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The history of seismic resolution

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Measurements of achieved resolution on data recorded in 1941 show better resolution than typical data recorded in 2007, and the data in intervening years are generally consistent with the long-term trend, though there may be a slight increase in resolution from a low point in the 1970s. Possible explanations include the use of increasing reflection angles, increased use of surface sources, and the use of multiple-fold techniques.

Keywords: history, resolution.

Introduction

How have we done at improving the resolution of seismic reflection data over the last eighty years? The very first seismic reflections were recorded using techniques, determined by trial and error, which produced usable reflections. For the next few decades, field techniques were designed in the same empirical manner. Then, as seismic data processing became a reality, we began to develop a more scientific understanding of signal, noise, and how to separate the two. The objective of this paper is to measure how much we, as an industry, have managed to improve resolution.

Measuring resolution

Various measures of seismic resolution have been proposed over the years, but they are all based on the concept of the dominant period of a reflection event; so comparisons of the resolution of different data sets can be made simply by measuring the dominant period of reflections on the two data sets: the resolution is inversely proportional to the period. For example, a reflection with a dominant period of 20 ms has twice the resolution of a reflection with a dominant period of 40 ms.

This is not really helpful in comparing many data sets, though. Different surveys have different objectives: the field techniques for a survey (whether designed empirically, or designed scientifically to optimise resolution) always balance resolution, signal-to-noise ratio, and cost. A deeper target will usually have a longer dominant period than a shallow one in the same area. We needed a way to normalise the resolution measurements.

An empirical observation is that the frequency content of a seismic reflection is inversely proportional to the reflection time. So we propose a resolution constant K, given by $K = tf$, where t is two-way reflection time in seconds, and f is the dominant frequency of the reflection. This constant usually varies with time within a data set (so it is not really a constant), almost always increasing with reflection time. The variation takes place to some slight extent due to geology, but largely because field and processing techniques are usually designed for a specific target depth. Reflections shallower than this depth often have degraded resolution because the parameters are not optimum. Deeper reflections (if any) may have degraded resolution because increasing noise has been removed by filtering.

With many of the data sets used for this study we have had no information on the intended target, so we have simply measured the value of K for reflection from the shallowest visible reflections to the deepest reflections, and used the largest value, K_{max}, as the inherent resolution of the data set.

The data

A historical perspective on data requires historical data. We have used four basic sources:

- Current or recent projects on which we have worked. This has provided mainly data from about 2000 to 2007, but several projects gave us access to data as old as 1972. In general, confidentiality requirements prohibit us from identifying this data other than in very general terms.
- Published data: the published data we have used was recorded between about 1930 and 1985. In most cases we can identify the location of this data precisely, though the exact date of recording may be uncertain. We have only used data where we can determine its approximate age. Most of the data used came from:
    - Data lodged with the Australian Government from 1959 to 1974 under the conditions of the *Petroleum Search Subsidy Act* of 1957.
    - Old paper records donated to the museum committee of the Geophysical Society of Houston. We know exactly when these were recorded, because they have the date on each record, but because the records are usually separated from the support data we often do not know where they were recorded.

For the older data, there is no choice of the version: the paper record is the only record (see Figure 1). For data since about 1965, data which has had at least some processing, the form we have used is the processed data set which would have been used

Fig. 1. *Seismic data on paper records.*

for structural interpretation. In other words, we have not considered derived attributes at all, but have used stacked data when it is available, and migrated data when available. We did not attempt to use any of the modern data processing techniques which attempt to extract a sparse reflector sequence from a seismic trace.

The earliest data is all land data, mainly recorded in the Gulf Coast. The data from the late 1950s onward includes some from Australia and Africa. The data from 1980 and later includes recordings from several different areas, both onshore and offshore, including North America, Latin America, Asia and Africa.

Measurements

The measurement of dominant frequency had to be one which could be applied with equal validity to 2D paper records from the 1930s and 3D digital recordings from 2009. In effect we made all the measurements on paper, though for the recent data we made the measurements on an image, rather than on paper.

