THE USE OF EARTHQUAKE ENERGY FOR STRUCTURE TOMOGRAPHY IN THE NORTHERN UCAYALI BASIN

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SUMMARY

Anadarko Peru Company conducted a Microseismic experiment in Block 84 to determine if earthquake seismic energy can be used for structure tomography. Twenty-two arrays placed over a one thousand square kilometer area recorded the regional earthquake signals. A three-dimensional velocity cube with a 500-meter resolution was generated from the data using the Biconjugate Gradient Method. The velocity cube showed good agreement with the structural model generated from the reflection seismic data. The recorded earthquakes came from shallow sources above 60 km and from the subducting slab at a depth of 130 km. The earthquake data also shows that the major faults are active which may affect their ability to trap hydrocarbons. An interpretation of the earthquake distribution and two-dimensional seismic data is that the Andean Orogeny has produced several seismically active shear zones.

INTRODUCTION

Anadarko Peru Company conducted a microseismic experiment on Block 84 in the northern part of the Ucayali Basin to determine if naturally occurring earthquakes can generate seismic information that can be used for structure tomography. The region in and around Block 84 is a perfect area to conduct this experiment because of the area' s high seismic activity; Figure1 shows the historical seismicity for Peru. The contractor for this experiment was Resource Exploration and Development Services (REDS) of Boulder, Colorado and it was conducted with assistance from the Institute Geofisico del Peru (IGP).

Accurately located earthquakes can be used to determine both structural geometry and acoustic velocity, however, to determine both parameters simultaneously is a mathematically complex nonlinear problem. The best method to use is to start with an initial velocity model and then change the velocity model to minimize the travel time residuals (that is, the differences between predicted model travel times and the observed travel times). The Biconjugate Gradient Method is used to define the new structural model by iteratively inverting the travel-time residual data from the earthquakes to generate successively more realistic and refined velocity models. (Archambeau, 1996). The travel-time residual is the difference between an observed signal arrival time and a theoretically predicted arrival time based on a current velocity model for the zone of interest. As each iterative model is generated the earthquakes are relocated and the travel-time residuals are recalculated to be used in the next iteration for velocity structure. More detailed description of the seismic structure tomography method can be seen in Figure 2.

FIELD OPERATIONS

The northern part of Block 84 was chosen for this experimental program because the aeromagnetic data indicated that there was a high probability of an anticlinal structure being present there. That area was also where the reflection seismic operation began which helped to expedite some of the logistical issues.

The first phase of this program began on June 15, 1997 when three arrays were deployed in the experimental area to determine the quality of the earthquake signal. Each array consisted of three vertical component geophones deployed 100 to 200 meters away from a central three-component geophone. Each array was powered by a solar panel and the earthquake data were recorded on a disc drive in an instrument vault (Figure 3).

The first phase recording showed that several earthquakes of various magnitudes were occurring each day. These earthquakes came from both shallow fault movement and from the subducting slab under the block at a depth of approximately 130 km. Most of the earthquakes had a high frequency content with a very good signal to noise ratio. The excellent signal quality led Anadarko to conduct a more detailed recording effort in the next phase.

The Phase II effort began with the deployment of an additional 17 arrays on October 27, 1997. These arrays were left in the field until April 20, 1998. The arrays were deployed with no tree cutting and with minimal disturbance to other plants. The equipment was transported to each location using helicopters and boats. The data recorded on disk were manually downloaded once every 10 to 15 days by a technician visiting each array. The equipment was robust and required little maintenance; the biggest problem in the field was theft of the equipment, particularly batteries.

EXPERIMENTAL RESULTS

Several thousand earthquakes were recorded in the northern part of Block 84 in the six-month Phase II period. Figure 4 shows that the earthquake population is divided into two main families: the shallow earthquakes at depths of 0 - 60 km and the earthquakes associated with the subducting slab at a depth of 120 – 140 km. Figure 5 shows the earthquake distribution (dots) in the northern part of Block 84. The numbers associated with the earthquake locations are the depths in kilometers to the earthquake focus. The recorded earthquake data was sent to Boulder, Colorado where the " first break" times for both P and S waves were picked and the earthquake raypaths were calculated. These data were then used to evaluate a structural model.

A two-dimensional reflection seismic program was conducted concurrently with the microseismic program. Figure 6 shows seismic line 97W84-01, which is a 90-fold reflection line that was shot across the microseismic test area. The seismic line was shot with a 4500m-split spread cable using a 4 kg dynamite charge, which yielded good quality reflections down to eight seconds. Line 97W84-01 shows a large structure that was uplifted during the Miocene known as the Rio Calleria structure. The red reflector is the top of Cretaceous, the blue reflector is the Base Cretaceous unconformity and the green reflector is the top of basement. A Base Cretaceous structure map (Figure 7) was constructed from the new and old reflection seismic; this map shows that an anticline can be drawn where the large structure seen on line 97W84-01 rolls into the thrust fault at shotpoint 1920. Since the reflection seismic data is sparse in this area, the microseismic data was used in an attempt to verify the existence of the structural closure and the fault trends.

A velocity model for the northern part of Block 84 was constructed from the Base Cretaceous map in order to perform the velocity inversions using the earthquake data. The constant interval velocities used for the model were:

Tertiary Section:	2240 – 2400 m/sec
Cretaceous and Pre-Cretaceous Section:	3100 m/sec
Basement:	5100 m/sec

Note that the Tertiary interval velocity changed because of varying thickness due to erosion.

Nine hundred and seventy of the best located earthquakes were used in the inversions. The earthquake data altered the initial velocity model. Figure 8 shows Time-Depth curves for the same area constructed from the original velocity model, the final velocity model, and from seismic velocities from line 97W84-01, shotpoint 1869. Notice that the earthquake Time-Depth relationship is slower than the original velocity model because of a slower measured Tertiary interval velocity. Figures 9a and 9b are North-South and east-west final P-wave velocity sections through the Rio Calleria structure showing the 0.5 to 2 km velocity blocks produced by the inversions. The Base Cretaceous section could be found at depths of1.8 – 3.0 km in these sections. Figure 10 is a horizontal P-wave velocity slice at –2.2 km. The blocky nature of the velocities seen in these figures are partially due to the structural features that occur in this area, but they are also due to the concentration of earthquake raypaths that occur within each block. The more raypaths that traverse a block, the more accurate the interval velocity is in that block. If the initial velocity model is wrong and the velocity volume has not been fully altered by the earthquake data due to incomplete sampling of the volume, the velocity figures will have this sort of blocky appearance. Figures 9a, 9b and 10 show that more recording of the earthquakes were needed. Although the arrays were in the field for six months, equipment problems (particularly theft of batteries) prevented the continuous operation of the arrays over the entire six month period. The final velocity volume was used to convert the Base Cretaceous Time Structure Map (Figure 7) into a depth map. Figure 11 shows the resulting depth map below the +100 m seismic datum. The mottled appearance of the map is also due to the incomplete sampling of the velocity volume with the earthquake raypaths. Notice the indention in the Rio Calleria structure on the map at shotpoint 1860 which corresponds to the indentation seen at the Base

Cretaceous level on line 97W84-01. This feature was ignored in the Time Structure map and the initial velocity model, yet the inversion process using the earthquake data was apparently able to produce this feature in the depth map. This correction of the model shows that a crustal volume adequately sampled with earthquake data should produce accurate structure maps.

