GEOLOGICAL SURVEY OF CANADA

OPEN FILE 1728

REPROCESSING OF INDUSTRY DATA OF THE NORTH NAHANNI REGION: IMPLICATIONS FOR THE INTERPRETATION OF THE NAHANNI EARTHQUAKE SEQUENCE

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Canada

1988

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Abstract

The proximity of a 1970 industry seismic profile to the 1985 Nahanni earthquakes (Ms 6.6 and 6.9) led the Geological Survey of Canada to reprocess the original data to obtain improved structural information about the Nahanni region of the Mackenzie mountains. Despite of the poor data quality, the reprocessing enhanced shallow reflectors. The interpretation of the English Chief anticline suggests that the position of its crest is different from the geological map. Deeper (7.5 km approx.) reflectors are seen for some of the shots. These reflectors may suggest that the sedimentary succession is at least 7.5 km thick in the Nahanni region.

A first break analysis of shot gathers defined near-surface zones of high velocities (approx. 6.0 km/sec) and of low velocity (approx. 4.5 km/sec) along the seismic profile. These velocity values are closely tied to the geology; the high and low velocities correspond to the Middle Devonian carbonates and to the Upper Devonian shale and sandstone, respectively. Station time delays are proposed to correct for the homogeneous velocity model by which the hypocentres are calculated.

In addition, supplementary geophysical and geological work is suggested. A new seismic reflection profile should be conducted in the Nahanni region to probe the deeper crustal structure of the region (5-10 km). Geological mapping of the region should be done on a more detailed scale with special attention on the structural geology. Finally, ground gravity and magnetic surveys should be conducted to complement the geological mapping of the area.

For future work at the GSC, the original industry data set and the related information has been documented.

Résumé

Ayant considéré la proximité d'un profil sismique industriel réalisé en 1970 par-rapport aux deux tremblements de terre de Nahanni de 1985 (Ms 6.6 et 6.9), la Commission géologique du Canada a décidé de retraiter les données de ce profil, afin d'extraire des informations structurales supplémentaires sur la région de Nahanni des monts Mackenzie. En dépit de la piètre qualité des données, le traitement a mis en évidence des reflecteurs peu profonds. L'interprétation de l'anticlinal English Chief suggère que la position de sa crête est différente de celle indiquée par la carte géologique. Des réflecteurs plus profonds (7.5 km approx.) sont notés pour certains tirs. Ces réflecteurs suggèrent une épaisseur d'au moins 7.5 km pour la séquence sédimentaire dans la région de Nahanni.

Une analyse des premières arrivées des regroupements de tirs définit des zones de grande vitesse sismique (6.0 km/sec approx.) et de basse vitesse sismique (approx. 4.5 km/sec) le long du profil. Ces valeurs de vitesse sismique sont liées à la géologie: les hautes et basses vitesses correspondent aux carbonates du Dévonien moyen et supérieur respectivement. Des corrections de temps sont suggérées pour compenser pour le modèle homogène de vitesse qui est utilisé pour localiser les hypocentres.

De plus, des travaux géophysiques supplémentaires sont suggérés. Un nouveau profil de sismique-réflexion devrait être effectué dans la région de Nahanni afin de sonder la structure crustale plus profonde de la région (5-10 km). Une cartographie géologique plus détaillée de la région devrait être faite, en protant une attention particulière à la géologie structurale. Finalement, des levés de terrain gravimétriques et magnétiques devraient être effectués afin de compléter la couverture géologique de la région.

Pour référence future à la CGC, les données industrielles originales et les informations pertinentes sont maintenant documentées.

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1- INTRODUCTION

The Foreland Fold belt of the northeastern Cordillera is an area where the links between seismicity and geological features need to be clarified. In October and December 1985, two large earthquakes of magnitude Ms 6.6 and 6.9 respectively occurred in the North Nahanni River region of the Mackenzie mountains, N.W.T. Weichert et al. (1986) showed that the main shock of December 23 initiated at 6 km depth. Wetmiller et al. (1988) concluded that the rupture propagated down to at least 10 km. The aftershock zones were largely confined between the English Chief Anticline and the Iverson thrust at depths from 4 to 16 km. The mapped thrust faults of the area were not associated with the main shocks or the aftershocks (Figure 1). Instead, a buried fault ("blind thrust") was suggested to explain the location of the aftershocks beneath an area without mapped faults (Wetmiller et al. 1988). Thus, any seismic reflection data for this area would be of prime importance to show a link between the seismicity and the deeper geological structures of the aftershock zone.

In the early 1970's, seismic profiles were conducted in the Foreland Thrust of the Mackenzie Fold Belt by many different oil companies. In the North Nahanni region, Texaco Exploration Canada Ltd carried out a seismic reflection profile to study the "English Chief Dome Structure".

Their seismic reflection line is located within 20 km of the two Nahanni epicentres (Figure 2) and was expected to provide geological information for the deep structure of the area. The seismic data set was obtained from Texaco by the GSC for analysis. This report presents the original industry seismic profile, its reprocessing, and the interpretation of the results. The first section will introduce the geology of the epicentral region and the location of the profile in respect to the epicentres. The second section will present the original data acquisition, processing and interpretation of the profile. The third section will deal with the reprocessing sequence that was used by the GSC. In the fourth section, an interpretation of the results with their implications for the interpretation of the Nahanni earthquake sequence will be presented. Finally, recommendations will be made for future work in the Nahanni region.

2- GEOLOGICAL CHARACTERISTICS AND ORIGINAL DATA

2.1 Geological Characteristics of the North Nahanni Region

The Mackenzie Plain, where the seismic profile is located, constitutes a structurally quiescent zone with some broad gentle folds and one major thrust fault (the Iverson Thrust). The almost flat-lying sedimentary formations of the area suggest that the Mackenzie plain may not represent a decollement zone but a plateau without important faults. However, the English Chief Anticline that parallels the Iverson Thrust could possibly represent the surface expression of a blind thrust (Wetmiller et al., 1988).

The geological units can be grouped into three major groups of rock; the Precambrian crystalline basement; the thick sequence of Proterozoic sedimentary rocks; and the Paleozoic carbonate and terrigeneous rocks (de Wit et al., 1973). The Precambrian basement is not exposed in the immediate region but from deep wells in the Interior Plain, it is known that the basement is probably of granitic and metamorphic composition similar to the Bear and Slave Geological Provinces. The Proterozoic sedimentary sequence is composed of shale interbedded with sandstone and dolomite. There is no basement-Proterozoic sedimentary rocks contact exposed in the region. Consequently, the total thickness of the Proterozoic sequence can only be approximated to be between 3.0 and 5.0 km. The Paleozoic succession is made of approximately 3.0 to 4.0 km of carbonate rocks (dolomite, limestone) and terrigeneous rocks (sandstone and shale). The carbonate sequence was deposited between Cambrian and Middle Devonian times (580-345 m.y.). The carbonates are locally covered by the weathered Upper Devonian shales of the Fort Simpson Formation and by some undifferentiated sandstone. The thickness of this cover varies between 0 and 0.8 km due to its local removal by erosion.

The Paleozoic stratigraphy of the area is certainly more complicated than previously assumed. The original geological mapping of the area was made on a regional level (1:250,000) mainly from air photograph interpretation and from one geology field party in 1957 (D.K. Norris, pers. comm.). Only large scale features were mapped in the North Nahanni region, and this could have left many geological characteristics undetected.

Formation velocities of the Mid and Upper Devonian formations are known from two oil wells within 30 km of the aftershock zone. These wells do not extend through the whole sedimentary sequence; they reach only the base of the Middle Devonian formations (approximately 1.5 km deep) (Texaco N. Nahanni N-42 and Texaco Teck Iverson Lake M-69) (Figure 2). The sonic well logs indicate high velocities for the Middle Devonian carbonate formations (6.2 km/s) and lower velocities for the surficial Upper Devonian shales (4.5 km/s).

