1994

Evaluation of a possible subsurface impact crater: the Newporte structure, northwestern Renville County, North Dakota

Timothy R. Gerlach
University of North Dakota

Recommended Citation

Gerlach, Timothy R., "Evaluation of a possible subsurface impact crater: the Newporte structure, northwestern Renville County, North Dakota" (1994). *Theses and Dissertations*. 106.
https://commons.und.edu/theses/106

EVALUATION OF A POSSIBLE SUBSURFACE IMPACT CRATER: THE NEWPORTE STRUCTURE, NORTHWESTERN RENVILLE COUNTY, NORTH DAKOTA

by

Timothy R. Gerlach

Bachelor of Science, University of North Dakota, 1987

A Thesis
Submitted to the Graduate Faculty
of the
University of North Dakota
in partial fulfillment of the requirements
for the degree of
Master of Science

Grand Forks, North Dakota

August
1994

This thesis, submitted by Timothy R. Gerlach in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

Nels F. Forsman
(Chairperson)

J. R. Reid

Richard D. LeFever

This thesis meets the standards for appearance, conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Dean of the Graduate School

Permission

Title	Evaluation of a Possible Subsurface Impact Crater: The Newporte Structure, Northwestern Renville County, North Dakota
Department	Geology
Degree	Master of Science

In presenting this thesis in partial fulfillment of the requirements for a graduate degree from the University of North Dakota, I agree that the library of this University shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by the professor who supervised my thesis work or, in his absence, by the Chairperson of the department or the Dean of the Graduate School. It is understood that any copying or publication or other use of this thesis or part thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of North Dakota in any scholarly use which may be made of any material in my thesis.

Signature

Date August 1994

TABLE OF CONTENTS

LIST OF FIGURES

ACKNOWLEDGEMENTS

I would like to gratefully thank my committee members, Drs. Nels F. Forsman (Chairman), Richard D. LeFever, and John R. Reid for their assistance, critical reviews, and advice. A very special thank you goes to Dr. Forsman for his guidance, time, and unceasing patience

The University of North Dakota Department of Geology and Geological Engineering, Department of Space Studies, the Energy and Environmental Research Center, and the North Dakota Geological Survey are recognized for their financial support and for the use of their facilities

The scientific and industrial contacts were a key element in the completion of this project. Some of these individuals are listed below.

Neil Anderson, geophysicist at the University of Missouri - Rolla, assisted in the handling of seismic data His digitizing of velocity logs and generation of synthetic seismograms were intricate portions of this study.

James H. Clement (retired), Jim Krater, and Duane Grossman of Shell Western, were instrumental in acquiring the seismic data of the structure. Bill Fenner, also of Shell, assisted in obtaining Newporte core samples. Sara Foland, of Amoco (Denver , provided copies of all available

wireline logs for the Newporte wells

The assistance and friendship of Julie LeFever, Sid Anderson (retired), and Kent Hollands, of the North Dakota Geological Survey, was appreciated throughout this study.

Hugh McCabe and Ruth Bezys of the Manitoba Department of Energy and Mines, loaned thin sections of the Lake St. Martin structure to the study. These thin sections were invaluable to the microscope investigation.

David Roddy (retired), of the United States Geological Survey, generously agreed to verify any macroscopic and microscopic evidence of shock found in the Newporte samples. Roddy is often called upon to assist investigators in verifying possible terrestrial impact craters.

To Wes Peck, geologist, teacher, software wizard and basement escapee, thanks for all the insanity prevention. If Ian and Charlie were here, they'd thank you too

Of course, some mention must be made of contributions made by the basement dwellers. So many of you have helped me in so many ways that it is impossible to mention you all Thanks to all of

Last, but certainly not least, thanks goes to my family and loving wife, Lisa. Yes, Lisa, there is life after graduate school.

ABSTRACT

The purpose of this study was to determine if enough evidence exists to support an impact origin hypothesis the Newporte structure. Newporte, a petroliferous, subsurface, crater-shaped feature is located one mile south of the North Dakota - Saskatchewan border in Renville County. It is evident in Precambrian through Ordovician strata at depths of 9100 to 9600 ft (2774 to 2926 m) structure is approximately 2.0 miles (3.2 km) in diameter. Shell Oil Company discovered Newporte field when testing this seismically-defined structure in 1977.

Seismic reflection profiling data and synthetic seismograms were used to generate maps that confirmed the circularity of the structure. Because no wells have been drilled in the central region of the structure, the seismic data were necessary for mapping and interpreting the morphology of the feature. Wireline logs of the seven wells, all located on the remaining rim, were used to identify lithologic units, verify the seismic data, and they were used in an attempt to interpret the age of the Newporte structure. All available well cores were described (Appendix B), and nearly 140 thin sections were evaluated microscopic evidence of shock metamorphism.

Interpretation of seismic data reveals a crater with a distinctive raised rim, and what may be vestiges of a central uplift. Intriguing breccias, resembling impact breccia, have been described from three well cores. Several examples of unusual microscopic features, perhaps indicative of low shock pressures, were discovered in quartz from sandstone and brecciated crystalline rock from the Mott 14-34 well. It has been concluded in this study, based on geophysical data, well core samples, and a thorough microscopic evaluation that there is much evidence to support an impact origin for the Newporte structure. The presence of a Deadwood breccia interval suggests the impact event may have occurred during or after Deadwood deposition,

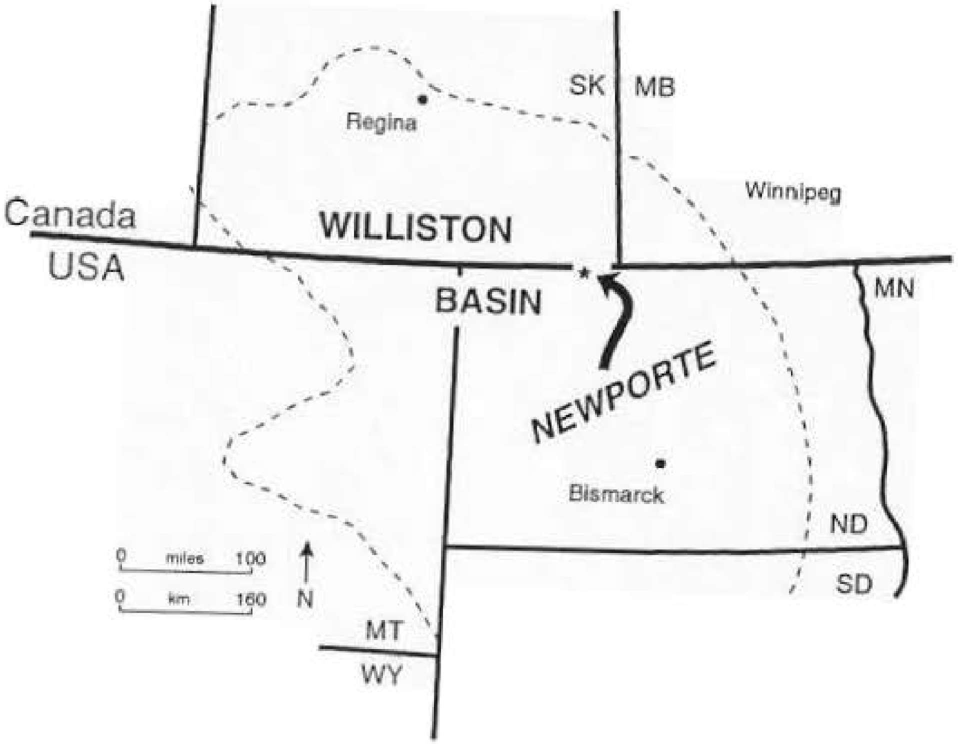
prior to deposition of the Winnipeg Group (Late Cambrian to Early Ordovician, or prior to Late Ordovician)

INTRODUCTION

Statement of Problem

The Newporte structure is a petroliferous, subsurface, crater-shaped feature, located one mile south of the United States-Canadian border in Renville County, North Dakota (Fig. 1). It is evident in Precambrian and Cambrian units at a depth of 9100 to 9600 ft (2774 to 2926 m), and is approximately 2.0 miles 3.2 km) in diameter. Maps of Newporte structure by Clement and Mayhew (1979 show the structure to be somewhat circular. In the seventeen years since its discovery, an informal debate has been waged between those who believe the Newporte structure to be of impact origin and those who do not, yet no study has been undertaken (since an initial investigation by Shell Oil Company) to shed light on this question. Logically, impact was one of the early ideas proposed for the structure's origin. However, much of the Shell Oil Company investigation, including the petrographic, biostratigraphic, and geochemical work, was never published

Industry workers and state personnel have for years spoken of the anomalous nature of the Newporte cores: vertical and deformed bedding, missing strata and brecciated intervals. In addition to the presence of hydrocarbons,


SK
MB
Regina
Winnipeg
Canada
USA
WILLISTON
BASIN
MN
NEWPORTE
Bismarck
ND
SD
0 miles 100
0 km 160
N
MT
WY

feeding an economic interest in the structure, the debate over its origin has brought renewed interest to the Newporte structure. This is the first thorough evaluation aimed at answering the question of an impact origin for the Newporte structure.

General Discussion

Apart from finding meteorite remnants, evidence for impact can include the identification of a crater morphology both macroscopic and microscopic features resulting from passage of shock waves through the ground. A simple crater morphology includes an encircling raised rim, a circular bowl-shaped depression and overturned strata. Macroscopic structures found at impact sites include shatter cones, impact breccias, and glass (Roddy and others, 1977; French and Short, 1968). Microscopic evidence of impact includes several high-pressure mineral phases and unusual mineral textures (Roddy and others, 1977; French and Short, 1968)

If the Newporte structure is an impact crater, it will be added to the growing list of known terrestrial impact craters. In recent decades a growing acceptance of impact as an important geologic process has occurred. Impact cratering is fundamental in that planets grow by accretion idea that Earth has undergone the same violent bombardment that is so evident on the moon and other planetary bodies can be difficult to imagine. For decades terrestrial impact craters were deemed "crypto-volcanic" or "crypto-explosion" structures (Gilbert, 1896, in Merrill, 1909); Branco and Fraas, 1905; Bucher, 1936 and 1963; Goguel, 1963), and any exogenetic cause was denied. Even today, in industry there are those who belittle impact's place as a true and important geologic phenomenon. Yet, the inventory of terrestrial impact craters has grown tremendously. Approximately 140 have been described to date, and impact has finally received the scientific consideration it deserves. In fact, there is finally a growing awareness in industry that impact craters can provide a suitable reservoir for hydrocarbons

Argument for an impact origin for the Newporte must consider the structure's morphologic features and any discoveries of shock metamorphism. An encircling raised rim and apparent central uplift are distinctive of impact craters of approximately the Newporte structure's size (Dence, 1968; Roddy, 1977). Discovery of shock-metamorphosed mineral phases, like quartz with planar deformations and kink-banded biotite (Cummings, 1968), could provide conclusive evidence of an impact origin for the Newporte structure.

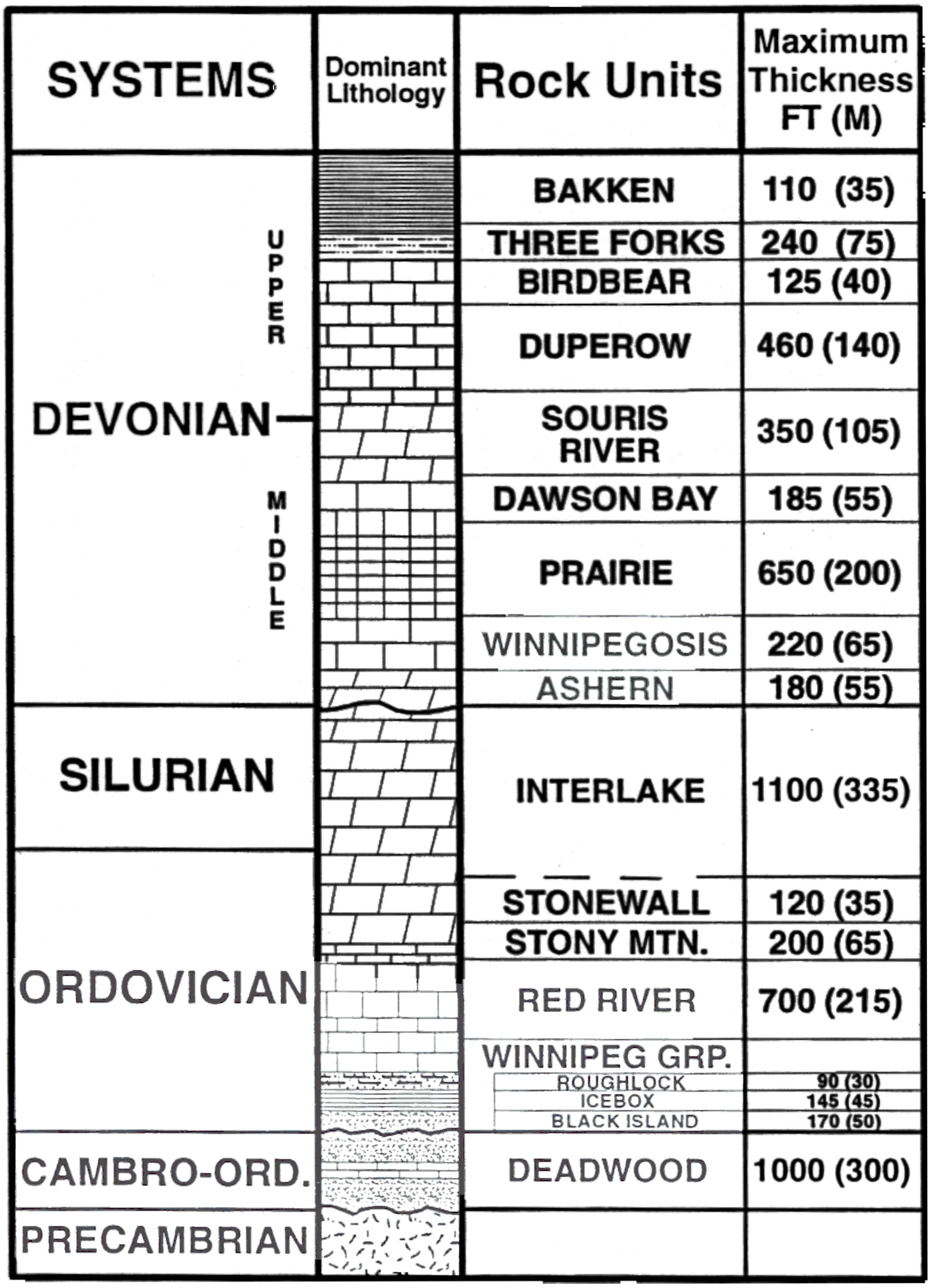
Regional Setting and Stratigraphy

The Newporte structure occurs within the Williston

Basin, a wide, shallow intracratonic basin covering over 50,000 mi^2 (129,500 km^2) of the northern Great Plains (Carlson and Anderson, 1965). The basin contains approximately 16,000 ft 4875 m) of sedimentary rock ranging in age from Late Cambrian to Recent (Gerhard and others, 1982). In figure 1 the basin outline is based on the zero elevation line for the Cretaceous Dakota Sandstone (Laird, 1956).

The Precambrian Superior and Churchill (Wyoming) suture trend extends north-south through central North Dakota (Ballard, 1963 , and the Newporte structure is approximately forty miles (64 km) to the west of this zone. Gerhard and others (1982) suggested that this boundary was an important factor in Phanerozoic basin development. LeFever and others (1987) proposed the Early Ordovician (Tremadocian Epoch) for the onset of basin subsidence. No evidence has been found to support a connection between the suture zone and the formation of the Newporte structure

The Precambrian crystalline metamorphic basement in the North Dakota Williston Basin is nonconformably overlain by the Upper Cambrian-Lower Ordovician Deadwood Formation, which in turn is disconformably overlain by the Middle Ordovician Winnipeg Group (Fig. 2). The Deadwood Formation consists of a mixture of siliciclastic sedimentary rocks, as well as lesser carbonate rocks. The overlying Winnipeg Group, in ascending order, consists of the Black Island



SYSTEMS		Dominant Lithology	Rock Units	Maximum Thickness FT (M)
DEVONIAN	UPPER		BAKKEN	110 (35)
			THREE FORKS	240 (75)
			BIRDBEAR	125 (40)
			DUPEROW	460 (140)
			SOURIS RIVER	350 (105)
	MIDDLE		DAWSON BAY	185 (55)
			PRAIRIE	650 (200)
			WINNIPEGOSIS	220 (65)
			ASHERN	180 (55)
SILURIAN			INTERLAKE	1100 (335)
ORDOVICIAN			STONEWALL	120 (35)
			STONY MTN.	200 (65)
			RED RIVER	700 (215)
			WINNIPEG GRP.	
			ROUGHLOCK	90 (30)
			ICEBOX	145 (45)
			BLACK ISLAND	170 (50)
CAMBRO-ORD.			DEADWOOD	1000 (300)
PRECAMBRIAN				

Figure 2 Lowermost lithostratigraphic units of the Williston Basin. Modified after Bluemle and others, 1986.

Formation, Icebox Formation, and Roughlock Formation. Black Island consists mostly of sandstone, the Icebox of clayshale and the Roughlock is transitional between the Icebox Formation and the overlying carbonates of the Red River Formation (Thompson, 1984).

Drilling History

Shell Oil Company discovered Newporte field (Des-Lacs Field) when testing this seismically-defined structure 3). In August 1977 a wildcat was spudded, Larson 23X-9, in section 8, T163N, R87W, Renville County, North Dakota. The well was completed in the Cambro-Ordovician Deadwood sandstone at 9574-9593 ft 2918 to 2924 m), flowing 31 barrels of oil per day (b/d) and 1.1 MMcf of gas per day (Petroleum Information, 1980). Clement and Mayhew 1979) suggested that although production increased to 63 b/d, completion, casing, and nitrogen gas-flow problems may have masked this discovery's true potential. The Larson well operated about eight months during which production ranged from approximately 700 to over 1200 barrels per month. The last recorded production was for November, 1978.

Following the Larson success, activity in the Newporte field gained momentum in 1978. Six wells were attempted with three eventually being completed. The Wisdahl 23-10, a one mile 1.6 km) step-out to the east, and the Lindblad 41X-16, approximately 3/4 mile 1.2 km) to the southeast,

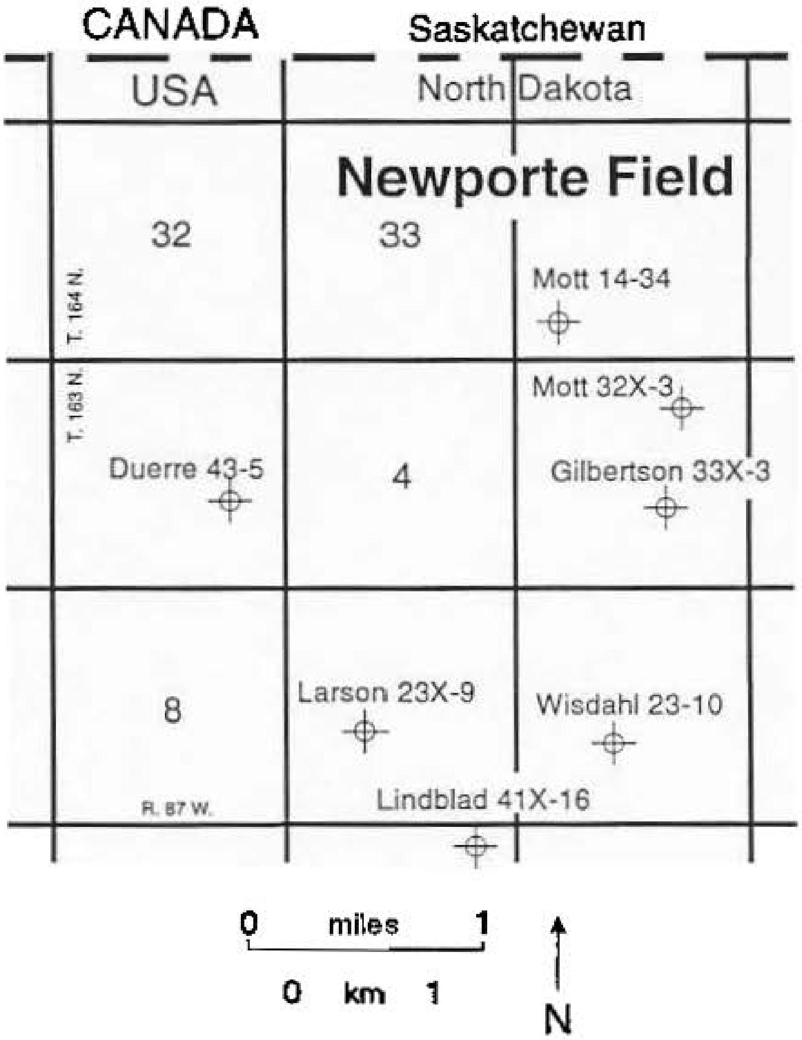


Figure 3 Map of the Newporte field

were both dry holes. Both of these wells were drilled to the Precambrian basement. The Lindblad is the field's deepest well at 9755 ft (2973 m)

The westernmost well of the Newporte field is the Duerre 43-5. It was slightly shallower than the Lindblad well. Drilling ceased in amphibolite greenstone at 9736 ft (2968 m). The Duerre producing zone was 9516-9526 ft (2900 to 2904 m). Initial production was approximately 60 b/d.

Mott 14-34, Mott 32X-3 and Gilbertson 33X-3 were drilled on the 'Mott hill'. This structural high is on the northeastern perimeter of the structure, and is less than a mile west of the Pleasant field. Although the Gilbertson well was abandoned, both Mott wells were completed. 32X-3, which remained in production in 1994 (Fig. 4), had an initial production of 20 b/d from Deadwood or Black Island at 9146-9186 ft (2788 to 2800 m). Mott 14-34 produced at 90 b/d from brecciated Precambrian basement at 9067-9086 ft (2764 to 2769 m). This well is believed to be the first and only Precambrian producer in the Williston Basin (Sidney Anderson, NDGS, oral commun., May 1994, Grand Forks, ND).

Methods

The methodology followed in this study included steps: 1) a survey of literature, 2) development of scientific and industrial community contacts (See

Figure 4 Photograph of Shell Mott 32X-3 in 1993. This is the last Newporte field producer.

Acknowledgments), 3) stratigraphic assessment, and 4) petrographic evaluation.

Literature Survey

An ongoing literature search has brought to light a polarization of views regarding the origin of the Newporte structure, as well as other subsurface circular structures within the Williston Basin. Although the Red Wing Creek structure in McKenzie County, North Dakota, is generally accepted as an impact crater, Bridges (1978, 1987) suggested wrench-faulting or the presence of a *concentricline*, a term he coined to explain this circular six-mile (9 km) wide feature and its central uplift. Shatter cones and high-pressure varieties of quartz have been found in rock recovered from wells penetrating the central region of the Red Wing Creek structure, strongly supporting an impact origin for that structure (Brenan and others, 1975).

Sawatzky 1975, 1977) catalogued several known and possible impact craters within the Williston Basin and adjacent areas. Some of these, like Red Wing Creek and Manitoba's West Hawk Lake, are generally accepted as the result of impact, but still others may be wholly or partly due to salt dissolution or some as yet unexplained process.

A detailed literature search was conducted to gather documents of value to the task of identifying impact structures, especially subsurface features. Studies dealing strictly with the impacting bodies themselves, or with other than terrestrial craters, were not included in the search Papers concerning nuclear explosive cratering and shock mechanics were included, as many contain details about and illustrations of associated mineral alterations.

Few articles were found that deal directly with the origin of the Newporte structure. Some of the same data and figures contained in Clement and Mayhew (1979) can be found in the North Dakota Industrial Commission (NDIC (1978)) hearing; both were written for Shell Oil Company. Donofrio (1981) suggested that the Newporte structure could represent first discovery of a "petroliferous basement astrobleme." Both Carlson and Thompson (1987 and Anderson (1988) described Newporte wells, but did not discuss the origin of the structure. The Newporte structure has been mentioned in the context of its importance in hydrocarbon production (Gerhard and others, 1982; Rountree, 1977).

Initially, there was concern that earlier investigators have already conducted extensive petrographic work on Newporte structure. This was not the case. Donofrio 1981 mentioned a plan to continue with a thorough examination of the available basement core, but he was unable to continue his work (Richard Donofrio, Astro Geological Resources Inc., written commun., 1992, Ridgefield, CT,).

