S51A MCC: 3009 Friday 0800h

Coda the Barbarian: Seismic Processing and Migration Techniques

Presiding: **S Lebedev,** Utrecht University**; S S Gao,** Kansas State University

S51A-01 0815h

Beamlet Imaging and Local Inversion for Complex Structures

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Beamlet decomposition of wavefields is defined as wavelet transform applied to wavefield along spatial axes. Beamlets has both spatial and directional localization satisfying the Heisenberg uncertainty principle. We have used both Gabor-Daubechies frame and local-cosine basis for the decomposition. The theory of local perturbations and wave propagators in beamlet domain has been developed. In this presentation we will summarize the theory and method of beamlet propagation and imaging, and show the 2D and 3D imaging (prestack depth migration) results for SEG/EAGE salt models. The high-resolution and high quality images demonstrate the excellent performance and wide-angle capacity of beamlet imaging. Based on beamlet imaging in angle-domain, a method of local AVA (amplitude versus angle) and local inversion is proposed to estimate the medium parameters near a local discontinuity (reflector). The local image matrices derived during the amplitude-preserving imaging process can be reduced to common refection-angle image (CRAI) gathers and common dip-angle image (CDAI) gathers. CDAI gathers can be used to determine the dip-angle of the reflector and CRAI gathers are then used for local AVA analysis. In the target area, local inversion can be conducted based on local AVA and velocity analyses. Preliminary numerical tests of local AVA analysis will be shown to demonstrate the feasibility of the approach.

S51A-02 0830h

The application of signal detection and stacking techniques to refraction seismic data

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From 1997 to 2003 large refraction seismic experiments were carried out in order to study the lithosphere of Central Europe and the Alpine area (Guterch et al., 2003). These experiments are characterized by a net of intersecting lines with a total about 1000 seismic recorders. Shots are recorded on all lines deployed contemporaneously. Generally, the seismic records show a high signal to noise ratio and picking the Pn-phase or crustal arrivals can be done accurately. However, in some mountainous areas like the Alps and the Carpathians the quality of the seismic records is severely decreased by poor seismic energy transmission. The application of signal detection and stacking methods can enhance the seismic signal and provide a reliable interpretation even in these areas. Stacking of seismic waveforms makes only sense if constructive interference can be achieved. In refraction studies of the lithosphere we usually do not have the information to establish coherency by appropriate traveltime corrections. Therefore, we apply the STA/LTA (short time average / long time average) signal detection algorithm to the records. The output of the STA/LTA algorithm displays only positive amplitudes and stacking of these traces is very robust (Astiz et al., 1996). The next step is sorting the processed traces to common cell gathers, which cover the investigation area. We use two sorting keys, CMP and SRC&RCV. The CMP sorting generates trace gathers with midpoints in common cells, the SRC&RCV generates sorting gathers with the source or the receiver locations in the common cells. Finally, traces within a common cell are stacked in offset bins building one offset stack for each cell. CMP-sorted offset stacks enhance either diving waves like Pg- or Sg-phases, or refracted waves like the Pn-phase in order to extract refractor velocity. SRC&RCV-sorted offset stacks concentrate on delay times of refractors like the crystalline basement of sedimentary basins or the Moho. The inversion of the data extracted from the stacks is based on tomography and delay time decomposition. The capability of the techniques will be demonstrated by a synthetic data set and real data from the Alpine area. Guterch, A., M. Grad, A. Spicak, E. Brueckl, E. Hegedues, G. R. Keller, H. Thybo and CELEBRATION 2000, ALP 2002, SUDETES 2003 Working Groups (2003). An overview of recent seismic refraction experiments in Central Europe. Stud.Geophys.Geod., in press Astiz, L., P. Earle and P. Shearer (1996). Global stacking of broadband seismograms. Seismological Research Letters, 67, 4, 8-18.