No direct velocity measurements exist for the Cambrian to lower Devonian Formations in the aftershock zone. However, well logs located 80 km to the east indicate high velocities (6.2 km/s) for the Ordovician to Lower Devonian rocks. In the same well logs, the Cambrian and the Precambrian rocks have lower velocities (5.0-5.5 km/s). Due to their deeper burial in the Mackenzie plain, higher velocities may be expected for these units than what are found to the east. Nevertheless, the overall high P-wave velocity of Devonian rocks indicates that a small impedance contrast occurs at the base of the sedimentary rocks in this region.

2.2 The Original Reflection Data

The seismic reflection data was collected in September and October 1970. The characteristics of the recording instruments and of the field procedure are summarized in Table I. The data was processed as shown in Table II. The seismic data was of poor quality due to problems occurring during the field work. Extremely difficult drilling conditions coupled with the adverse weather and rugged terrain made drilling in the permafrost impossible. Surface shooting with shaped charge was used to counterbalance the poor coupling with the ground. However, the surface charges could not yield sufficient penetration of the seismic energy. Thus, the original processed data (Figure 3) showed few strong events that could be correlated with any degree of certainty. The results were disappointing enough for Texaco to abandon their plans for two more seismic lines in the same area.

Despite the generally poor quality, the northeastern portion of the profile showed many well-defined events, with some being as deep as 2.8 sec (reflector "B" of Figure 3). The deepest event has been interpreted to be at a depth of 7.5 km assuming an average velocity of 5.5 km/sec. If the deepest reflector represents the crystalline basement, then 7.5 km is the minimum thickness for the sedimentary rock cover of the region.

3- REPROCESSING OF THE SEISMIC DATA AND RESULTS

The original data were obtained from Texaco Canada. The data set was analysed using facilities of the Lithosphere and Canadian Shield Division. The reprocessing operations followed the flow chart of Figure 4.

3.1 First Break Analysis

The data recorded on 24 channels were used to measure the apparent velocities of the upper two layers assuming a simple plane-layered model of the crust. A two-velocity model seemed relevant to the travel-times in most cases (Figure 5). However in some cases, a more complicated structure could be seen (Figure 6). For these complicated travel-times, elevation differences, lateral velocity variations, dipping layers, and also the quality of the data might explain the scatter in the calculated values.

3.1A Results

The first break analysis revealed some important features of the near-surface velocity structure (Figure 7). Firstly, in most places, the first layer was made of approximately 150 m of low velocity weathered rock. The velocity of these altered rocks varied between 2.7 and 3.5 km/sec along the seismic line. Secondly, strong lateral velocity variations can be observed for the second layer along the profile. High apparent velocity values (in the 5.5 to 6.2 km/sec range) are seen mainly in the northeastern part of the profile where the Middle Devonian Carbonate rocks outcrop. In the southwest part of the profile the velocities are noticeably lower (approximately 4.8 km/sec).

3.1B Interpretation

The velocity changes correspond to different geological units; the rocks of the northernmost part are mainly Middle Devonian carbonate rocks while in the southwesternmost part the rocks are mainly Upper Devonian low-velocity sandstones and shales. These velocity values are very similar to the ones reported from well logs of the region. A fault may exist between the two parts of the profile, however; field observations suggest that the sharp transition in velocity values is linked to the stratigraphic changes along the seismic profile. Faults were carefully looked for in the area between the two parts of the profile, but none was found.

The velocity information obtained from the first break analysis was used for the static correction. The 450 m level was used as the new datum.

3.2 Filtering and Data Gathering

The data set was processed using spectral balancing followed by F-K filtering. The seismic traces were examined to find any continuous events. Because only relatively shallow events were seen along the whole profile (Figure 8), it was decided to concentrate the effort on the first 1.5 sec of the time series. Common mid-point gathering (6-fold) and interactive velocity analysis based on velocity stacks were applied to the data. The data was finally stacked using optimized stacking velocities for both parts of the profile.

4- INTERPRETATION AND IMPLICATIONS OF THE RESULTS

4.1 Interpretation of the Seismic Profile

Despite the low fold, the reprocessing improved the quality of the near-surface portion of the profile and enhanced the anticlinal structure (Figures 9 and 10). Whereas, in the original version of the profile, very few events could be seen in the southwesternmost part of the profile, in the reprocessed profile, many events could be observed on both parts of the profile. In Figure 10, the reflectors are weighted A, B or C based on the quality of the reflectors.

The English Chief anticline is in evidence from the A and B reflectors (Figure 10). The dipping layers defining the anticline are apparent down to a depth of approximately 2.0 km. The crest of the anticline is located to the southwest of its mapped position. Due to the large scale of mapping (1:250,000), the position of the anticline indicated by the seismic profile should be more accurate.

The poor data quality hides smaller structural features. Continuous reflectors cannot be determined accurately across the profile and this hampers the determination of fault positions. However, field observations indicate unmapped faults in the Nahanni region. In the northeastern part of the profile, a fault with minor vertical displacement was observed at the large October 1985 rock avalanche site (Wetmiller et al. 1988). By breaking the continuity in the reflectors, it is possible that undetected faults may have caused the observed distortion and scatter of the the seismic signal.

The southwest part of the profile shows two systems of bedding, one well defined (A and B) and one presumed (C). The reflectors A and B dips at about 25 +/- 5 degrees to the southwest and may represent the southwestern flank of the anticline structure. In the same portion of the profile, the "C" reflectors are interpreted to correspond to the Upper Devonian shale and sandstone.

The apparent change in dip between the shallower "C" and the deeper reflectors "A" and "B" cannot be explained. The whole Devonian sequence was deposited in a continuous fashion without discordances, without any interruption related to orogenic movements. The Cretaceous folding of the lower units should have affected the whole sequence, without affecting the stratigraphic continuity. In addition, a change in dip between the shallow and deep reflectors is not supported by preliminary field observations. As a consequence, the shallow sub-horizontal bedding in the southeasternmost part of the profile may not be representative of the real geological structure.

4.2 Implications of the Results

A synthesis of the velocity information is shown in Figure 11. The first-break analysis shows lateral velocity variations and the presence of approximately 150m of altered rock on surface. Near the crest of the anticline, areas with high velocity values are found as opposed to the flanks of the anticline where thick low-velocity sequences exist. In addition, velocity values for deeper geological formations are poorly known at the present time. As a consequence, the lack of velocity information precludes any homogeneous or layered velocity model for the Nahanni aftershock zone. How should we use this information to correct aftershock arrival times recorded by portable seismographs during the aftershock surveys ? At present, the best correction for the near-surface velocity variations remains a homogeneous velocity model with station time corrections.

Twelve sites out of the seventeen of the three aftershock surveys are located directly on middle Devonian carbonates (Figure 12). For these stations, the homogeneous 6.2 km/sec model is acceptable. The remaining five stations that were on Upper Devonian rocks, must be compensated for the low-velocity layers. For these five stations, time correction values are proposed (Table III) based on available geological and geophysical information.

Most of the aftershock activity probably occurs below the carbonate rocks, in the Precambrian crystalline and sedimentary rocks. In the Nahanni zone, most of the aftershocks are located between 4 and 10 km. From the seismic profile and well logs, the middle Devonian carbonate rocks are not assumed to extend deeper than 3 or 4 km. Thus, active faulting occurs deeper than the carbonate rocks. Assuming a 7.5 km depth for the crystalline basement, the aftershocks are probably occurring within the precambrian sedimentary and crystalline rocks.

The existence of a blind thrust fault in the region can neither be ruled out nor supported by this analysis. The lack of resolution of the reflectors due to poor data quality and the low fold of data hamper the determination of a deep thrust fault. The lack of geological information on the east part of the anticline structure where the maximum deformation could have taken place also limits the testing of the model. As a consequence, more geophysical and geological work is needed before the blind thrust fault can be proposed with confidence.

5- RECOMMENDATIONS

The variations in the near-surface velocity values suggest that the stability of earthquake locations should be tested in respect to the velocity models and different velocity and time correction values. Such corrections will be especially important for stations 6, 8 and 17 that sit on low-velocity sedimentary rocks. These three stations are extremely important in defining the hypocentre trends. In consequence, the poorly defined velocity model must be kept in mind in analysing the aftershock activity. Take-off angles for focal mechanisms of the aftershocks will also be affected.