Stratigraphic Assessment

General. Stratigraphic assessment of the Newporte structure included wireline log correlation, core sample examination and description, and the use of seismic reflection profiling data. Stratigraphic assessment was critical to this study, in that determination of the morphology of the Newporte structure is fundamental to deciphering its origin

Wireline Log Correlation. Wireline logs from seven wells in the study area are available on microfiche at the Wilson M. Laird Core and Sample Library (NDGS Core Library). Lithologic contacts derived from the dual laterologs, primarily gamma-ray logs (Appendix B), were compared to the contacts observed in available core. This work was necessary to evaluate actual thinning and thickening trends across the Newporte structure, to determine the relative age of the structure and to evaluate whether faulting produced and/or significantly modified the structure. Often well loggers' depth records (based on drilling time, cuttings, etc. are inaccurate, sometimes by as much as fifty feet 15 m) or more. This leads to the misreading of core depths, thereby causing erroneous correlations and interpretations Thus, first-hand correlations were necessary for this study. When the Newporte core depths were compared to the log depths, differences were as much as six feet (1.8 m) (Appendix A). Final correlations are consistent with those in the NDIC (1978) hearing report, in Clement and Mayhew (1979), Anderson (1988), and Carlson and Thompson (1987) Available lithologic logs and dual laterologs of the nearest wells outside Newporte field were also considered when making these correlations

Core Sample Examination. Description of available core samples was completed at the NDGS Core Library in Grand Forks, North Dakota (Appendix A). The Newporte structure is relatively well-cored, and has seven wells of sufficient depth to make the cores useful to this study. Approximately 815 ft (250 m) of core were described. It is difficult to locate brecciated intervals on well logs alone, so the availability of cored, brecciated intervals on the Newporte structure is fortuitous. A better understanding of the Newporte structure and associated rock units was developed through the process of core evaluation and description. All of the Newporte wells penetrate to Precambrian basement Drill cuttings were available for all uncored intervals of interest, except for the Gilbertson well, where limited samples became available only near the close of this study

Descriptions by Anderson (1988) were used as a model for this study. The rocks were examined with a 10X handlens and a 10X to 30X binocular microscope. Lithologic classification was done, according to Gilbert (1954) for sandstones and Potter and others 1980) for siltstones and claystones. Except for cementing material, very little if any carbonates exist in the intervals of interest. Moist core colors were described using the Geological Society of America rock color chart (Goddard and others, 1948). log depths are interpretations, while core depths are original Shell Oil Company designations, and are recorded directly on the core. Thus, depth footages were taken directly from the core for the descriptions, and have not been adjusted to the log depths in Appendix A.

Seismic Data. Lack of well control in the central region of the structure necessitated the use of seismic data in deciphering the Newporte structure morphology. Twelve of the seismic sections crossing the structure were kindly provided by Shell Western E&P, Inc. (Fig. 5).

A synthetic seismogram is a modelled seismic reflection record usually created from sonic well log data. Synthetic seismograms allow the subsurface geology (known only from the well log data) to be correlated with the seismic reflection data.

Typically, a synthetic seismogram is created from seismic and density data from a well site near the seismic profile being studied. A well log is digitized, and along with the required seismic parameters (frequency, time interval, etc.), is recorded. These data are entered into a synthetic seismogram-generating computer program. After

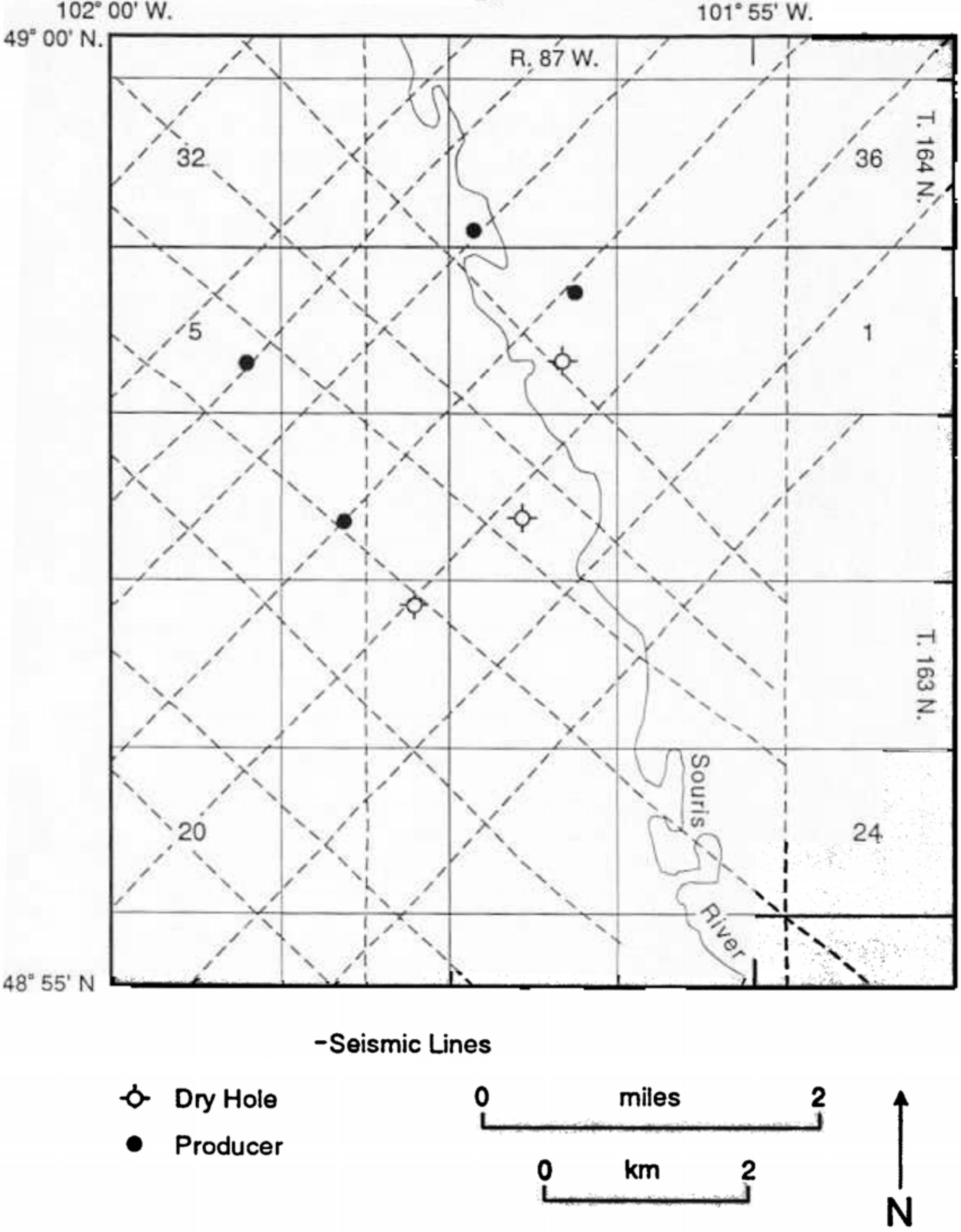


Figure 5 A map of the Newporte field vicinity, showing location of wells and seismic lines. Twelve of these lines were obtained from Shell Oil Company.

synthetic seismogram is generated, it is superimposed on seismic profile and correlated to it by moving the synthetic seismogram up and down until the reflection patterns match. Key reflectors, those lithologic horizons that produce high amplitude peaks or troughs, should match well if the synthetic and seismic profiles are correctly tied. This geology/seismic correlation may then be extrapolated to other seismic data in the study area.

Neil Anderson, a geophysicist at the Kansas Geological Survey, assisted with construction of the synthetic seismograms and helped with the initial geologic/seismic correlations. Synthetic seismograms were generated with LOG-M software, a Geophysical MicroComputer Applications product. These seismograms were created using digitized borehole sonic log data only. Except for the Prairie Evaporite-Icebox Formation interval, where rock salt is present, the velocity log provides a reasonable representation of the strata's acoustic impedance function (product of velocity and density). Perhaps most importantly, the velocity log can properly transform horizon depths into two-way time vertical seismic scale).

An interpreted, normal-polarity, seismic line is presented in figure 6. These twenty-four fold, dynamite-sourced data were acquired in 1977 and 1978, using source, group and near-offset interval spacings of 150 ft (45.7 m) These data were correlated to the one-dimensional synthetic

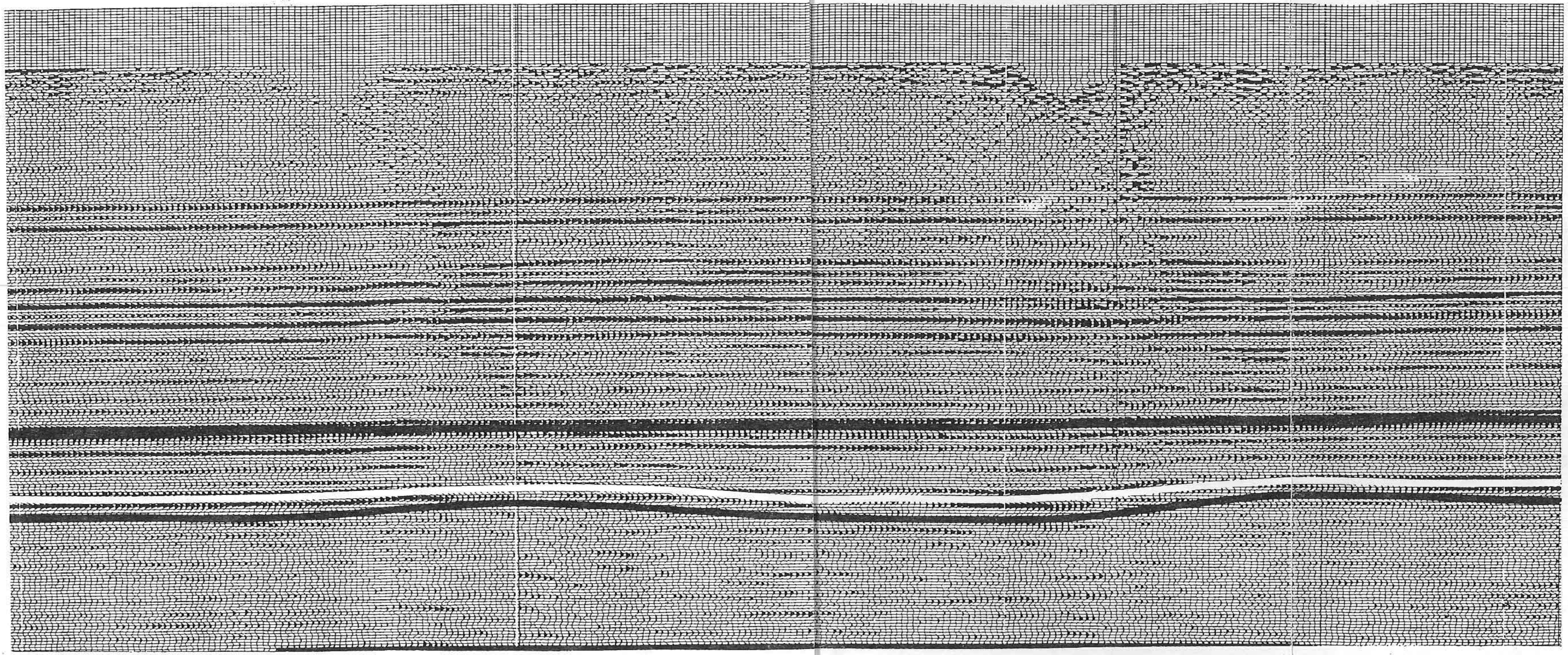


Figure 6 Interpreted seismic line. This line trends SW to NE across southern one-hal of the structure. Upper (black) line marks tp of the Devonian Prairie Evaporite (at 1.38seconds). White line marks top of Ordovician Winipeg Icebox Formation (at 1.59 seconds), and lowst (black) line marks seismic basement (at 1.66 econds). Shot points, well locations, and verticl time scale are not given here due to proprietry concerns.

seismogram for the Larson 23X-9 well (Fig. 7), located less than 200 ft (60 m) from the seismic line

The synthetic seismogram was generated using zero-phase Ricker wavelets with a dominant wavelength of 30 ms (26 This means that on the normal-polarity synthetic seismogram display (Fig. 7) an abrupt increase in seismic velocity corresponds to a peak (e.g., shale/limestone contact); an abrupt decrease in velocity corresponds to a trough. The wavelength used in this model, 30 ms (26 hz), is a reasonable representation of the dominant wavelength of real seismic data. The wavelength of the seismic data restricts vertical resolution. Generally speaking, beds with thicknesses of less than 1/4- or 1/2-wavelength (depending upon the relative acoustic impedance contrasts at the top and base of the bed) cannot be resolved accurately.

These synthetic seismograms were then compared to the actual seismic sections. Three key reflectors, the seismic basement, the Winnipeg Group Icebox (shale) Formation the Prairie Evaporite, were used to tie the synthetic data to the seismic lines (Figs. 6 and 7 The lowest event, identified here as the seismic basement, is a best guess for the contact between the Precambrian crystalline basement and the overlying sedimentary units. In actuality, this reflector could represent either the actual contact, the base of weathering or alteration zones, shear zones, and/or the base of brecciation. Upon finding a match with the

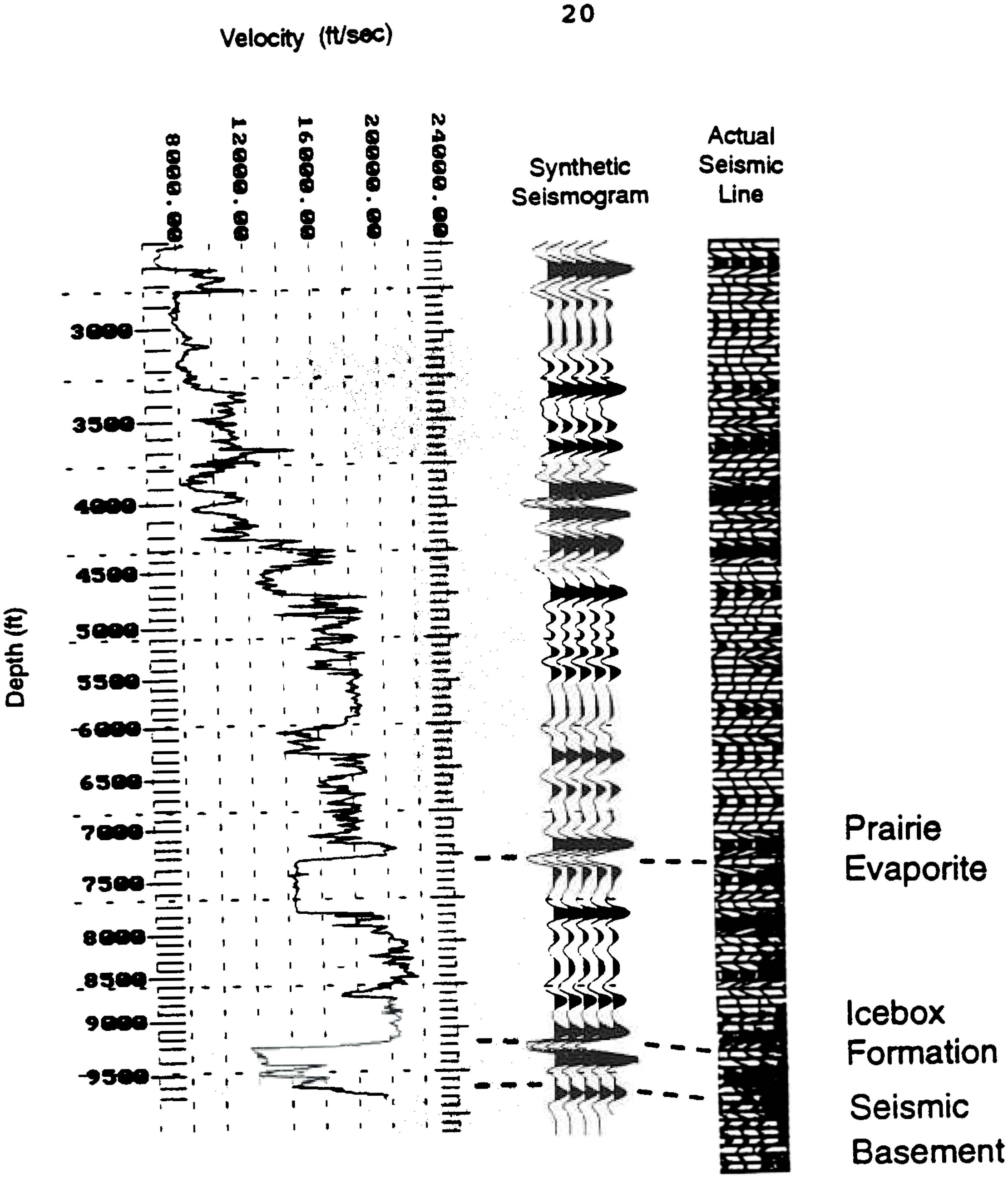


Figure 7 Correlation of velocity log and synthetic seismogram of the Larson 23X-9 well, and a portion of the nearest seismic survey line.

actual seismic survey line nearest each well, an interval thickness versus transit time scale was created for each of two formation intervals, the Prairie Evaporite to Winnipeg Group Icebox Formation and the Icebox Formation to the seismic basement. These synthetic scales were used to estimate interval thicknesses along five lines in the seismic survey. Interval thicknesses were estimated at every other trace along the five profiles (a point to point distance of approximately 300 ft (91 m) In total, over 300 seismic data points, combined with the seven well points, were entered into a spreadsheet program, and mapped using Golden Software's Surfer program (Golden Software Incorporated, 1990). These were then imported to a Corel Corporation CorelDRAW graphics program by which the maps were finalized (Corel Corporation, 1992)

Petrographic Evaluation

General. The petrographic portion of the study involved the selection of core and drill cuttings, followed by sample preparation and microscope investigation. Core descriptions are listed in Appendix A. Well cores were used primarily to locate intervals most likely to contain evidence of shock (e.g., brecciated intervals)

Sampling and Sample Preparation. Selection of materials for sampling was based on an assessment of which areas were most likely to exhibit evidence of shock metamorphism as well as availability of adequate core material for sampling.

The brecciated zones in both the Duerre and Mott 14-34 wells were initially chosen for study. These zones show similarities to impact breccia illustrated in the literature (Kirschner and others, 1992; McCabe and Bannatyne, 1970; Stearns and others, 1968; Beals, 1960).

Twenty-six previously prepared thin sections from the Duerre, Gilbertson and Mott 32X-3 wells were acquired from the NDGS Core Library. Thirty additional standard thin sections were made from chips of brecciated basement from the Mott 14-34 well, interval 9060 to 9167 ft (2761 to 2794 m). In addition, seventy-one grain-mount thin sections were made from drill cuttings of the Duerre, Larson, Lindblad, Mott 32X-3 and Wisdahl wells. These cuttings had been separated to include mostly quartz, quartzose sandstone and a few feldspars. After the preliminary investigation of these, seven additional standard thin sections were made from Wisdahl 23-10 and Mott 14-34 core and chips, and thin sections were made from the two nearest basement-cored wells, Osterberg 22X-1 and Osterberg 21-2. The Wisdahl specimen was of interest because of the extreme deformation exhibited over the interval sampled. The Mott thin section was stained with a combination feldspar stain to assist in distinguishing untwinned feldspar from quartz. The Osterberg specimens were prepared so a comparison could be made with the basement thin sections from the Newporte wells. All thin sections made for this study were prepared by Quality Thin Sections of Tucson, Arizona.

Microscope Investigation. Reference thin sections of granites, gneisses and sandstones were examined to develop a base of knowledge of typical, unshocked Earth materials. A reference petrographic collection of shocked materials from the Lake St. Martin structure in Manitoba was loaned by the Manitoba Department of Energy and Mines in Winnipeg.

All Newporte thin sections were thoroughly evaluated for any microscopic evidence of shock metamorphism, using a Leitz-Wetzlar HM-POL polarizing microscope. Photomicrographs were taken using a Nikon Optishot-POL. Shock metamorphism in the context of this study means any planar (deformation) features (PDF), other than twinning, in feldspars or quartz, offset twinning in feldspars, kink bands in micas, granular or planar features in zircons, isotropic materials impact glass), or unusual cleavage or fracturing. Any unusual features deemed likely candidates of shock metamorphism were sent to David Roddy of the United States Geological Survey, Flagstaff, Arizona for a second opinion.

PREVIOUS STUDIES

Impact Studies

No previous studies, other than the initial investigation by Shell Oil Company, have specifically examined available evidence to address the possibility of an impact origin for the Newporte structure. However, at least a few authors did mention the possibility of such an origin Prior to this study, Clement and Mayhew 1979) had completed the most comprehensive study of the structure. They proposed localized, Late Precambrian-Early Paleozoic differential vertical basement faulting as the cause of the Newporte structure. However, the impact hypothesis was mentioned. Donofrio (1981 also proposed the possibility of an impact origin for the feature. He stated that if evidence of an impact were found, it would represent the first known discovery of a petroliferous, basement astrobleme. Castano and others 1994), working on the hydrocarbon geochemistry, believed the Newporte structure to be of impact origin. Their work is a continuation of some results originally published in Clement and Mayhew (1979)

General Studies

Carlson and Thompson 1987) included three Newporte wells in their discussion of the Winnipeg Group within the Williston Basin. They correlated these wells (in cross section) to the Stone Ones #1 well approximately six miles (10 km) southeast of the structure. Anderson (1988) described core from Wisdahl 23-10, one of the more stratigraphically normal wells on the structure, in his regional study of the Deadwood Formation. Mescher and Pol (1985) published a brief abstract discussing the sedimentation of the Cambro-Ordovician Newporte lithologies. Although they did not mention an impact origin, they believed basement block movement occurred during middle Deadwood deposition. The economic importance of anomalous structures, like the Newporte and especially the Red Wing Creek structure, were discussed briefly in Gerhard and others (1982). Peterman and Goldich (1982) reported a biotite-garnet gneiss Rb-Sr date of 1.76 Ga for Mott 14-34 core. In a hydrocarbon study of the Ames structure in Major County, Oklahoma, and the Newporte structure, Castano and others (1994) concluded that unusual geochemical signatures pointed to a lacustrine source rock. For the Newporte structure they identified the locally-developed Ordovician Winnipeg Shale as the source of the Cambro-Ordovician Deadwood production

RESULTS

Morphology and Local Stratigraphy

At the study area the Precambrian basement is nonconformably overlain by the Deadwood Formation, which, in turn, is disconformably overlain by the formations of the Winnipeg Group. Due to the lack of well control in the central region, and in the nearby areas surrounding the structure, mapping is highly dependent on seismic data.

The two seismic data isopach maps of the structure (Figs. 8 and 9) represent the Icebox Formation-seismic basement interval and the Prairie Evaporate-Icebox Formation interval, respectively. The isopach maps have a contour interval of fifty feet 15.2 m). These maps are valuable in proving the circular morphology of the structure, and in showing the thickening and thinning trends across the depression

In the generation of the structure-contour map of the seismic basement (Fig. 10), thickness values for these two seismic intervals were summed, and the negative value was then mapped. Figure 10 is a representation of how the actual crystalline basement may look. A raised rim is shown to encircle a bowl-shaped depression. The rim is higher to the northeast, and what appear to be breaches in the rim

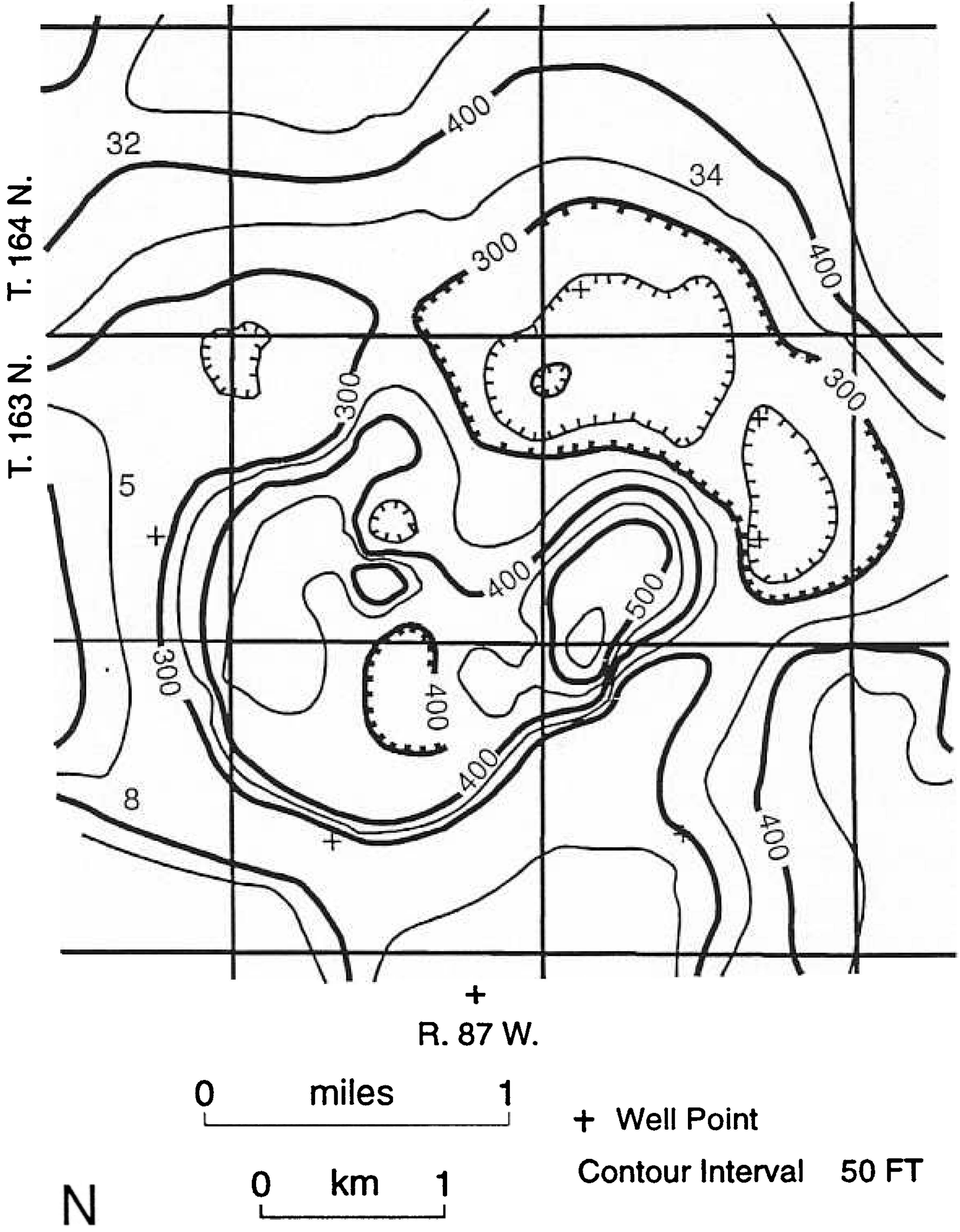


Figure 8 Isopach map of the Icebox - Seismic basement interval.