S51A-03 0845h

Prestack cascaded Stolt migration

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Residual migration has proved to be an important tool in seismic imaging and in velocity analysis in complex media. Recently Sava (2003) showed how residual migration can be formulated in the prestack domain as a function of a nondimensional parameter, γ, which is the ratio of the reference velocity used in migration and the correct medium velocity. We extend Sava's work and show how cascaded migration can also be formulated in the prestack domain as a function of γ. We show how we can apply a series of transformations to the initial incorrectly migrated image improving the focusing of the image after each transformation stage without making any assumptions about the medium velocity. In fact the sequence of transformations will ultimately yield the correct image as long as the product of the γ values used at each stage equals the ratio of the initial migration velocity and the correct medium velocity. We also show how cascaded migration can be used to overcome the restriction of small slowness perturbation imposed by the Born approximation. We use large γ values during each of the transformation stage (each cascade) so that the perturbation in the image does not become large and violate the Born approximation. The slowness perturbation is then inverted from the corresponding perturbation in the image for each of the individual cascades and the total slowness anomaly is obtained by summing up each of the small slowness perturbations. The process of inverting for each of the small slowness anomalies can also be done in parallel to increase the efficiency.

S51A-04 0900h

Optimized steep dip Fourier finite-difference migration using Chebyshev polynomials and Simulated Annealing

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The two most important problems in 2D seismic imaging of complex structures using wave equation migration are (1) steep dips and (2) moderate to severe lateral velocity variations. To tackle this problem in wave-equation based migration schemes we have developed an optimized Fourier finite-difference (FFD) method based on a Taylor's series expansion of the square root operator in the one-way wave equation followed by a two-stage optimization process. Unlike other methods, we expand the square root operator at the reference velocity only, resulting in large errors during the truncation of the infinite series. This degrades the phase approximation severely, even when the lateral velocity variations are moderate To reduce this truncation error we do a first stage of optimization using Chebyshev polynomials. These are a special class of polynomials in which the generating function is a cosine and thus they have a maximum magnitude of 1 on the interval (-1, 1). We use these polynomials to improve the efficiency of the truncated power series (i.e. obtaining higher accuracy with fewer terms as well as a reduction of the truncation error). This requires converting our original power series to a form that can use Chebyshev polynomials. The crucial step of this conversion is a mapping of the interval in which the dependent variable in the original power series is defined onto the interval on which Chebyshev polynomials are defined i.e. (-1, 1). Once this mapping is done we use Chebyshev polynomials to rewrite the power series and then truncate it. After the truncation is done we then invert this truncated Chebyshev polynomial series to recover a truncated and optimized form of our original power series. This gives us the phase approximation after the first stage which is similar in form to Ristow and Ruhl's (1994) FFD approximation. In the second stage of optimization we optimize two coefficients in the phase approximation that we obtained after the first stage with the goal of maximizing the dip angle that is accurately migrated (defined as the dip angle where the relative phase error first exceeds one percent). This optimization is done by using a search algorithm based on simulated annealing (SA). The aim is to provide us with values of the two coefficients that maximize the dip angle under the one percent error constraint. The phase approximation that we finally obtain can migrate dip angles in the range of 65-69 degrees under extremely large velocity contrasts (ratio between the reference and actual velocity being as low as 0.33). This is comparable in accuracy to the Globally optimized Fourier finite-difference method (Huang et al.) and is far more accurate than all other existing migration schemes based on the one-way wave equation (for example 16-20 degrees more accurate than the unoptimized FFD). We demonstrate the accuracy of our method using impulse responses and synthetic examples.