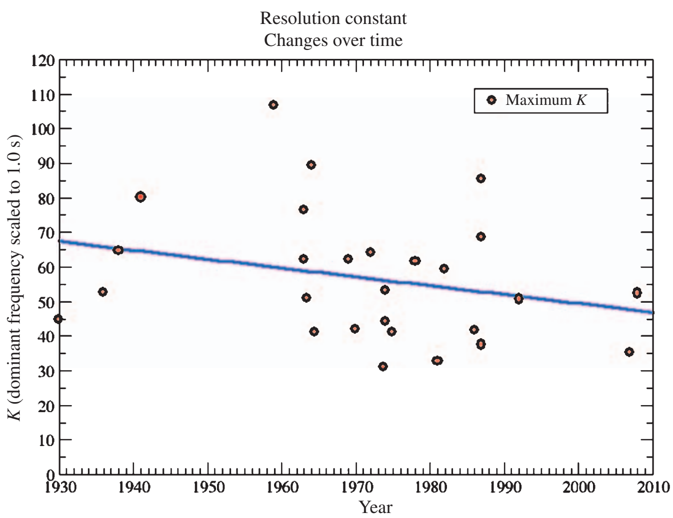

Fig. 2. *The changes of seismic resolution with time.*

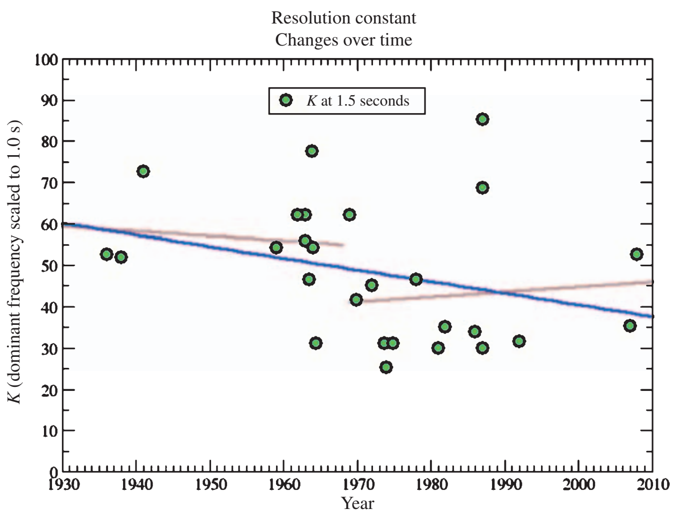

Fig. 3. *The changes of seismic resolution at 1.5 s since the 1930s.*

The actual measurement was a count of cycles – usually a count of either peaks or troughs – in a measured time interval, typically 0.1, 0.2 or 0.5 seconds, between timing lines. On the early data, we made a measurement on every trace of a record (all twelve of them). Once there was a record section, we measured at intervals along the section. In each case, we looked at reflections from the shallowest we could identify to about 4.0 seconds (or the end of the record or the deepest reflection).

A typical measurement found about 20 cycles total (with nine counts of cycles over a 0.2 s time interval) which gives a precision of ±5% for the measurement of *f*. The measurement of

