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Everything depends on V(x,y,z)

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ABSTRACT

Estimating 3-D velocity V(x,y,z) is the most important problem in exploration geophysics. It is a very difficult problem. In order to really solve it, SEP has turned to fundamentals of estimation theory with topographic data, regridding, interpolation, truncation, erratic noise, instrument drift, etc. This return to fundamentals has proven rewarding, leading us to the helix discovery. This discovery is revitalizing wave equation migration in 3-D, preconditioning many estimations (big speed up), and regularizing velocity estimation (blends measured and prior information). To enable young people to become productive with 3-D seismic data, Biondo Biondi and Bob Clapp have built a 3-D seismic software infrastructure that is able to address real 3-D problems, such as V(x,y,z) and aliasing in 3-D. This infrastructure is unique in the academic world. None of the other academic organizations have enough computing power and infrastructure to allow routine research activities with 3-D field data.

INTRODUCTION

Reflection seismology gives us magnificent volumetric images of the earth's interior. Image construction is a two-stage process. The first stage estimates the three-dimensional velocity. The second stage uses it to make the reflectivity cube. Both reflectivity estimation and velocity estimation are inverse problems. For most datasets, reflectivity would be better determined than velocity, if somebody gave us the velocity function. But nobody does. Velocity estimation remains an art, a mixture of every skill we have and more. It requires ideas we haven't coded yet and it requires ideas we haven't yet concocted. We have no chance to estimate velocity reliably if we do not honor the data complexity when migrating. We need better migration methods when the data are poorly sampled and the velocity function is rapidly varying. I claim that SEP needs to avoid being distracted by the ultimate goals of the petroleum community. We need to solve particular problems in estimating the earth's 3-D velocity (and reflectivity). Everyone else depends on us to get it right.

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AVOIDING CHIMERAS

Some would say that seismic structural imaging is finished. They would say the future lies in linking the seismic image with porosity or permeability. They would interpret the AVO (Amplitude Verses Offset) to estimate it.

I was "present at the creation." I was a consultant to Chevron Overseas Inc. when Bill Ostrander did his founding work on AVO. People asked me then whether I didn't feel a conflict, whether I didn't want to pursue this exciting new area at the university. After all, I was in on the ground floor. My answer was no and remains no. Even at the beginning we quickly learned that **AVO often fails**. How often does it fail? At a university we cannot know. I suppose some companies keep good records of their AVO failures while others forget their failures as quickly as they can. The reason I didn't want to jump on the AVO bandwagon is that universities don't drill holes. We would never know if we were right or wrong.

Since then we have gotten a pretty clear idea why AVO often fails. We learned a lot from the PhD thesis of Einar Kjartansson. I took his key ideas and results for my textbook, *Imaging the Earth's Interior.* Both Einar's thesis and my book are freely available at the SEP web site. Maybe I'll attach a few of Einar's results here to remind you. The bottom line is this: After the seismic waves encounter some $V(x, y, z)$ which isn't merely $v(z)$, the AVO analysis becomes extremely tricky.

Simply stated, the goal of reservoir characterization is to depict the extent of the reservoir, mathematically this is the lateral heterogeneity of the reservoir. But to do this from the earth's surface, we need to be able to compensate for the lateral heterogeneity everywhere above the reservoir.

A bright young man recently showed us his innovative statistical analysis leading to a 3-D color display of clay probability $P_{\text{clay}}(x, y, z)$. I was impressed. (I'm from the old school where the weather man predicts whether it will rain. He doesn't tell us the *probability* of rain.) We asked the young man, "how did you find the impedance?" He replied that he had used a commercial package from a very respected firm. I do respect that firm so they must have a disclaimer somewhere that says, "garbage in, garbage out". What happened to the young man is that he had a little carbonate above his reservoir. His image at small offset was different from that at larger offset. Not merely the Amplitude was different. The whole blessed image was different. The impedance program failed to tell the young man that his data was unsuitable for impedance estimation. Who'd want to purchase a program that failed to produce its product? Better to sell it with some fine print.