Supplementary field work should be carried out as follows:

1) A new seismic profile should be performed with emphasis on the first 6 seconds two-way travel time. Recording should be done with higher fold and broadband sources. The use of controlled sources is recommended to resolve the complex near-surface velocity model. If necessary, explosive charges should be deeply buried to yield sufficient energy. This was critically lacking in 1970. Due to the complexity of the geological structure, data should also be recorded off the main seismic line. This would bring more constraints in the definition of a 3-D model of the aftershock zone.

2) The structural geology of the Mackenzie Plain should be mapped on a more detailed scale (say 1:50,000). The mapping should investigate some puzzling facts exposed by geological

observations; the non-continuity of some beds, the presence of small faults, and the deformation of the incompetent rocks that could be indicative of a blind thrust structure. A study of the faults and joints of the region may also indicate multiple deformation phases in the area. As the field observations were limited to the gap area between the two parts of the profile, a surface rupture should also be looked for throughout the whole aftershock zone. Two weeks of field mapping in the area should yield much information on the geological characteristics of the area.

3) Magnetics or gravity surveys could also be conducted in the area. These methods could indicate depth variations of the Precambrian basement.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Mr. Robert Baden of Texaco Ltd. who allowed the reprocessing of the 1970 dataset. The authors are also indebted to Drs. D.K. Norris and S.G. Evans for the geological information. During the September 1986 survey, the patience and understanding of Mr. R.B. Horner towards a geologist's enthusiasm for rocks was also appreciated. The critical review of this paper by R.J. Wetmiller, J.E. Adams and C. Spencer was very much appreciated.

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trend of the profile is less than 300m.

Figure 10. Interpretation of the reprocessed reflection line based on the geology map (Douglas and Norris, 1974) and on field observations. The reflector positions are weighted according to their quality from A to C. Note the anticline shape. The symbols to describe the geological units are; uD: Upper Devonian formations; mD: Middle Devonian formations; lD: Lower Devonian formations; and C: Cambrian formations. The depth is measured from the datum level (450m), and is calculated using a 5.5 km/sec velocity value. The projection of the gap separating the two parts of the profile along the main trend of the profile is less than 300m.

Figure 11: Cross-section along the seismic profile summarizing the information obtained in this analysis. Thicknesses are only approximative. The thin low-velocity veneer of altered surface rocks is indicated by dots.

Figure 12; Location of the 17 stations used during the three Nahanni aftershock surveys. The location of well Texaco North Nahanni N-42 is also indicated. Dotted surfaces represent areas where carbonates are found near the surface.

1-RECORDING INSTRUMENTS

TIAC DFS III BINARY GAIN INSTRUMENT.

ELECTROSTATIC CAMERA.

GEOSPACE MODEL II-D 14 CYCLE GEOPHONES.

2-FIELD PROCEDURE

A) RECORDING PARAMETERS

SHOT POINT SPACING FOR 600% CDP COVERAGE:	440 FT (134 m).
GROUP INTERVAL:	220 FT (67 m).
GEOPHONES PER GROUPS:	8.
NUMBER OF GROUPS:	24.
TYPE OF SPREAD:	VARIABLE (GENERALLY 5280 FT).

B)CHARGE SIZE

AVERAGE:	25 LBS (11.3kg).
TOTAL POWDER USED:	6596 LBS(2992 kg).

C)INSTRUMENT SETTINGS

SAMPLE RATE:		.002 SEC
RELEASE RATE:		120 dB/sec.
FINAL GAIN:		120 dB
FIELD FILTERING:	LOW	36 Hz
	HIGH	120 Hz

TABLE I

ORIGINAL DATA PROCESSING

BINARY GAIN RECOVERY

TRUE AMPLITUDE RECOVERY

EDIT DEMULTIPLEXNG

NORMAL MOVEOUT

DECONVOLUTION

DIGITAL FILTER

STATICS STRUCTURAL

DATUM = 1000 FT (305 m).

VELOCITY = 10 000 FT/SEC (3.05 KM/S).