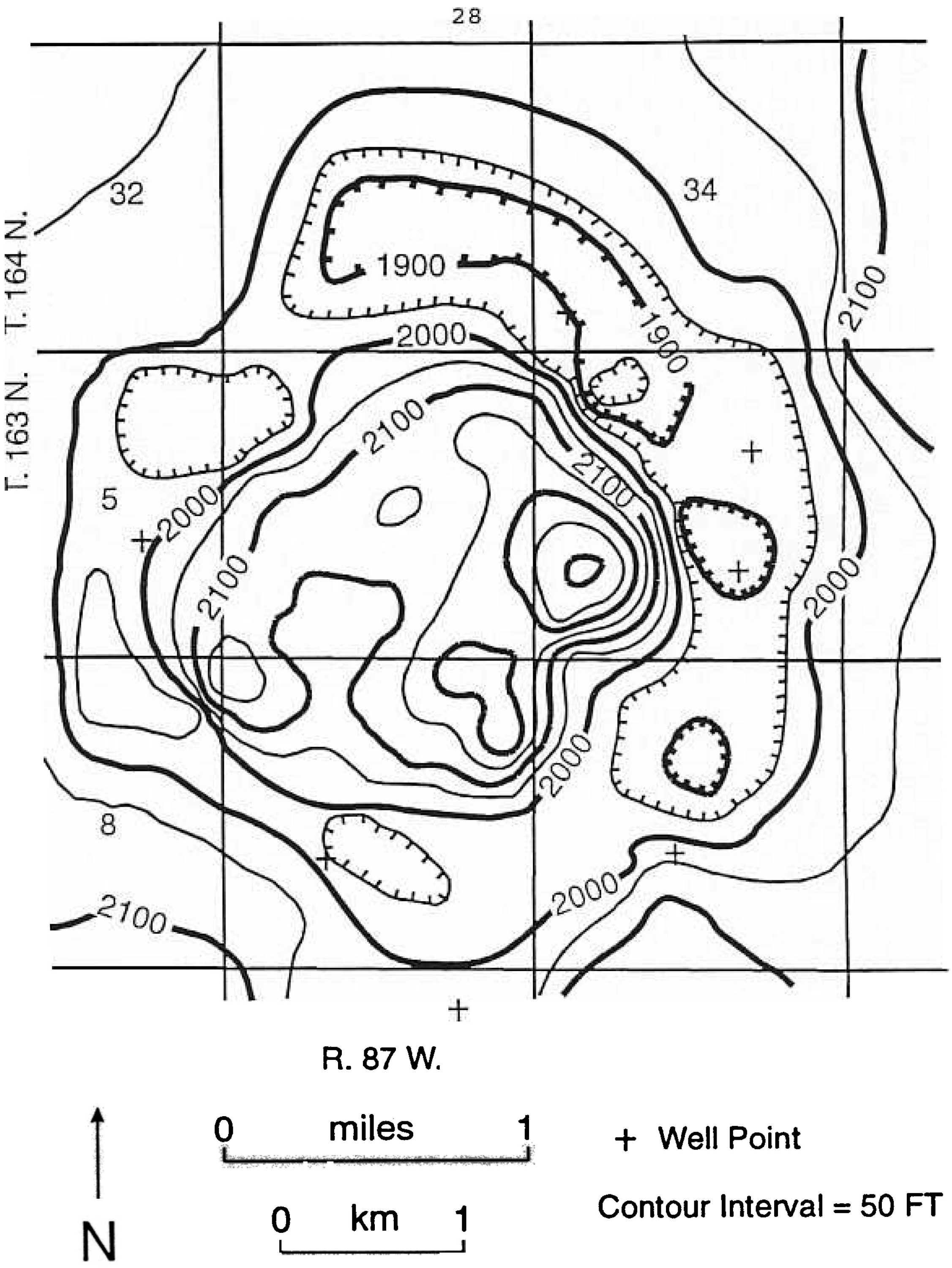


Figure 9 Isopach map of the Prairie - Icebox interval

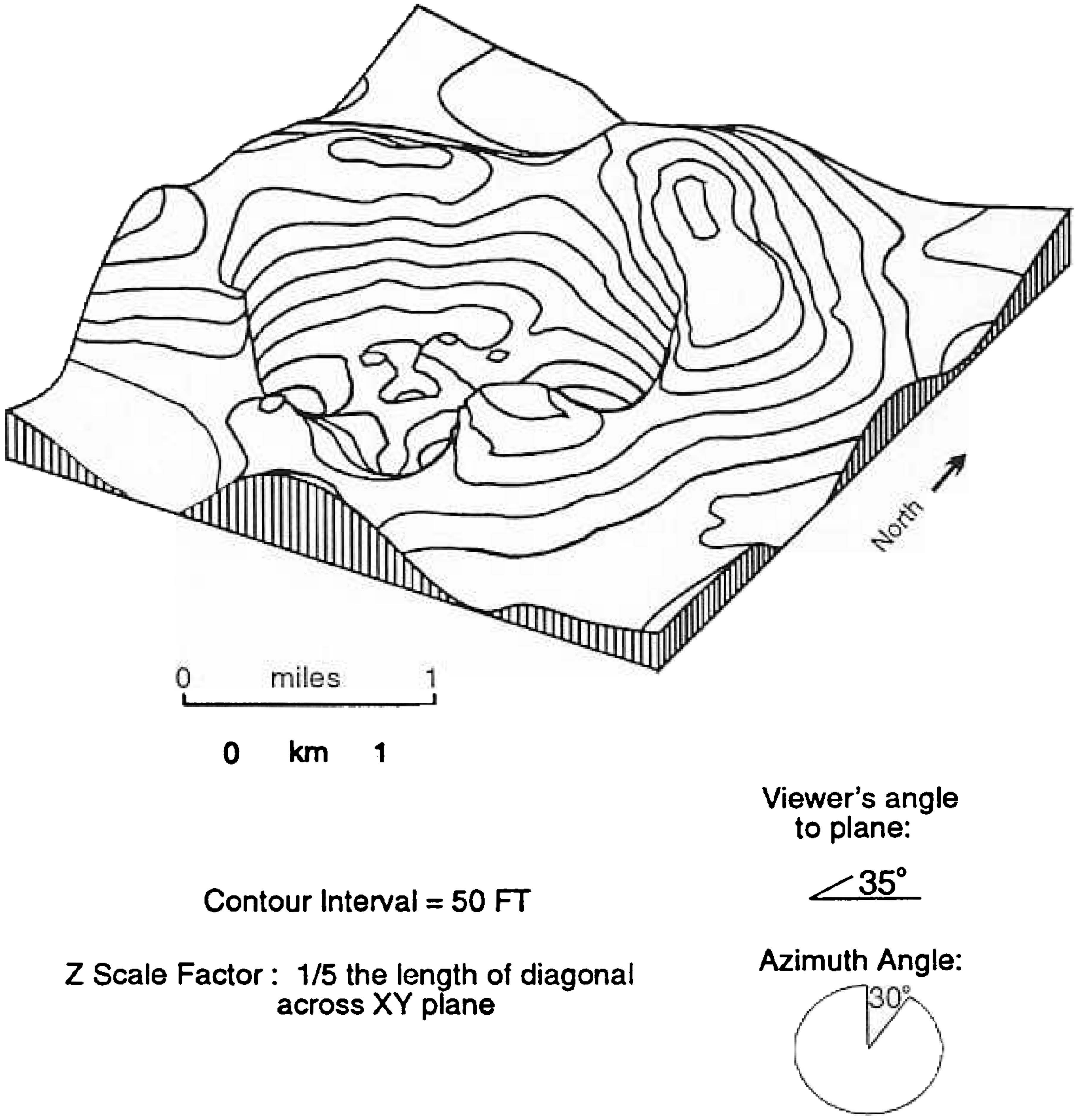


Figure 10 Oblique view of generalized structure-contour map on seismic basement.

occur occasionally. Whether or not the breaches are real or artifacts of the mapping program is debatable. Again, limitations of the seismic data and the mapping technique do exist. The deepest portion in the eastern region of the structure is partially obscured in this view by the southeast rim

Thicknesses of the Deadwood through Black Island Formations vary considerably over the Newporte structure. For example, from well log data, Deadwood thicknesses on the structure's rim range from zero in the northeastern Mott 32X-3 and Mott 14-34 wells to over 200 ft (61 m) in the southern wells (Fig. 11).

Anderson (1988) subdivided the Deadwood Formation into six informal members (members A through F , based on gamma-ray characteristics. The Deadwood sandstone preserved at the Newporte structure is difficult to correlate to these members, perhaps due to the structurally and stratigraphically anomalous character of the structure itself Wells that contain a thicker preserved Deadwood section Wisdahl 23-10 and Lindblad 41X-16, hold the best chance for differentiating members. Anderson 1988) used "undifferentiated members A & B" for his core description of the Deadwood Formation in Wisdahl 23-10.

The Black Island Formation thickness (the lowermost Winnipeg sand) follows the Deadwood trend to some degree. It is thinnest at 10 ft (3 m) in the Mott 14-34, in the

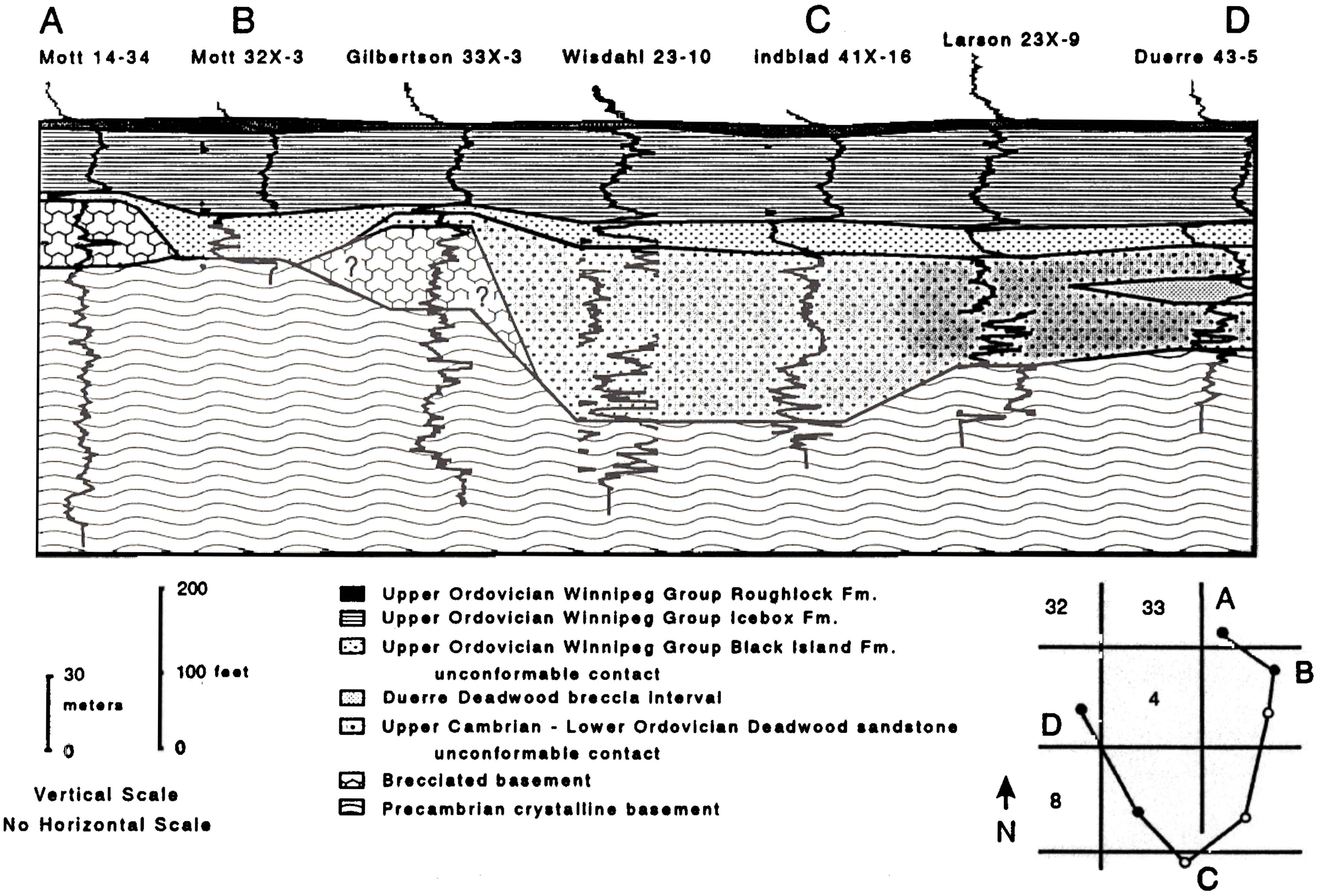


Figure 11 Cross section around rim of the Newporte structure. Reproductions of each of the gamma ray logs are shown. Note that positions of all wells are on or near the rim of the structure.

northeast, and in the Gilbertson 33X-3, on the east rim. Thickening is evident in wells to the south and west where the maximum thickness is approximately 40 ft (12 m). This thickening is most likely due to the well positions relative to the rim of the structure. Wells lying slightly more distal to the high points exhibit a thicker preserved section. This appears to be the case in Mott 32X-3. The thicker Winnipeg Group section there can be explained this way.

The Icebox and Roughlock Formations are relatively uniform in thickness across the structure, with the exception of the Mott 32X-3 well location. Thus, the Newporte structure may have been completely obscured by burial prior to or during deposition of the Icebox Formation

As mentioned earlier, figure 8 presents characteristics of the lowermost seismic interval, the Icebox Formation to seismic basement. The most obvious feature is the circularity of the structure. In addition, two thicker areas in excess of 450 ft (137 m) can be seen, one on the eastern and one on the western interior. These are separated by what appears to be a thinner region in the central portion of the structure. The thinnest areas are over the northern and eastern rim. At these locations the interval thins to less than 250 ft 75 m).

Figure 9, an isopach of the Devonian Prairie Evaporite to Icebox Formation interval, mimics most of the features found on figure 8. It also verifies the circularity of Newporte structure. Thinning is evident over the northern rim, to less than 1900 ft (575 m). The lowest region on the structure is on the eastern interior. Here, interval thicknesses reach a maximum of over 2200 ft (670 m). Also, the existence of a higher central region on the crystalline basement appears to be shown by the thinning of this interval.

Microscopic Investigation

The probability of finding microscopic evidence of shock in the Newporte samples was not high, because shock intensities diminish quickly with distance from the point of impact (Melosh, 1989). All wells on the Newporte structure are on or adjacent to the structure's rim. Chances of finding microscopic evidence of shock metamorphism are even less likely when the crater has undergone extensive erosion Still, strongly shocked minerals may have been incorporated in ejecta breccia on the rim and/or low shock pressures may have produced weakly shocked material along the rim of structure.

Shock metamorphism in this case means any planar (deformation) features (PDF other than twinning, in feldspars or quartz, offset twinning in feldspars, granular or planar features in zircons, isotropic materials impact glass), or unusual cleavage or fracturing. Kink bands in micas are also presented here, as further evidence of impact, although they can be found in non-impact settings.

Previously prepared specimens were examined from Mott 32X-3, Gilbertson 33X-3 and Duerre 43-5, all of which are housed at the NDGS Core Library. Of special interest were the Duerre thin sections covering the brecciated interval penetrated by that well. These all contain portions of both clast and matrix material. However, examination of these and all other previously prepared Newporte thin sections revealed no evidence of shock metamorphism

The brecciated zones in both the Duerre and Mott 14-34 wells were initially chosen for study because of their similarity to known impact breccias (Kirschner and others, 1992; McCabe and Bannatyne, 1970; Stearns and others, 1968; Beals, 1960). For this study, thirty standard thin sections were made from chips of brecciated basement from the Mott 14-34 well, interval 9060 to 9167 ft (2761 to 2794 m)

In addition, seventy-one grain mount thin sections were made from drill cuttings of the Duerre, Larson, Lindblad, Mott 32X-3 and Wisdahl wells (No cuttings were available for Gilbertson 33X-3). Drill cutting samples were separated to concentrate mostly quartz, quartzose sandstone and few feldspars. None of these thin sections displayed any unusual features

After the preliminary investigation of the thin sections, seven additional standard thin sections were made from Wisdahl 23-10 and Mott 14-34 core and chips. Six of these were from samples of the deformed interval in Wisdahl 23-10, depth 9370 to 9400 ft (2856 to 2865 m). One thin section was of the previously sampled Mott 14-34, depth 9072 ft (2765 m). This slide was stained for potassium feldspar and plagioclase to facilitate distinguishing quartz from untwinned feldspar

In addition, two thin sections were made from each of the Osterberg wells (21-2 and 22x-1). These are approximately twelve miles (20 km) southeast of Newporte field, and represent the closest known basement-cored wells to the Newporte structure. Osterberg specimens were prepared so a comparison could be made to the basement examples from the Newporte wells. Peterman and Goldich (1982 described the Osterberg 22X-1 basement rock as hypersthene gneiss and Osterberg 21-2 basement as a garnet-biotite-cordierite gneiss. This is consistent with what was found in the thin sections from 9261 ft (2823 m) for Osterberg 21-2 and 9313 ft (2838 m) for Osterberg 22X-1 Their composition and texture are significantly different from the Newporte samples. None of the shock features represented in the following Newporte photomicrographs was found in the Osterberg thin sections

Figures 12 through 31 are all photomicrographs of thin sections from the Mott 14-34 (except two from Lake St

Martin, Manitoba). Below is a description of each of these photomicrographs and their characteristics.

A five-foot (1.5 m) thick sandstone is the highest cored interval in Mott 14-34. Photomicrographs of this coarse sandstone from 9060 ft (2761 m) are provided as figures 12, 13 and 14. Unusual, linear features appear in quartz grains throughout this thin section. If these are PDF due to shock metamorphism, they are examples of weakly shocked material. The best example of this texture is found in an angular quartz grain (Fig. 14), where a single, parallel set of planar features is exhibited. No unusual fracturing was displayed surrounding the grain contacts in this thin section

Several subparallel features were also found in grains and rock fragments within this sandstone interval (Figs. 15, 16 and 17 Multiple parallel and subparallel planar features are evident in the two quartz grains shown in figure 17. The sample of figure 17 represents the lowest portion of the coarse sandstone overlying the brecciated crystalline basement of Mott 14-34. These photomicrographs verify that the unusual texture found in the quartz grains occur not only in the brecciated basement, but throughout the overlying sandstone

Photomicrographs also were taken of two thin sections from 9072 ft (2765 m) (Figs. 18 through 29). This interval, within the brecciated basement zone, seems to exhibit the

Figure 12 Photomicrograph (crossed polars) of coarse sandstone that overlies breccia in Mott 14-34. This sample was taken from 9060 ft (2761 m), and represents the highest cored interval of Mott 14-34. This sandstone contains few glauconite pellets, and is approximately 5 feet (1.5 m) thick. Arrow indicates quartz grain exhibiting planar features. Scale bar, approximately 500 microns.

Figure 13 Photomicrograph (plane light) of coarse sandstone that overlies breccia in Mott 14-34.

Figure 12

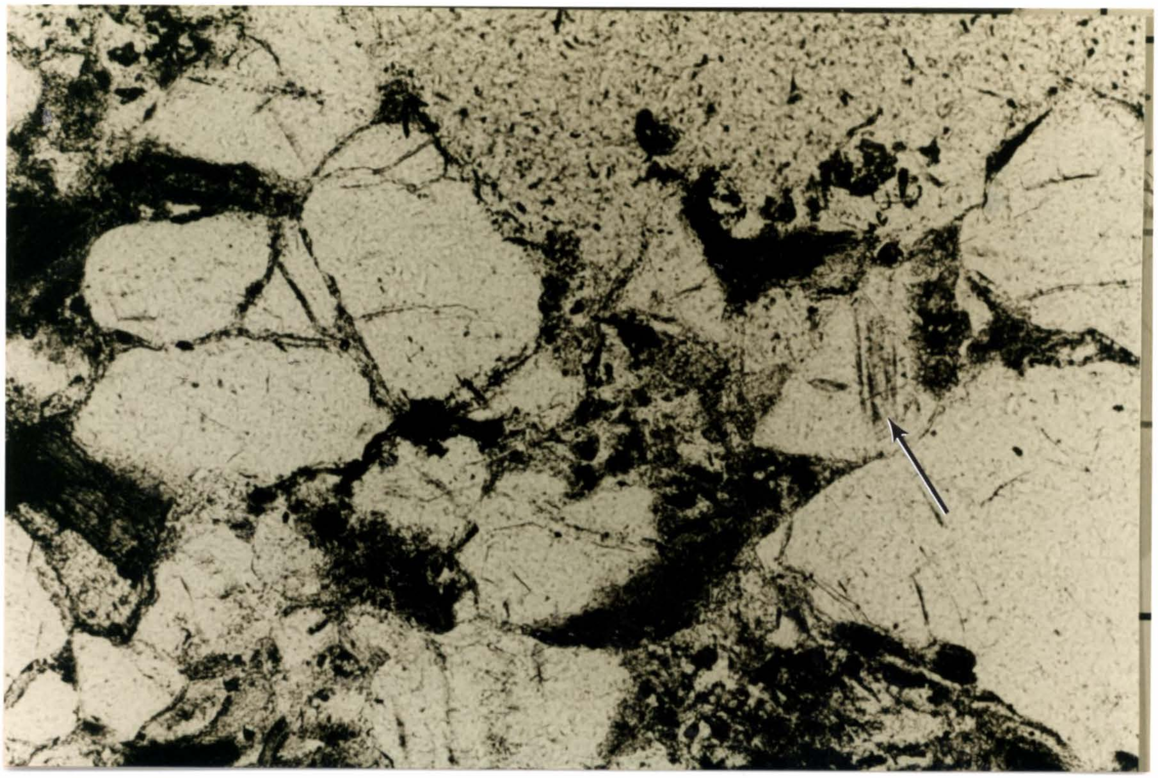


Figure 13

Figure 14 Detail of a single quartz grain from same thin section as seen in Figures 12 and 13 (plane light). Note single set of planar features. Scale bar, approximately 150 microns.

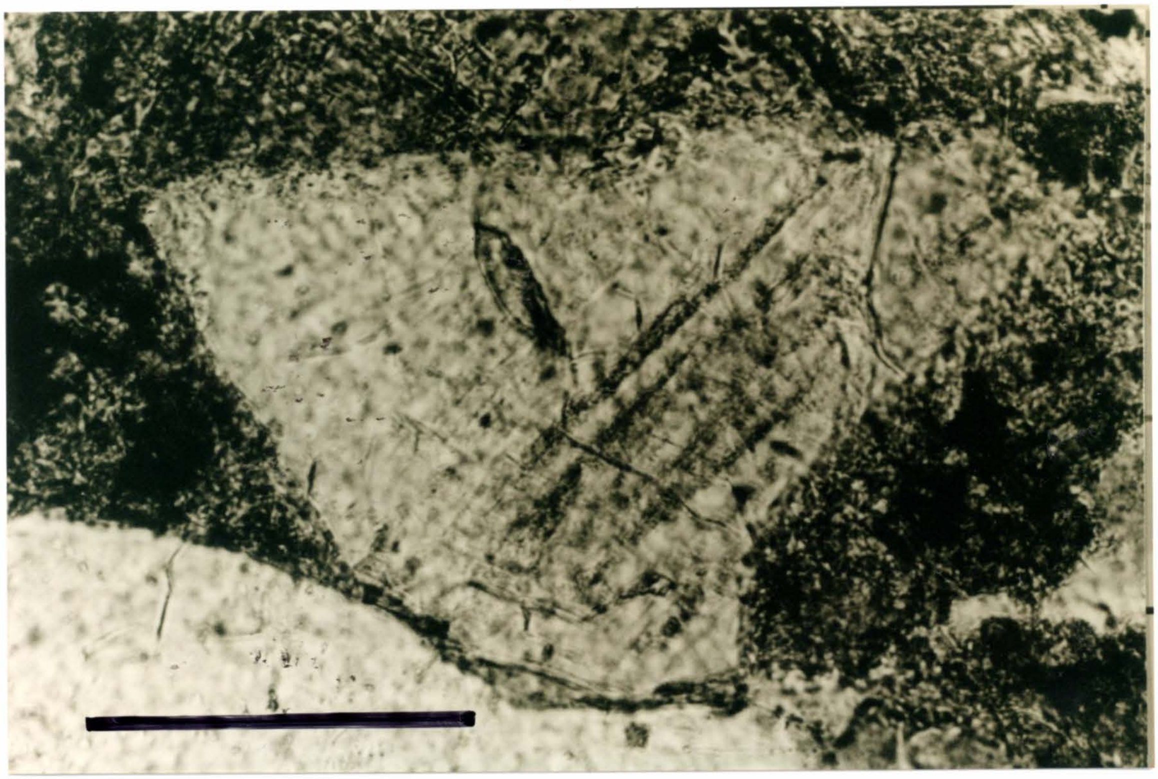


Figure 14

Figure 15 Photomicrograph (crossed polars) of same coarse sandstone previously shown (Fig. 12, 13 and 14). Mineral grains and rock fragments are shown. Note the subparallel features indicated by arrows on Figure 16. Scale bar, approximately 500 microns.