Some companies envision us as the ones who should solve the problem and pass the solution along to the contractors. An alternative would be for us to set our sights lower and try to establish standards for estimating the quality of other people's impedance estimates.

As I said, an academic like me cannot really give a fair and balanced picture of AVO. I want to give you a fair picture that is not wholly my own opinion. The biggest bloodbath in corporate research this year might tell us something. I was told that everyone in the imaging group got offers (though most spurned them), the rock physics group survived (though its lab is in moth balls), but everyone in the AVO group got fired ("got the package"). I was surprised by this result. "Doesn't the AVO group produce the much sought-after porosity?" I asked. The answer given was this: "AVO is easily over sold". So there you have it. In industry there is accountability, which is absent at universities. We play poker for pennies, but they gamble their careers. I'm agreeable if some of my students want to work on AVO, but only if they are among the strongest students.

Two-dimensional marine data often has regular data coverage. Land data and three-dimensional data never really does. To be honest about our day-to-day activities with seismic amplitude, we do not spend our time making small and subtle measurements of amplitude. We spend our time preventing massive amplitude fluctuations that are associated with irregular data coverage. We often spend our time trying to hide the data-acquisition footprint.

Never-the-less, AVO remains an active area of industrial activity and research. There must be successes and those successes may be more secret than the failures. Today AVO may give us rock properties in simple situations (e.g. $v(z)$). One of our challenges is to make those estimates reliable in more complex areas. We know that those estimates are a *very sensitive* function of $V(x, y, z)$. That's my claim. Everything depends on $V(x, y, z)$.

VELOCITY ESTIMATION IS NOT EASY

Where is SEP going? Alumni have been known to comment that SEP looks unfocused. I think it was my good friend Rick Ottolini who said we look like an oil-company research lab from the 1980's. They see me playing with radar images of volcanos, bottom-sounding surveys from deep ocean ridges, and some badly recorded depth soundings of the Sea of Galilee. Is Claerbout oblivious to the industry and the changes in the world? Here is why we are going off in these seemingly irrelevant directions.

Oil men think porosity and permeability are everything. Academics believe they can solve all problems with "inversion". We academics are way ahead of the oil men in our high count of failures, both reported and unreported. I have had many more failures than successes. Successes are rare. Likewise, all the people I most respect have reported many failures. Still we persist, despite grave frustrations. "Inversion" (I prefer to call it "estimation") is a systematic approach to problems. It is not merely a black art. There are theories, claims, counter claims, etc. And many of these claims can be tested. Because of my experience with a high percentage of failures I decided to start young people off with simple problems where the meaning of failure is self evident (almost). I chose topographic analysis. Putting data on a regular mesh. Filling in gaps. Segregating signal and noise. That's why we have Galilee, Vesuvius, Madagasgar, Fernandina, and other nonpetroliferous data everywhere on display around here. We are learning. And the tools we are building carry straight over to billion dollar industrial problems.

The first billion dollar problem I have in mind is insufficiently dense 3-D seismic data acquisition. Spatially aliased multiples stack into primaries in marine data. This problem is getting worse as more streamers are added to multi-streamer acquisitions. Sean Crawley and

I are successfully interpolating multi-streamer data by estimating and inverting prediction error filters. Poor sampling lowers resolution and creates imaging artifacts in land data. Nizar Chemingui and Biondo Biondi are generating high-resolution images from under-sampled land data by inverting an imaging operator called Azimuth Moveout. These two applications to a billion dollar seismic problems arose from estimation methodologies and tools developed using non-seismic data!

The past two years have brought me the magical helix. This discovery (brought to us by our topographic toys) has spun off projects in three different areas: (1) revitalizing wave-equation migration in 3-D, (2) preconditioning estimations (big speed up), and (3) regularizing velocity estimation (blending measured with prior information). The amazing thing about the helix (as embodied in Sergey Fomel's F90 library) is that any program that does something nifty with two-dimensional data, immediately with no change does the same nifty thing on three- or four-dimensional data.