STACK: SIX FOLD

NOISE SUPPRESSION

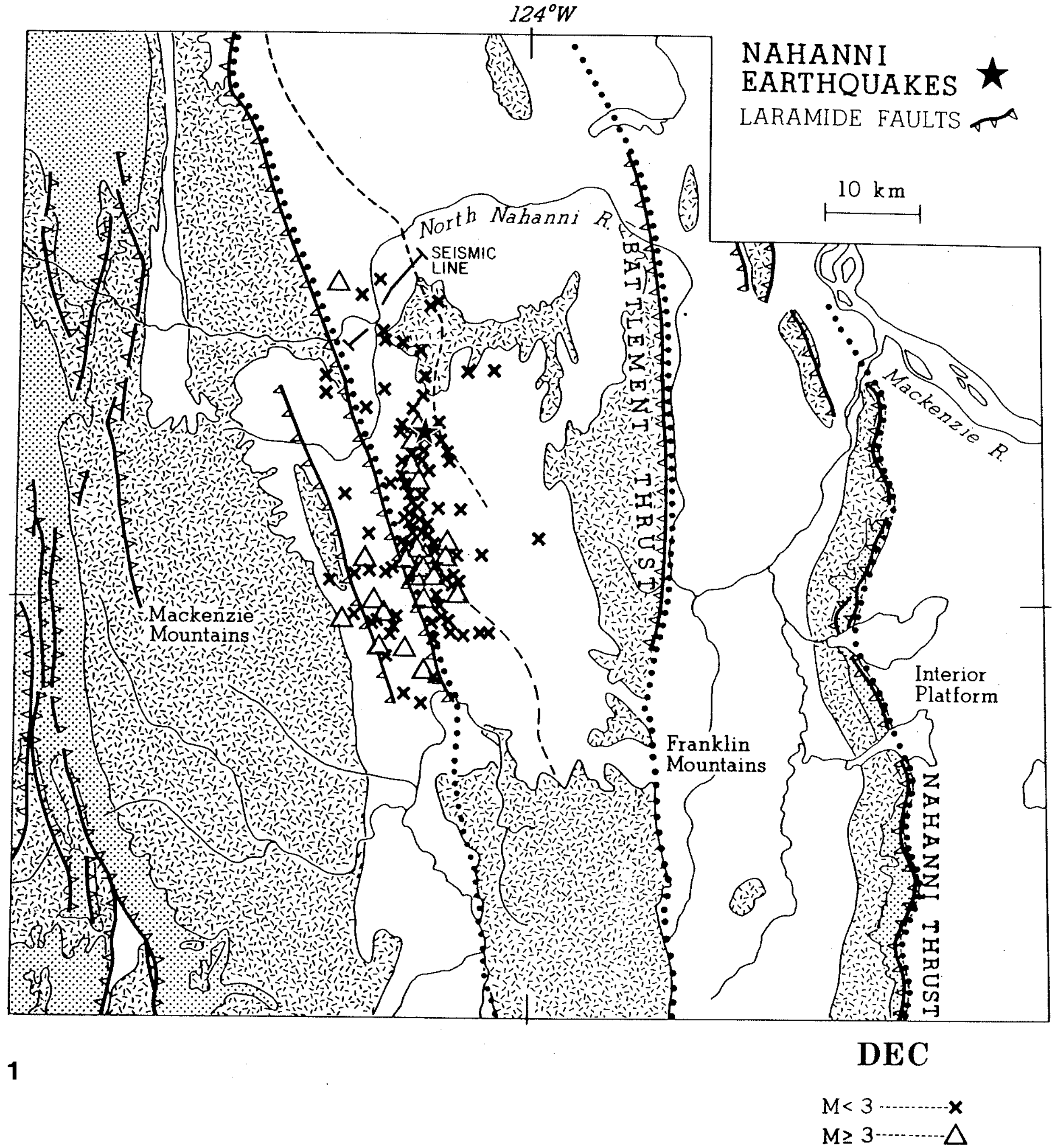
TIME VARIANT SCALING AFTER STACK

TABLE II

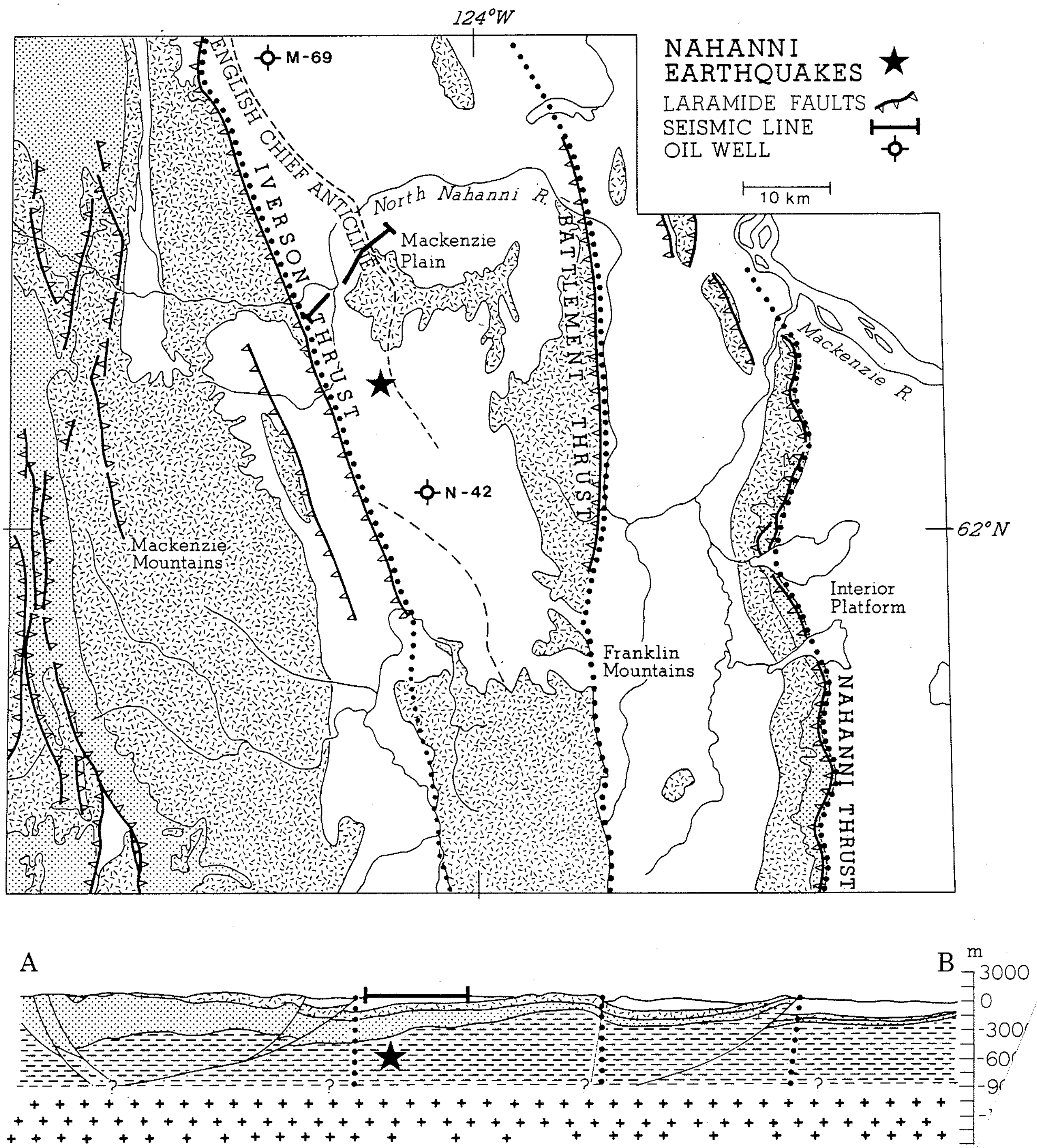
STATION no.	GEOLOGICAL UNIT	TIME CORRECTION
2	CARBONATES	NONE
3	CARBONATES	NONE
4	SANDSTONE	-0.5 sec
5	CARBONATES	NONE
6	FT SIMPSON FM OR SANDSTONE	-0.5 sec
7	FT SIMPSON	- (?)
8	FT SIMPSON FM OR SANDSTONE	-0.5 sec
9	CARBONATES	NONE
10	CARBONATES	NONE
11	FORT SIMPSON (CLOSE TO THRUST FRONT)	NONE
12	CARBONATES	NONE
13	CARBONATES	NONE
14	CARBONATES	NONE
15	FT SIMPSON FM	-0.5 sec
16	CARBONATES	NONE
17	SANDSTONE / SHALE	-0.5 sec (?)
18	CARBONATES	NONE

TABLE III

Geological setting and proposed P-wave time corrections for the sites used during the three field surveys.

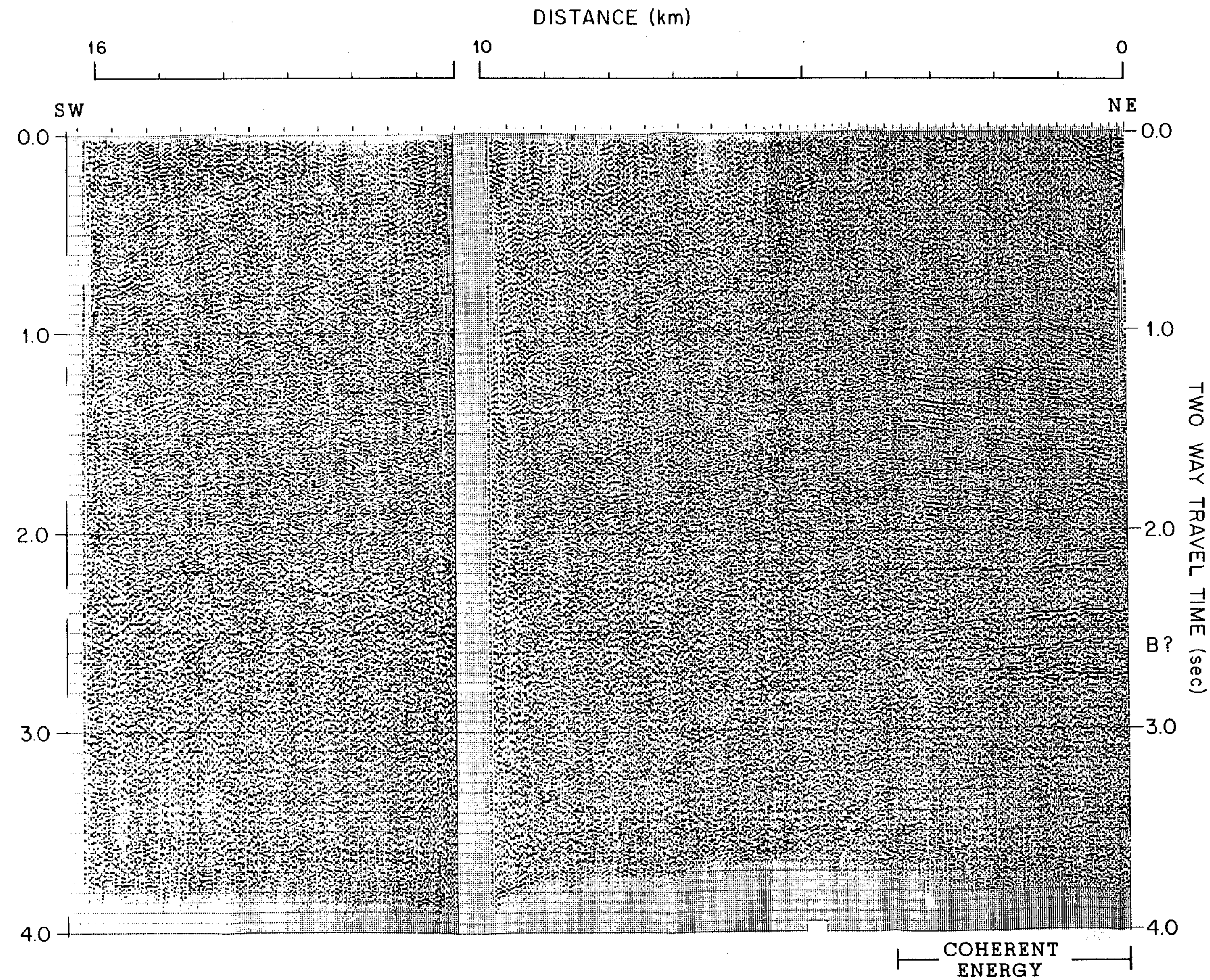

124°W
62°N
NAHANNI
EARTHQUAKES
LARAMIDE FAULTS
10 km
North Nahanni R.
SEISMIC
LINE
BATTLEMENT THRUST
Mackenzie R.
Mackenzie
Mountains
Franklin
Mountains
Interior
Platform
NAHANNI THRUST
DEC
M< 3
M≥ 3