The short recording times made it impossible to map individual fault trends by using earthquake locations. However, two main earthquake populations can be seen at depths of 20-40 km and 130-140 km (Figure 4). The 130-140 km earthquakes are associated with the subducting slab beneath Block 84. The earthquakes recorded at the 20-40 km depths seem to occur uniformly on a map view over the northern part of Block 84. This uniform distribution of earthquakes suggests that a slightly dipping shear zone exists at a depth of 20-40 km. The two-dimensional seismic reflection data show that many of the thrust faults that cut the sedimentary section coalesce into a common surface in the Basement. An interpretation of all of these data is that the Andean Orogeny has produced several shear zones in the earth' s crust, each of which can produce earthquakes.

The high rate of seismic activity in the northern part of the Ucayali Basin raises concerns about the ability of faults to trap hydrocarbons. It is postulated that the largest hydrocarbon volumes will be found in anticlines that are not cut by seismically active faults.

CONCLUSIONS

1) Earthquake energy can be used to generate velocity volumes and structural images. However, the technology used to do this is new and expensive; costs must come down in order to make it an economic alternative to conventional reflection seismic data.

2) The northern part of the Ucayali Basin is very seismically active which raises concerns about the ability of faults to trap hydrocarbons. It is postulated that the largest hydrocarbon volumes will be found in anticlines that are not cut by seismically active faults.

3) An interpretation of the earthquake location distribution and the two- dimensional reflection seismic data is that several shear zones exist in the crust as a result of the Andean Orogeny. The most seismically active zones can be found at depths of 20-40 km and 130-140 km.

TECHNICAL CONTRIBUTION

Earthquake energy can be used to generate a velocity volume for structural tomography. This velocity volume combined with two-dimensional seismic data can produce structure maps for oil exploration.

REFERENCE

Archambeau, Charles (1996), Passive Structure Tomography: Analytical Framework, Technology and Resource Assessment Corporation Technical Report, Boulder, Colorado.

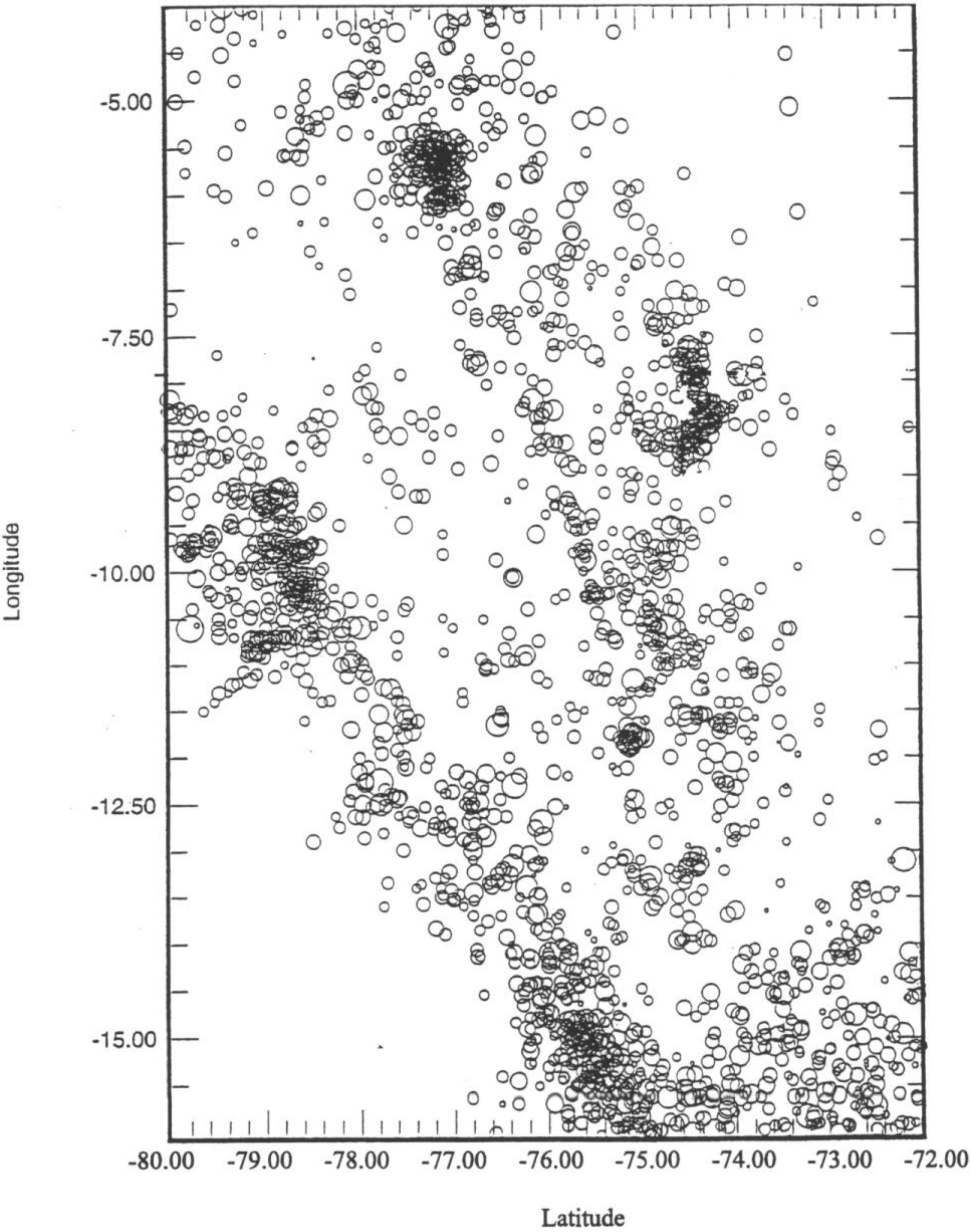


Figure 1 - Seismicity for larger magnitude earthquakes (above 4.5) in Peru.

FIGURE 2

P Wave Velocity Structure Tomography

The procedure used to determine seismic velocity structure from earthquakes involves solving for corrections to a starting velocity model using the observed travel time residuals. The residuals are the differences between predicted model travel-times and the observed travel times. The inversion equation in matrix form is:

$[\tau]\ (\partial V/V) = -[\delta T]$

$\delta T = T_{observed} - T_{theoretical}$

δT is a column matrix of length N of travel time residuals.