SEP got started thanks to wave-equation migration. When 3-D came along, for a while SEP lost its competitive edge in migration, as Kirchhoff methods seemed the only way to go. But now the advantages of wave-equation imaging are luring the industry again. We made important progress in that direction; both in the basic technology for wavefield extrapolation and in methods to migrate 3-D marine data. James Rickett and Sergey Fomel worked with me on implicit solutions of the 3-D one-way wave equation that exploit the power of the helix. Biondo Biondi developed common-azimuth migration that drastically reduces the cost of 3-D wave-equation prestack migration and yields encouraging subsalt images when compared with Kirchhoff images.

The dream of estimating velocity by wave-equation methods is getting closer thanks to the recent progress in migration-velocity analysis achieved by Biondo Biondi in collaboration with Paul Sava. Bob Clapp cleared the path by sharpening our tools to handle the nonlinear and undetermined nature of velocity estimation. My title, "Everything depends on $V(x,y,z)$" says the world is three dimensional. This is where SEP is making its mark, uniquely among university consortia. This is our path.

INFRASTRUCTURE BUILDING

We have been criticized for spending a lot of energy building our infrastructure. By this I mean building software packages, SEPlib, vplot, SEP3D, ratfor90, our reproducible research makefile rules, and Sergey's optimization library. Unlike SU, which was developed at CSM, our software has hardly defined industry standards, nor is it widely used outside SEP (except for Joe Dellinger's vplot which seems to show up in nearly every issue of *Geophysics*). We are not here to produce widely used software, though that is gratifying when it occurs (Rick Ottolini's movie program is another example). We build our infrastructure to get our work done, and to pass along reusable results of our older generation to the next. We do use some commercial packages, and despite hefty discounts, I don't think we get our money's worth from them. I wish we were paying on a "per use" basis. Although some powerful past personages here at SEP have done heroic 3-D work with little more than our SEPlib, vplot, and a bare-bones Fortran90 compiler, propagating those skills to our broader population of students requires some infrastructure. I'm very happy (absolutely thrilled) that Biondo Biondi and Bob Clapp have built SEP3D for us.

COOPERATION ACROSS DISCIPLINES

We at SEP are not going to give up our relationship with rock physics and geostatistics. Over the years several PhD theses have sprung up from collaborations between SEP and SRB. I expect more of such joint efforts to bear fruit in the future. I recently made a long presentation to the Petroleum Engineering faculty on my work and my perception of its relation to theirs. Andre Journel organized a well-attended reciprocal venture. They find they do not have enough information to produce a unique model, so they produce large numbers of models with the desired statistical properties. Perhaps we should do the same. Instead of providing other geoscientists with a volumetric earth image, we might produce a zillion image cubes (each differing by members of the null space in our best estimate of $V(x, y, z)$). I'm joking of course. They don't want a zillion image cubes. They want us to get a single "right" value for the velocity and give them the "right" cube. Everything depends on it.

KJARTANSSON'S RESULTS

The primary reference for Kjartanson's results is his doctoral dissertation available as SEP report 23. Electronically, this thesis is at