Figure 16 Photomicrograph (plane light) of same coarse sandstone previously shown (Fig. 12, 13 and 14).

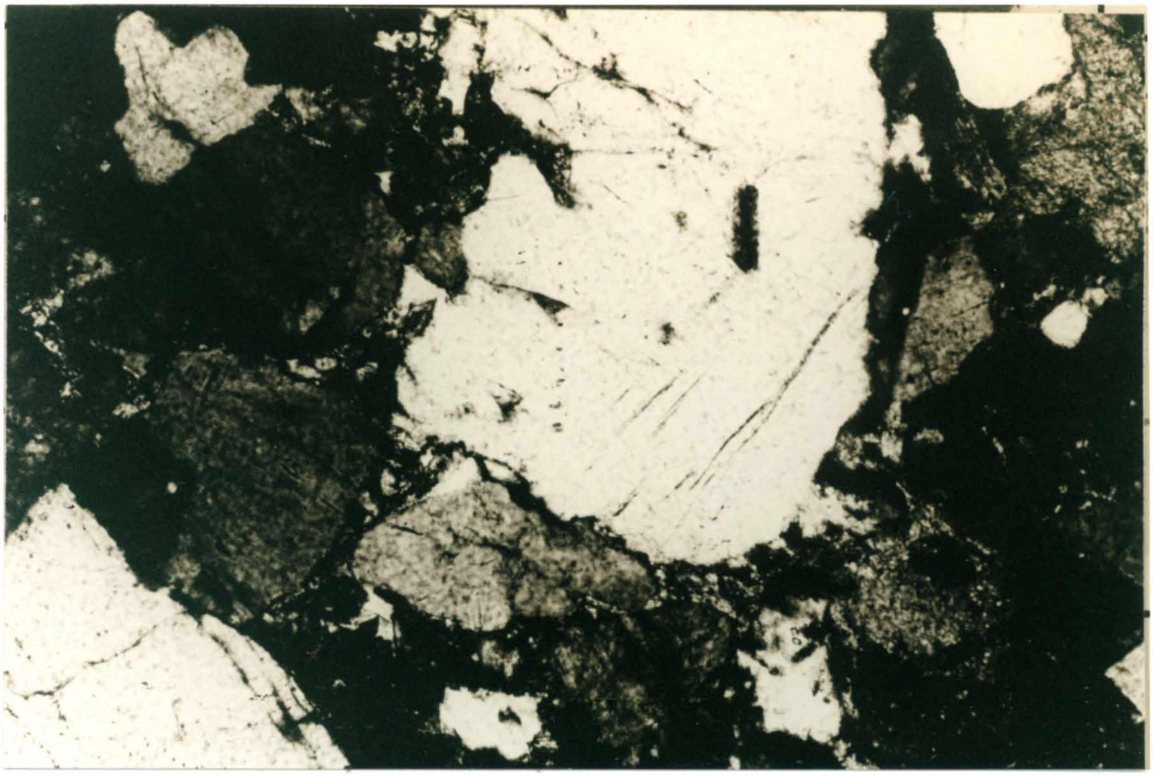


Figure 15

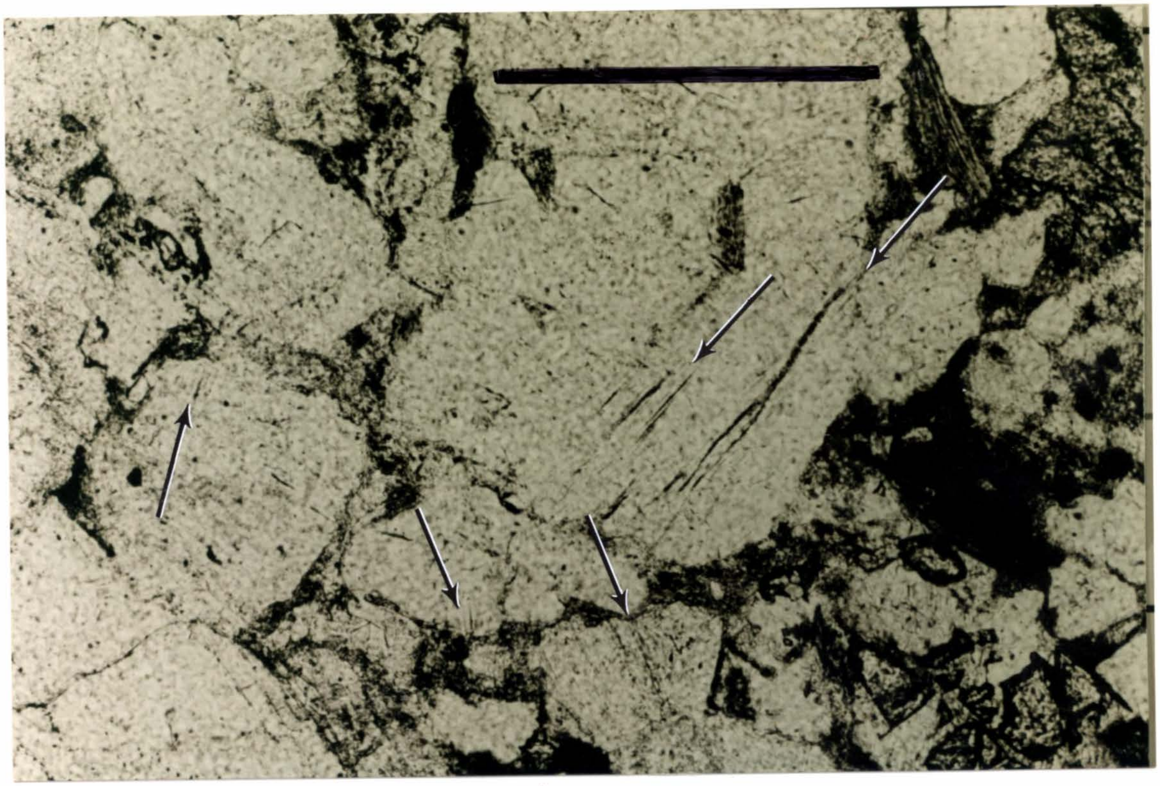


Figure 16

Figure 17 Photomicrograph of a quartzose clast from 9064-65 ft (2763 m). This is approximately the contact between the brecciated crystalline basement and the overlying sandstone. Multiple parallel and subparallel planar features in two quartz grains are evident. Scale bar, approximately 500 microns.

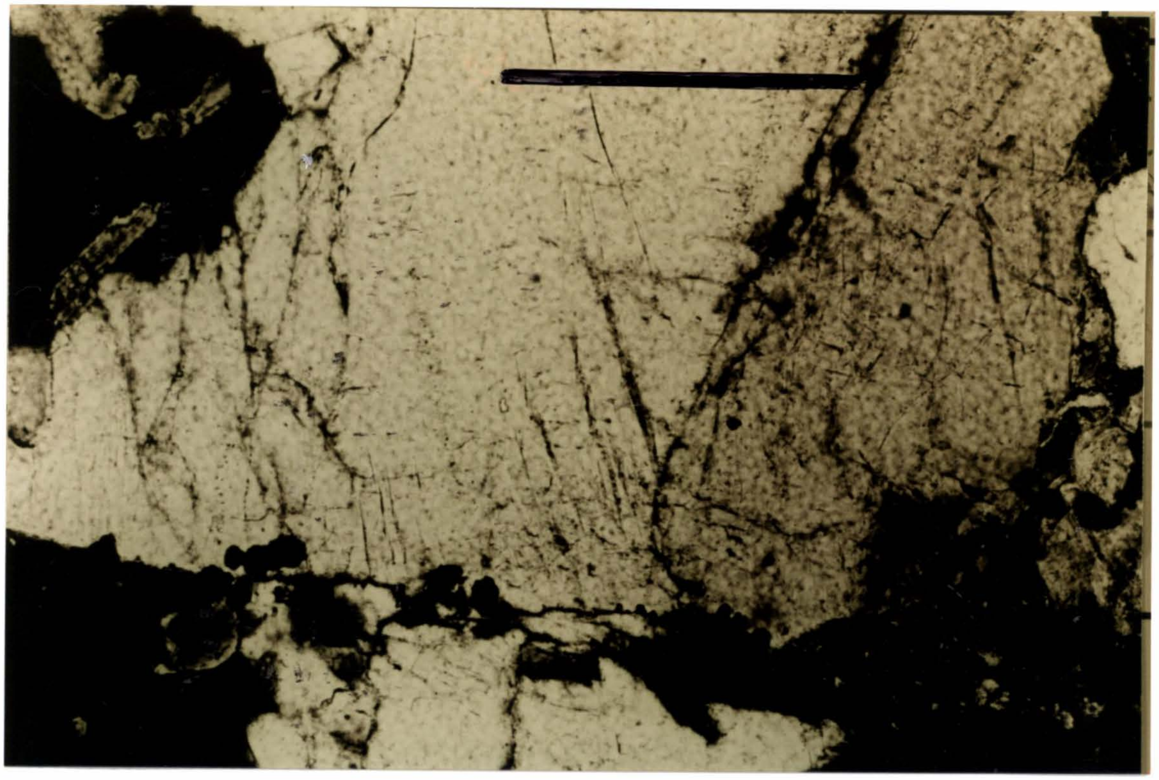


Figure 17

best examples of shock. One thin section was impregnated with combination feldspar staining and one was not. The staining had no effect on the visibility of the planar features described.

Textures (PDF) similar to those found at Lake Acraman Australia (Williams, 1986), were located in the Newporte specimen (Figs. 18 and 19). The orientation of these features varies between the two adjacent quartz grains shown.

Intersecting sets of planar features within a single grain may also be present. Figures 20, 21 and 22 exhibit one fairly parallel set and possibly one poorly developed set of planar features in a quartz grain. Again, these are presented here as evidence of low-level shock deformation. The biotite grain in the center of the photo (Fig. 22) may also be weakly shocked, but kink bands are not distinguishable

Figures 23 and 24 were of a single fractured quartz grain that fills the frame. At least one set of subparallel planar features can be distinguished. One set can also be seen in the next photomicrograph (Fig. 25). Staining can be seen on the feldspar grain in the lower region, distinguishing it from the quartz grains in the upper left. Note the biotite mica grain in the center of the photomicrograph. Kink bands trend N to S, and are

Figure 18 Photomicrograph (crossed polars) of two quartz grains, Mott 14-34, 9072 ft (2765 m). These photomicrographs (Fig. 18 and 19) are of an unstained thin section. Portions of two quartz grains with differing extinction orientations are shown. Note the planar features, trending ENE to WSW across the larger grain. Those within the smaller grain on the left trend NW to SE. Scale bar, approximately 150 microns.

Figure 19 Photomicrograph (plane light) of two quartz grains, Mott 14-34, 9072 ft (2765 m).

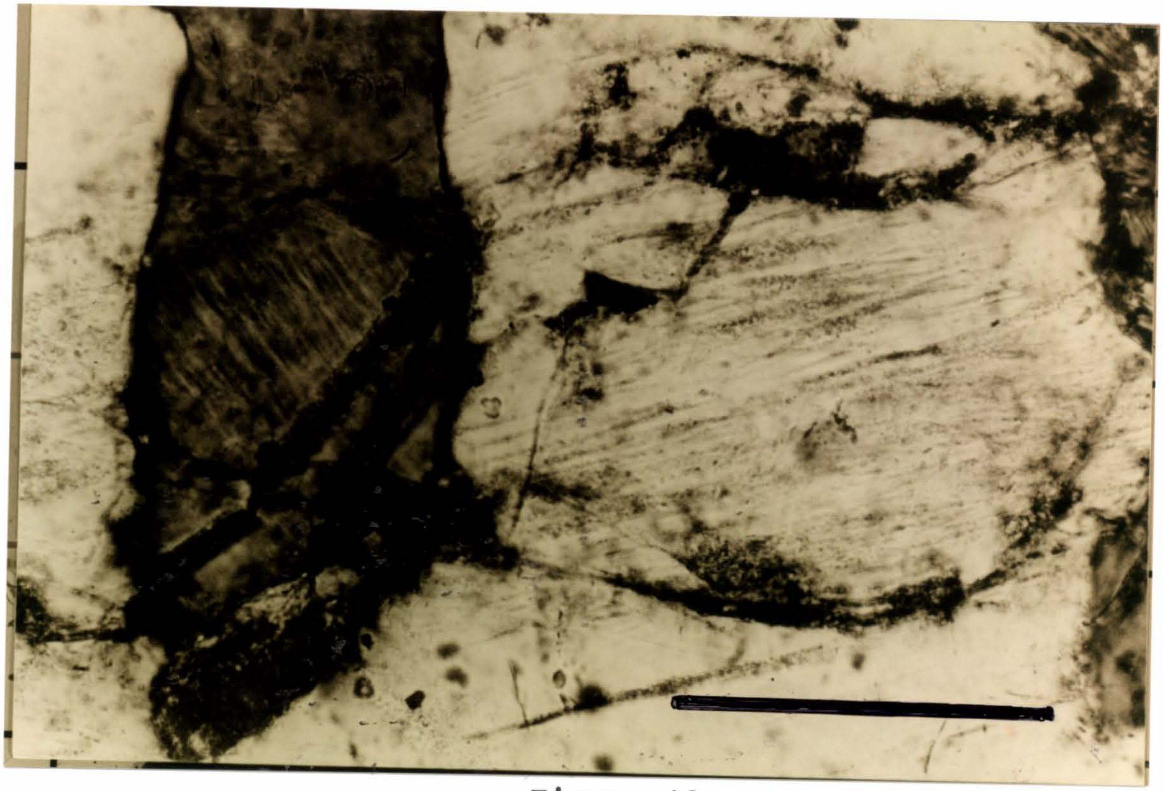


Figure 18

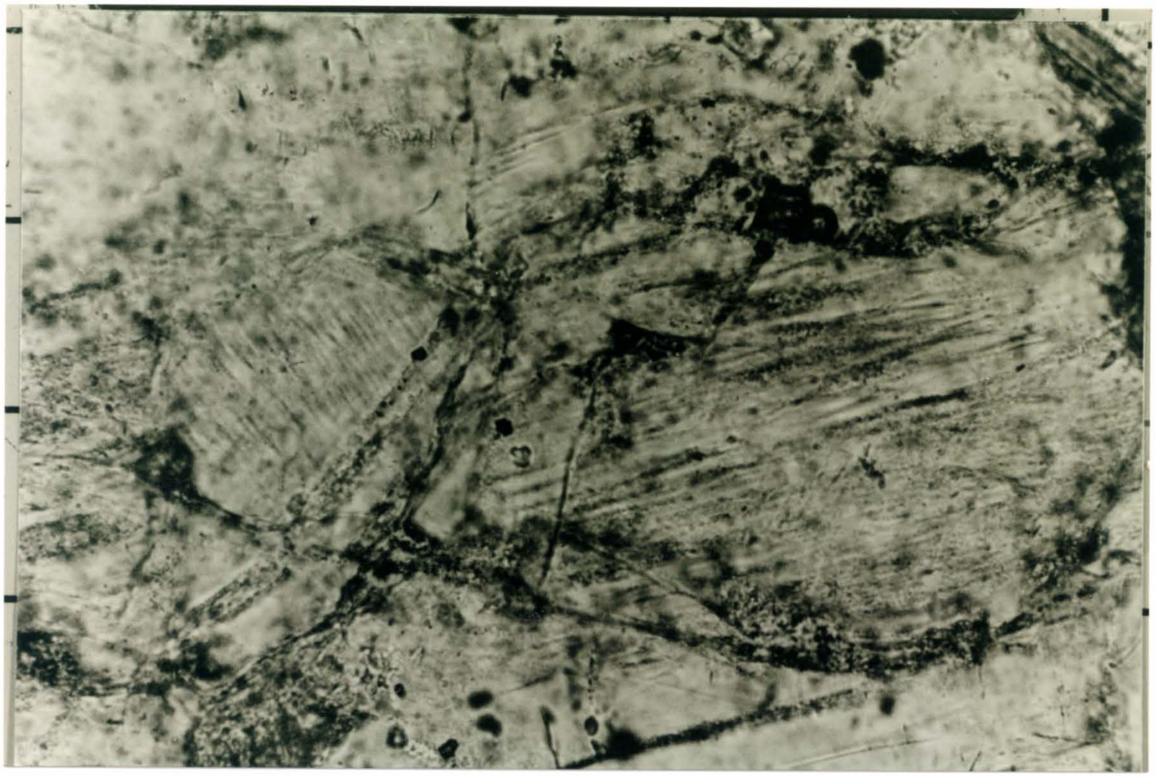


Figure 19

Figure 20 Photomicrograph (crossed polars) of a single quartz grain, Mott 14-34, 9072 ft (2765 m). One fairly parallel set and one poorly developed set of planar features are exhibited in this single quartz grain. Scale bar, approximately 150 microns.

Figure 21 Photomicrograph (plane light) of a single quartz grain, Mott 14-34, 9072 ft (2765 m).

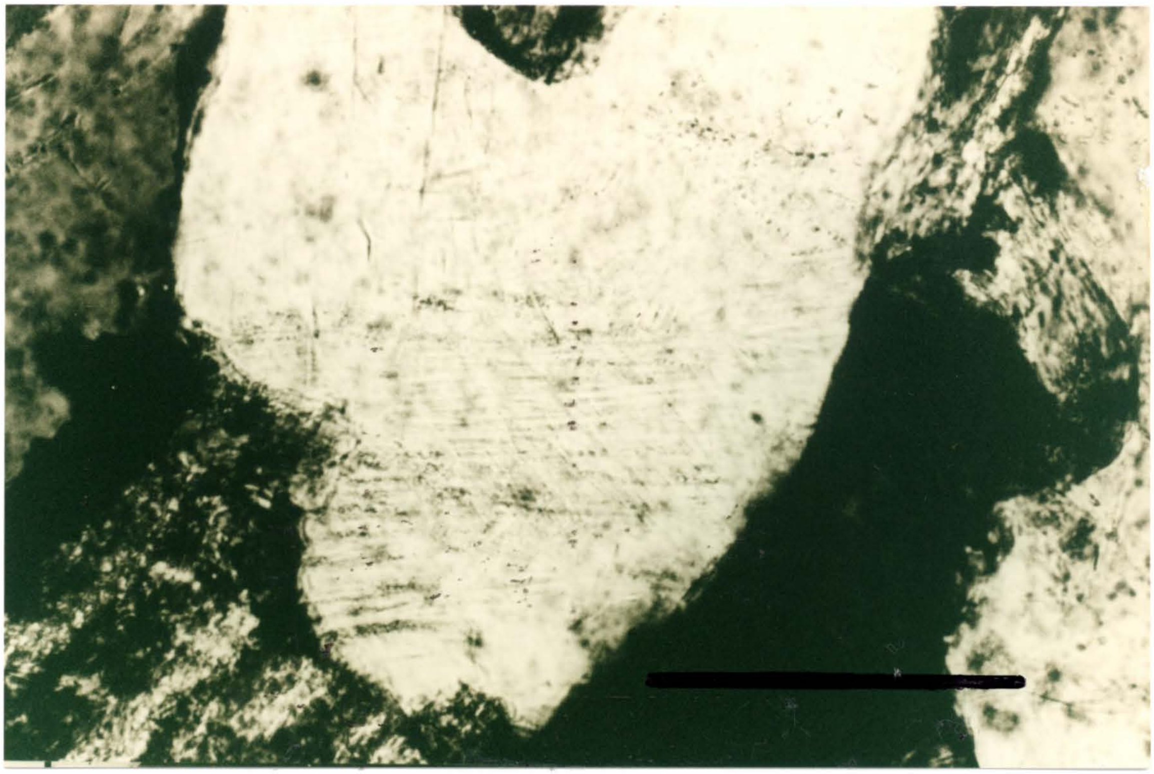


Figure 20

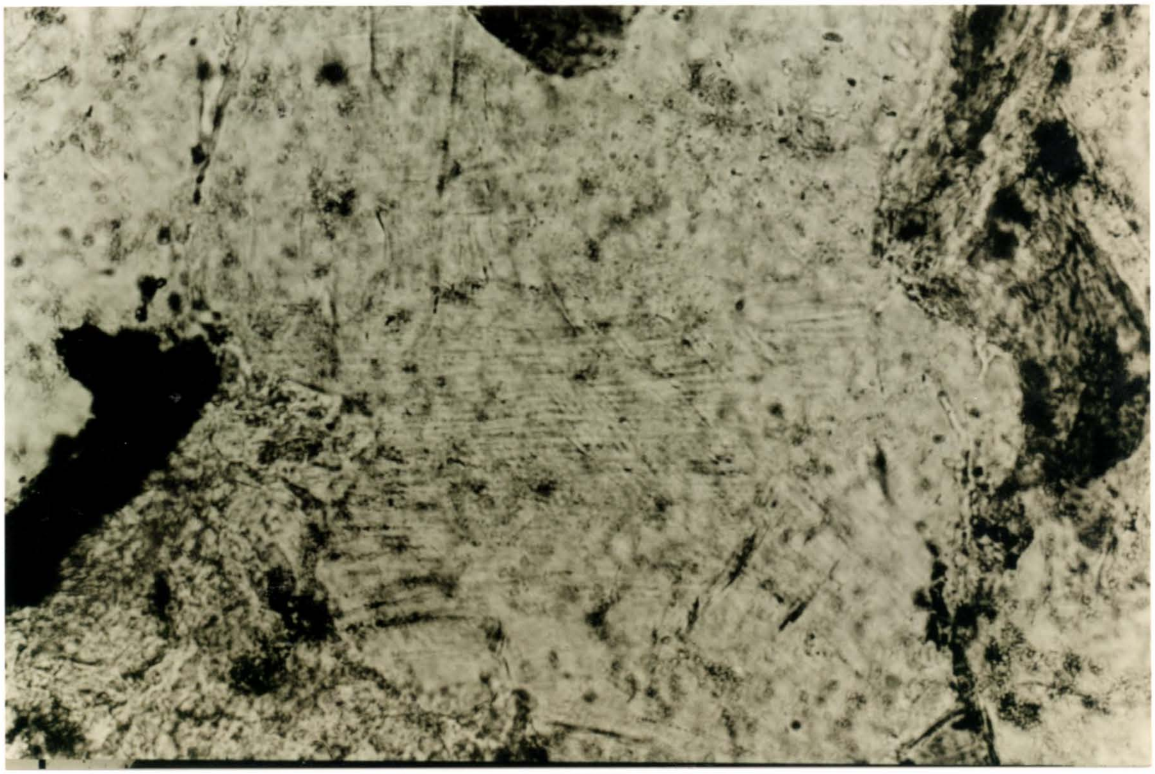


Figure 21

Figure 22 Photomicrograph (plane light) of quartz, feldspar and biotite grains within brecciated granitic-gneiss basement, Mott 14-34, 9072 ft (2765 m). One subparallel set or two poorly developed sets of planar features are exhibited in the quartz grain in lower left. The biotite grain in the center of the photo may be weakly shocked, but kink bands are not clear. Scale bar, approximately 150 microns.

