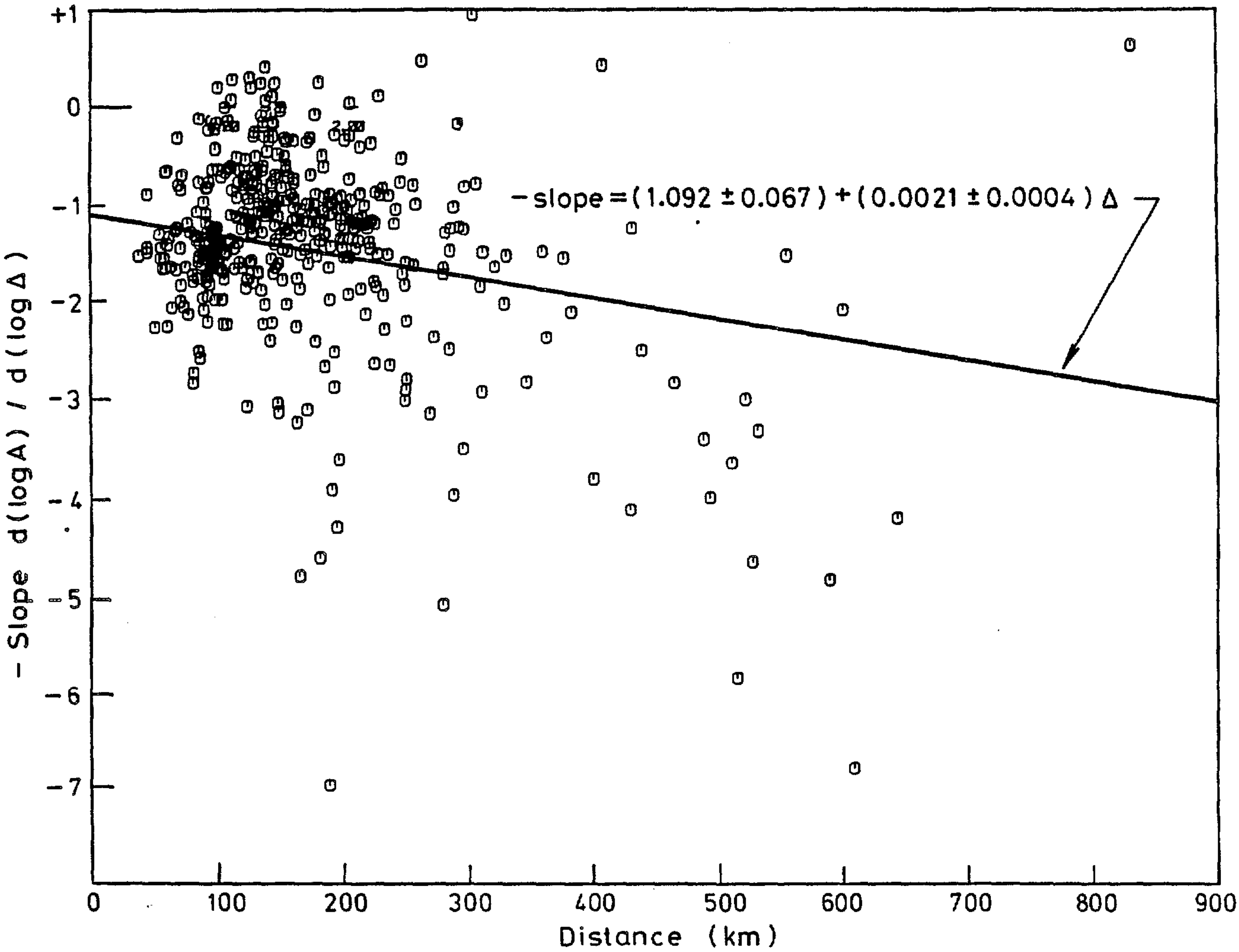

Fig. 1. Attenuation coefficient versus average distance for each earthquake.