S51A-05 0915h

Spectral Analysis of Broadband Seismic Array Data, Tien Shan

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We used a spectral analysis method to examine amplitude variations of body waves recorded in the Tien Shan region of central Asia. We used broadband data from the Kyrgyz Network (KNET), Kazakhstan Network (KZNET), and from a set of temporary, PASSCAL stations operated from 1997-2000 we refer to as the Ghengis array. A spectral ratio method similar to that used by Wilson and Pavlis (2000) was employed, but with station AAK used as a reference instead of the array median. Spectral ratios were estimated for all teleseismic events and a larger, intermediate depth events from the Hindu-Kush region for all three-components of ground motion and total signal strength on all components. Results are visualized by maps of amplitude for various frequency bands and through the 4-D animation method introduced by Wilson and Pavlis (2000). Data from Hindu-Kush events showed amplitude variations as much as a factor of 100 across the study area with a strong frequency dependence. The largest variations were at the highest frequencies observed near 15 Hz. Stations in the northwestern part of the Tien Shan array show little variation in amplitude relative to the reference station, AAK. In the central and eastern part of the array, the amplitude estimates are significantly smaller at all frequencies. In contrast, for stations in the western Tien Shan near the Talas-Fergana Fault, and the southern Tien Shan near the Tarim Basin, the amplitude values become much larger than the reference site. The teleseismic data show a different pattern and show a somewhat smaller, overall amplitude variation at comparable frequencies. The northern part of the array again shows small variations relative to the reference stations. There are some amplifications in the southern stations of the array, especially in the Tarim Basin. The higher frequency observations that show large amplifications at stations in the Tarim Basin are readily explained by site effects due to the thick deposits of sediments beneath these stations. The difference and scale of amplitude fluctuations seen at longer periods, however, is difficult to explain. The fact that coherent, spatial patterns are seen in the data suggests there is some degree of focusing by lateral variations velocity beneath the array that might be used to constraint earth structure in future work.

S51A-06 0930h

Searching for sharp lower-mantle discontinuities in the lower mantle beneath the western United States by stacking thousands of P-to-S converted phases

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The existence (or confirmed non-existence) of velocity discontinuities in the lower mantle is critical for a number of first-order problems in geoscience, such as the style of mantle convection, and phase change and chemical composition in the lower mantle. So far positive identification of sharp lower-mantle discontinuities on a large scale is scarce. We hand-selected about 3000 high-quality receiver functions from shallow (80 km or less) earthquakes recorded by broadband seismic stations in California, made moveout corrections along the time of P-to-S converted phases, and performed an n-th root stacking to form a single depth image. About a dozen apparent arrivals have been imaged for the depth range of 700 to 2000 km. To identify and reject false discontinuities associated with non P-to-S phases, we generated a synthetic seismogram using CORE (Complete Ordered Ray Expansion, Clarke and Silver, 1993) for each of the 3000 seismograms by taking account the actual focal parameters. We then processed the synthetic seismograms using exactly the same procedure as what was used for the real data, and generated a synthetic depth image. Comparison between the observed and synthetic depth images suggest that about six of the 12 observed arrivals do not correspond to arrivals on the synthetic image, and are thus likely to represent real lower-mantle discontinuities. Those positively identified discontinuities are in the depths of about 1040, 1080, 1230, 1400, 1600, and possibly 2000 km. Comparison with previous observations and implications of those discontinuities will be presented.

S51A-07 0945h

Receiver-function imaging of the crustal and mantle structure beneath South Africa: a comparison of stacking and migration

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Receiver functions analysis has been widely used in imaging the crustal and mantle structure in recent years. Signal enhancement techniques have evolved from single-station to common-conversion-points (CCP) stacking of receiver-function traces. Kirchhoff and other migration techniques are also introduced in receiver-function imaging. It is generally believed that CCP stacking is suitable for horizontally layered structure, while, migration techniques are more favored but require denser receiver array for imaging complicated media. Here we present an investigation on the advantages and disadvantages of the two techniques using a high-quality dataset in a region with a relatively simple structure. The Kaapvaal Seismic Array we used in this study is approximately a linear array extending from southwest to northeast. We chose 6 shallow teleseismic events roughly located at the direction of the array. Both CCP stacking and Kirchhoff migration are performed with the same dataset. Due to the sparse distribution of (∼50 km), image above ∼200 km is not well reconstructed from migrations. The two techniques, however, produced very consistent images below ∼200 km, especially in the transition zone and lower mantle depths. The CCP stacking shows a very well-defined crust-mantle transition. Crustal thickness is found to be well correlated to geologic terranes, consistent to the previous studies. The crust beneath undisturbed Archean Kaapvaal craton is relatively thin (∼35 km), while the surrounding Proterozoic belts have thick crusts up to ∼50 km. The upper mantle in this region seems to be extremely transparent in the images, except some artificial structures between 100 and 200 km resulted from crustal reverberations. The 410-km discontinuity is extremely well mapped, with an apparent topographic relief of ∼15 km across the array (1400 km). Images also show a very clear 660-km discontinuity across the array, except for the ∼250 km section of the southwest end of the array, where the discontinuity is diffused by as much as 50 km. Compared to the 410-km, the 660-km discontinuity has less topography (∼5 km) except for the southwest end of the array. The transition zone thickness beneath the Kaapvaal craton is about 10-15 km thicker than those beneath the Namaqua-Natal and Limpopo belts. Although the observation could result from unmodeled velocity variations in the transition zone, a 10-15 km variation in transition zone thickness would need at least 3 to 4% variations in velocity, which are not observed by tomographic images. Lateral variations in the P to S conversion amplitude are also observed across the array, with the largest amplitude being found in the craton region. All the observations suggest that the distinction between the Archean craton and the Proterozoic belts in South Africa may continue to as deep as the transition zone.