`http://sepwww.stanford.edu/theses/sep23/`

A "digested" version of the thesis is in chapter 4 of my textbook IEI at

`http://sepwww.stanford.edu/oldreports/sep40/`

The particular section is available in html at

`http://sepwww.stanford.edu/sep/prof/iei/ofs/paper_html/node6.html`

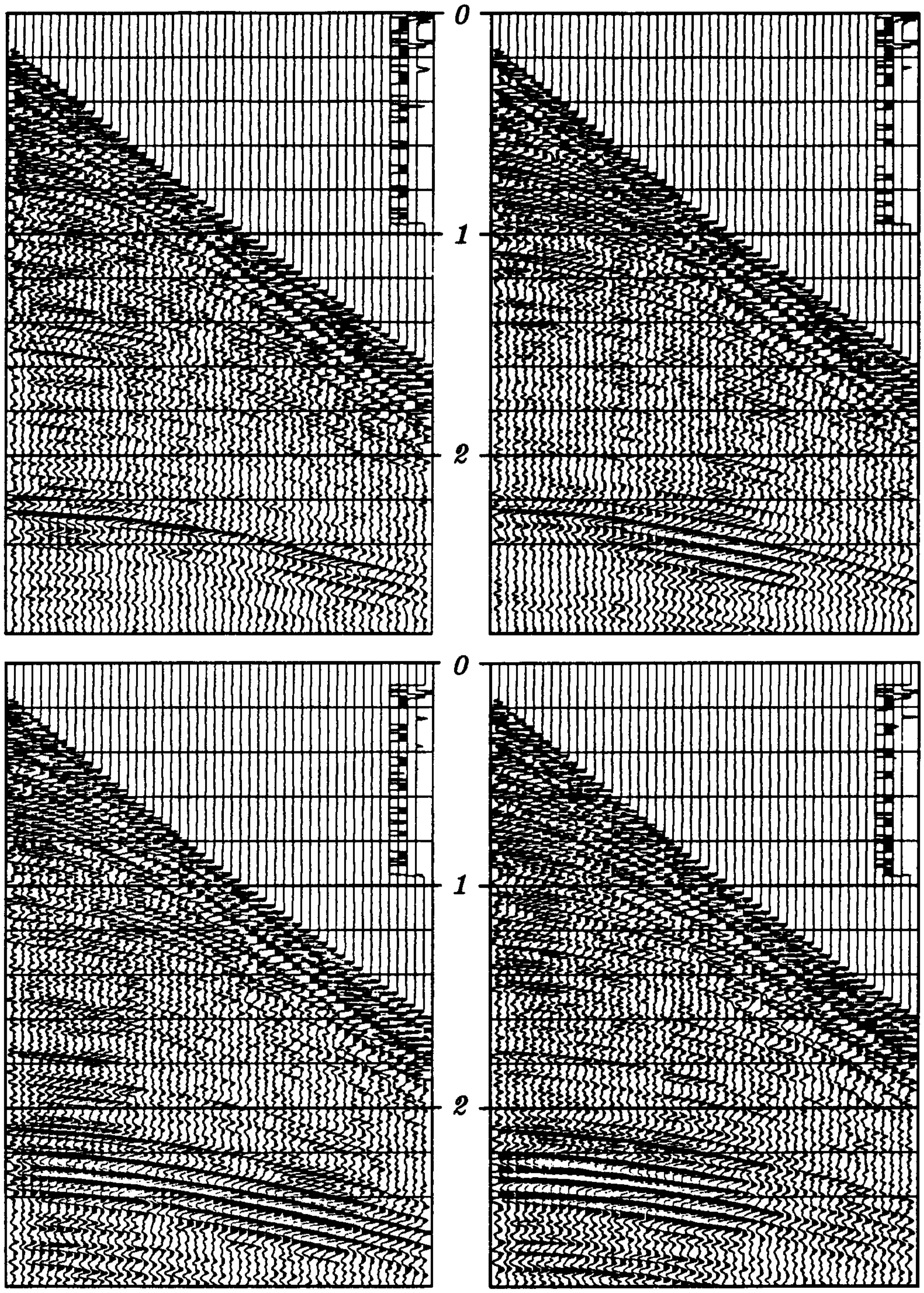

Figure 1: Top left is shot point 210; top right is shot point 220. No processing has been applied to the data except for a display gain proportional to time. Bottom shows shot points 305 and 315. The AVO is too large for realistic layered media models and it changes rapidly from one midpoint to another one nearby. jon1-kjcmg [NR]