$\partial V/V$ is the fractional change in a model cell's velocities that produce the residuals δT.

$[\tau] \Rightarrow$ an MXN matrix composed of elements that are the partial travel times of the P wave signals through individual cells for the source-receiver signal ray paths represented in δT. $[\tau]$ elements are zero if the cell is not traversed by an earthquake source-receiver raypath.

The inversion procedure solves for $(\partial V/V)$ by inverting $[\tau]$. This is done through several iterations where approximate travel times in a cell are computed from the starting velocity model. An inverse τ is then computed by the Biconjugate Gradient Method.

From Archambeau (1996)

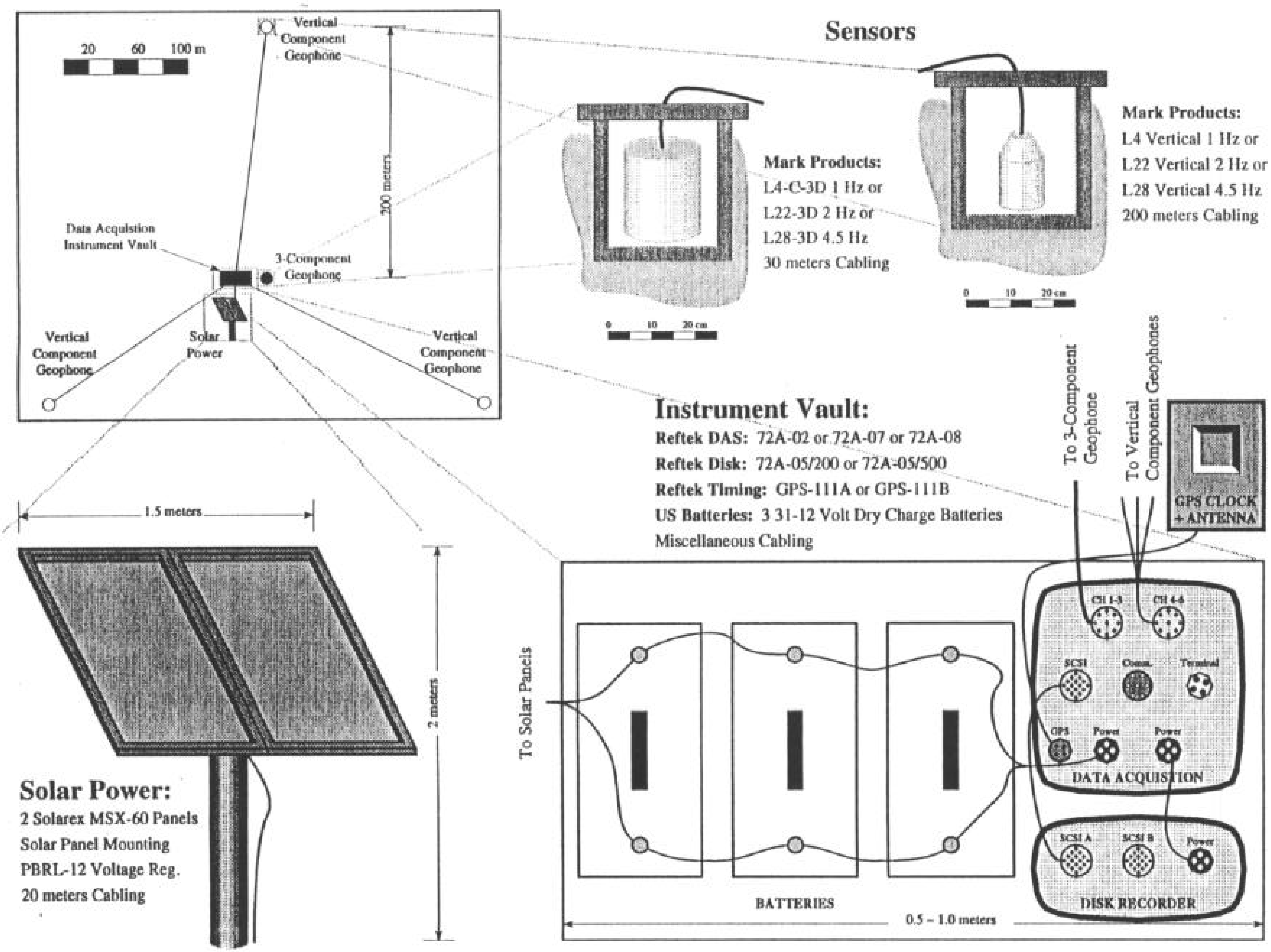


Figure 3 - Detailed schematic of a typical Micro-Array.