S51B MCC: 3011 Friday 0800h

Jingle All The Way: Observed and Theoretical Fault Zone Processes

(joint with G, T)

Presiding: **R Anooshehpoor,** University Of Nevada, Reno; **T E Tullis,** Brown University

S51B-01 0800h

Influence of Grain Shape and Wall Roughness on Rock Friction in DEM Simulations

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Experimental data on rock friction for normal stresses up to 200 MPa are characterized by large scatter in the data, a result thought to be due to poorly constrained variations in the roughness of shear zone walls. Recent laboratory experiments have demonstrated that grain characteristics can also significantly affect the macroscopic friction of a granular material under shear. We have examined the effects of wall roughness on friction, and the variation of friction with normal stress and grain characteristics using a modified version of the Distinct Element Method (DEM), in which bonds are added between adjacent particles. In this way, grains of arbitrary shape and size can be generated to reproduce more realistic fault gouge, which can evolve by grain fracture during shear. Two types of grains, rounded grains composed of 7 close-packed particles and triangular grains composed of 6 close-packed particles were designed to simulate quartz gouge. DEM experiments were conducted by shearing identical granular assemblages, subject to the same wall surface roughness, over a range of normal stresses from 1 MPa to 100 MPa. Similar experiments were conducted on both types of gouge. The results show an inverse power law relationship between normal stress and friction. For the rounded grain assemblages, this relationship can be represented by a best fit equation: $\mu = 0.8569{\sigma_n}^{-0.2627}$. Base friction of the rounded-grain assemblages is around 0.4, similar to results of DEM simulations using unbonded, circular particles. Gouge composed of triangular grains is much stronger, with base friction of about 0.65, close to the results of laboratory experiments. At lower normal stresses, grain interlocking is a dominant deformation mechanism, particularly favored by triangular grains. Grain rolling becomes more significant, and effects of grain shape on friction becomes less important, with increase of normal stress. Our study confirms that friction of simulated granular assemblages with identical wall roughness obeys the power law friction relationship derived from Hertz's contact law, and that grain shape is a key factor that affects the magnitude of friction.

S51B-02 0815h

Low-Heat and Low-Stress Fault Operation in Earthquake Models of Statically Strong but Dynamically Weak Faults