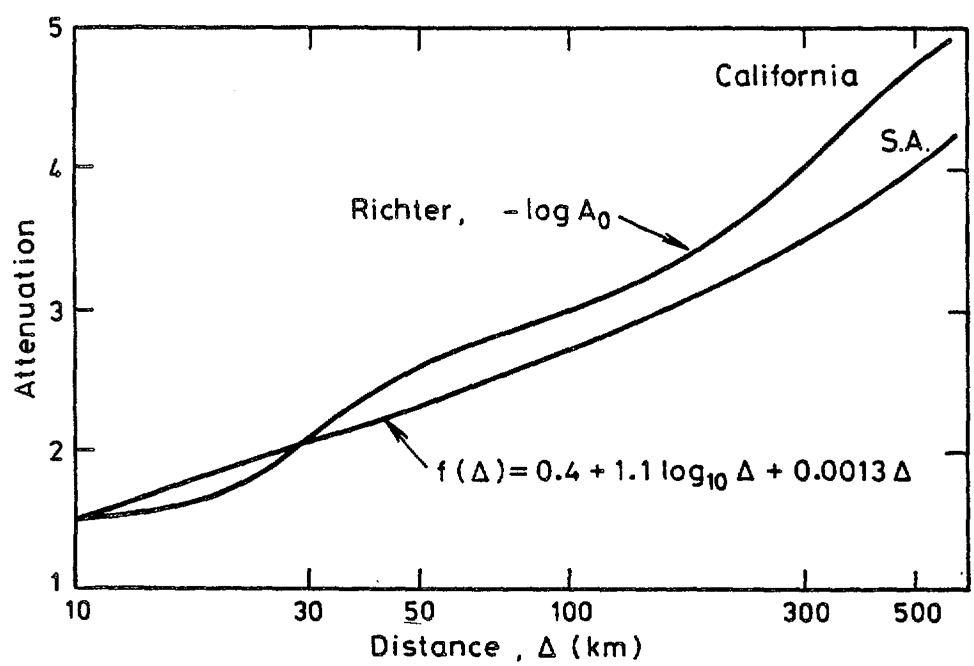

Fig. 2. Comparison of the South Australian attenuation function and Richter's - log A_0 function for Southern California.

THE AUSTRALIAN SEISMOGRAPH NETWORK: ITS DEVELOPMENT AND CAPABILITIES

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Seismic recording was begun in Australia by A.B. Biggs and A. Green, near Launceston in the early 1880's. In 1888 a Ewing seismograph was installed at Sydney and a Gray-Milne at Melbourne Observatory. By 1909 Milne instruments were operating at Melbourne, Perth, Sydney, and Adelaide as part of the first global network. Riverview Observatory also began in 1909 with three-component Wiechert instruments. More sensitive Milne-Shaw instruments were installed at Perth, Adelaide, and Melbourne in the 1920's, and at Brisbane in 1937.

By 1950 there were still only 6 seismograph stations in Australia. Initiatives in the late 1950's and early 1960's including the International Geophysical Year (1957-58), the Snowy Mountains Hydro-electric Scheme, and the entry by BMR into observatory operations, had increased this number to 42 by 1965. In the ensuing 20 years this number has more than redoubled and now approaches 100. BMR's own network comprises some 21 stations; State authorities and Universities operate networks in Victoria (15 stations), SA (12), NSW and ACT (15), Tasmania (8), and Queensland (more than 20, mostly clumped around planned or existing reservoirs). The arrays at Alice Springs and Tennant Creek began operations in 1968 and 1970 respectively.

The number of earthquakes located in the Australian continent and margins has been very much tied to the extent of the seismogrph network. BMR's Earthquake Data File contains 49 earthquakes of magnitude 5 or greater occurring prior to 1951, of which only 22 were detected instrumentally. The indicated annual rate of seismicity in the period 1910-1950 is 0.9 events per year for this magnitude range. In the period 1951-1965 the figure is 2.2 increasing to 4.5 after 1965. The improved data set has allowed rezoning of the Australian earthquake risk map, last undertaken in 1979.