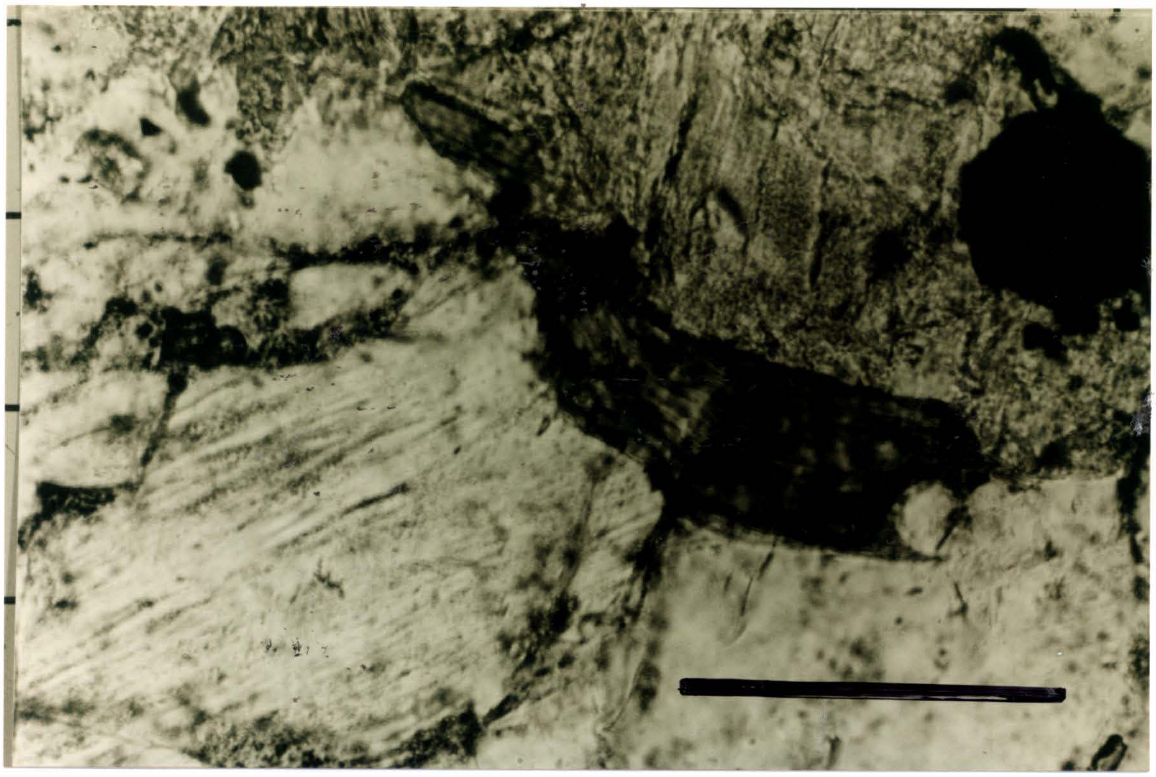


Figure 22

Figure 23 Photomicrograph (crossed polars) of a fractured quartz grain from Mott 14-34, 9072 ft (2765 m). One set of subparallel planar features can be distinguished. Note the pink tint of the feldspar stain along the bottom edge of the plane light view (Fig. 24). Scale bar, approximately 150 microns.

Figure 24 Photomicrograph (plane light) of a fractured quartz grain from Mott 14-34, 9072 ft (2765 m).

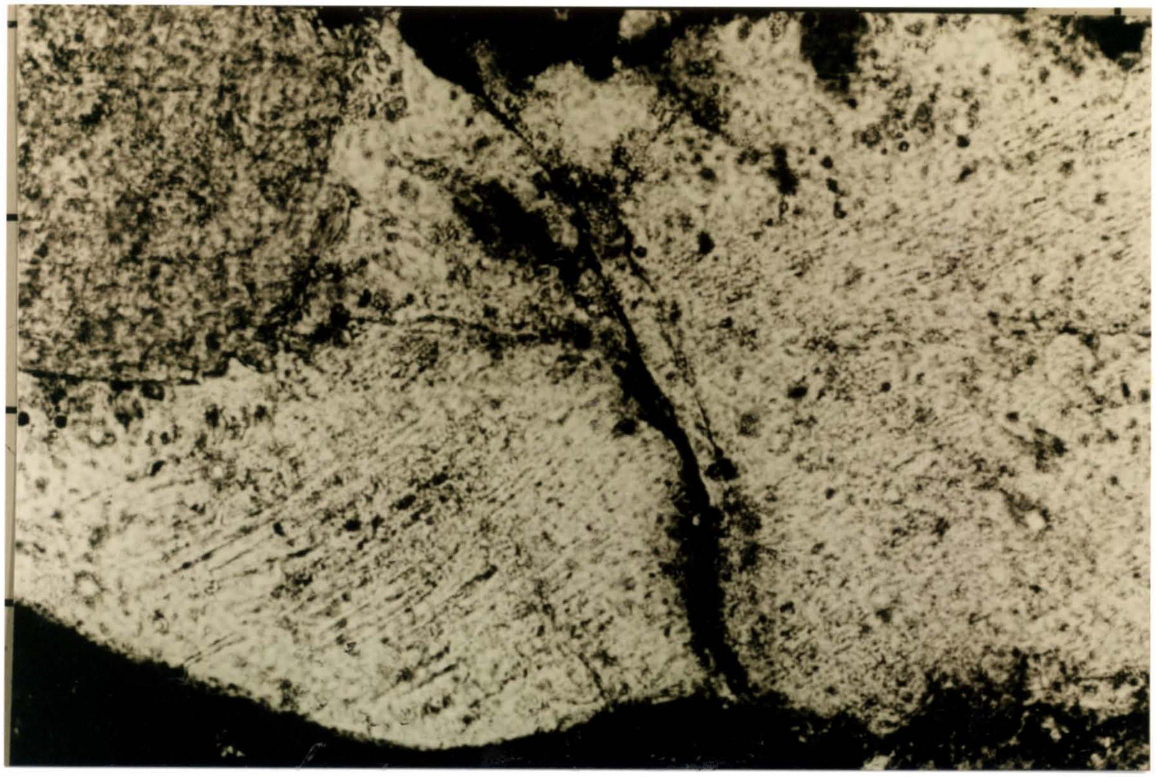


Figure 23

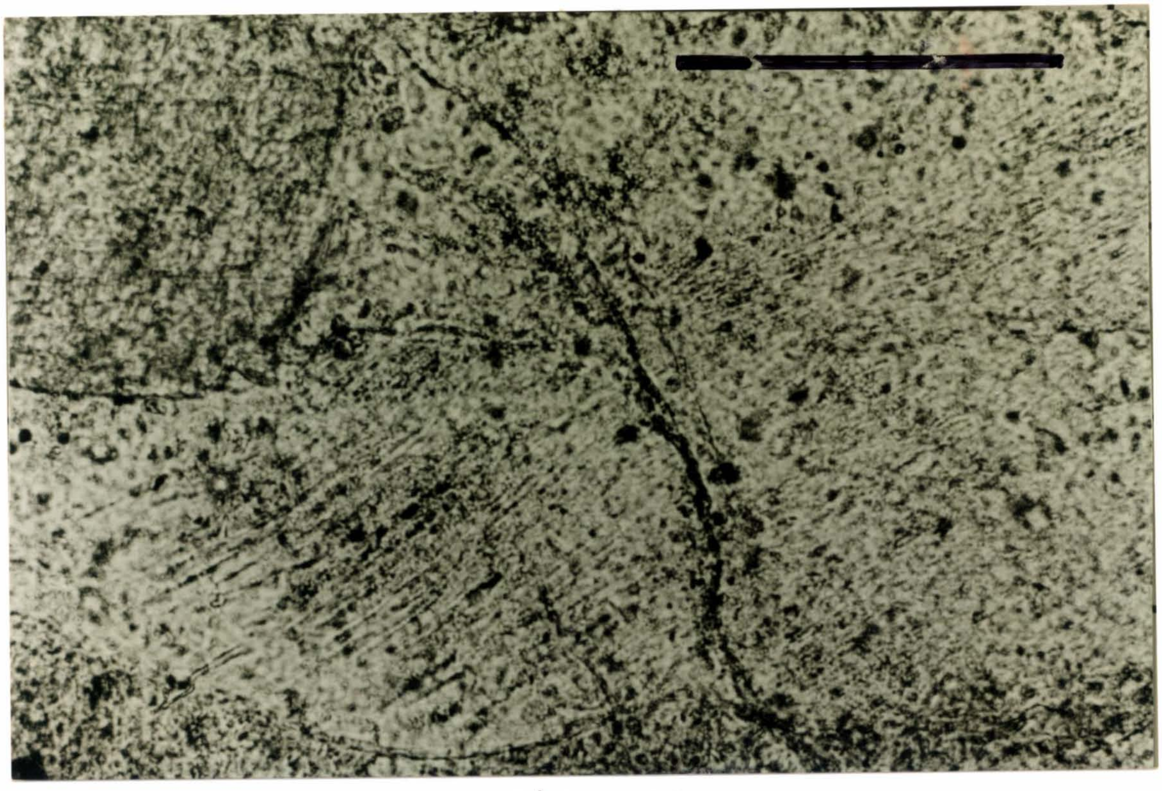


Figure 24

Figure 25 Photomicrograph (crossed polars) of a deformed biotite grain from Mott 14-34, 9072 ft (2765 m). Kink bands within this biotite grain trend N to S. These examples are subparallel to cleavage. Arrows indicate kink bands. Scale bar, approximately 150 microns.

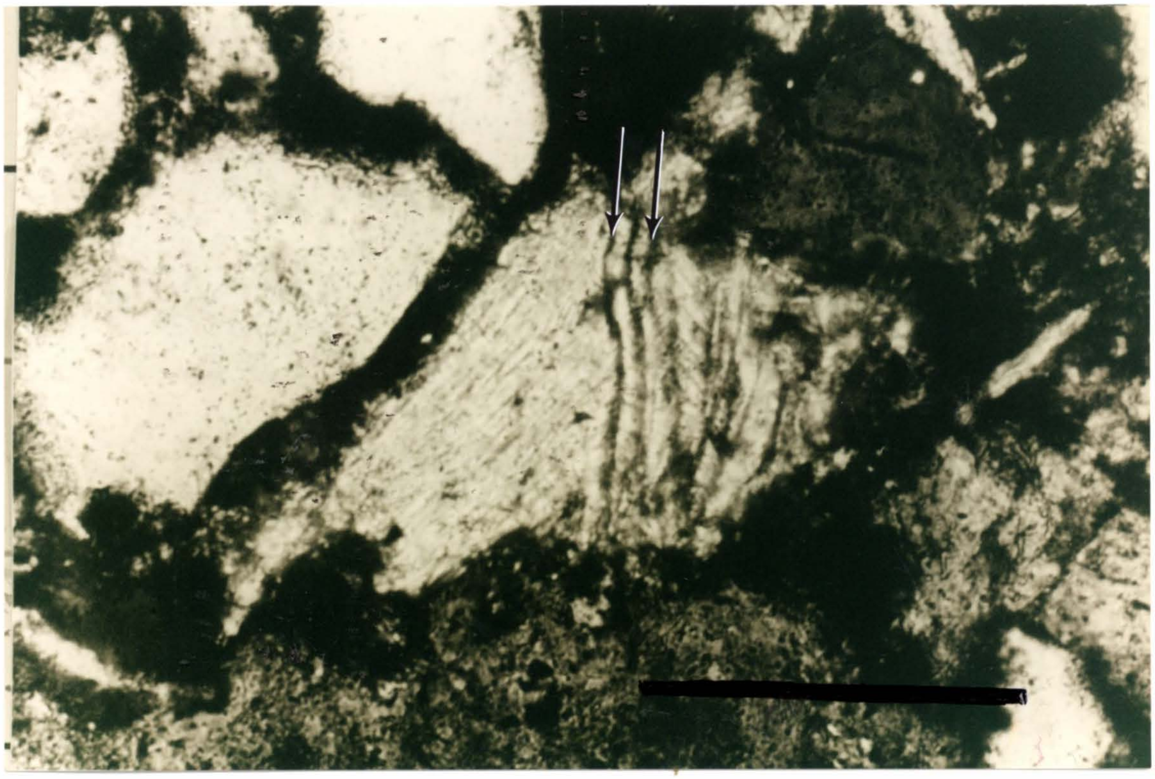


Figure 25

subparallel to the cleavage which trends from the lower left to upper right

The two photomicrographs, figures 26 and 27, were taken at different stage orientations (45° to each other). Well-developed kink bands are exhibited here in a single biotite mica grain. These kink bands are normal to the direction of cleavage, which is offset and deformed. The deformed character of the cleavage and fracturing are best observed in figure 27.

Some thin sections apparently reveal two directions of PDF (Fig. 28 and 29). Note the planar features trending from the upper left to lower right across the two photomicrographs. This texture is especially interesting when compared to similar features in figures 30 and 31, which represent a sample from the Lake St. Martin impact structure, Manitoba. This sample is from a granite outcrop on the northeast perimeter of the structure, from what may be the remnants of the structure rim (McCabe and Bannatyne 1970). Although the Lake St. Martin sample appears to have undergone a higher degree of shock metamorphism (quartz exhibits shock mosaicism and small zones of deformation lamellae), it closely mimics the texture exhibited in figures 28 and 29 from the Newporte structure. These planar features trend from upper left to lower right across figures 28 and 29, and from upper right to lower left in figures 30 and 31.

Figure 26 Photomicrograph (crossed polars) of kink-banded biotite grain from Mott 14-34, 9072 ft (2765 m) Well-developed kink bands are exhibited in this biotite grain (note arrows). Scale bar, approximately 150 microns.

Figure 27 Photomicrograph (plane light) of kink-banded biotite grain from Mott 14-34, 9072 ft (2765 m)

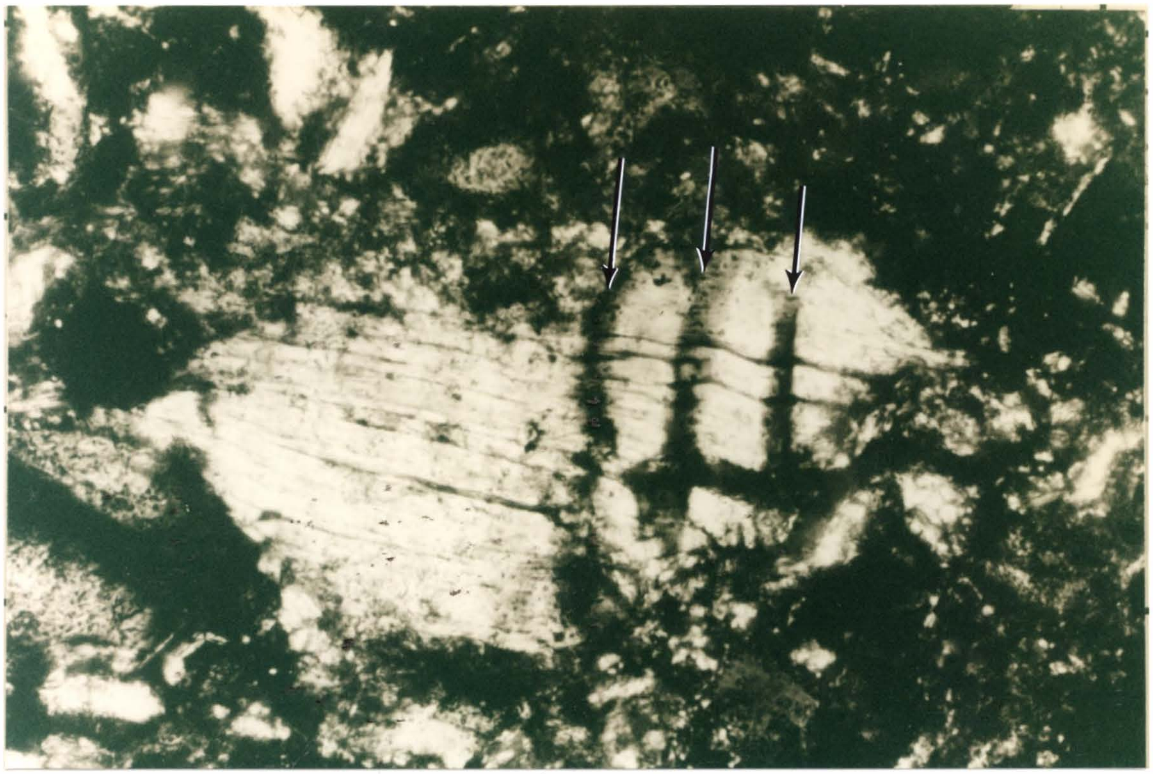


Figure 26

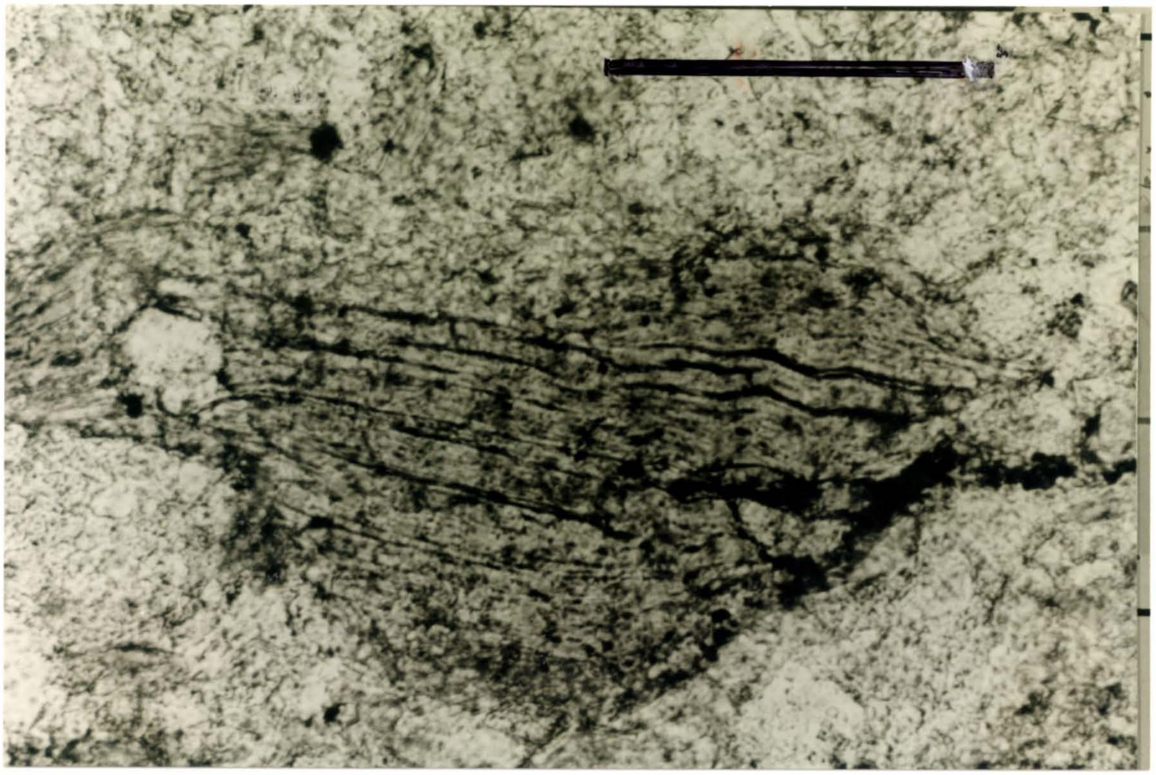


Figure 27

Figure 28 Photomicrograph (crossed polars) of a quartz grain from Mott 14-34, 9072 ft (2765 m). Two directions of planar features are exhibited (note arrows, Fig. 29). The second set, which is clearest in Figure 29, but quite faint, is near the center of the photograph (running from east to west across the grain). Scale bar, approximately 150 microns.

Figure 29 Photomicrograph (plane light) of a quartz grain from Mott 14-34, 9072 ft (2765 m).

Figure 28

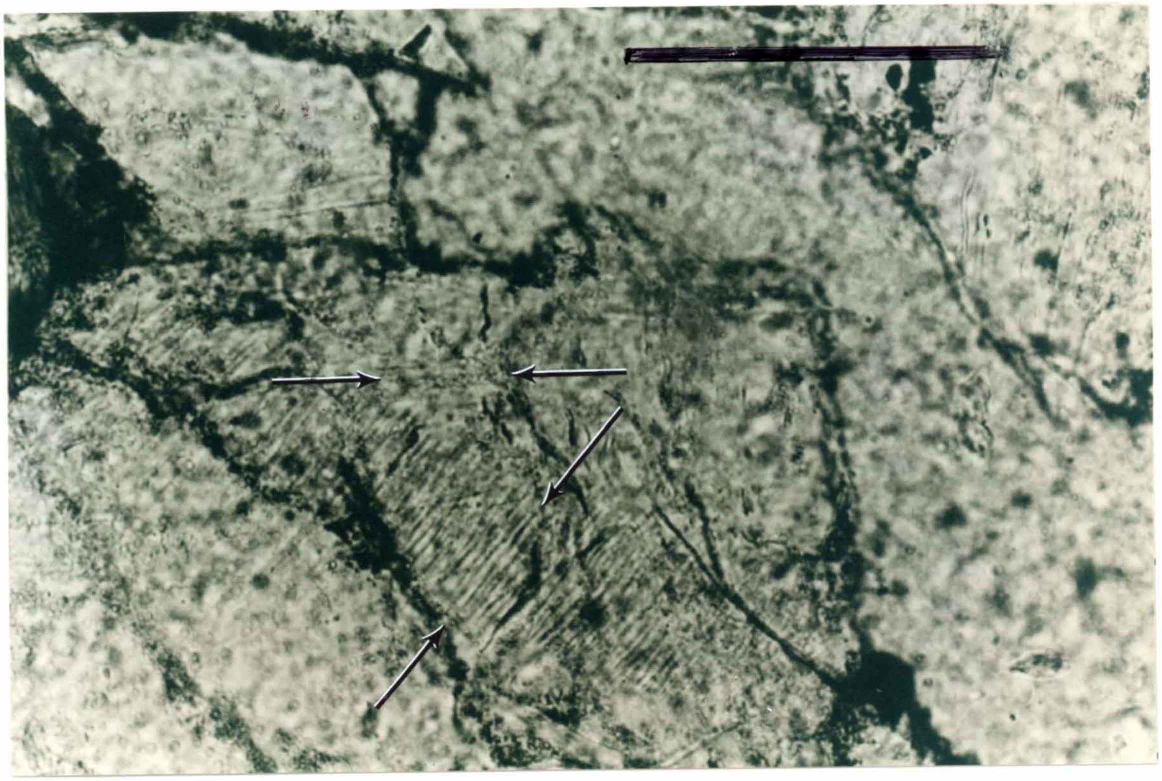


Figure 29

Figure 30 Photomicrograph (crossed polars) of a shocked quartz grain from a granite outcrop near northeast rim of Lake St. Martin structure, Manitoba. The distinct texture (note arrows) within this quartz grain from a known impact crater resembles that seen in the Mott 14-34, 9072 ft (2765 m) sample (Fig. 28 and 29). Scale bar, approximately 150 microns.

Figure 31 Photomicrograph (plane light) of a shocked quartz grain from a granite outcrop near northeast rim of Lake St. Martin structure, Manitoba.