1



124°W
NAHANNI
EARTHQUAKES
LARAMIDE FAULTS
SEISMIC LINE
OIL WELL
10 km
M-69
N-42
ENGLISH CHIEF ANTICLINE
IVERSON THRUST
North Nahanni R.
Mackenzie
Plain
BATTLEMENT THRUST
Mackenzie R.
62°N
Mackenzie
Mountains
Interior
Platform
Franklin
Mountains
NAHANNI THRUST
A
B
m
3000
0

2


DISTANCE (km)
16
10
0
SW
NE
0.0
1.0
2.0
3.0
4.0
TWO WAY TRAVEL TIME (sec)
B?
COHERENT ENERGY

3

FIRST BREAK ANALYSIS

↓

NEAR SURFACE VELOCITIES

↓

STATIC CORRECTIONS (DATUM=450m)

↓

SPECTRAL AND AMPLITUDE BALANCING

↓

F-K FILTER

↓

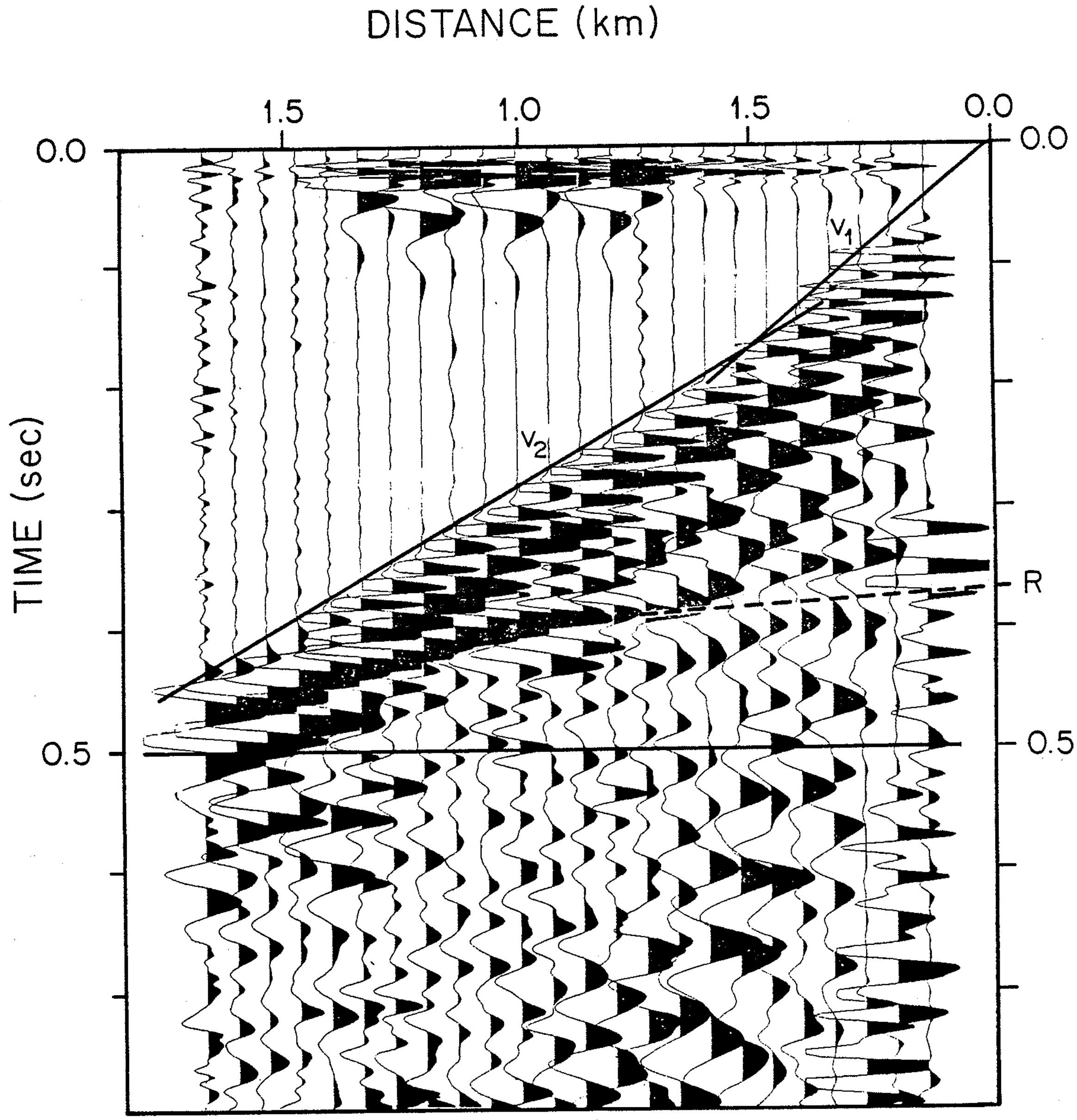
COMMON MID-POINT GATHERING

↓

STACKING VELOCITY TESTS

↓

END



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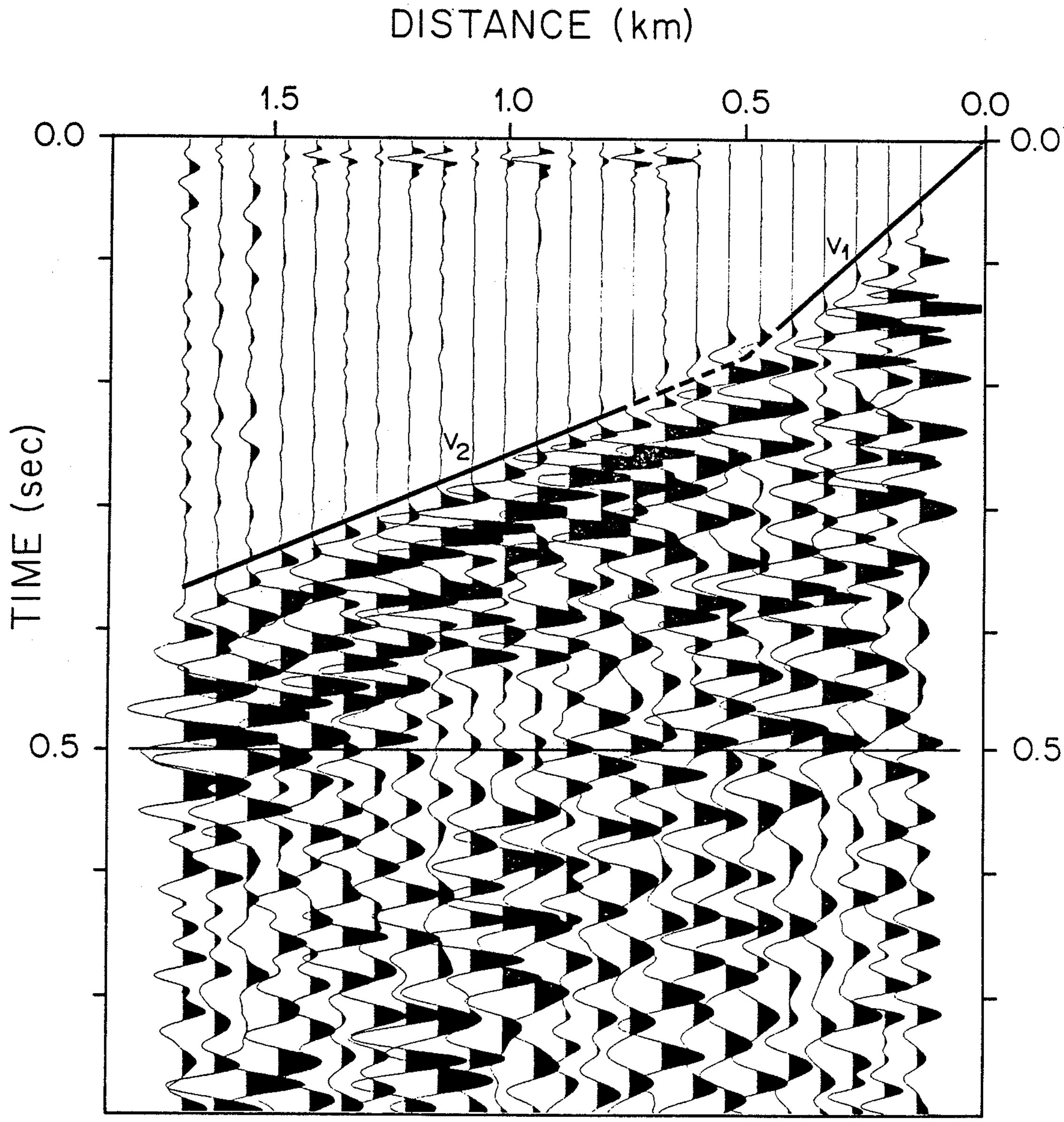