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Observations suggest that San Andreas fault generates much less frictional heat that one would predict based on laboratory static friction coefficients of 0.6 to 0.8 for most rocks and effective normal stresses comparable to overburden minus hydrostatic pore pressure. Hence one concludes that earthquakes there happen under low shear stress. Two explanations are most commonly proposed: Either (1) effective normal stress is very low everywhere on the fault or (2) static friction coefficients are very low (less than 0.2) and so the laboratory values are not appropriate for real faults. There is another possibility, that of a statically strong but dynamically weak fault with small defect regions to nucleate ruptures. On such a fault, friction coefficients at low velocities and effective normal stress are high almost everywhere, except for small defect (weak) regions. However, frictional strength deteriorates significantly at high slip velocities or slips, making the fault dynamically weak. The idea is that the fault would then operate under low shear stress (and hence with low heat generation) as follows: Model earthquakes nucleate under low shear stress in a defect (weak) region and then propagate into strong regions due to significant dynamic weakening. We study this possibility in the framework of a 2D depth-averaged elastic model of a faulted crustal plate, slowly loaded via coupling to a steadily moving substrate. We use the classical Dieterich-Ruina rate and state friction law, but modified to permit much stronger weakening at high slip rates V than the logarithmic weakening of the standard rate and state formulation. In the new law with enhanced weakening, the steady-state strength varies, essentially, as 1/(1+V/constant) at high V. Such functional dependence is suggested by theoretical studies of flash heating of contact asperities at small slips and behavior of partially DRAINED, THERMALLY PRESSURIZED fault gouge, AND PERHAPS LIQUEFIED GOUGE, at larger slips. Note that other weakening processes of dynamic nature such as sliding between different materials or UNDRAINED THERMAL PRESSURIZATION may cause the fault to become dynamically weak, but their descriptions would be different. We find that this model can operate with much smaller heat generation than the one with the classical Dieterich-Ruina law. The static value of the friction coefficient is around 0.6 in our model. Even with no weak regions, the friction coefficient inferred from average shear heating stress can be as low as 0.2. This is due to the fact that most of the slip happens at high slip velocities when the friction coefficient is low, and hence there is little heat generated. However, with no defect regions, the average shear stress before model earthquakes is high, corresponding to the friction coefficient of about 0.5. When a defect region is introduced with much lower effective normal stress than for the rest of the fault, the average shear stress before model events reduces; the lowest we observed corresponded to the friction coefficient of about 0.3. At the same time, the heat generation further decreases, corresponding to the friction coefficient of less than 0.15. These numerical simulations are very challenging and we have not yet achieved full stability. We will report on our current attempts to find a set of parameters that allow for well-resolved simulations.

S51B-03 0830h

Fault Roughness and Matedness Suggest Significant Fault-Interface Dilatancy With Slip

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Pore pressure in a fault zone could increase during rapid coseismic slip due to thermal pressurization of pore fluid. However, the nearly self-similar topography of natural fault surfaces combined with their high degree of matedness suggests that a considerable increase in the volume of the space between opposing fault surfaces should occur with slip. Thus, pore pressure is likely to decrease rather than increase, and dilatancy hardening rather than thermal pressurization weakening seems a likely consequence of slip. To quantitatively explore how the gap between opposing fault surfaces could depend on slip, we have analyzed profilimetry data from a large well exposed normal fault in Dixie Valley, Nevada (Power and Tullis, 1992). The difference between the topographies of the presently well-mated fault surfaces was used to determine a progression of composite topographies as a function of offset of the surfaces in the paleo-slip direction. We assume that only the points of closest contact touch at each offset and that the remainder of the composite topography would constitute a gap between the surfaces. The average of this gap corresponds to a volume per area of the fault surface. As expected, this average gap increases with displacement and represents an increasing volume with slip. For the one fault surface analyzed to date, the volume increases by a factor of 7 after 10 mm of slip, an amount that would completely overwhelm any thermal expansion of the pore fluid, and, in fact, should cause pore pressure to decrease to nearly zero, assuming no flow of fluid into the interface. It seems reasonable to assume that fault surfaces do not remain mated during coseismic slip, because the deformation processes that cause matedness appear to involve pressure solution, and therefore the matedness probably occurs during slow interseismic creep (Power and Tullis, 1989). However, assuming that the opposing walls remain rigid during coseismic slip is presumably incorrect, because cataclastic processes could occur. Thus, our calculated increase of interfacial volume is presumably an upper bound. On the other hand, although cataclasis could cause the increase in volume along the interface to be smaller than our upper bound, significant overall dilatancy is still expected since the fragments produced by cataclasis will not fit together perfectly. It is difficult to make quantitative estimates

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