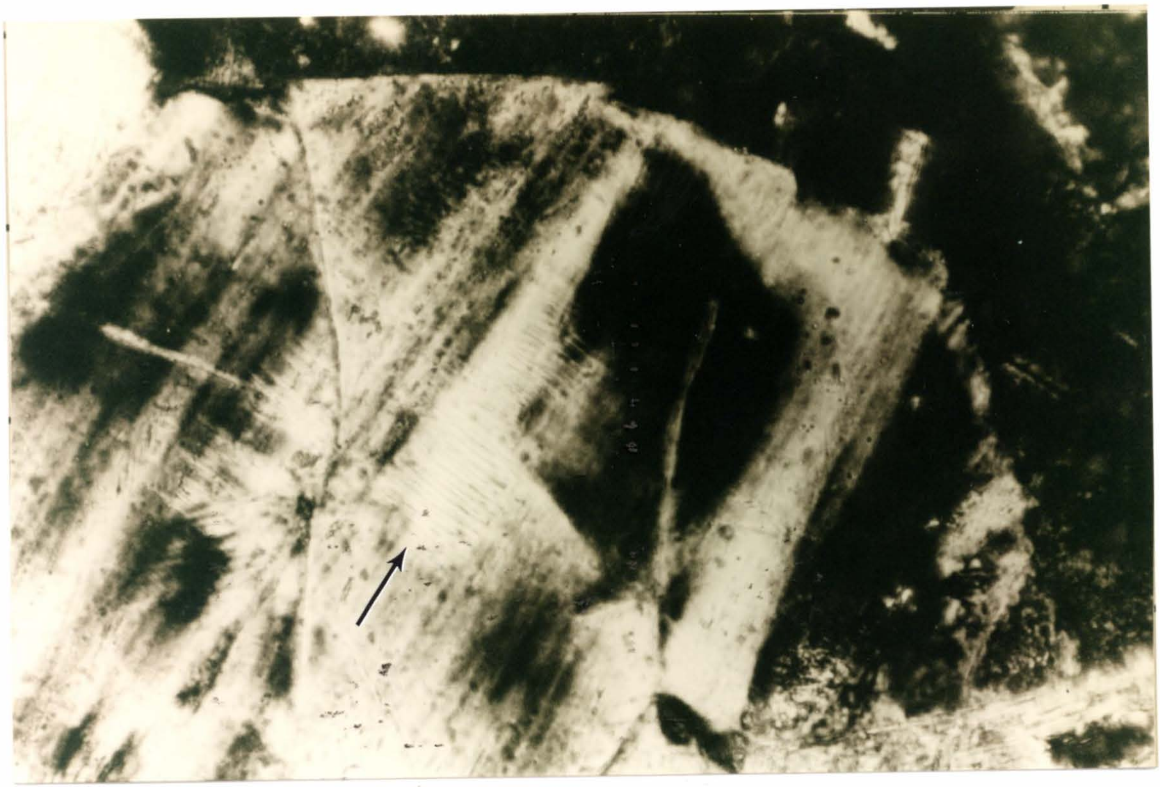


Figure 30

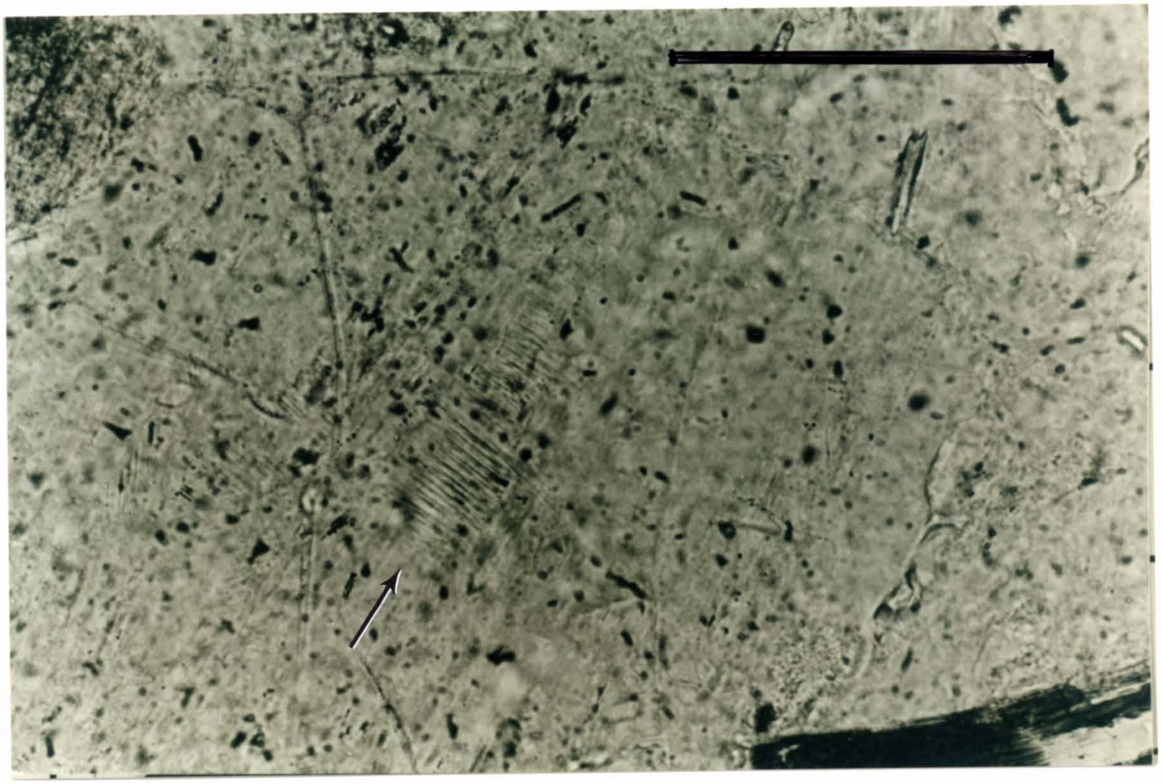


Figure 31

INTERPRETATIONS AND DISCUSSION

Morphologic Evidence

The maps generated from the geophysical data substantiate the Clement and Mayhew (1979) interpretation that the Newporte structure is circular. Results (Fig. also show the presence of an encircling, raised rim. The resemblance of the structure to known terrestrial impact craters is obvious. Apparent breaches of the rim, and the low relief of the structure, estimated at 350 to 550 ft (105 to 165 m), indicate that the structure may have undergone extensive erosion prior to final burial. Slight thinning of the seismic intervals to the north and east, shown in figures 8 and 9, is attributed to less deposition occurring on topographically higher parts of the structure. Large scale features of the structure, the circular depression and rim areas, compare quite well between the two isopach In the central region there appears to be a somewhat higher area represented by thinning on both isopachs. One possible interpretation of this central high is that it is a remnant of a central uplift. Subtle, smaller closures on the interior, and any features found beyond data control cannot be interpreted with certainty. Where control is lacking, the mapping program bases its contouring on the statistical method chosen and the nearest available data. In addition, the seismic basement is a best-guess interpretation of the true crystalline contact. The key seismic reflector, upon which the mapping interpretation is based, could be any combination of things: breccia, weathering zones, shear zones, or the actual crystalline basement contact. Therefore, care must be exercised when making conclusions based on the bumps and bulges displayed on the profiles of the seismic basement (Fig. 32). Again, there is no core or well control for this central region.

Features exhibited within the central area of the structure resemble what is seen in other craters, like the 6.5 mile (11 km) Deep Bay, Saskatchewan, one which also is preserved in Precambrian rocks (Dence and others, 1968) Central uplifts within impact craters have been attributed to a rebound mechanism, whereby rock is displaced inward and upward, although the exact processes are still debated (Melosh, 1989). The central feature exhibited on the Newporte maps, especially figure 32, seems to be small and malformed. The southwest-northeast profile, which is slightly northwest of center, displays what may be more than one peak.

Five possibilities can explain these central features: 1 they are the result of slumping and post-impact modification of a crater, 2 they are of volcanic origin, 3)

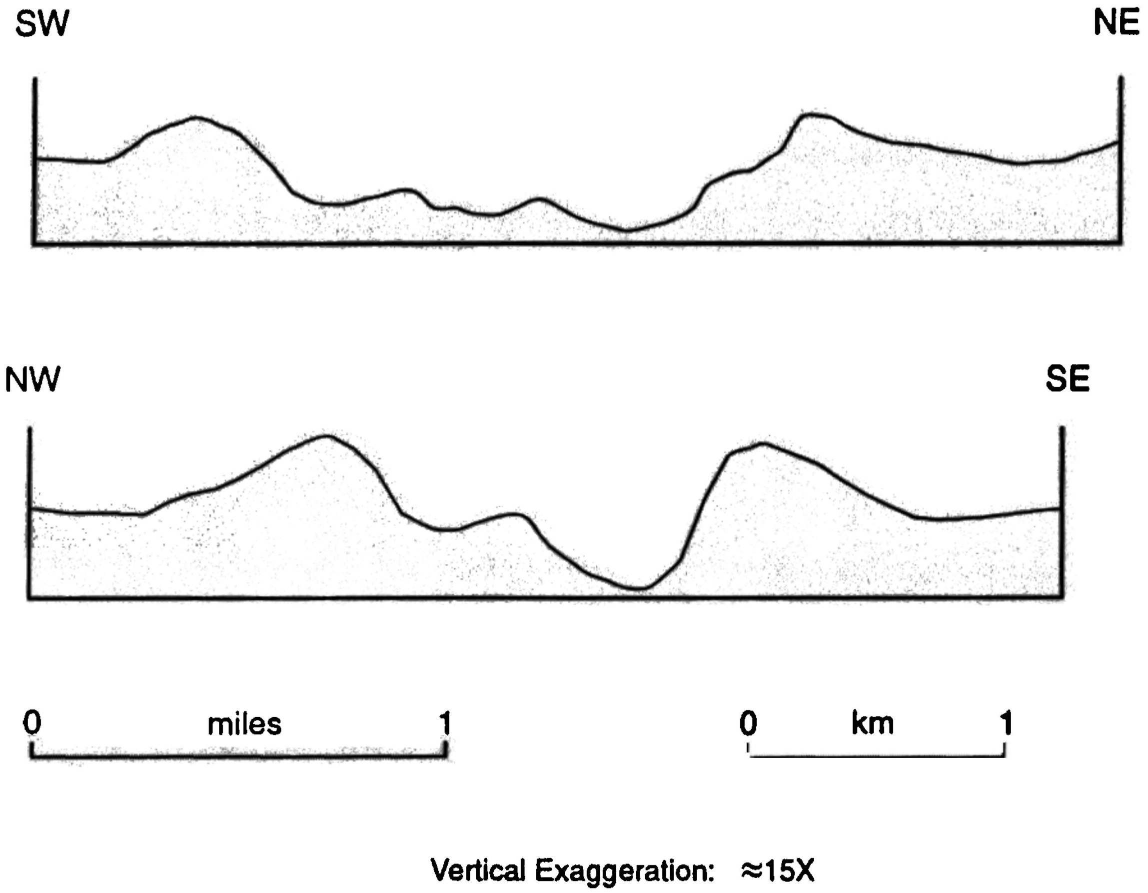


Figure 32 Profiles of two selected seismic lines crossing near the center of the Newporte structure.

they are artifacts of the seismic data, as previously mentioned, or of the computer mapping, 4) they are remnants of a central uplift, or 5) they were emplaced by some yet unexplained process. The first seems unlikely, because slumping would occur along the steep rim walls, and large slump blocks would not likely come to rest in the center of an impact crater. The second possibility may be argued for by doubters of an impact origin. However, it is highly unlikely these features are constructional peaks within a volcanic crater; no volcanic rocks have been found near or within hundreds of miles of the Newporte structure. The third and fourth possibilities have already been discussed, and the fifth can only be speculated about. If all seismic data were obtainable and better mapping techniques and equipment used, almost certainly the nature of this central area could be resolved better.

According to Grieve and others (1988), complex craters those having central peaks) generally have a 1.9 mile (3 km) or greater diameter. But, Roddy 1977), Pike (1977) Wood (1973) estimated that energies that would form a crater with a 6-mile 10 km) diameter are required for formation of a well-developed central uplift. However, no Newporte-size craters, 10,000 to 10,500 ft 3.0 to 3.2 km) in diameter, containing a central uplift, have ever been described. slightly larger craters, the Flynn Creek structure, Tennessee, with an approximate diameter of 2.2 miles (3.6

and the Decaturville structure, Missouri (Paul, 1970), with an estimated diameter of 2.5 miles (4 km) both have well developed central peaks. If the Newporte structure actually has a central peak, it more closely supports the estimation of Grieve and others 1988).

Another impact crater, West Hawk Lake, Manitoba, is presently 11,700 ft (3.5 km) in diameter and is exposed in crystalline rock (Short, 1970). Dence and others (1968) calculated that its original diameter was 9,000 ft (2.7 km). It is a simple (bowl-shaped) crater in Precambrian crystalline rock, and exhibits no central uplift. Both the West Hawk Lake and Newporte structures involve crystalline rock and are presently about the same size. This suggests that the relict on the floor of the Newporte structure may be a central uplift.

Riachao ring, a 2.5-mile 4 km) diameter crater on the Brazilian pampas, was discovered by astronauts during the Apollo-Soyuz Test Project (McHone, 1979). The structure has not been well-studied, but large, disturbed blocks of sedimentary rock appear in the center of the crater. Although not formed in crystalline target rock, the description and photographs of the central blocks at Riachao ring compare well with features on Newporte structure maps As will be discussed below, target rock at the Newporte structure may have involved both crystalline basement and sedimentary rocks. Therefore, the central blocks at Riachao ring may be analogous to the features within the central region of the Newporte structure.

Age of the Newporte structure

Presently, at least two possible interpretations exist the time of formation of the Newporte structure: 1 the structure can be concluded to be an impact structure of Deadwood (Late Cambrian to Early Ordovician) age, or 2) the Newporte-forming event happened no earlier than Middle to Late Proterozoic. The structure has not been obliterated by the erosion and/or tectonic deformation that would be expected if it had been in existence prior to the Hudsonian orogeny 1.6 to 1.9 Ga).

The Newporte structure involves both crystalline basement and the sedimentary units above it. Figure 33 provides locations of the Newporte wells relative to the approximate limit of disturbed crystalline basement rocks as determined from core samples and seismic data. A portion of the coarse sandstone that directly overlies brecciated basement in Mott 14-34, 9060 ft (2761 m) (See Figs. 12, 13, 15, and 16 has been sampled. This sandstone is the stratigraphically highest representative available from the Mott 14-34 core. Quartz grains exhibiting low levels of shock deformation are apparent. This coarse, poorly-sorted, angular sandstone may be explained as sediment that was either: 1 present prior to impact, or 2) derived after impact through erosion and redeposition of shocked basement

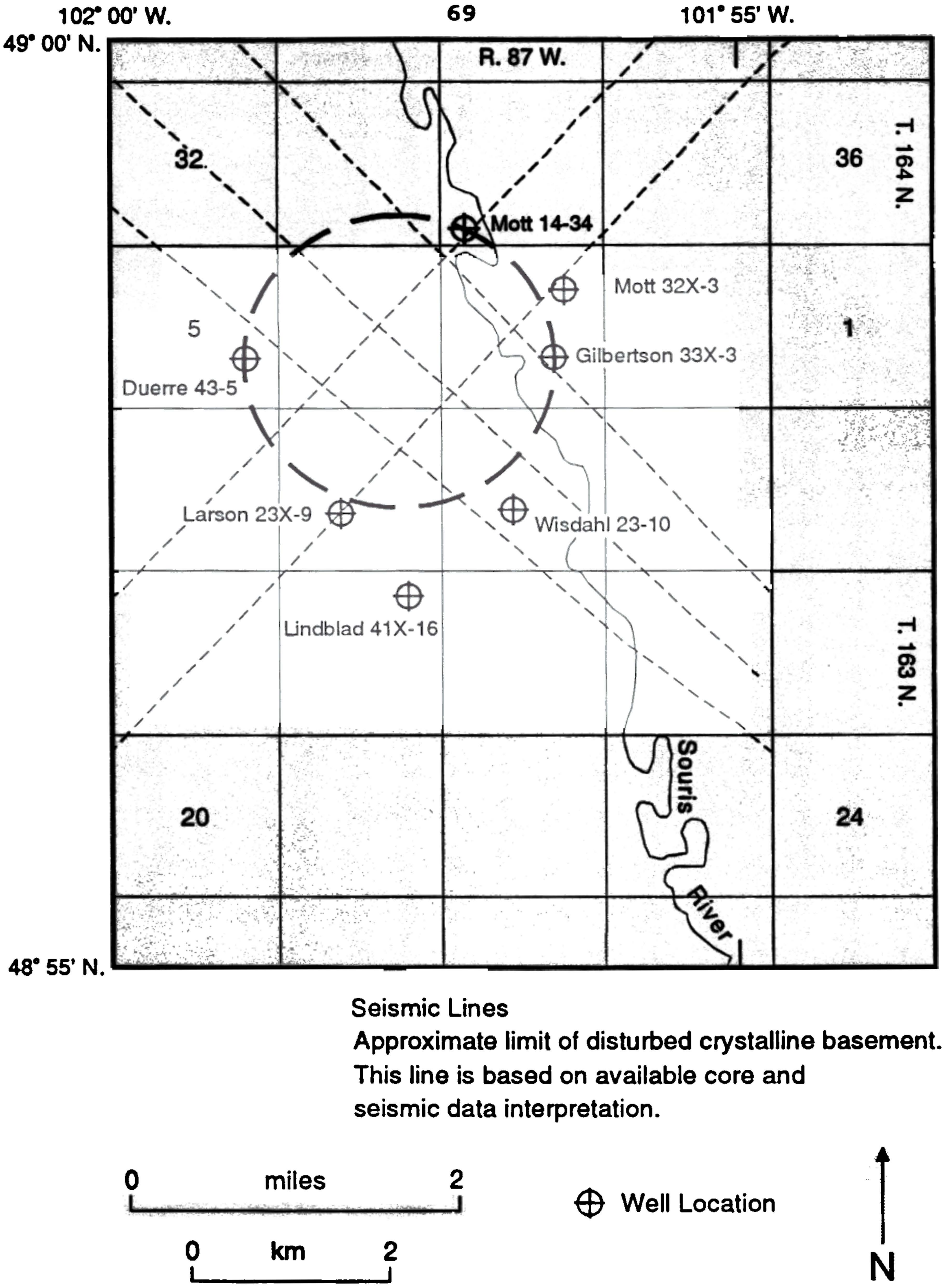


Figure 33 Map showing well and seismic line locations relative to the approximate limit of disturbed crystalline basement.

rock. Carlson and Thompson (1987) and Clement and Mayhew (1979) interpreted this sandstone above crystalline basement in Mott 14-34 as Black Island Formation (Late Ordovician) Based on wireline log interpretation, Anderson (1988) called this sandstone undifferentiated members A and B (Late Cambrian) of the Deadwood Formation. No fossil evidence found in this thin section or core. Thus, pin-pointing an age, using paleontological dating of the sandstone, may prove difficult. However, a few scattered glauconite pellets, which may have formed by alteration of fecal matter, are present within the thin section of this sandstone (Mott 14-34, 9060 ft), so a careful search for identifiable fossils may yet prove worthwhile.

Recognizable Deadwood sandstone is preserved in the Wisdahl, Lindblad and Duerre cores. The Deadwood breccia interval in the Duerre core, 9482 to 9454 ft (2890 to 2882 m), overlies Deadwood sandstone (Figs. 34, 35, 36, and 37). The bottom portion of the Deadwood section in this well not been cored, but the total Deadwood thickness is known from wireline logs.

The target of the Duerre well was the structural high on the western edge of the Newporte structure (Fig. 10). The Deadwood breccia interval, found only in this well, is recognized by gneissic clasts within a sandy matrix. Clasts of gneiss begin at 9482 ft 2890 m), continue throughout the breccia, and extend upward to 9454 ft (2882 m), where a

Figure 34 Core slab of uppermost Deadwood breccia, Duerre 43-5, 9454 ft (2882 m). This breccia contains clasts of crystalline basement within a matrix of glauconitic, clayey, quartzose sandstone. Cobble-size clast (near scale bar) is soft, and appears to have undergone extensive alteration.

Figure 34

Figure 35 Core slab of Deadwood breccia, Duerre 43-5, 9460 ft (2883 m). This breccia contains numerous feldspar-rich, pebble-size clasts within a clayey sandstone matrix.

Figure 35

Figure 36 Core slab of gneissic boulder-size clast, Deadwood breccia, Duerre 43-5, 9480 ft (2890 m). The original size of this gneissic clast cannot be determined, but it was in excess of 8 inches (20 cm).

Figure 36

Figure 37 Core slab of lowermost Deadwood breccia in Duerre 43-5. This breccia consists of gneissic clasts within a fine-grained, sandstone matrix. Arrow marks contact of breccia with underlying sandstone (glauconite/quartz wacke) at 9482.5 ft (2890.3 m).

Figure 37

conglomerate marks the top of the Deadwood Formation. Underlying the Deadwood breccia interval at this location is ten feet 3 m) of disturbed sandstone (e.g., faulting, chaotic bedding). The passage of a shock wave can explain the chaotic bedding and breccia observed in this well. Thus, it appears that the Deadwood breccia interval may represent excavated basement deposited atop Deadwood sandstone. Therefore, an impact event may have produced the Newporte structure during Deadwood time. Alternatively, the Deadwood breccia interval may simply be a result of erosion and redeposition of a basement high during Deadwood time.

The Lindblad core also shows anomalous dips and faulting within Deadwood sandstone from at least 9516 to 9547 ft (2900 to 2910 m). Dips increase upward, starting at 5° to 10° and increasing to nearly 45° before diminishing again to less than 10° near 9516 ft (2900 m).

The Wisdahl Deadwood interval preserves the most deformation characteristics. From 9349 to 9400 ft (2850 to 2865 m) the clay shale and sandstone laminae are extremely disturbed. The deformation ranges from vertical and overturned bedding in the lower portion to slightly inclined bedding near the top of the interval.

It has not proven possible to deduce with certainty whether the disruption in Deadwood sandstone in either the Duerre, Lindblad, or Wisdahl wells is due to impact, slumping and/or soft-sediment deformation, or some other process. No evidence of shock metamorphism was found in four thin sections from deformed Lindblad core, 9541 ft (2908 m), in a single highly deformed sample of Wisdahl 23-10, 9376 ft (2858 m), or in any of the Duerre thin sections.

Clement and Mayhew 1979) did not consider the Gilbertson well, which was the last to be drilled on the structure. Brecciated basement in this core seems sporadic. Although some intervals are definitely brecciated, others exhibit only fracturing and faulting (Appendix A). addition, the final driller's log, based on drilling time, side wall core samples and drill cuttings, indicates four repeating crystalline rock (gneiss) intervals between 9060 and 9190 ft (2761 to 2801 m). Dolostone, sandstone, siltstone and shale are found between the four gneiss occurrences. Apparently, the actual basement was not reached until approximately 9190 ft 2801 m). Both Gilbertson and Mott 14-34 wells are in the highest part of the structure (Fig. 10).

The brecciated basement intervals in Mott 14-34 and Gilbertson 33X-3 are thought to be remnants of a brecciated crater rim (Figs. 38, 39, 40 and 41). Their lithologic similarities and brecciated character support this interpretation (Appendix A).

Again, the Deadwood breccia interval in Duerre 43-5 differs from the brecciated basement in Mott 14-34 Gilbertson 33X-3. Its sandy matrix, granitic gneiss-schist

Figure 38 Core slab of brecciated Precambrian basement (greenschist) from 9290 ft (2831 m), Gilbertson 33X-3. The basement rock is well indurated in this core.

Figure 38

Figure 39 Core slab of brecciated Precambrian basement (greenschist) from 9341 ft (2847 m), Gilbertson 33X-3. Note the two larger (cobble-size) clasts in upper half of slab. These clasts represent the largest examples found in the Gilberston core.

Figure 39

Figure 40 Core slab of brecciated Precambrian basement (gneiss) from 9119 ft (2779 m), Mott 14-34. Although portions are well indurated, this core is in places quite vuggy. The photograph shows numerous calcite-lined cavities.

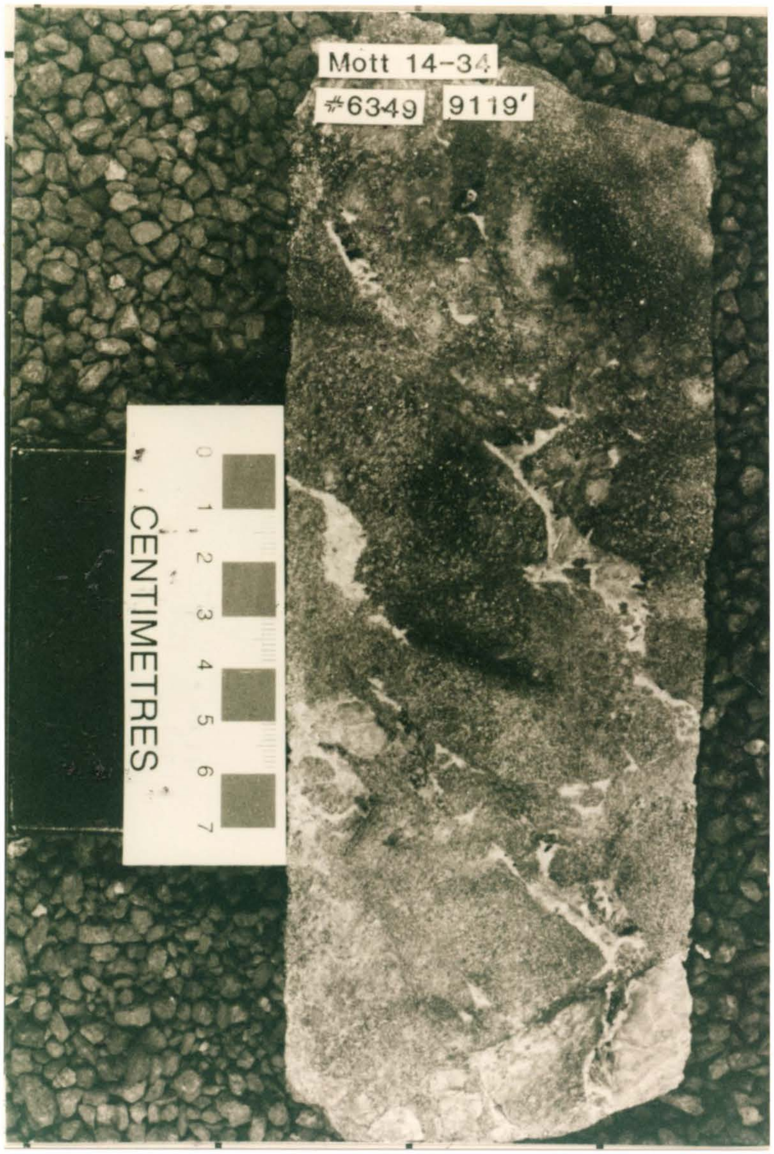


Figure 40

Figure 41 Core slab of brecciated Precambrian basement (gneiss) from 9130 ft (2783 m), Mott 14-34. Well indurated and containing fine to pebble-size clasts, this interval resembles the Gilbertson breccias.

Figure 41

clasts, and position overlying some sixty feet (18 m) of sandstone, seemingly set it apart from the brecciated basement to the north and east, which lacks matrix material No shock features were identified from the Duerre Deadwood breccia interval. These thirty feet (9 m) of breccia in Duerre 43-5 could represent deposits of a later debris flow. Mescher and Pol (1985) referred to this interval as containing fanglomerate material. Alternatively, the Duerre Deadwood breccia interval may represent impact-derived fallback breccia (inside rim) or ejecta (outside rim); the lack of shock metamorphosed minerals does not negate the possibility of an impact origin

Donofrio (1981 reasoned, based on calculations from Pike (1977) and an estimated 3.0 km transient crater diameter, that the Newporte structure would have had a depth below original surface of 1950 ft 595 m). This depth would have been the depth of the original unmodified crater, and should not be confused with its present depth of burial

If the target rock at the Newporte structure had been Deadwood sandstone, the difference between Donofrio's estimated original depth and the present depth is too great to be accounted for by previous estimates of erosion. The present relief (rim to crater floor distance) of the seismic basement has been estimated from figures 10 and 32 to be less than 600 ft (185 m). This is an estimate of actual depth to original floor of the crater, rather than to a shallower floor resulting from infilling; recall that figures 10 and 32 are based on seismic data, using the seismic basement as the top of the Precambrian basement. If Donofrio's estimate of original crater depth is correct, at least 1450 ft (442 m) of pre-Chazyan (Middle Ordovician) erosion would be required (Fig. 42).