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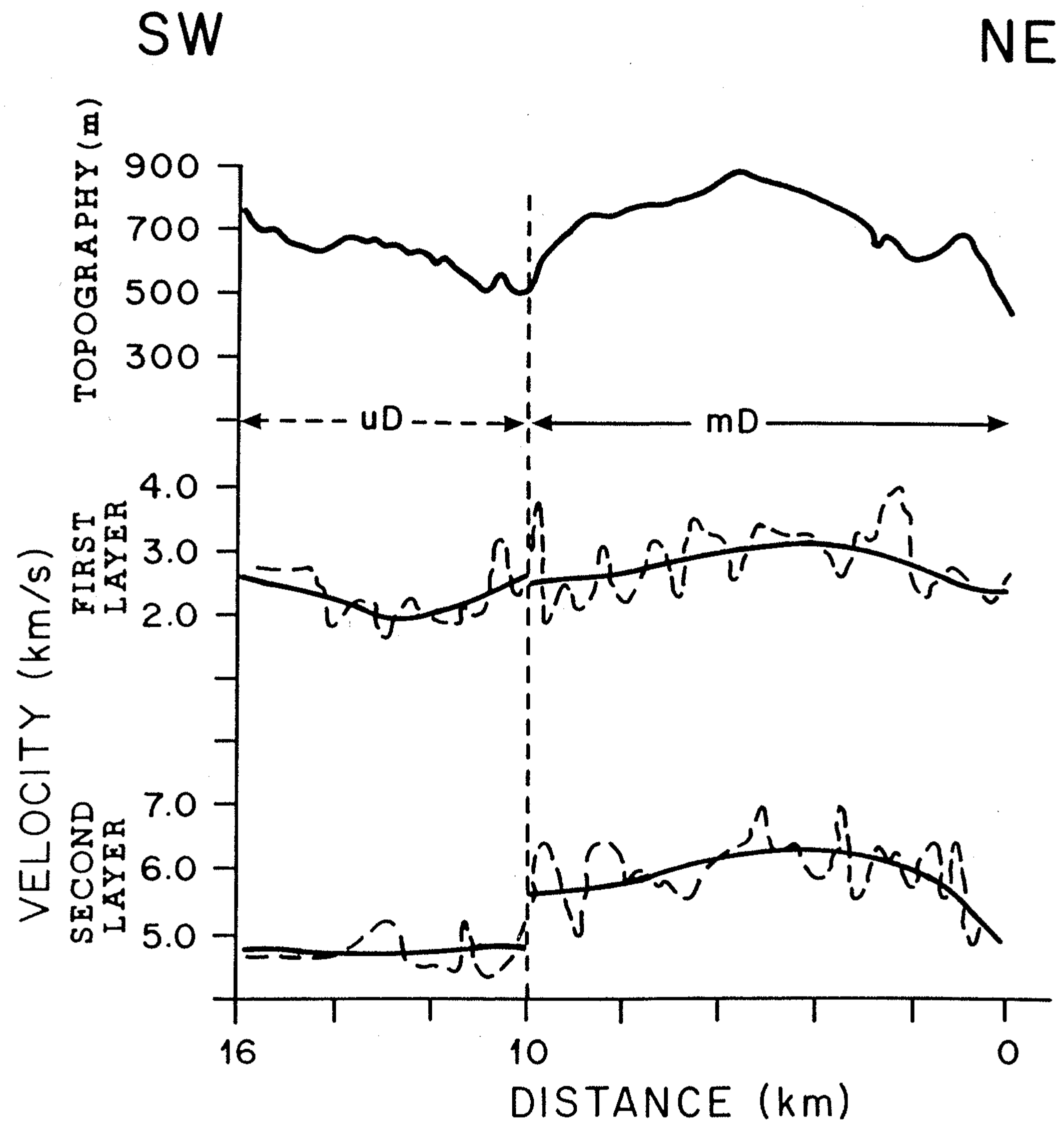
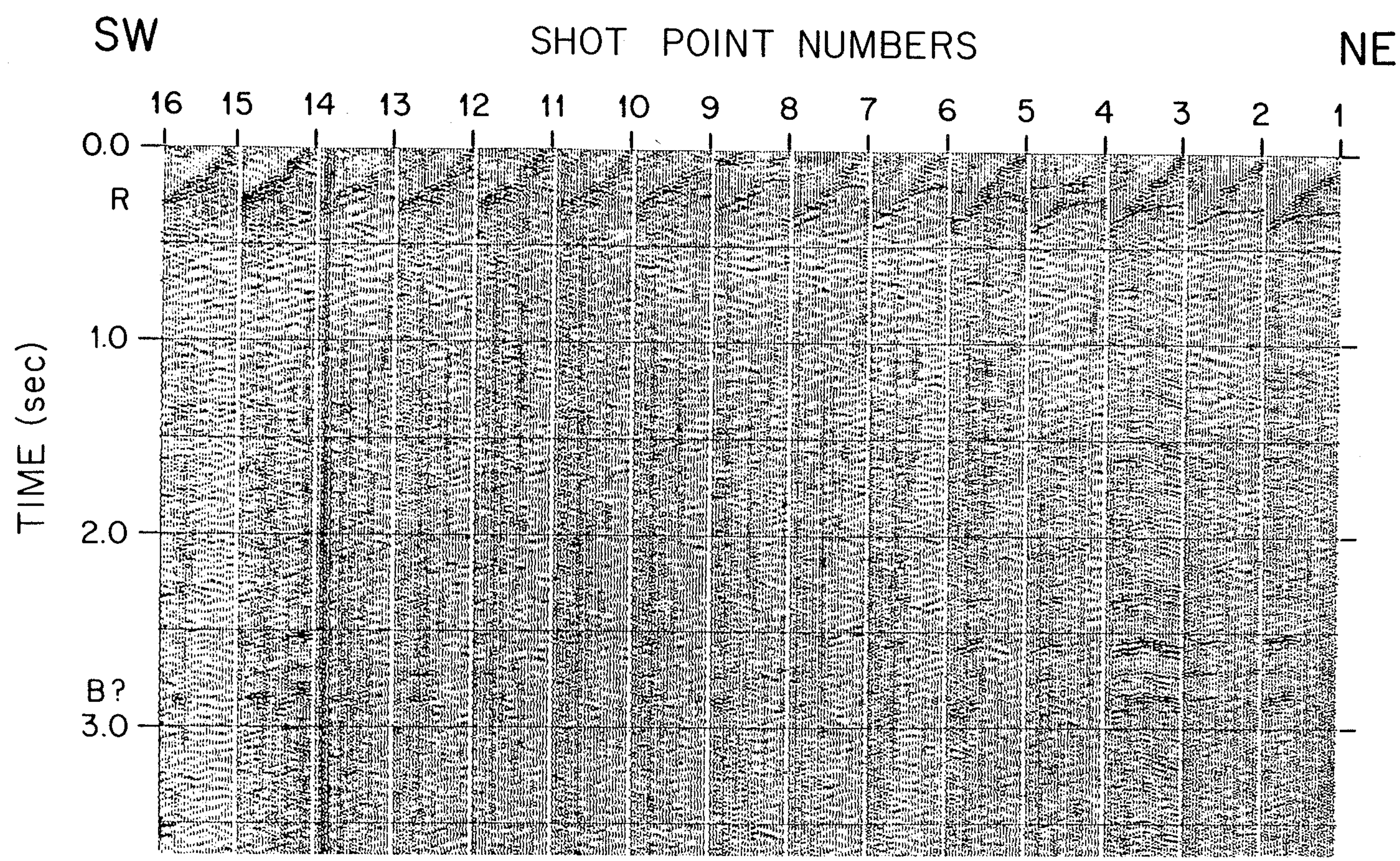