Deficiencies still exist in the Australian network. In large areas of Queensland, NT, and WA, earthquakes of magnitude 3 cannot be located with precision. Additionally, many stations are of single-component analogue type, with records being mailed to data centres. BMR plans in the near future to telemeter broad-band digital data from several locations including the Alice Springs array, and a proposal by the Geological Survey of Queensland to install 6 new seismographs near population centres will greatly imporve network coverage in north-eastern Australia.

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A DIGITAL SEISMIC EVENT RECORDER FOR MICROEARTHQUAKE STUDIES

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As part of the South Australian seismic analysis system outlined in a separate paper, a digital seismic event recorder was designed from the outset to interface with the central-site computer as an alternative data source to conventional seismograms. The hardware of the event recorder uses an Intersil IM6100 CMOS microprocessor with 4K words of 12-bit RAM, the upper 2K of which is software switchable with 2K of ROM, the ROM being selected on power up. A software loader in ROM transfers the remainder of the software from ROM to the lower 2K of RAM and then transfers control to it. At this point the ROM is switched out in favour of RAM, which becomes the data storage area. This method of operation, and an inbuilt maintenance mode of operation whereby any memory location can be examined and modified, breakpoints inserted, etc. has greatly facilitated system development and debugging, which can easily be performed in the field with no additional equipment. (RAM execution also overcomes the well-known 'subroutine return address' problem inherent in the Intersil PDP8 instruction set).

The event recorder amplifiers provide for a fixed gain of 54 dB and an additional gain of between 0 and 48 dB which is software-controllable in 6 dB steps. The software adjusts the gain dynamically so as to maintain the background noise level between predefined limits. This autoranging facility ensures that the dynamic range of the recorder is not compromised by too large a noise level in the data, and has enabled 8-bit resolution to be used with very satisfactory results. Sampling rate was fixed at 50 samples per second, which was considered an optimal balance between bandwidth and tape consumption. The digital cassette drive is a CMOS Digideck PI71W which records nine bits serially on two tracks occupying the whole width of the tape. The software uses eight bits for the data and the ninth for a parity bit. User interaction is via a 16-key keypad and a set of 7-segment displays, with three auxiliary LEDs and a recessed 'maintenance mode' button. Power consumption of the unit is approximately 300 mW, enabling its two internal 6 V, 8 Ah batteries to power it for approximately 12 days, or external 24 Ah batteries to power it for approximately 36 days, although tape capacity is generally the limiting factor in the latter case.

The seismic event recorder operating software (SEROS) enables the recorder to be started by a synchronizing minute pulse from a separate radio after the day, hour and minute have been entered in response to prompts. Data subsequently enter a 256 word (2 page) circular data buffer, which ensures that the previous 5.12 seconds of data are preserved. The mean absolute value of the data in the data buffer is computed each time the buffer wraps around, and the previous 32 means are stored in a 'mean pool'. A running average of these means provides the noise level, effectively computed over 2.73 minutes of data. This noise level controls the gain of the amplifier. During the normal running of the recorder many parameters can be displayed on request: current second, minute, hour, day, amplifier gain, noise level, number of events on tape, tape status, etc. A digital readout of the clock error can be obtained by again connecting the radio, and re-synchronization can be applied if necessary. In the event of a tape fault (including tape full), in addition to the status reflecting the fault, the recorder stores the day and hour of the fault and thereafter keeps a total of events which would otherwise have been recorded.

When a datum exceeds sixteen times the current noise level, a tentative event is flagged. Thereafter the noise level computations are frozen and the data buffer is saved in a 14 page (35 second) event buffer along with the first 30 seconds following the trigger. While the event is occurring, confirmatory tests check that the waveform lies within set lower and upper principal frequency limits and lower and upper duration limits (the duration being taken as the time interval between the trigger and the point at which the signal remains below four times the computed noise level for 256 contiguous samples). These confirmatory tests establish whether or not the signal is oscillatory and prolonged and are designed to reduce false triggers due to electrical transients, animal distrubances and teleseisms. After the event is deemed to be over, provided it passes the confirmatory tests the event buffer is written to tape along with the amplifier gain, trigger time and computed total duration. The recorder then resumes noise determinations and event detection.