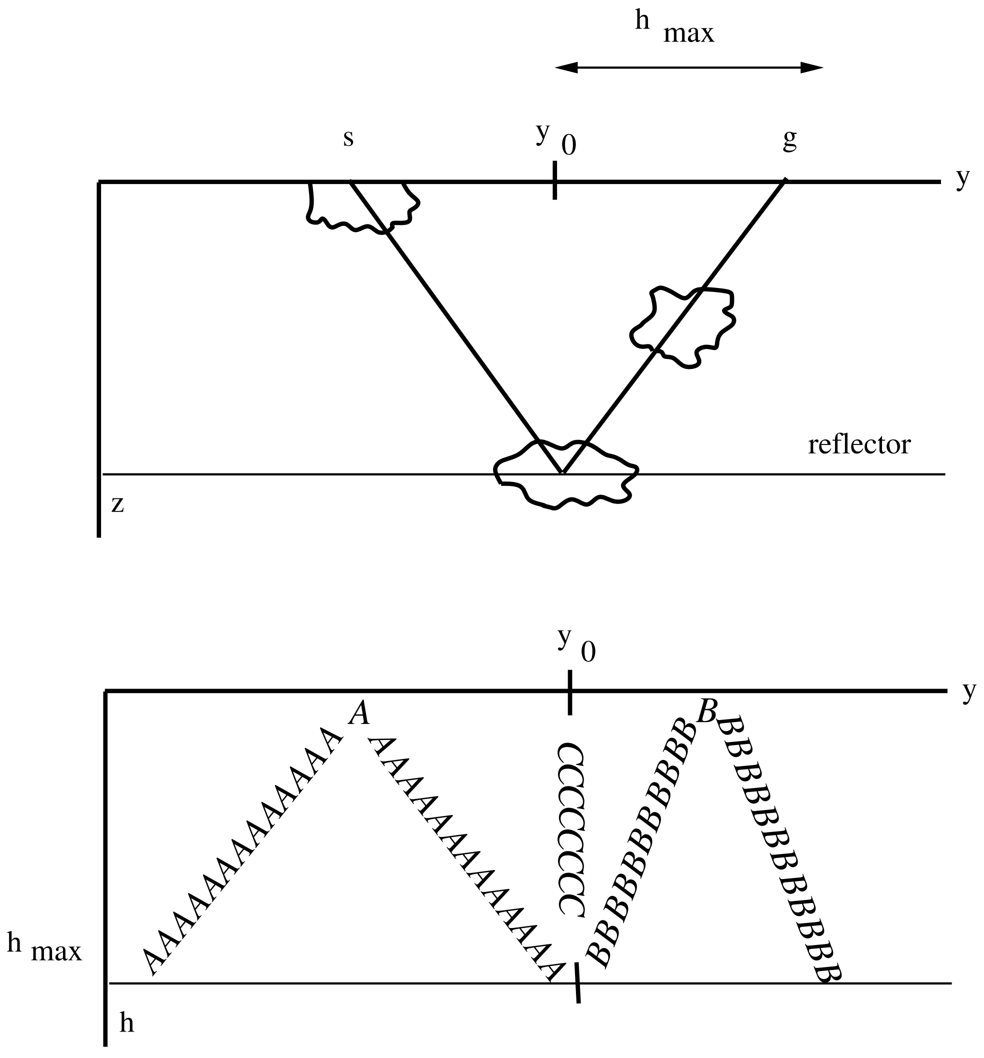

Figure 2: Kjartansson's model. The model on the top produces the disturbed data space sketched below it. Anomalous material in pods A, B, and C may be detected by its effect on reflections from a deeper layer. Midpoint is y. Offset is h. jon1-kjidea [NR]