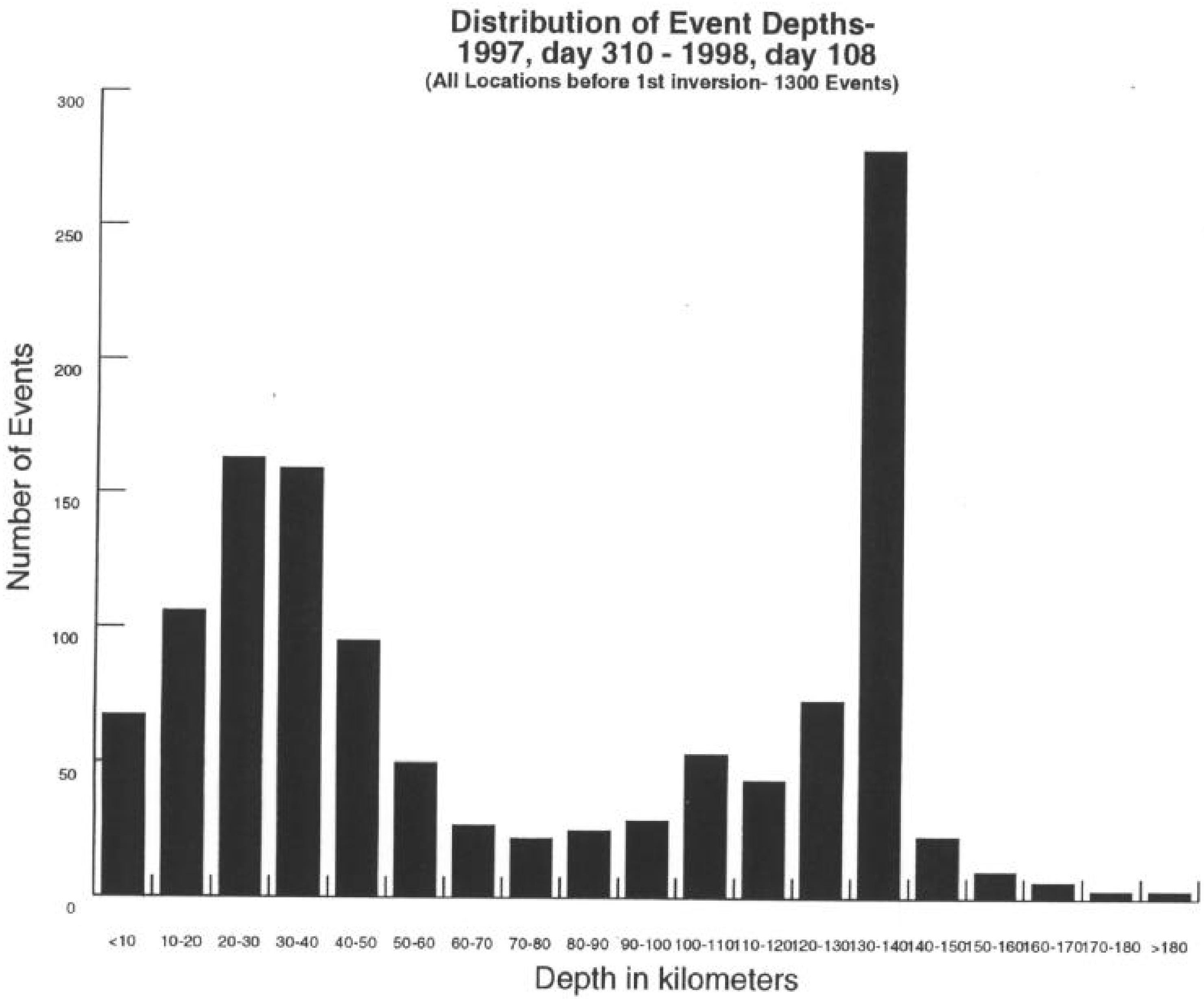


Figure 4 - Depth distribution of all the located earthquakes detected (1300 events.). The peak at large depth (at about 135 km) is at the top of the subducting plate.

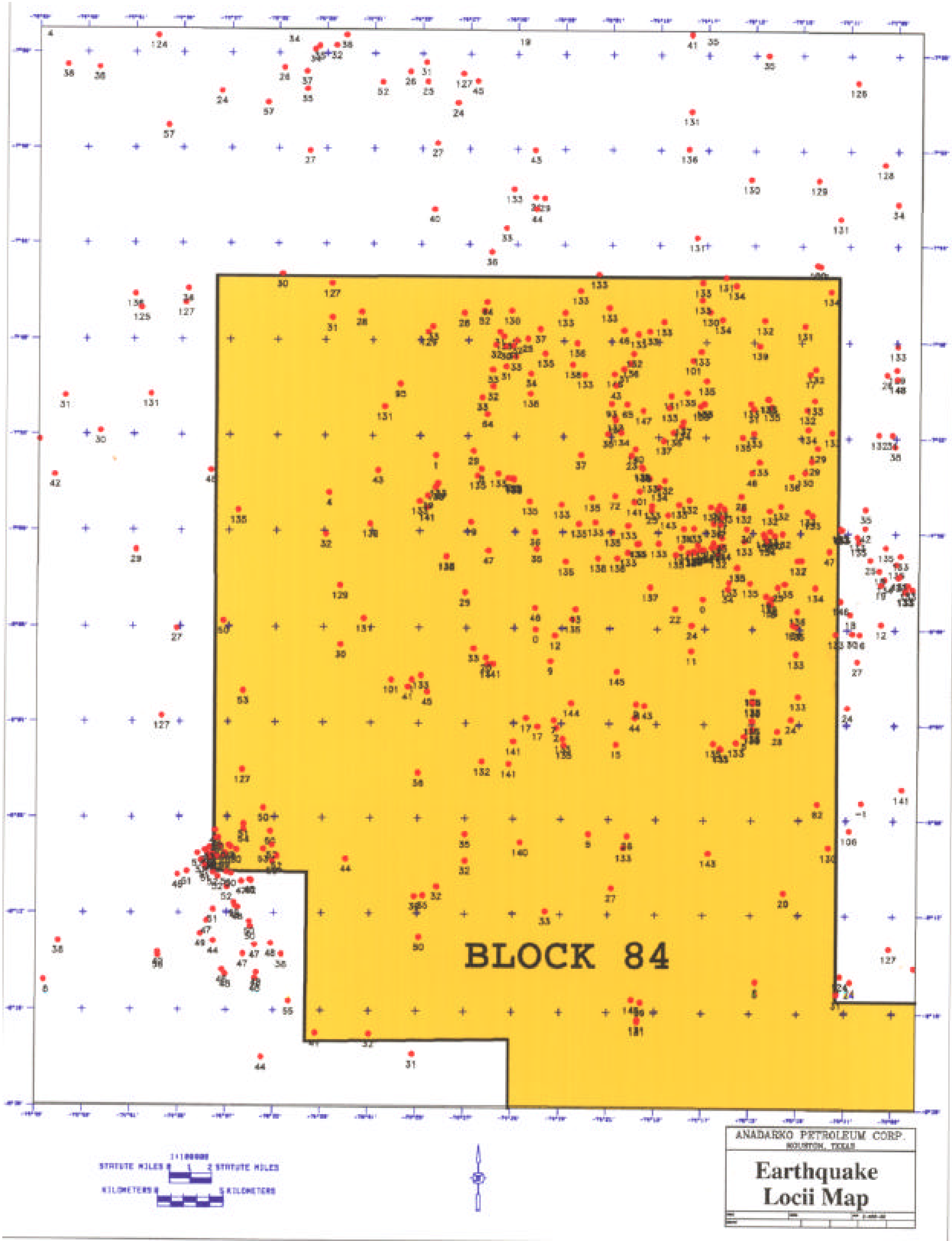
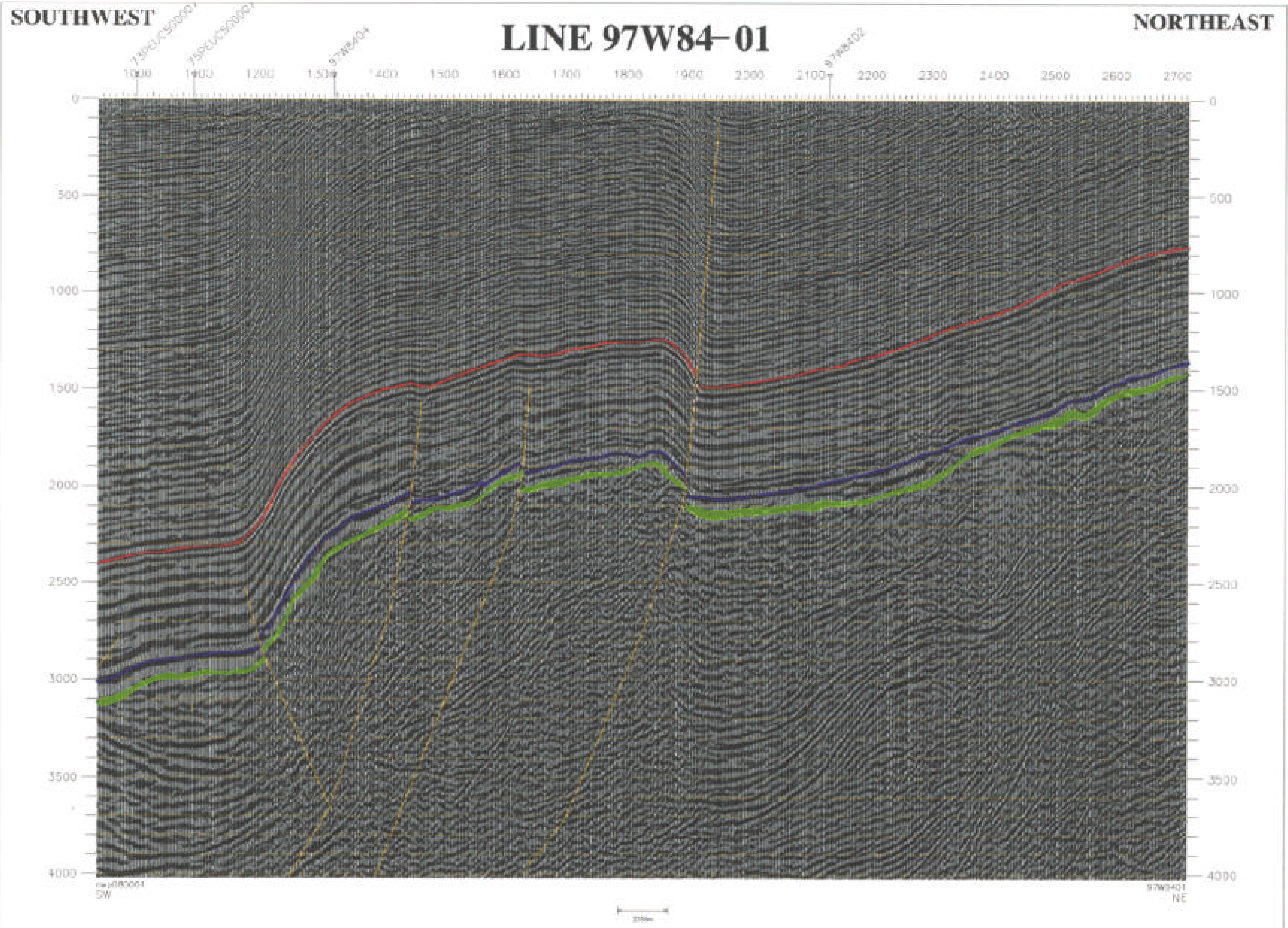