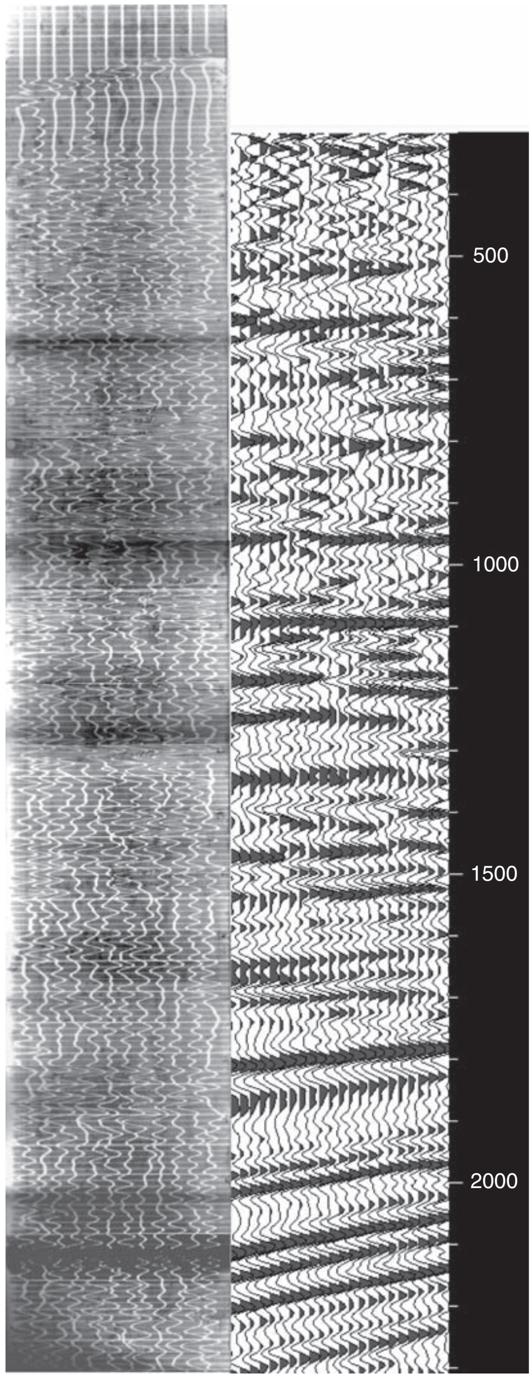

Fig. 4. *On the left, a land record from 1941, on the right, a marine 3D record from 2006. The display is scaled so that the times are the same on both recordings.*

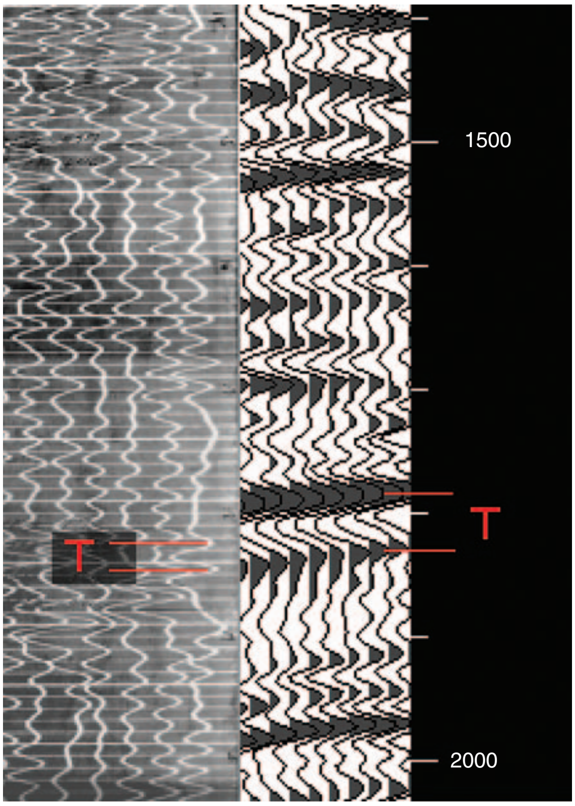

Fig. 5. *A closer look at the data in Figure 3. The period T of the reflection closest to 1.8 s is shown for each record.*

t, the centre of the time window, was better than ±1%, so the accuracy of K_{max} calculated from these measurements is about ±5%.

Results

The results are shown in Figures 2 and 3. In spite of all our technological advances over the years, seismic resolution has not improved. It even looks as if it has deteriorated. A direct comparison between 1941 and 2006 is shown in Figures 4 and 5. The 1941 recording is believed to be a shothole record from the Gulf coast, probably from Texas. The 2006 record is from offshore West Africa. Even if we try to make the comparison more equal by just considering the dominant frequency at 1.5 s

Fig. 6. *Historical field acquisition photographs.*

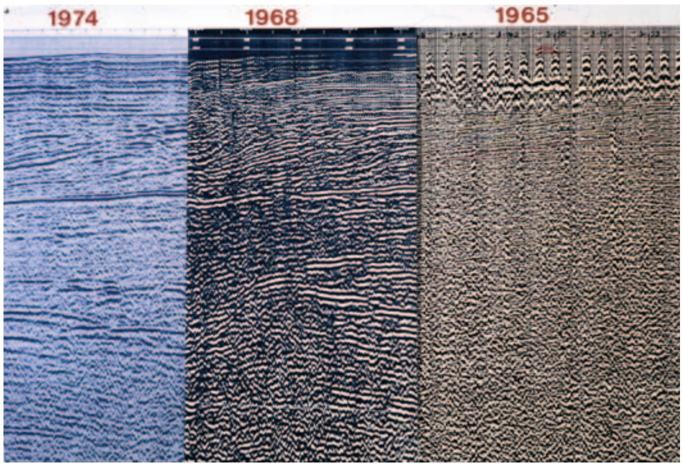

Fig. 7. *A comparison of three surveys in 1965, 1968 and 1974 along almost the same line in the offshore Gippsland Basin.*

(Figure 3), we find the resolution typically achieved in 2007 is worse than it was more than sixty years earlier.