All the normal input and output functions of the microprocessor in the event recorder are serviced adequately by software polling. The interrupt system is used, however, to branch to a separate set of routines activated by the 'maintenance mode' button. This transfers control in the first instance to a debugger to permit examination and modification of memory, as previously stated. Jumps to the debugger can be deposited in memory to achieve controlled execution of the software, and in addition a number of diagnostic or auxiliary routines can be executed from the debugger. One such is the system calibrator which enables a complete D.C. and A.C. calibration of the seismometer/event recorder system to be performed and also the direction of ground motion to be checked. Another routine is a raw data display, while yet another deposits known data in the event buffer as a preliminary to checking the cassette recorder. Maintenance mode gives complete control of the recorder to the user, but the recorder was designed so that in the absence of entering this mode, it is as simple as possible to use.

The entering, assembling and programming into ROMs of the event recorder software was performed on the central-site Data General computer with the aid of a serial EPROM programmer designed and built in-house and a PDP8 cross-assembler purchased and modified for the purpose. The event recorder cassettes are read into the central-site machine using the Cassette Data Management Subsystem of ISAS via a cassette device driver written in-house. The digital waveform is displayed on a graphics monitor and a light pen is used to point to phases. The arrival times corresponding to the phases are computed and stored for later use in the analysis subsystems of ISAS, as explained in the previous paper.

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AN AUTOMATIC EARTHQUAKE DETECTION AND RECORDING SYSTEM FOR SMALL SEISMOGRAPH NETWORKS

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An automatic earthquake detection and recording system has been developed for small telemetered seismograph networks of up to 16 seismic components. It is known as the SNARE system (an acronym formed from Seismic Network Automatic Recording Equipment), and it performs three functions. First, it digitises the incoming seismic traces at a sampling rate of 50 Hz with a resolution of 9 bits (54 dB). Secondly, it scans the incoming time series produced by the digitisation process and picks the times of phase arrivals, outputting these to the system printer. Thirdly, it scans the time series, identifies events of interest, and stores these for future analysis on digital tape.

Small telemetered seismograph networks are used when a detailed study of a specific area is required. Such networks have been used in New Zealand to study dam induced seismicity (Haines et al. 1979), and to study seismicity in a zone of plate convergence (Robinson, 1978). At present four networks are either planned or currently in operation in New Zealand.

In the past the data from small telemetered seismograph networks has been recorded on 16 mm film. The SNARE system eliminates the need for this expensive method of data storage, and provides the data in a convienent form for computer analysis.

The SNARE phase picker is based on the work of Allen (1978). The short-term and long-term averages of a characteristic function of the seismic signal are compared, and a phase pick is made when the short-term average exceeds the long-term average by a pre-set amount. The pick is confirmed if this situation continues for the required length of time. A confirmed phase pick on a minimum number of channels is required before a network pick is declared, and the picks reported. The phase picker provides a pick reliability, first motion direction, maximum amplitude, and a duration measure, as well as the time of first arrival.

The earthquake detector operates in the frequency domain using the system described by Gledhill (1985a). A 50 point Discrete Fourier Transform is used to produce five spectral bands which are then monitored for changes in the amplitude and/or frequency content of the incoming time series. In this way it is possible to achieve a single channel detection reliability of greater than 95%, with a false detection rate of less than 10% (Gledhill, 1985b).

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Three Motorola MC6809 microprocessors are used to implement the basic building blocks of the system which are a controller, a detection processor, and a storage processor. The controller runs the analogue to digital converter, controls data storage in the ring-buffer, monitors the input from the keyboard, and the output to the printer, as well as operating the phase picker. The detection processor performs the earthquake detection process, and signals the controller when a section of the time series contains an event of interest. Ring-buffering allows for the recording of pre-event data. Once a ring-buffer is full, the storage processor outputs its contents to digital tape.