FIGURE 5: Distribution of Earthquakes associated with the subducting slab. Numbers are the depth of the Earthquakes in kilometers from a 300 meter datum.


SOUTHWEST
NORTHEAST
LINE 97W84-01
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
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2500
2600
2700
0
500
1000
1500
2000
2500
3000
3500
4000
SW
NE

FIGURE 6

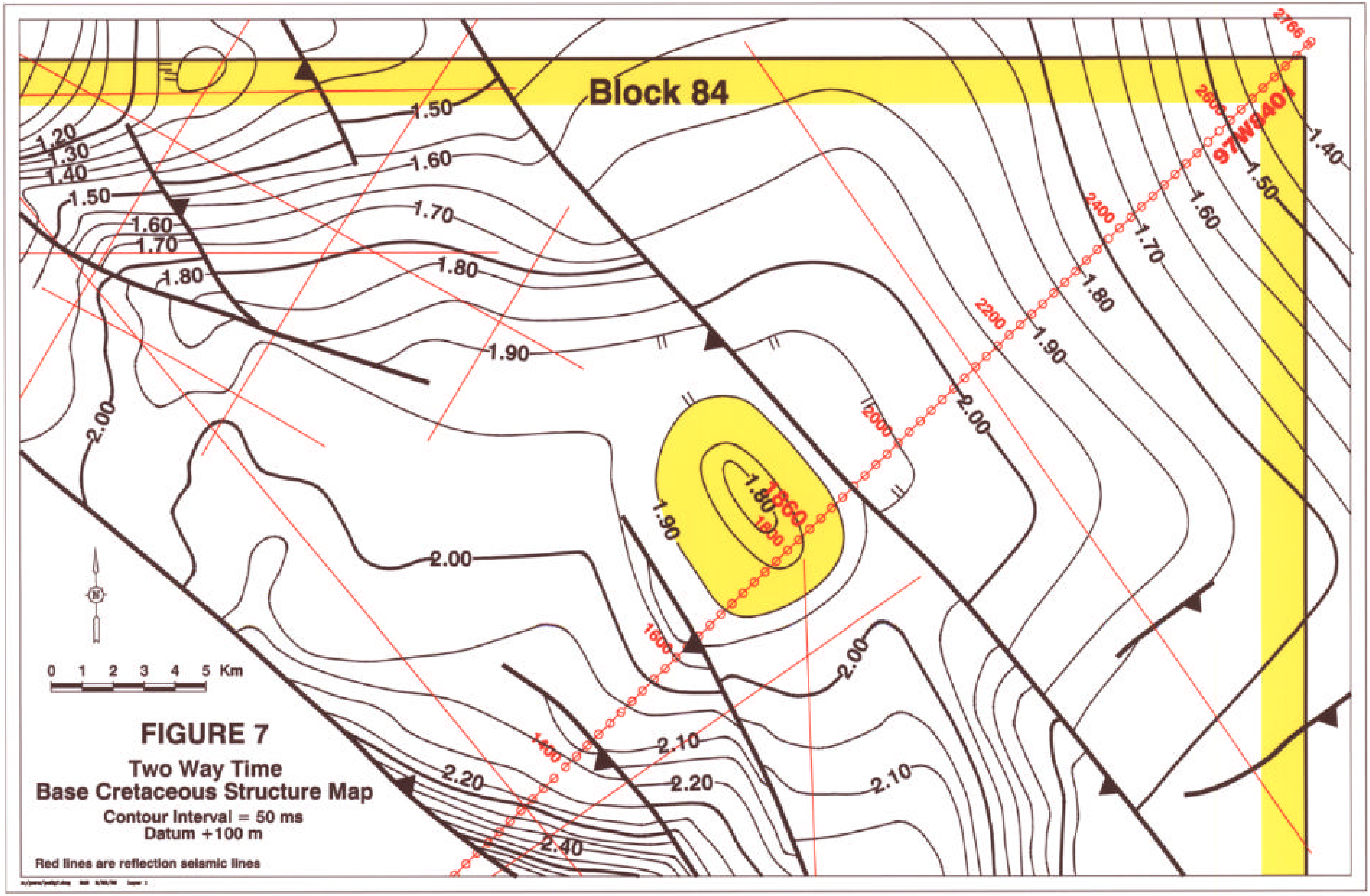
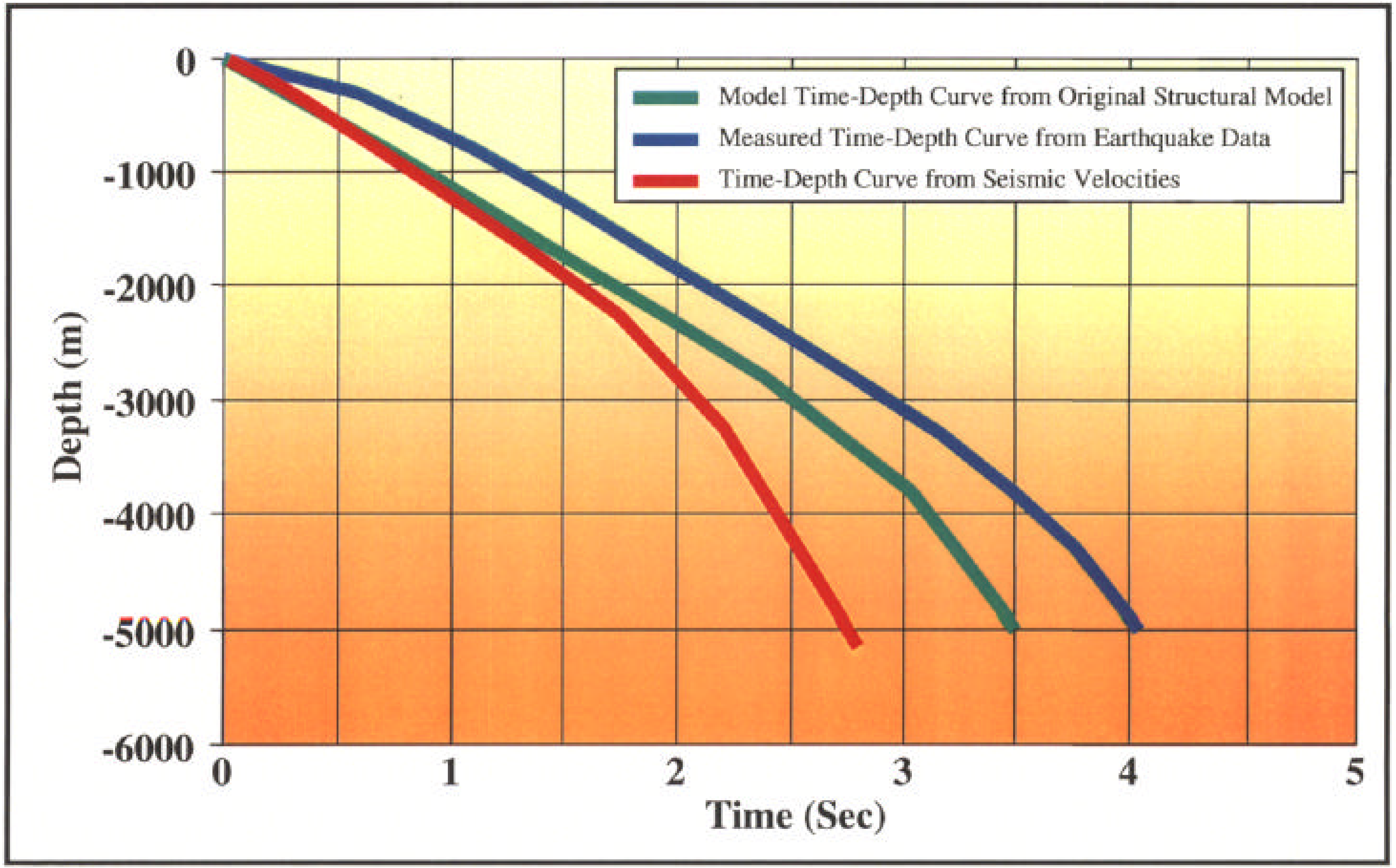