As much as 590 ft (180 m) of Deadwood may have been removed from the center of the Williston Basin by pre-Chazyan erosion, according to Anderson (1988). His estimate was based on the assumption that approximately 295 ft (90 m) of sediment was deposited in each of the preserved Lower Ordovician progradational successions (members B and A). Greater erosion of the top of the Deadwood Formation is evident with increased distance from the central area of the Williston Basin (Thompson, 1984 He stated (p.113) that an additional 400 ft 120 m) of section are missing from the upper portion of the Deadwood in Adams County, as compared to the Deadwood section in McKenzie County near the present center of the Williston Basin. These estimates of Deadwood erosion are speculative at best, especially when considering the anomalous Newporte structure. Exactly how sedimentation and erosion may have been affected by the Newporte structure is difficult to determine. Insufficient evidence exists to determine if Donofrio's original Newporte depth calculation is correct. However, if his calculation is correct, not enough original Deadwood section existed to account for this

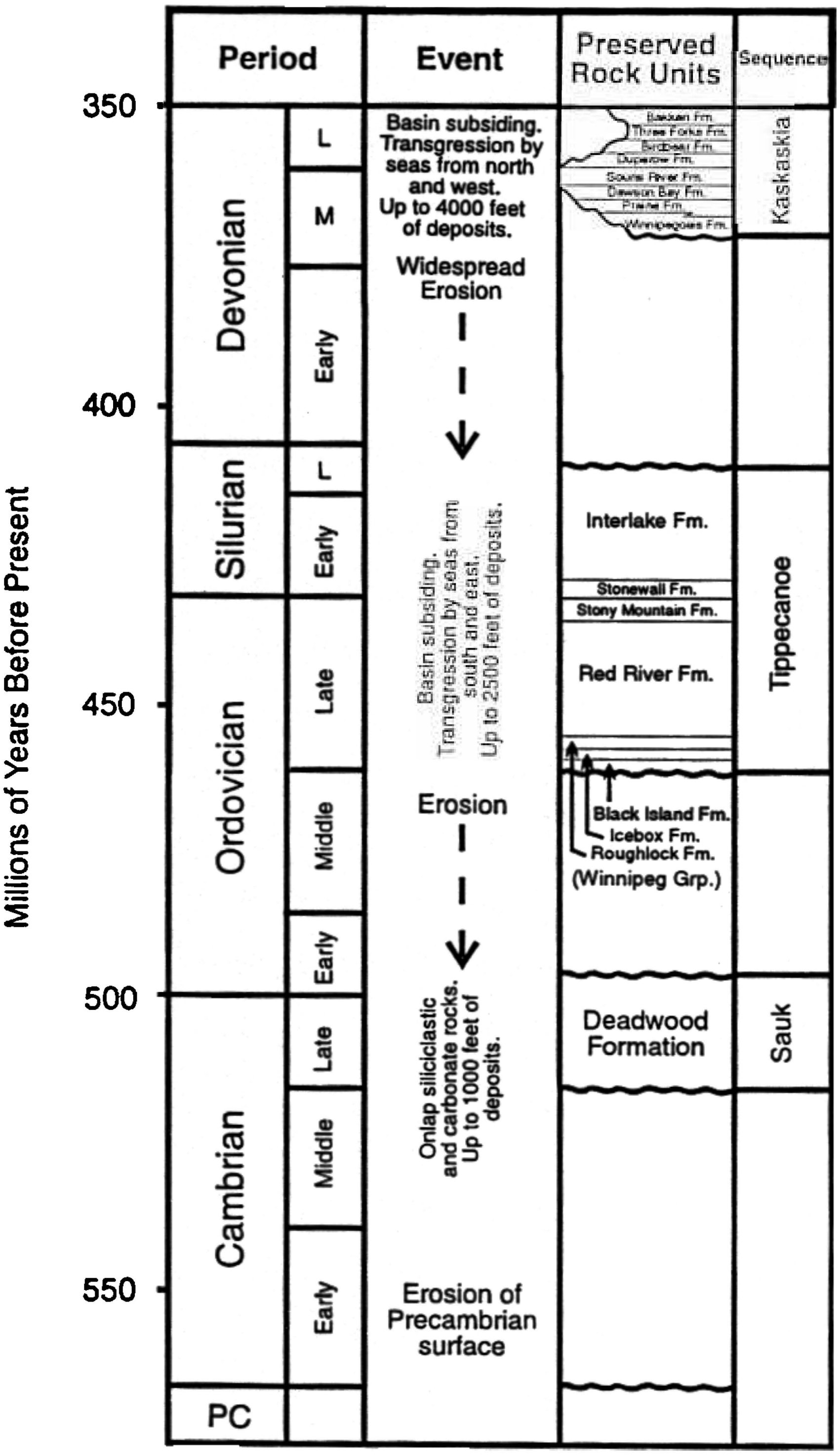


Figure 42 Generalized chronostratigraphic - lithostratigraphic relationship of units in this study. Modified after Bluemle and others, 1981.

crater depth, and a younger than Early Ordovician (late Deadwood time) impact event may be suggested. But, this seems unlikely. The existence of the Deadwood breccia interval, the repeated basement occurrences in Gilbertson well, and the distribution of the Black Island (Fig. 11 seem to argue against a post-Deadwood event.

Anderson (1988) illustrated on a Deadwood isopach that member C is preserved over most of Renville County. Again, Anderson included *only* undifferentiated members A and B in his core description of Wisdahl 23-10, a well containing one of the thickest Deadwood sections on the Newporte structure An argument may be made for a portion of the next stratigraphically higher unit, member C, being preserved, based on the higher gamma ray log responses exhibited, as compared to wireline logs of Shell Svangstu 24-18 of northeastern Divide County (40 miles (64 km) to the west). The gamma-ray log of Lindblad 41X-16, less than a mile 1.6 km) to the northeast, also reveals that part of member C may be preserved there. Members A and B have been interpreted as Late Cambrian in age and members C through F to be Early Ordovician in age (Anderson, 1988). Thus, if it could be proven that disturbed (i.e., by impact) member C is preserved locally, the Newporte-forming event happened no earlier than the Early Ordovician.

The only biostratigraphic work in the area is still unpublished (Clement and Mayhew, 1979). Apparently, trilobites, brachiopods and conodonts were used to date the productive Deadwood sandstones as "Upper Cambrian" age (assumed to mean Late Cambrian). The upper portion of the Clement and Mayhew (1979) Deadwood division was dated as Upper (Late?) Cambrian through Lower (Early?) Ordovician age. They mentioned that this age may range through Early Middle Ordovician. Although geologic ages were given in Clement and Mayhew (1979), no specific biostratigraphic data were presented

Clement and Mayhew (1979) believed the formation of the Newporte structure occurred during the late stages of Deadwood deposition or post-Deadwood, but pre-Winnipeg deposition. Because of the uncertainty of correlating some of the Newporte wells, they also recognized that a Late Precambrian event may have formed the structure.

Presently, not enough information exists to make a firm conclusion as to the age of the Newporte structure. However, several clues do suggest a Deadwood (Late Cambrian to Early Ordovician) age. The Deadwood breccia interval, although seemingly free of microscopic evidence of shock, does resemble impact breccia. Repeating intervals of basement and sedimentary rock, described from Gilbertson 33X-3 samples, may hint at a pre-Winnipeg Group/post-Precambrian age. A cross section through the Newporte wells shows the Black Island Formation to be thinner on the structural highs (rim high points), and thicker in wells that are located slightly more distal to the rim (Fig. 11). Thus, the structure appears to have been in existence prior to Black Island deposition (Late Ordovician). Due to the uniform thickness of the Icebox Formation in all of Newporte wells the structure must have been completely buried during Icebox deposition (Later Ordovician).

The earliest time at which the structure may have been formed appears to be post-Precambrian, but pre-Late Ordovician. Again, the Deadwood breccia interval (Duerre well) overlying disturbed Deadwood sandstone, and the disrupted Deadwood found in other wells seem to indicate that formation occurred during or following Deadwood deposition. And, thinner Black Island Formation over the rim of the structure may mean that the structure was in existence prior to Black Island deposition (Late Ordovician)

Microscopic Evidence of Shock Deformation

Excellent photographs of shock deformation features can be found in Williams 1986), Hargraves and others 1990), and Alexopoulos and others 1988). Several of these photographs exhibit microscopic textures similar to those seen in this study. Alexopoulos and others (1988) compared lamellar deformation features in quartz from known impacts, nuclear tests, explosive volcanism, Terre Neuve ophiolite, and sites of unknown origin. They argued against the claim that deformation lamellae are not indicative of impact. Their photomicrographs of tectonically and volcanically (weakly) shocked samples resemble some of the subparallel PDF in the Newporte thin sections. However, no other evidence of volcanic activity exists within the Newporte study area. Also, basement samples from the nearby Osterberg wells were studied to compare them to the Newporte thin sections. None of the unusual microscopic features discovered at the Newporte structure was found in the Osterberg thin sections. Given the proximity of the two locations, it is believed they would have experienced similar tectonic histories.

The Beaverhead impact structure, Montana, was identified from shatter cones and shocked rocks (Hargraves and others, 1990). Apparently, only a small portion of the actual crater is recognizable. Two photomicrographs of quartz grains from the Beaverhead site have PDF that resemble Newporte specimens.

A photomicrograph included in Williams 1986 reveals decorated planar features in quartz from Lake Acraman, Australia. These decorations are actually microscopic fluid and/or glass inclusions. The Acraman structure is a large impact site, possibly in excess of 100 miles 160 km) in diameter. Again, these decorated PDF are similar to textures in the Newporte samples.

Classic examples of planar deformation features or deformation lamellae from known terrestrial impact craters are generally crisp, parallel linear textures. Impact crater studies are often illustrated with photomicrographs showing several intersecting sets of lamellae. The Newporte examples (Figs. 12 to 29) mostly exhibit one parallel set of PDF. A few photomicrographs (Figs. 18 to 21 display two indistinct sets of PDF.

Kink bands in biotite have been observed in impact crater and nuclear explosion specimens, but it is not unusual to find tectonically produced examples (David Roddy, USGS, oral commun., March 1994, Flagstaff, AZ,). Newporte examples are shown in figures 25, 26 and 27. They are presented because of their quality, and because of their association with the quartz PDF. In combination with quartz PDF, the presence of kink-banded biotite adds support to the impact hypothesis

An excellent example of two sets of PDF is presented in figures 28 and 29. Although one set is poorly developed, the second is parallel and distinct. When compared to textures associated with Lake St. Martin Figs. 31 and 32 the similarities are quite evident. The distinct set of PDF in the Newporte specimen is nearly identical to the Lake St Martin example

Microscopic, morphologic and lithologic evidence in support of an impact origin for the Newporte structure is strong. The Newporte structure is known to be a closed, circular depression surrounded by a raised rim. Highly fractured crystalline basement rock has been described from two of its well cores. Brecciated rock, resembling breccia from known impact sites, has been described from three of the Newporte wells. Two of these wells involve basement rock only, and one involves crystalline clasts within a sandstone matrix. Examples of weakly shocked quartz and biotite mica are described in this study. Numerous quartz grains, exhibiting single sets of lamellae, were discovered in sandstone and brecciated basement. These lamellae, or planar features, are similar to the weakly shocked examples discussed by Sharpton and Grieve 1990). The microscopic evidence is suggestive, but not definitive of an impact origin. This may be a function of borehole location and the present capabilities of recognizing impact-generated, low-grade shock, rather than an argument against an impact origin for the Newporte structure.

CONCLUSIONS

There is evidence in support of an impact origin for the Newporte structure. Presently, the evidence includes the following:

1 The structure is a circular, crater-like depression retaining the root of an encircling, raised rim. The seismic data interpretation also reveal an unusual feature within the depression, which may be interpreted as the remains of a central uplift. This morphology is consistent with known terrestrial impact craters.

2) Thin sections of rock specimens from wells on the structure rim exhibit unusual mineral textures. Samples from Mott 14-34 show what has been verified as planar features in quartz. Presently, only nuclear explosions and large impact events have been proven to induce this type of deformation, although some authors argue in favor of other processes. PDF identified in this study may indicate only low shock pressures. This is reasonable when considering the positions of the wells on the crater rim, where, because of diminishing shock pressures, the probability of finding any such

features is extremely low. In addition, basement thin sections from two nearby wells were examined for any textural similarities to the Newporte samples. No features resembling the PDF were found in these thin sections. Thus, the Newporte structure thin section PDF are suggestive, but not definitive, of an impact origin for the Newporte structure

3) The event that created the Newporte structure is believed to have occurred prior to deposition of the Winnipeg Group Black Island Formation (Late Ordovician), and most probably occurred during mid-Deadwood deposition. This determination is based on gamma-ray log correlation of the seven rim wells, and the presence of breccia (Duerre 43-5 well overlying Deadwood sandstone

Suggestions for Future Work

1 Further study of the Newporte lithologies with comparison to well-classified regional formation/member descriptions would help to further delineate the age of the structure. It is difficult to speculate about what work the Shell Oil Company may have done in the area of sedimentology, and difficulties in correlating the wells will remain until their data are published.

2) Better or more detailed mapping techniques could clear up questions about the crater interior. Until well control includes the central region of the Newporte structure, questions on its morphology will remain.

3) Paleontological work might provide a better age determination for the Newporte structure. If microfossils were found, they may be used with sedimentological data to pinpoint a date for the formation of the structure. Near the close of this study, Shell Oil Company sent its entire holding of Newporte cores to the NDGS Core Library. This may aid future studies. Also, in the near future, parts of the Shell Oil Company's original data may be published.

4) Apatite fission track analyses also may shed light on the age of the Newporte structure. For instance, radiometric or other specialized dating techniques (e.g., apatite fission-track) could be employed. The thermal energy released in an impact would have reset the fission track and radiometric clocks.

5) If a basement well is ever attempted within the interior region of the Newporte structure, lithologic samples from such a borehole should provide investigators with additional evidence of the structure

origin. If the Newporte structure is indeed of impact origin, definitive, highly shocked material should be found in this zone.

APPENDICES

APPENDIX A

CORE DESCRIPTIONS

Core descriptions are arranged numerically by their North Dakota Geological Survey well number. All depths are those listed on core and core boxes. These depths are all in feet, and have not been matched with or corrected against the wireline log depths. Description classifications are Gilbert's 1954) for sandstones and Potter and others' (1980) for silt to clay-sized sediments. Other than a minor dolostone occurrence, no carbonate rocks were described in this study. The moist rock color was described using the Geological Society of America rock color chart (Goddard and others, 1948).

NDGS #6296
Shell Oil Company
Larson 23X-9
Renville County, North Dakota
NE SW Sec. 9, T163N, R87W
Intervals: 9577′ to 9592 and 9607′ to 9640′

Depth	Description
9577-9580	**Sandstone and Clay Shale:** interlaminated, quartz arenite, fine-grained, rounded, little glauconite (<5%), shale is fissile, slightly calcareous, soft-sediment deformation, some possible bioturbation, much of interval is missing. (N3 to N8 Very Light Gray to Dark Gray)
9580-9584	**Sandstone:** quartz arenite, fine to coarse-grained, rounded, friable, shale stringers in upper portion, brown oil staining. (5YR 4/1 Brownish Gray)
9584-9587	**NO CORE**
9587-9592.2	**Sandstone:** quartz arenite with remnant laminations of clayey material, fine to coarse-grained, rounded, well indurated, some bioturbation, dark brown oil staining, portions of interval are missing. (5Y 4/1 Olive Gray)
9592.2-9599.5	**NO CORE**
9599.5-9606	**Amphibolite Greenstone:** Precambrian basement, weathered/altered, chlorite-rich, fracturing with calcite infillings, fracturing does not follow preferred pattern (such as foliation planes), portions appear metasomatized. (5G 2/1 Greenish Black with various shades of green)
9606-9609	**NO CORE**
9609-9640	**Amphibolite Greenstone:** appears to be of medium-rank metamorphism, portions show gneissic banding, foliation is inclined 30 to 40 degrees, calcite-filled fractures are common and appear to parallel foliation planes, possible ‘metabasite’ or ‘meta-graywacke’. (5G 2/1 Greenish Black)

NDGS #6349
Shell Oil Company
Mott 14-34
Renville County, North Dakota
SW SW Sec. 34, T164N, R87W
Interval: 9060′ to 9169′

Depth	Description
9060-9065	**Conglomerate:** quartz dominant with much feldspar, pyrite and brown mica very common, very coarse sandstone to pebble-gravel conglomerate, very fine-grained to pebble-size material, orientation of biotite shows in planar laminations and stringers, largest clasts are of 6 to 8 mm in diameter. (N3 Dark Gray)
9067-9136	**Breccia:**
9067-9073	**Zone 1:** mafic, granitic to gneissic clasts, angular, pebble to cobble and boulder-size, calcite and gypsum-filled fractures, matrix appears to be clayey, dominantly clast-supported. (N2 Grayish Black)
9073-9081	**Zone 2:** more felsic granite clasts, K-spar-rich, angular, extremely vuggy, oil staining, metasomatized?, very little matrix (if any), definately clast-supported. (10R 6/6 Moderate Reddish Orange)
9081-9094	**Zone 3:** amphibolite and gneissic clasts, abundant plagioclase and some quartz, pebble to cobble-size, angular, calcite and gypsum miarolitic-like cavities, dark greenish matrix appears clayey (alterations?) and pyrite-rich, exhibits both clast and matrix-supported character. (5GY 4/1 Dark Greenish Gray)
9094-9098	**Zone 4:** red granitic (pegmatitic) clasts dominate, pebble to cobble-size, angular, oil staining, vugs, matrix is coarse tan sand, an 8 cm thick sandy bed located at 9095′, matrix-supported. (10R 4/6 Moderate Reddish Brown)
9098-9136	**Zone 5:** gneiss clasts, mafic, pebble to boulder-size, some examples could approach a meter in diameter, angular, less vuggy than above, matrix is a coarse sand, appears more highly indurated, definately clast-supported

(N2 Grayish Black)

9136-9169 **Amphibolite Gneiss:** Precambrian basement, mafic to ultramafic, calcite-anhydrite-gypsum-filled cavities and fractures, upper portion appears to be metasomatized, pegmatitic quartz and hornblende, garnets, and a few tiny (1-2 mm) smoky quartz prisms at 9150′. (N3 to 5Y 2/1 Dark Gray to Olive Black)

NDGS #6401
Shell Oil Company
Wisdahl #23-10
Renville County, North Dakota
NE SW Sec. 10, T.163N, R.87W
Intervals: 9244' to 9474' and 9515' to 9534'

Depth	Description
9244-9262.5	¦**Clay Shale:** noncalcareous and fissile. (N5 Medium Gray)
9262.5-9265	**Clay Shale:** minor quartz content, fine-grained, well rounded, fissile to well indurated, calcite-filled microfractures, noncalcareous. (N2 Grayish Black)
9265-9265.3	¦**Sandstone:** quartz wacke, very fine to coarse-grained, rounded, well indurated, stylolites. (5Y 6/1 Light Olive Gray)
9265.3-9266	**Sandstone:** quartz arenite, medium grained rounded, oil-stained. (5Y 7/2 Yellowish Gray)
9266-9268	NO CORE
9268-9268.6	¦**Sandstone:** quartz wacke with minor clay laminations, medium to coarse-grained, well indurated, stylolites. (N7 to N5 Light Gray to Medium Gray)
9268.6-9269	**Sandstone:** quartz arenite, medium to coarse-grained, well rounded, oil-stained. (N7 Light Gray)
9269-9270.8	**Sandstone:** quartz wacke with minor clay laminations, medium-grained. (N7 to N5 Light Gray to Medium Gray)
9270.8-9273.8	¦**Conglomerate:** matrix: quartz arenite, medium to coarse-grained, well rounded; clasts: metamorphic, largest measures 5 mm in length, angular. (N5 to 10YR 8/6 Medium Gray to Pale Yellowish Orange)
9273.8-9280	**Sandstone:** quartz wacke with minor clay laminations, coarse-grained, fairly well indurated, appears to be bioturbated, inverted triangular deformations. (N7 Light Gray)

9280-9281	**Sandstone and Mudstone:** interbedded, medium to coarse-grained sand, fairly well indurated, beds range from 6 mm to 5 cm, appears to be bioturbated. (N3 to N7 Dark Gray to Light Gray)
9281-9281.4	**Sandstone:** quartz wacke, medium to coarse-grained, rounded, well sorted, bioturbated (N7 Light Gray)
9281.4-9291.3	**Mudstone With Minor Sand Interbeds:** blocky, noncalcareous, fine with some coarser sand beds, fine pyrite crystals, rounded, bioturbated. (N2 Grayish Black)
9291.3-9291.7	**NO CORE**
9291.7-9293.7	**Sandstone:** quartz arenite, fine to medium-grained, glauconitic with clasts of shale and occasional pebbles, well indurated. (5GY 6/1 Greenish Gray)
9293.7-9294.5	**Mudstone:** glauconitic and quartz-rich, iron-stained, soft-sediment deformation. (5GY 6/1 Greenish Gray)
9294.5-9295.9	**Sandstone:** glauconitic/quartz wacke, fine to medium-grained, bioturbated or soft-sediment deformation, abundant clay, fairly well indurated. (5GY 6/1 Greenish Gray)
9295.9-9296.8	**Sandstone to Conglomerate:** matrix: glauconitic and quartz sand, fine to medium-grained; clasts: Metamorphic rock, diameter < 1 cm, angular and elongate. (5G 2/1 Greenish Black)
9296.8-9298.3	**Sandstone:** quartz wacke, medium-grained, well indurated, iron-stained, hematite-rich seams, bioturbated. (5GY 2/1 Greenish Black)
9298.3-9299	**NO CORE**
9299-9299.5	**Sandstone:** quartz wacke, wispy glauconitic seams, fine-grained, limonite-rich. (5GY 6/1 Greenish Gray to N3 Dark Gray)
9299.5-9300.3	**Sandstone:** quartz wacke, glauconitic, clay shale laminae, very fine to fine-grained. (5G 2/1 Greenish Black)

9300.3-9300.6	**Sandstone:** quartz/glauconitic arenite, planar laminations, very fine to fine-grained, well rounded. (5GY 6/1 to 5B 7/1 Greenish Gray to Light Bluish Gray)
9300.6-9303.3	**Sandstone:** quartz/glauconitic arenite to wacke, very fine to fine-grained, well rounded, planar laminations, bioturbated, well indurated, occasional shaly clasts. (5GY 4/1 to N3 Dark Greenish Gray to Dark Gray)
9303.3-9304	**NO CORE**
9304-9306.7	**Sandstone:** quartz arenite to wacke, fine-grained, rounded to well rounded, bioturbated and soft-sediment deformation, well indurated. (5Y 6/1 Light Olive Gray with 5GY 2/1 Greenish Black seams)
9306.7-9307.2	**Sandstone:** quartz arenite, fine-grained rounded. (N4 Medium Dark Gray)
9307.2-9309.1	**Sandstone:** quartz dominant arenite to wacke, fine-grained, some fossil debris, some planar laminations survive, micro-fractures, a few possible burrows, soft-sediment deformation. (5Y 6/1 to N4 Light Olive Gray to Medium Dark Gray)
9309.1-9313.1	**Sandstone:** quartz/glauconitic wacke (0.7ft.), consisting of very fine-grained quartz arenite clasts (rip-ups) in a medium-grained, glauconite dominant matrix, some planar laminations survive. (clasts: N6 Medium Light Gray, matrix: 5GY 2/1 Greenish Black), shaly laminations with limonite (glauconite) alterations (0.7 ft.), followed by quartz wacke (1 ft.) with less glauconite, bioturbated and soft- sediment deformation. (N4 to 5Y 6/1 Medium Dark Gray to Light Olive Gray)
9313.1-9314.3	**Sandstone:** quartz arenite (0.8 ft.): faint laminations, fine-grained, inclined 25 degrees, fractures. (N3 Dark Gray)
9314.3-9315.3	**NO CORE**
9315.3-9317.7	**Sandstone:** quartz arenite, fine-grained, subrounded, bioturbated and soft-sediment

	deformation, some clasts (rip-ups) with remnant planar laminations. (N6 Medium Gray)
9317.7-9320	**Conglomerate:** <u>matrix</u>: glauconitic sandstone fine-grained, <u>clasts</u>: quartz-rich, fine-grained, well-rounded, elongate and ranging from 6 mm to 10 cm length, some remnant planar laminations, upper portion appears to be inclined 30 degrees, while lower portion shows clasts randomly aligned, small fractures filled with calcite or dolomite. (N6 to 5G 2/1 Medium Light Gray to Greenish Black) 1.2 ft of missing core.
9320-9321	**Sandstone:** highly deformed, what appears to be dark glauconitic sandstoneclasts in a lighter quartz/glauconite sand matrix, some zones are calcite/dolomite-rich, thin iron-rich bed is present (limonite?), [High degree of soft-sediment deformation?] (5G 2/1 to 5G 6/1 Greenish Black to Greenish Gray)
9321-9330	**Sandstone:** upper portion is a quartz (glauconite < 10%) arenite, fine-grained, rounded, containing clay shale laminae, lower portion is a wacke with increasing clay shale laminations, bioturbation, specks of iron staining, pyrite. Core was previously sampled. (5Y 6/1 to N3 Light Olive Gray to Dark Gray)
9330-9332	**Sandstone:** quartz arenite, fine-grained, planar laminations with alternating light and dark laminae, Dark laminae are glauconitic, zones of limonite staining, occasional clay shale laminae, some bioturbation, inclined beds of glauconite at 9331', partially altered to pyrite, clay shale laminae inclined at 60 degrees. (5GY 2/1 Greenish Black)
9332-9340	**Sandstone:** glauconitic/quartz wacke with interlaminated clay shale, fine to medium-grained, rounded, some planar laminations, specks of iron staining, <50% bioturbation, limonite-rich zones, two microfaults between 9332-9334', occasional pyrite crystals. (5Y 4/1 to N2 Olive Gray to Grayish Black)
9340-9349	NO CORE