SW
NE
TOPOGRAPHY (m)
900
700
500
300
uD
mD
VELOCITY (km/s)
FIRST LAYER
4.0
3.0
2.0
SECOND LAYER
7.0
6.0
5.0
16
10
0
DISTANCE (km)

7


SW
SHOT POINT NUMBERS
NE
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TIME (sec)
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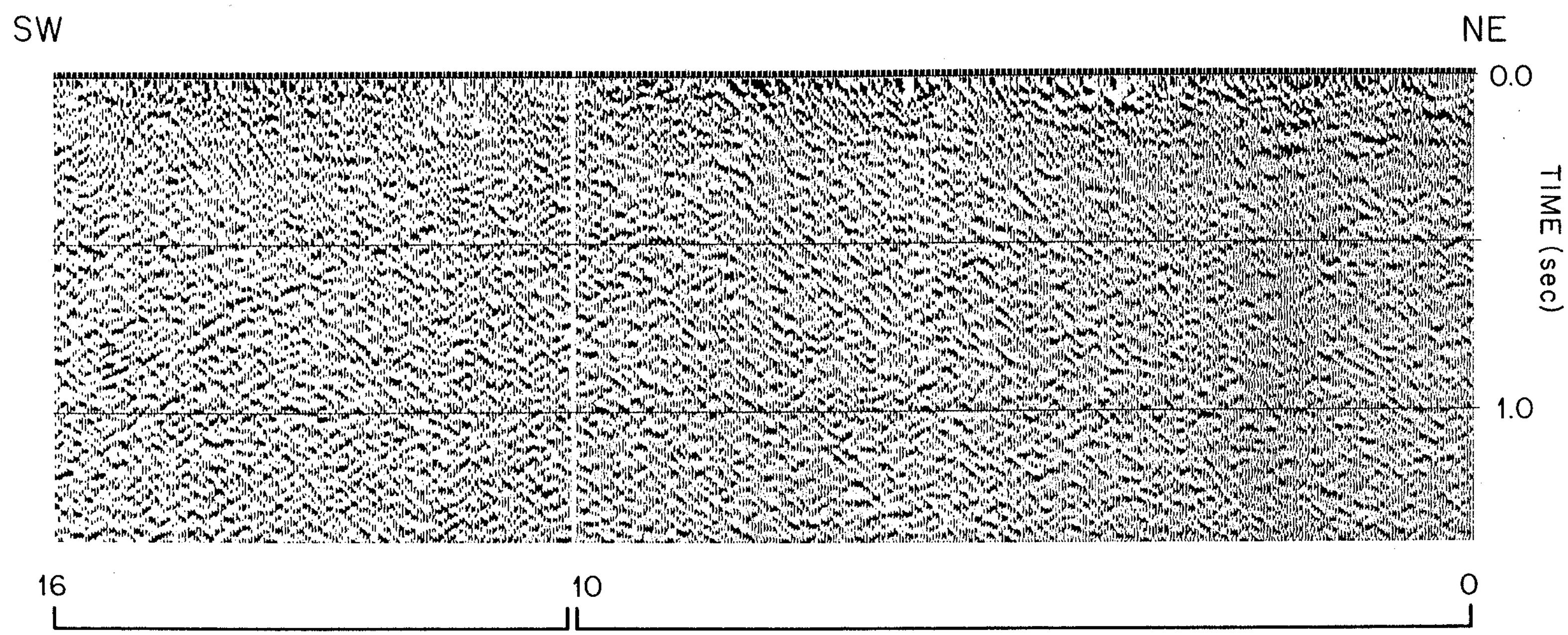
R
1.0
2.0
B?
3.0