Block 84
97W9401
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20
2.40
0 1 2 3 4 5 Km
FIGURE 7
Two Way Time
Base Cretaceous Structure Map
Contour Interval = 50 ms
Datum +100 m
Red lines are reflection seismic lines

FIGURE 8

Time Depth Curves



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The Time depth curves are set to the reflection seismic datum of +100 meters.

FIGURE 9A: Inline 84, an east-west P wave velocity vertical section through the Rio Calleria structure. The section is 40km long and 10.5km deep. Velocity color values are in meters/second.

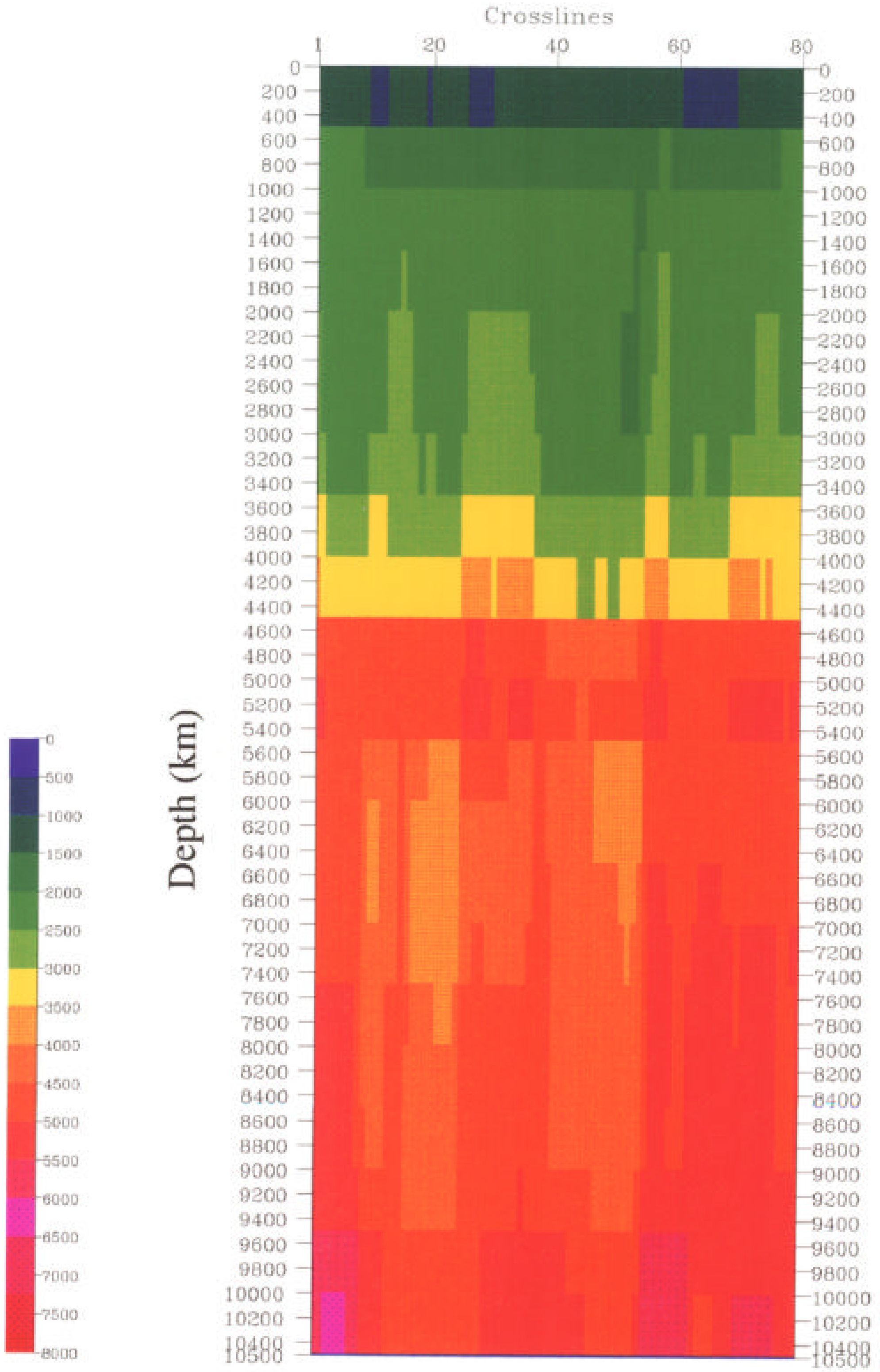


FIGURE 9B: Crossline 34, a north-south P wave velocity vertical section through the Rio Calleria structure. The section is 60km long and 10.5 km deep. Velocity color values are in meters/second.