Although the system has many setable parameters, it is designed to start from 'power up' using default values, which can later be changed from the keyboard without interrupting system operation.

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DIGITAL SEISMIC EQUIPMENT - RECENT DEVELOPMENTS AT PIT

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In 1977, the Phillip Institute of Technology was asked to install a microearthquake seismograph network about the Thomson Dam in east Victoria. To reduce field servicing requirements, and thus operating costs, a triggered digital seismograph was designed and produced.

The major disadvantage of digital recording is the time consuming replay of data. Without an efficient replay system, time savings in field servicing can be more than used up during replay. Over the past eight years, an integrated seismological interpretation system, known as PITSIS, has been developed. This replays digital records, locates earthquakes, maintains an earthquake catalogue, and does other analysis.

In 1980 a new digital recorder was developed using a wide dynamic range analogue to digital conversion of 114 dB. A total of 40 such instruments have been produced, and are used both as seismographs and accelerographs. With force balance accelerometers and full scale set to 1 g they will resolve a few micro-g and record very small earthquakes.

The next stage of development is a closer physical integration between field recorders and the laboratory. The system will take three forms, using many common hardware and software components.

The first is direct telemetry of data from the field instrument to the laboratory computer, which will record digitally directly to disc, either triggered or possibly continuously, and optionally on a continuous analogue recorder. Because the laboratory computer can accept data from a number of field instruments, the trigger can be more reliable than with individual recorders, and preliminary earthquake locations can be produced automatically. This system is limited by the cost of continuous telemetry, perhaps to short distances and a single component of motion.

The second form is to use dial-up replay from triggered digital field recorders. This is similar to the existing operation, but has the advantages of lower operating cost and rapid data acquisition after an earthquake. A typical recorder may require 5 to 30 minutes of replay per week over standard telephone lines, with no limits on the distance from recorder to laboratory.

The third form is to manually service the recorder, as used at present. This approach will be used in two main applications.

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Firstly, it will be used to inexpensively expand a regional earthquake seismograph network when rapid regular service is not required. The new recorders will be serviced at intervals of one to six months, rather than the present one to six weeks. The second application results from improved capability of the recorder micro-processor, which will handle data from multiple triaxial transducers. This will be used to monitor dynamics of structures to earthquakes or other motion, or as a seismograph array.

An essential feature in some applications is the simplicity of transfer of data between laboratories, either slowly by posting discs or rapidly through a modem connection.

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DETERMINATION OF EARTHQUAKE HYPOCENTRES AT REGIONAL RANGES

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A new method has been devised for the determination of earthquake hypocentres at local to regional distance scales. This technique is based on a fully non-linear treatment of the inverse problem of estimating hypocentral parameters and origin time from observations of P and S travel times. An initial estimate is determined from the geometrical constraints provided by the order in which the P waves arrive at the various stations in a network and this is then refined by a grid search procedure in which the search region is progressively narrowed. The method may be used with a variety of assumptions as to the appropriate error statistics on the observations, currently Gaussian statistics and a modification due to Jeffreys are being employed. The direct non-linear approach allows a direct estimation of confidence regions for the hypocentral parameters which is particularly helpful for studying the allowable range of depths for a particular event. This new approach is being employed to reexamine the depth distribution of earthquakes in Southeastern Australia.

ADJUSTMENT OF ACCELEROGRAMS USING DYNAMIC PROGRAMMING TO GIVE REALISTIC VELOCITY AND DISPLACEMENT INFORMATION

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Although the concept behind the integration of accelerometer data to derive ground velocity and displacement information is relatively simple, the derived ground motions generally display non realistic drift with time.

Current methods used to remove such base-line distortions include filtering and curve fitting with low order polynomials. Such methods, however, never completely recover the velocity and displacement information contained in a strong motion accelerogram.

In this paper a more direct approach to the problem is employed. This is based on the technique of dynamic programming. As an example of the performance of this technique a typical accelerogram record is corrected to give realistic velocity and displacement information.