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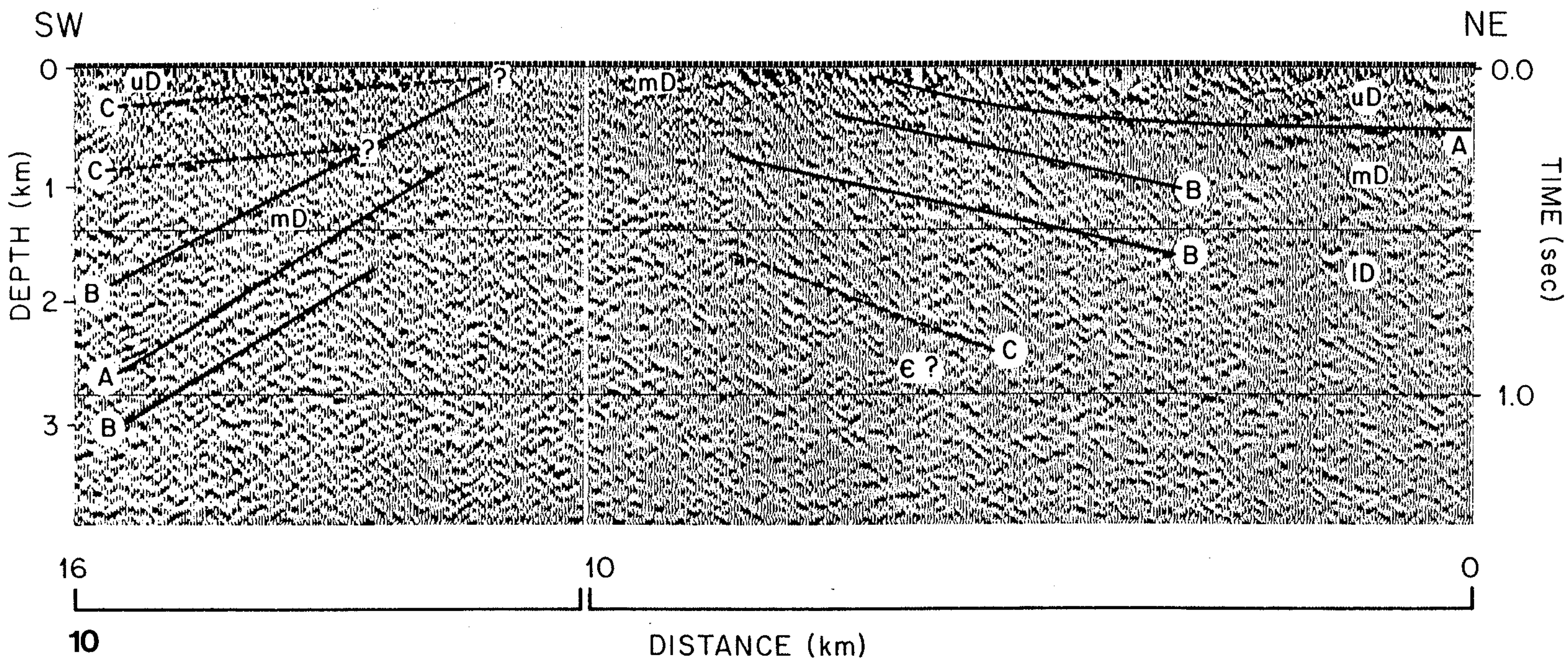
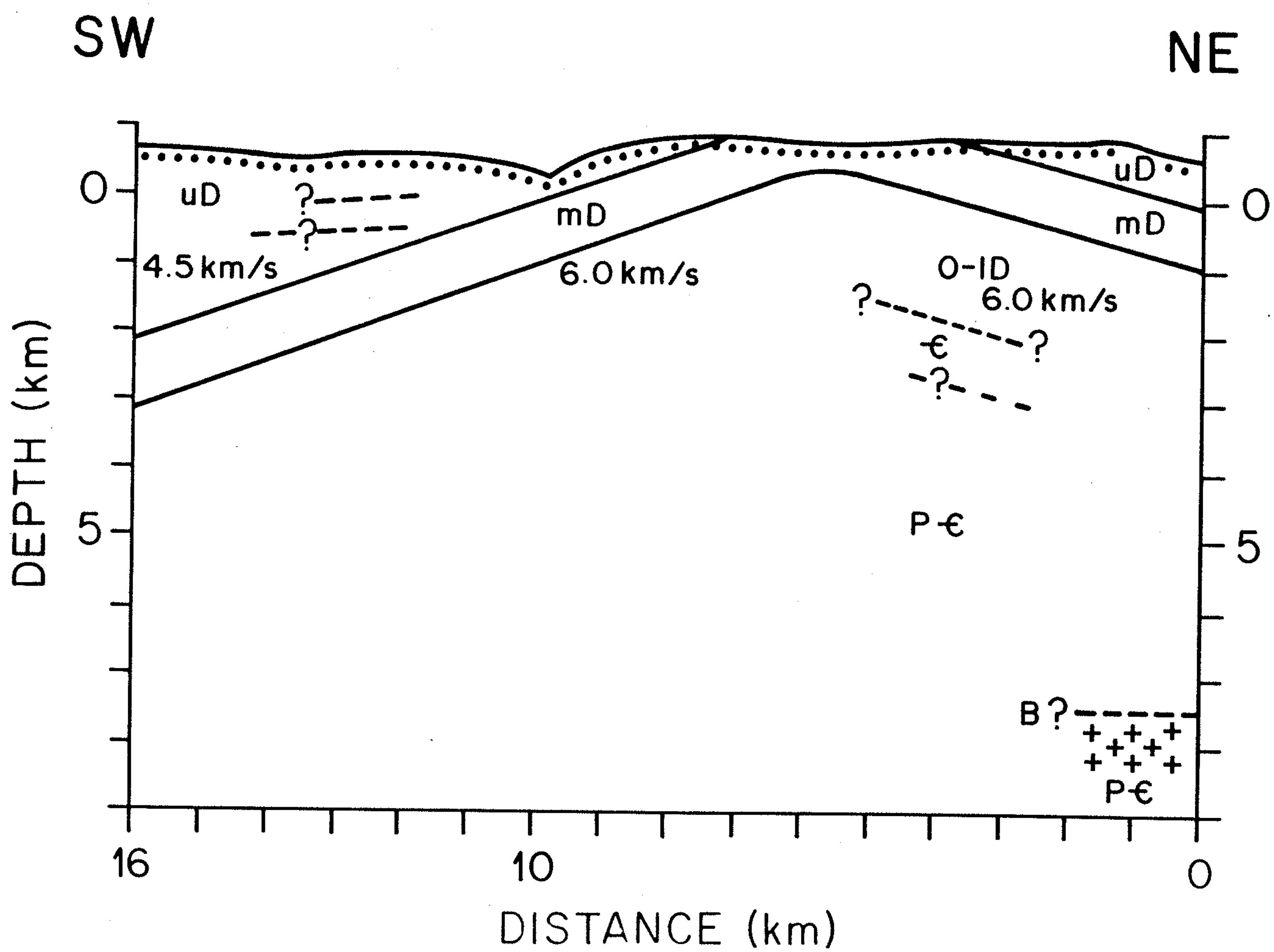
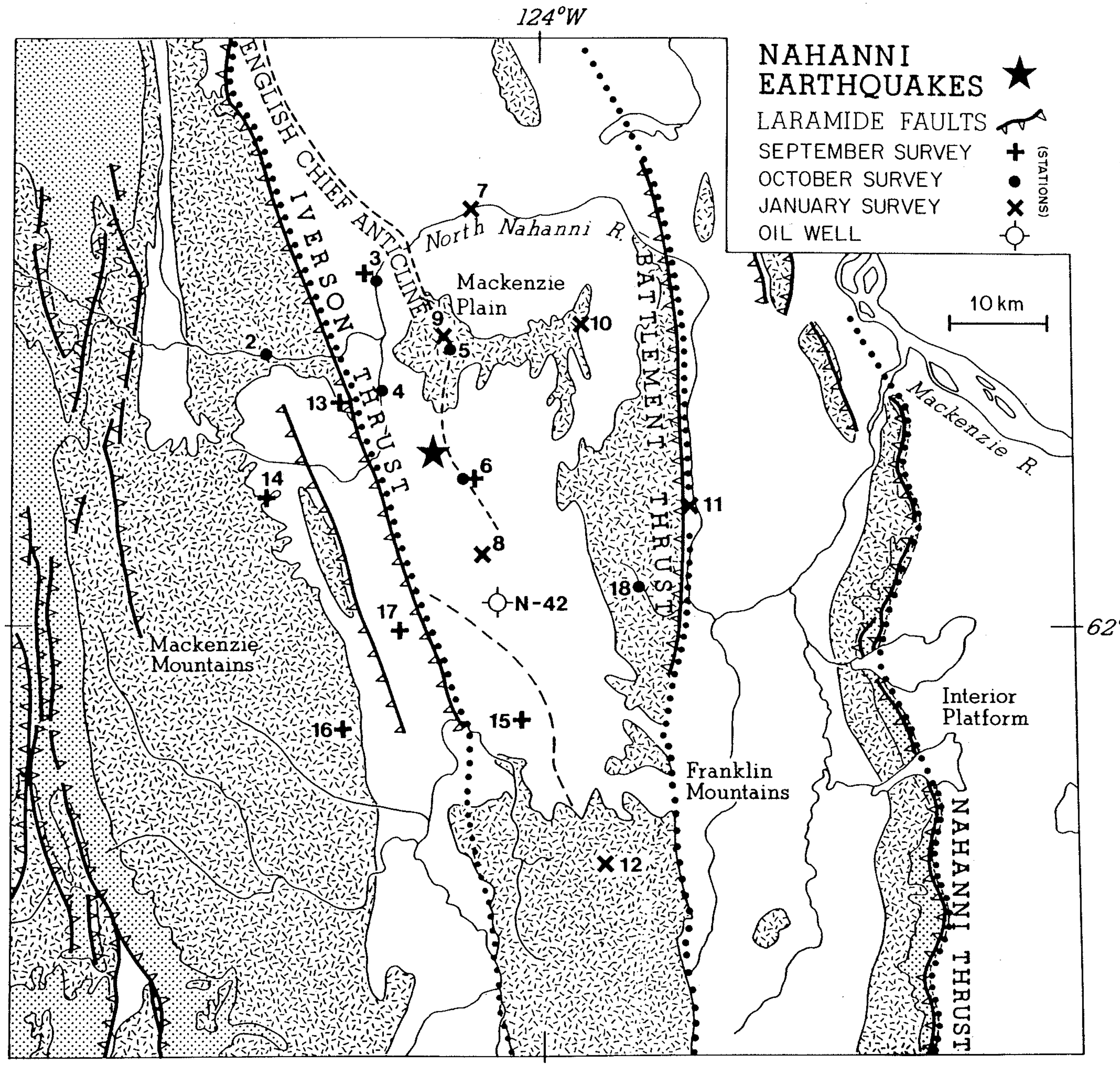


SW
NE
DEPTH (km)
TIME (sec)
0
1
2
3
0.0
1.0
uD
C
C
?
?
mD
B
A
B
mD
uD
A
mD
B
B
lD
C
є ?
16
10
0
DISTANCE (km)

10


SW
NE
uD
mD
4.5 km/s
6.0 km/s
O-lD
6.0 km/s
Є
P-Є
B?
P-Є
DEPTH (km)
0
5
0
5
16
10
0
DISTANCE (km)

11


124°W
62°N
NAHANNI EARTHQUAKES
LARAMIDE FAULTS
SEPTEMBER SURVEY
OCTOBER SURVEY
JANUARY SURVEY
OIL WELL
(STATIONS)
10 km
Mackenzie R.
NAHANNI THRUST
Interior Platform
Franklin Mountains
BATTLEMENT THRUST
North Nahanni R.
Mackenzie Plain
ENGLISH CHIEF ANTICLINE
IVERSON THRUST
Mackenzie Mountains
N-42
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