Figure 3 shows the trend in resolution in two ways: the long term straight-line trend, and the data split into two segments: 1930 to 1968, and since 1969. This separates the data recorded single-fold (all the points before 1969) from those recorded multifold. While some data was recorded multifold before 1969, and some recorded singlefold after 1968, there is no overlap in the data sets we have been able to use for this study. With the exception of the abnormally low point in 1964, which used a vibrator energy source, all the data before 1969 is land data with a shothole energy source.

Discussion

For at least thirty years we have consciously tried to improve the resolution of seismic data (Denham, 1981; Knapp and Steeples, 1986; Taylor, 1989; Knapp, 1990; Levin, 1998; Blache-Fraser and Neep, 2004) – and it appears to be worse than it was before we were born. What has gone wrong?

Firstly, there are physical constraints on what can be done about improving resolution: the earth attenuates seismic signals in proportion to the number of wavelengths in the path (Schoenberger and Levin, 1978), so increasing resolution is inherently difficult. But this affects both old and new data equally, and today we have the advantage of many more techniques to improve resolution.

Table 1. Comparison of typical seismic survey parameters in the 1940s and 2000s

Parameter	1940s	2000s
Source	Shothole	Vibrator
Source array	Single point	Array
Receiver type	10 Hz EM geophone	8 Hz EM geophone
Receiver array	Single geophone	Array
Fold	100%	4800%
Geometry	2D	3D
Maximum reflection angle	15°	60°

The area where the data were recorded is also important. The Gulf Coast, where much of the old data comes from, is generally favourable for seismic resolution. But some of the new data is from offshore areas, where data is generally better in resolution than onshore.

Different field acquisition techniques are probably the most important factor (see Table 1 and Figure 6). There are valid reasons for changes in field techniques in the last seventy years, but almost all of these changes can reduce resolution.

The change from an explosive source in a drilled shothole to a surface source such as vibrators almost certainly reduces resolution: the signal has to pass through the near-surface velocity variations (which contribute much of the high frequency losses) twice instead of once. Associated with this is usually a large source array, which also acts as a high-cut filter (even under ideal conditions) for non-vertical propagation.

The receiver type has not changed drastically (in most cases – none of the data we had available used three-component digital detectors, which are now available): modern geophones are similar in response to those used before World War 2. But the new geophones are much smaller and generate much less distortion. That should allow better resolution; but the almost universal use of receiver arrays reduces resolution by mixing signals with varying time delays, with differences coming from the variation in normal moveout, in static correction, and in dip moveout across the array. The effect of this is shown by Sheriff and Geldart (1982, p. 151).

Single-fold recording does not mix data with different propagation paths; multifold recording does. While this is excellent for discriminating against many types of noise, even with perfect dynamic and static corrections (which are never achieved in real data) the signals being mixed will have different wavelets (due to the variation of a reflector's response with reflection angle).

The adoption of 3D techniques for many modern surveys has certainly improved the uniqueness of interpretation. But mixing data from varying azimuths without taking anisotropy into account is sure to reduce resolution, and the lack of short-offset, narrow-angle raypaths in many bins also reduces resolution.

The reflection angle is also important: early reflection surveys only recorded narrow-angle reflections; today, many surveys record reflection angles up to 60°. A reflection raypath at that angle can be up to twice as long as the raypath for coincident source and receiver, and the longer raypath inherently cuts high frequencies. A worse effect is the stretching of the wide-angle trace so that the reflection times coincide with the narrow-angle trace. Figure 7 shows a comparison of three surveys, where the improvement in reflection quality is obvious – but closer examination shows that resolution has actually decreased. The three sections are almost the same line, and are from the offshore Gippsland Basin.

Conclusions

Actual time resolution achieved in typical seismic exploration has not improved since 1930. There appears to be an abrupt drop in resolution at the time when multifold techniques were introduced about forty years ago, and since then there may have been a slow improvement in resolution; but the achieved resolution is still not as good as that achieved in the very earliest reflection surveys. Many of the techniques used to improve other aspects of the data – signal-to-noise ratio, horizontal resolution and lithology discrimination, in particular – probably limit time resolution. In most projects there is a trade-off between cost, resolution and noise. The chosen techniques always seem to result in similar resolution, and this suggests that the cost – in money or other desirable signal characteristics – of improving resolution beyond this level is very high.

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