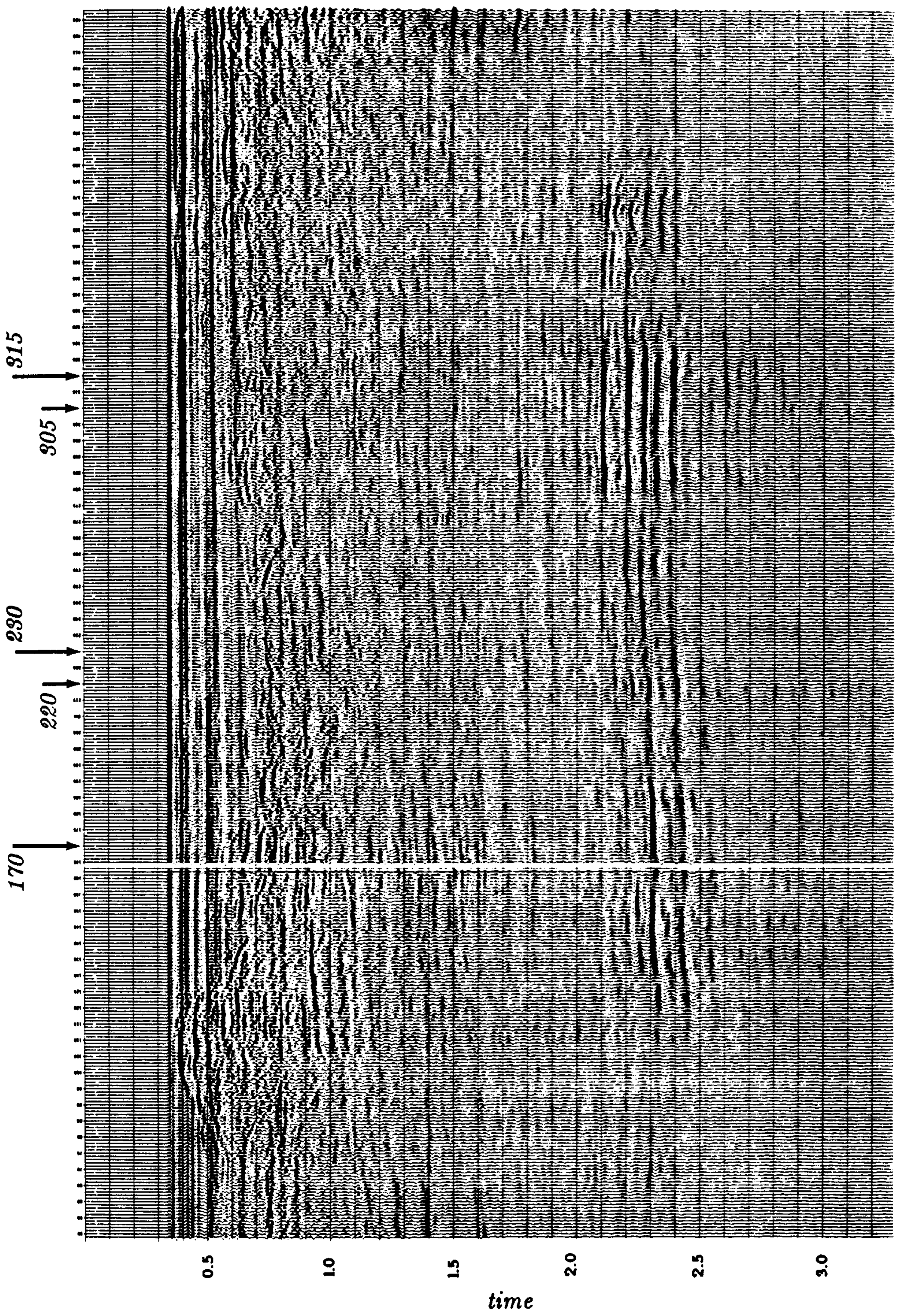

Figure 3: A constant-offset section across the Grand Isle gas field. The offset shown is the fifth from the near trace. (Kjartansson, Gulf) Notice that anomalous amplitudes are not limited to thin "reservoir thickness" zones. They tend to expand over the time axis. Notice a missing trace. jon1-kjcos [NR]