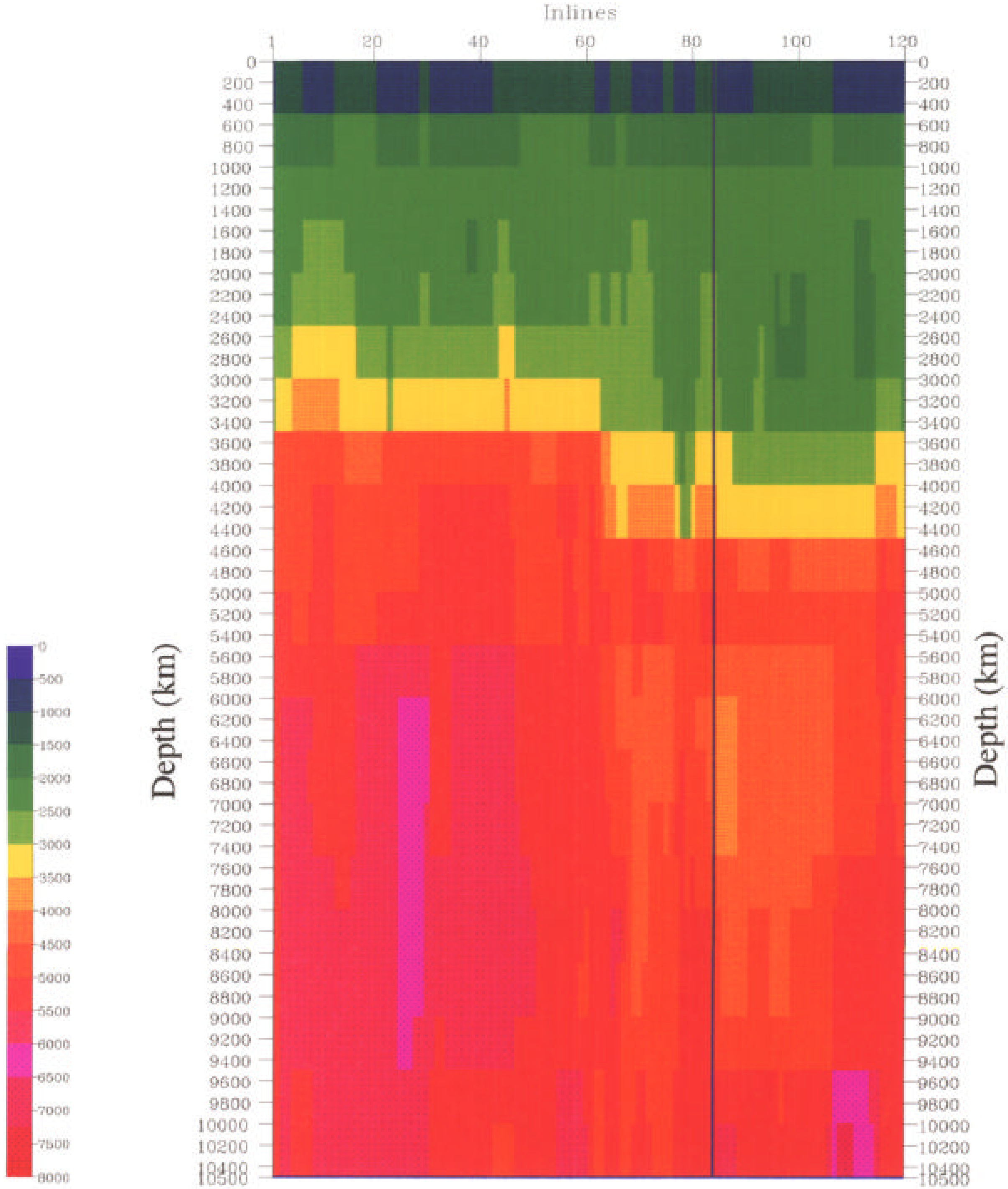
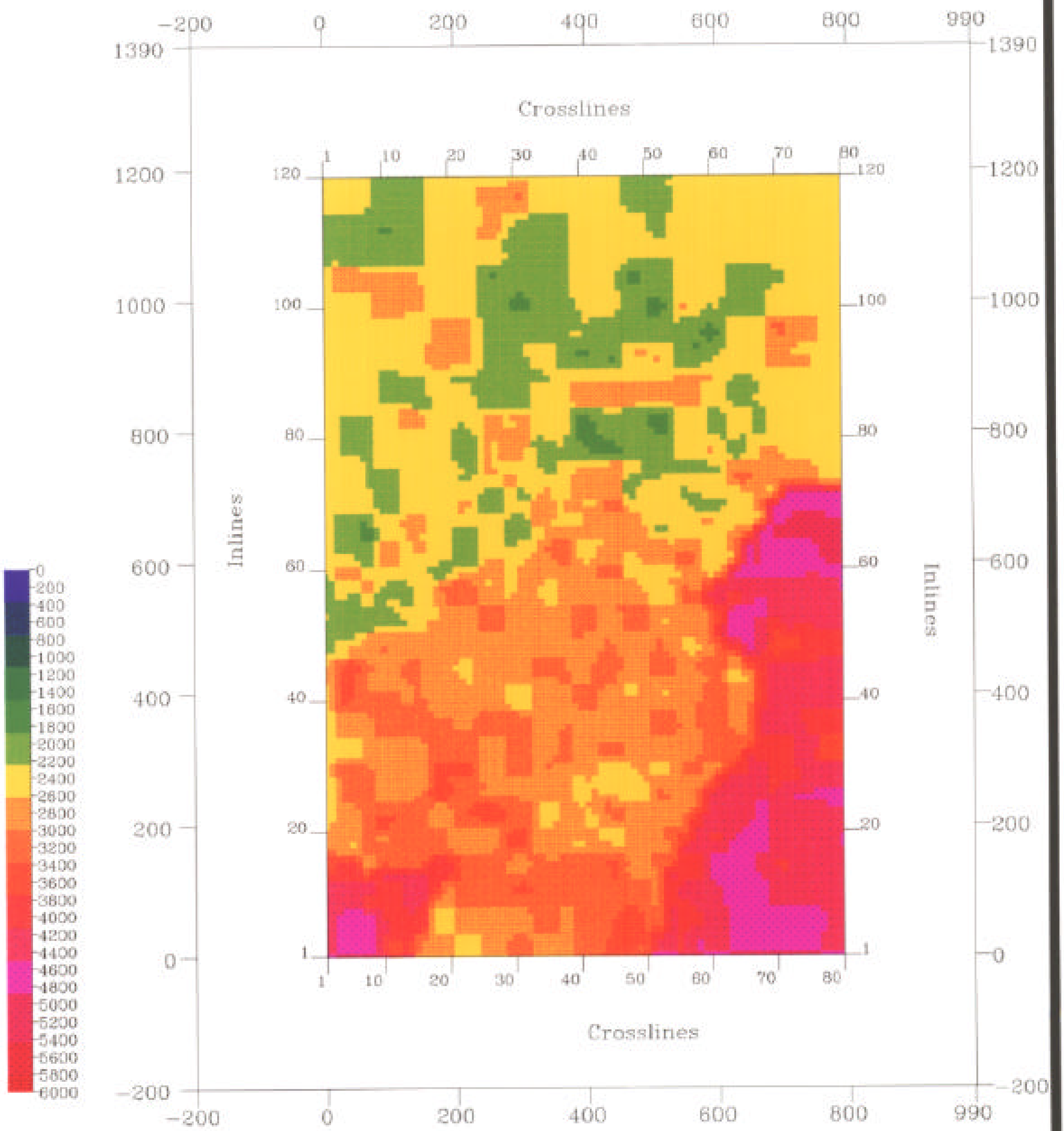
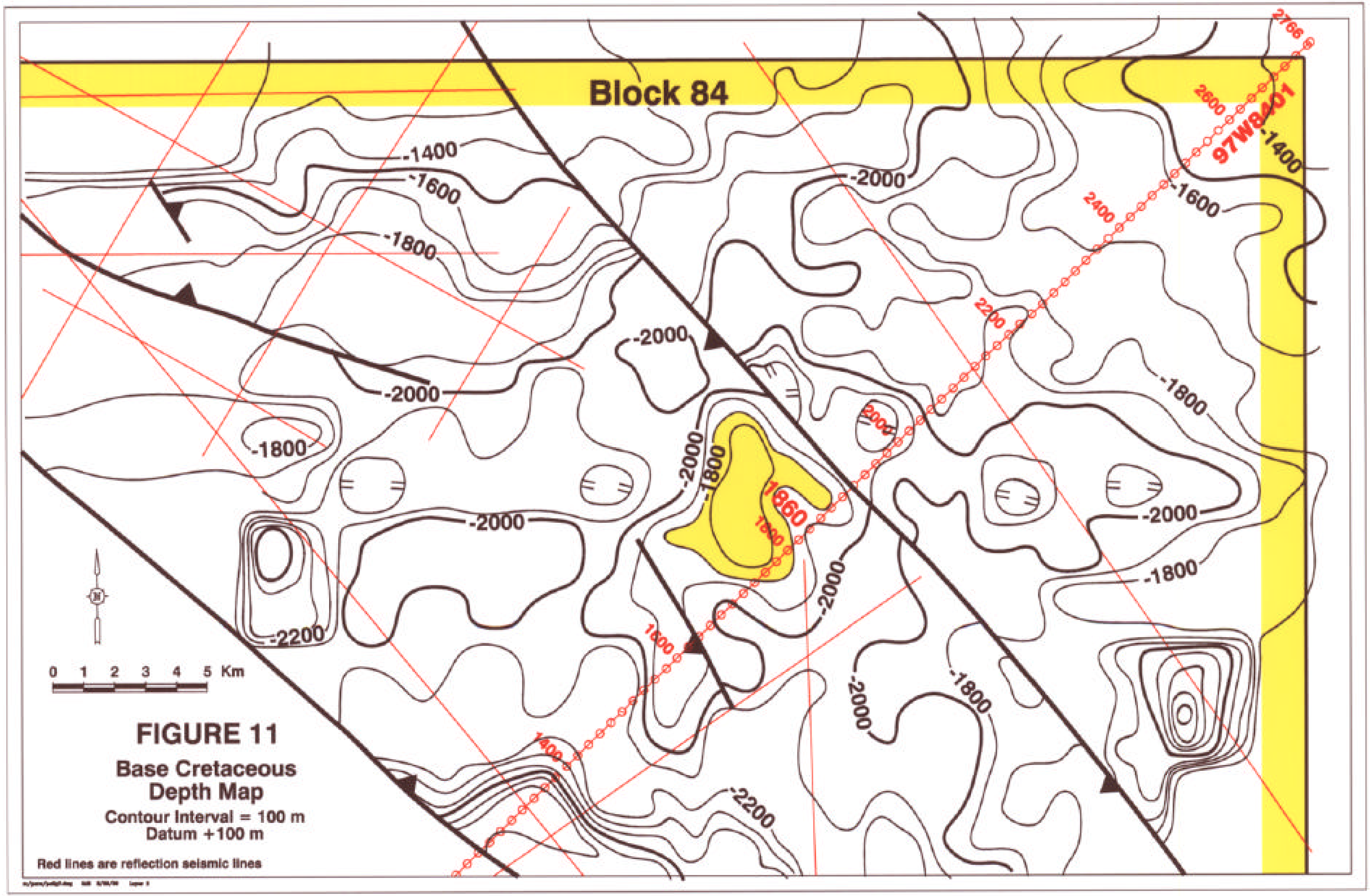


FIGURE 10: This is a horizontal section at 2.5km (2.2km subsea) showing the P wave velocity values for the 40 x 60 km section. The color velocity values are in meters/second.




Block 84
97W8401
2766
2600
2400
2200
2000
1860
1800
1600
1400
-1400
-1600
-1800
-2000
-2200
0 1 2 3 4 5 Km
FIGURE 11
Base Cretaceous
Depth Map
Contour Interval = 100 m
Datum +100 m
Red lines are reflection seismic lines