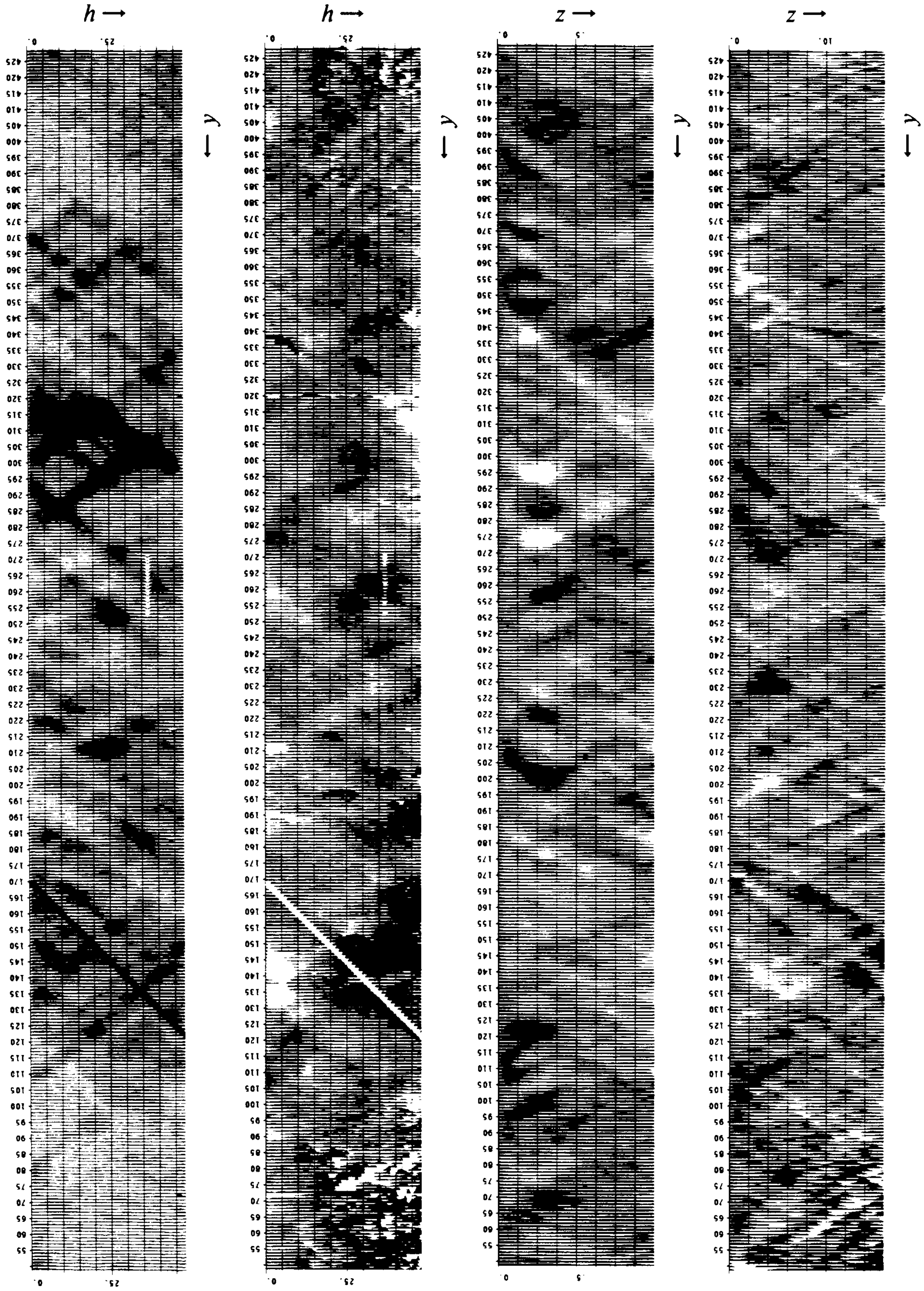

Figure 4: (a) amplitude (h,y), (b) timing (h,y) (c) amplitude (z,y), (d) timing (d,y) The missing trace anomaly shows up exactly at a 45 degree angle. Other anomalies are at lessor angles indicating their nonzero depth. jon1-kja [NR]