9349-9360.2	**Clay Shale/Siltstone/Sandstone:** intercalated, siltstone intervals have little glauconite (<10%), occasional beds are extremely glauconitic (80%), very fine to fine-grained, rounded, microfaulting evident in some siltstone intervals, calcite-filled fractures, pyrite 'nodules' (3 mm diameter), bioturbation, soft-sediment deformation, possible oil stain at 9353',increased inclination of bedding with depth (horizontal to 40 degrees). (5Y 6/1 to 5GY 2/1 Light Olive Gray to Greenish Black)
9360.2-9364	**Clay Shale:** minor siltstone interlaminations, {Condition of siltstone is glauconitic (>50%), soft-core is poor} sediment deformation, limonite staining, calcite-rich zones, bedding is inclined approximately 30 degrees. (5Y 2/1 Olive Black)
9364-9379	**Clay Shale/Mudstone/Siltstone:** intercalated, highly deformed (soft-sediment deformation?), siltstone varies from 40% to <10% glauconite, several faults and fractures, bedding in upper portion is nearly horizontal, becoming vertical with depth, possibly overturned near 9374' and/or 9377', some zones are calcite-rich, limonite staining. (5Y 5/2, N4, N2 Light Olive Gray, Medium Dark Gray and Grayish Black)
9379-9381	**NO CORE**
9381-9399.5	**Sandstone:** quartz/glauconite wacke, contains minor clay shale and siltstone, very fine to fine-grained, rounded, near horizontal to vertical and overturned bedding, becoming more deformed with depth, calcite-filled fractures and zones, three microfaults observed. (N3, 5G 2/1, 5Y 6/1 Dark Gray, Greenish Black and Light Olive Gray)
9399.5-9399.9	**Sandstone to Quartz/Clay Shale Conglomerate:** glauconitic (50%) wacke, fine-grained, quartz and clay shale matrix, subangular clayey clasts (0.1 to 0.8 inch diameter), no remnant laminations. (N3, N8 and 5GY 2/1 Dark Gray, Very Light Gray and Greenish Black)
9399.9-9404.1	**Siltstone/Clay Shale/Glauconitic Wacke:** glauconitic (>50%), very fine to fine-grained, occasional 'rip-ups' of lighter

quartz/glauconitic siltstone, wispy laminations of clay shale, bioturbation in some zones, limonite-rich laminae at 9303.5' calcareous. (N8, N5, 5GY 2/1 Very Light Gray, Medium Gray and Greenish Black)

9404.1-9406.3¦**Sandstone with Clay Shale Laminae:** wacke, glauconitic, fine-grained, subrounded, limonite, microfault near 9406', calcareous. (5GY 2/1 Greenish Black)

9406.3-9406.7¦**Sandstone with Quartz/Glauconitic Siltstone Clasts:** wacke, glauconitic matrix (50%), fine-grained, subrounded, near horizontal bedding, hematite stained, light gray clasts have remnant planar laminations, very fine to fine-grained, rounded. (N7 and 5GY 4/1 Light Gray and Dark Greenish Gray)

9406.7-9417.7¦**Clay Shale, Quartz/Glauconitic Wacke and Quartz Siltstone:** some laminae are much more glauconitic (80% to <10%), light gray clasts of siltstone, very fine-grained, well rounded, limonite-rich laminae, calcareous in places, small calcite-filled fractures, microfault near 9412', hematite staining near 9415' and 9417', bedding is horizontal to slightly inclined (15 degrees). (5GY 2/1 and N7 Greenish Black and Light Gray)

9417.7-9421.1¦**Siltstone/Sandstone:** wacke, quartz/glauconite, very fine to fine-grained, subrounded to rounded, fine-wispy clay shale laminae, calcite-filled microfractures, possible rip-ups near 9420' (soft-sediment deformation?). (5GY 4/1 to 5GY 2/1 Dark Greenish Gray to Greenish Black)

9421.1-9422.6¦**Sandstone:** alternating dark (quartz/glauconitic (<50%)) and light (calcareous) horizontal laminations, very fine to fine-grained, rounded, minor laminations containing some clay shale. (5G 4/1 Dark Greenish Gray)

9422.6-9423.1¦**Dolostone/Sandstone:** quartz/glauconite wacke very fine to fine-grained, subrounded, hematite stained, calcite-filled microfractures, rip-ups of glauconitic wacke found below, bioturbation, some faint crossbedding. (5R 7/4 and N7 Moderate Red and Light Gray)

9423.1-9429.1	**Sandstone:** quartz/glauconite wacke, minor clay shale interlaminations and some zones of which may be dolomite-rich, remnant planar laminations, possible rip-ups of wacke, bioturbation in clay shale, calcareous. (5G 4/1 to N7 Dark Greenish Gray to Light Gray)
9429.1-9445.6	**Sandstone:** quartz arenite, very fine to fine -grained, subrounded to well rounded, occasional wispy clay laminae, varies from planar laminations to massive bedding, some limonite staining, increasing clay and bioturbation with depth. (5GY 6/1 Greenish Gray)
9445.6-9448	**Sandstone:** quartz wacke, wispy clay, <10% glauconite, mostly fine-grained, rounded, nearly 100% bioturbation. (10GY 5/2 Grayish Green)
9448-9453.3	**Sandstone:** quartz arenite (<10% glauconite), fine to medium-grained, rounded, crossbedding at 9449′ and 9452′, mostly planar laminations, graded-bedding interval (fine to upper medium-grained), alternating light (quartz) and dark (glauconitic) beds (5 mm thickness), a few areas of bioturbation, specks of iron staining at 9451′ and 9453′, calcareous. (N3 and N7 Light Gray and Dark Gray)
9453.3-9464.8	**Sandstone:** quartz arenite, virtually glauconite-free, very fine to fine, subrounded to rounded, crossbedding (15 degrees), stylolites, microfault at 9456′, some limonite stained, concretion (or nodule?) at 9464′, occasional fossil debris. (5Y 8/1 Yellowish Gray)
9464.8-9465.6	**Sandstone with Clay Shale Stringers:** quartz arenite with clay shale wisps, 5-10% glauconite, very fine to medium-grained, rounded, bioturbated, occasional pyrite, calcareous. (N3 to 5Y 8/1 Dark Gray to Yellowish Gray)
9465.6-9474	**Sandstone:** quartz arenite, 10% glauconite, very fine to fine-grained, rounded, crossbedded (5-20 degrees), fossil debris (brachiopod?), bioturbation in lower portion rounded-elongate feldspar grains (2 mm x 3

	mm) at 9466.3′, subrounded-very fine grained sandstone clast (10 mm x 20 mm) at 9467.9′, interval of subangular to subrounded-coarse grained sandstone at 9469.6′ to 9469.9′, this interval contains ‘clasts’ of fine-grained sandstone, much fossil debris and limonite, calcareous. (N7 to 5Y 8/1 Light Gray to Yellowish Gray)
9474-9515	NO CORE
9515-9534	**Greenstone:** Precambrian basement, chlorite-rich, fine to medium-grained biotite with little quartz, potassium feldspar and occassional pyrite, gneissic banding in upper and lower two meters, appears to be metasomatized in areas, many calcite-filled fractures, migmatic appearance in places, a melange-like interval at 9529′ of what appears to be monomineralic and polymineralic clasts, angular and rounded (faulting?). (5GY 4/1 Dark Greenish Gray with a variety of grays, greens and reds)

NDGS #6436
Shell Oil Company
Duerre 43-5
Renville County, North Dakota
NE SE Sec. 5, T163N, R87W
Intervals: 9414' to 9494' and 9550' to 9595'

Depth	Description
9414-9449.7	**Clay Shale:** fine interlaminations of quartz arenite, well rounded, noncalcareous, very fine to medium-grained brown mica flakes and very fine pyrite throughout, occasional very fine potassium feldspar grains, upper portion contains much more quartz while laminations and 'lenses' of sand are larger, lower portion has fewer lenses and laminations are finer, two areas (9419' and 9440') have 'clasts' of pyrite and quartz grains, well-formed crystals with both cubic and radiating habit at 9440', most laminations are on the order of 1 mm in thickness. (N4 to N1 Medium Dark Gray to Black)
9449.7-9454.2	**Conglomerate and Sandstone/Shale:** conglomerate: there are approximately twelve beds ranging in size from 1 cm to 10 cm. <u>matrix</u>: subarkose sandstone, 5% glauconite, medium to coarse-grained, rounded; <u>clasts</u>: quartz and feldspar grains, shale, and metamorphic pebbles, subangular to subrounded, calcareous cementing, occasional pyrite nodules, no grading or preferential orientations. sandstone/shale: quartz dominant, 10%< glauconite, very fine to medium-grained, rounded to well rounded, noncalcareous. (5GY 4/1 to 5GY 6/1 Dark Greenish Gray to Greenish Gray)
9454.2-9482.3	**Breccia:** (Clasts are matrix supported.)
9454.2-9457.7	**Zone 1:** granitic and gneissic clasts, pebble-size, subangular, clay/shale stringers and clasts, areas seem to exhibit bedding - although clasts show no preferential orientation, at least three cobble-size clasts found in interval, no grading is evident, matrix supported, matrix appears to be a clayey quartzose sand. (5Y 4/1 Olive Gray, clasts vary from felsic to more mafic coloration)

9457.7-9466	**Zone 2:** clasts are both monomineralic (large potassium feldspar crystals) and polymineralic (gneiss), gneissic clasts dominate, one boulder-size clast which resembles amphibolite greenstone from lower section (below 9550′) of this core found at 9464′, most clasts are pebble to cobble size, angular to subangular, matrix supported; matrix: subarkose sandstone, 10% micas, fine to medium-grained, subrounded to rounded, some alteration apparent (weathering of clasts?), calcareous in places. (5GY 4/1 Dark Greenish Gray)
9466-9473	**Zone 3:** arkosic-granitic clasts dominate, some light-colored gneiss clasts, pebble to cobble size, angular, matrix: subarkose, fine to very fine-grained, subrounded to subangular, orange staining, weathered area near 9471′. (5 GY 4/1 to 10R 6/6 Dark Greenish Gray to Moderate Reddish Orange)
9473-9482.3	**Zone 4:** gneissic clasts dominate, small portions of interval are missing, lower portion appears more mafic, pebble to boulder size, angular to subangular, matrix is consistent with Zone 3, interval between 9476′ to 9478′ is extremely fragile, slickensides. (5GY 2/1 Greenish Black)
9482.3-9491	**Sandstone:** glauconite/quartz wacke, small portions of interval are missing, fine-grained, subrounded, calcareous and wispy clay shale laminations, soft-sediment deformation, slickensides in clay shale, fault at 9487.5′, well rounded - weathered gneiss clast (2 cm x 4 cm) and several small pebbles between 9484′ and 9484.4′. (5G 4/1 to 5Y 6/1 Dark Greenish Gray to Light Olive Gray)
9491-9494.3	**Clay Shale and Sandstone:** interlaminated, quartz arenite, 30%> glauconite, very fine to fine-grained, rounded, less deformed than above interval, some intervals of arenite rip-ups, rip-ups exhibit remnant laminations, rip-up interval has little clay shale, a few small calcite-filled fractures, calcareous. (N3 to 5Y 6/1 Dark Gray to Light Olive Gray)
9494.3-9550	NO CORE

9550-9595.8 **Amphibolite greenstone:** Precambrian basement, upper 1 m resembles augen gneiss, ultramafic with potassium feldspar augen, banding is inclined 45°, becomes less augen with less potassium feldspar below 9554′, numerous calcite-filled fractures throughout, fractures do not parallel foliation, large calcite-filled void (5 cm x 10 cm) at 9560′, potassium feldspar-rich ‘vein’ (2 cm in thickness) crosses core at 9589′. (mottled N1 to 5G 2/1 Black to Greenish Black)

NDGS #6466
Shell Oil Company
Mott 32X-3
Renville County, North Dakota
SW NE Sec. 3, T164N, R87W
Intervals: 9099′ to 9106′ and 9155′ to 9234′

Depth	Description
9099-9106	**Clay Shale:** fissile, fossiliferous (trilobite fragments? 1 mm to 2 mm), waxy, slickensides. (5G 2/1 Greenish Black)
9106-9155	NO CORE
9155-9161	**Green Shale and Sandstone:** fissile, appears 'wispy' where shale and sandstone are interlaminated, green coloring seems to originate from glauconite - although its percentage is low (<5%) - or perhaps it is related to chlorite content, noncalcareous, sandstone is a quartz arenite, 5%> glauconite, medium to coarse-grained, rounded to subrounded, well sorted, occasional thin (1 mm to 2 mm) areas of limonite staining, dark oil staining between 9155′ and 9158′, beds range from 3 cm to 7.5 cm in thickness. (shale: 5G 5/2 to 5G 4/1 Grayish Green to Dark Greenish Gray; sandstone: 5Y 4/1 to 5Y 6/1 Olive Gray to Light Olive Gray)
9161-9166.2	**Sandstone:** quartz arenite, fine to coarse-grained, rounded, 'wispy' appearance, mottled green and white coloring appears in these wispy laminations in some areas, specks of iron staining, upper portion is primarily a brownish sand (no green) - grading into a mottled color, lower portion is oil stained, entire interval is very friable, noncalcareous, apparent burrowing. (5Y 6/1 to 5G 5/2 Light Olive Gray to Grayish Green)
9166.2-9171.5	**Sandstone:** quartz arenite, fine to coarse-grained, rounded to well rounded, upper portion is oil stained, lower portion is mottled with less oil staining. (5Y 8/1 to 5Y 4/1 Yellowish Gray to Olive Gray)
9171.5-9173	**Shale:** wispy appearance with no laminations evident, some lenses of quartz arenite, soft-sediment deformation, fairly well indurated to fissile, tiny (<1 mm) pyrite crystals

throughout, fossile debris. (5G 4/1 Dark Greenish Gray)

9173-9175.2	**Sandstone:** quartz arenite, fine to medium-grained, rounded, occasional pyrite crystals, oil staining, green-brown and white mottling. (5Y 6/1 to 5G 5/2 Light Olive Gray to Grayish Green)
9175.2-9184	**Sandstone:** quartz arenite, medium to coarse-grained, subrounded, occasional fine pyrite crystals and brown mica flakes, dark oil staining with occasional white zones, upper portion (to 9179.5') has green shaley stringers, varying from horizontal laminations to pod-like rip-ups, fissile, a single angular potassium feldspar grain (4 mm in diameter) at 9179.9', possible burrowing. (5YR 4/1 Brownish Gray)
9184-9193	**Sandstone:** quartz arenite with wispy appearance, fine to coarse-grained, subangular to rounded, wispy green laminations exhibit a low (if any) shale content, nearly horizontal lamination at 9191.3', a few fine pyrite crystals, brown mica flakes and mafic rock particles, specks of iron staining, oil stained areas near 9185' and 9188'. (5GY 8/1 to 5G 8/1 Light Greenish Gray to Light Greenish Gray)
9193-9234	**Gneiss:** Precambrian basement, containing quartz, potassium feldspar, plagioclase, biotite and chlorite, olivine, hematite, pyrite, slightly schistose in areas, differentiation and gneissic banding of felsic and mafic minerals, occasional calcite-filled microfractures, slickensides at 9193', 9209', 9216', 9218', 9219' and 9224'. (coloration is highly variable between greens, browns, grays, blacks and pinks)

NDGS #6473
Shell Oil Company
Lindblad 41X-16
Renville County, North Dakota
NE NE Sec. 16, T163N, R87W
Intervals: 9516′ to 9695′

Depth	Description
9516-9539	**Sandstone and Clay Shale:** interbedded, quartz arenite, very fine to fine grained, rounded, 10-30% glauconite, composition varies from quartzose to quartz/glauconite, fine grained, quartz arenite rip-ups in >90% glauconite sandstone to clay shale stringers, lower portion is inclined 15° to 20°, mid-section is inclined 30° to 45°, inclination of upper portion is <10°, soft-sediment deformation at 9528.8′, several microfaults and accompanying slickensides: 9516.5′, 9518.5′, 9519′, 9524′ and 9527′, fossil debris in calcareous zone at 9526.5′, bioturbation throughout - but a few zones are undisturbed: 9616.3′, 9534′, 9537′ and 9539′, specks of iron staining at 9516.3′, clay shale is darker, while sandstone retains a lighter color. (5Y 6/1, 5GY 2/1 and 5Y 8/1 Light Olive Gray, Greenish Black and Yellowish Gray)
9539-9540.2	**Sandstone:** quartz wacke, <50% glauconite, very fine to fine-grained, rounded, limonite-rich bed with fossil debris, contains calcite-rich zone, bedding is inclined 15°. (5GY 2/1 Greenish Black)
9540.2-9540.8	**Sandstone Clasts in Glauconite Matrix:** quartz arenite, <5% glauconite, very fine-grained, rounded; matrix is >>50% glauconite, fine to coarse-grained, calcareous, appears to have little bioturbation. (N7 to 5G 4/1 Light Gray to Dark Greenish Gray)
9540.8-9541.9	**Conglomerate:** <u>matrix</u>: quartz wacke, very fine to coarse-grained, well rounded, calcareous; <u>clasts</u>: sandstone and clay shale, mostly very fine to medium-grained, subangular to subrounded, largest having 3 cm diameter, variable colors (whites, grays and pink) and grain sizes; appears matrix supported, no bioturbation. (N2 Grayish Black)

9541.9-9542.8	**Sandstone Clasts in a Calcite-rich Matrix:** <u>matrix</u>: quartz arenite, <5% glauconite, very fine to fine-grained, calcareous; <u>clasts</u>: quartzose, very fine-grained, rounded, elongate, most are several centimeters in length, some exhibit remnant laminations. (N8 to N5 Very Light Gray to Medium Gray)
9542.8-9545	**Sandstone and Clay Shale:** interlaminated, quartz arenite, 5% glauconite, very fine to fine-grained, rounded to subrounded, planar laminations, some intervals are nearly 100% bioturbated, others appear to be undisturbed (5GY 4/1 Dark Greenish Gray)
9545-9545.5	**Sandstone Clasts in Glauconite/Clay Shale Matrix:** <u>matrix</u>: >>50% glauconite, some zones are clay shale; <u>clasts</u>: quartz arenite, <5% glauconite, very fine to fine-grained, rounded, some clasts exhibit remnant laminations, calcite wisps throughout. (5G 2/1 to N7 Greenish Black to Light Gray)
9545.5-9547.5	**Sandstone and Clay Shale:** interlaminated, quartz arenite, <10% glauconite, very fine-grained, rounded, calcareous, thickest sandstone bed is approximately 7 cm, portions are bioturbated, microfaulting, inclined bedding (5° to 10°). (5GY 4/1 to N3 Light Olive Gray to Dark Gray)
9547.5-9549.5	**Sandstone Clasts in Glauconitic Sandstone Matrix:** <u>matrix</u>: >>50% glauconite, fine-grained, rounded, some minor clay shale; <u>clasts</u>: quartz-rich, 5% glauconite, very fine-grained, rounded and well sorted, some exhibit remnant laminations, calcareous. (5Y 6/1 and 5GY 4/1 Light Olive Gray and Dark Greenish Gray)
9549.5-9565.5	**Sandstone:** interbedded, quartz wacke and grained, rounded, clay shale wacke beds are nearly 100% bioturbated, the arenite exhibits planar laminations which alternate between quartzose and glauconitic, thickest arenite bed measured at 1.25 m, possible crossbedding at 9553.5'. (5GY 2/1 Greenish Black)
9565.5-9572	**Sandstone:** quartz-rich, 5% > glauconite, wispy clay shale, very fine to fine-grained, rounded, calcareous, some remnant

	laminations, nearly 100% bioturbated. (5GY 2/1 Greenish Black)
9572-9597	**Sandstone, Siltstone and Clay Shale:** interlaminated, Sandstones range from a 'very clean' quartz arenite to a dark glauconitic sandstone, silty to medium-grained, rounded, color differences between lithologies is quite dramatic (greens, browns, grays and blacks), soft-sediment deformation, microfaulting, stylolites, bioturbation, dendritic burrow or pyritized/carbonitized soft-bodied organism in bedding plane at 9594', hematite staining at 9582.3, <u>Skolithos</u> burrows at 9576' and 9574', 15 cm of noncalcareous, fissile, clayey shale at 9589'. (5GY 8/1, N3 and 5GY 4/1 Light Greenish Gray, Dark Gray and Dark Greenish Gray)
9597-9602.5	**Sandstone with Clay Shale Laminae:** quartz <50%, 50%< glauconite, very fine to fine-grained, subrounded, calcareous, soft-sediment deformation, portions show possible bioturbation, clay content increases upward, planar laminated. (5GY 2/1 Greenish Black)
9602.5-9604.7	**Sandstone with Clay Shale Clasts:** clay shale clasts in 'matrix' of fine-grained quartz sandstone, 10% glauconite, at least one rip-up of sandstone, very fine grained, rounded, portions are bioturbated, calcareous, hematite staining near 9604'. (5GY 4/1 Greenish Gray)
9604.7-9610	**Sandstone:** quartz arenite is dominant, portions are >10% glauconite, very fine to medium-grained, subrounded, rip-ups of the same appear near 9609', clay shale laminations near 9606' and 9607.5', lower portion appears 'whiter' and is slightly calcareous, occasional stylolites, planar lamination throughout, no bioturbation observed until upper 30 cm. (5G 6/1 to 5GY 4/1 Greenish Gray to Dark Greenish Gray)
9610-9611.9	**Sandstone and Clay shale Wisps:** interlaminated, quartz arenite, <10% glauconite, fine to medium-grained, subrounded to rounded, near 100% bioturbation, interval has hematite staining, some minor calcite wisps. (5GY 4/1 to 10R

	2/2 Dark Greenish Gray - Very Dusky Red)
9611.9-9614.8	**Sandstone and Clay Shale:** interlaminated, quartz arenite, >10% glauconite, very fine to fine-grained, rounded, some limonite staining, planar laminations, thickest sandstone bed is 6.5 cm, clay shale contains occasional slickensides, microfault at 9614′, little bioturbation if any, hematite staining appears in several clay shale laminations near 9614′. (N3 to 5GY 6/1 Dark Gray to Greenish Gray)
9614.8-9624	**Sandstone:** quartz arenite, 5% to 10% glauconite, very fine to medium-grained, rounded, some cross-bedding near 9617′ and 9622′, minor clay shale wisps, occasional stylolites, upper 15 cm appears to have undergone soft-sediment deformation, occasional calcite 'wisps'. (5GY 6/1 Greenish Gray)
9624-9640.4	**Sandstone and Clay Shale Laminae:** sandstone is interlaminated quartz and glauconite, very fine to fine-grained, rounded, cross-bedding (15°) near 9635′, planar laminations near 9632′ and 9637′, clay shale/sandstone laminations are nearly 100% bioturbated, thickest sandstone bed is 33.5 cm and clay shale is 70 cm, occasional stylolites, specks of iron staining. (5G 6/1 Grayish Green)
9640.4-9647.2	**Sandstone:** quartz arenite, 5%> glauconite, fine to coarse-grained, rounded, cross-bedding (15°), 'horsetail' stylolites, bioturbation, specks of iron staining, numerous limonite - carbonaceous rip-ups at 9641′, minor clay wisps, well indurated. (5Y 8/1 Yellowish Gray)
9647.2-9647.8	**Sandstone Clasts in Quartzose/Glauconitic Matrix:** <u>matrix</u>: quartz dominant, 10% glauconite, very fine to fine-grained, rounded; <u>clasts</u>: quartz arenite, 5%>> glauconite, fine to medium-grained, rounded. (5GY 6/1 to 5GY 4/1 Light Olive Gray to Dark Greenish Gray)
9647.8-9653.2	**Sandstone and Clay Shale:** intercalated, quartz arenite, 10% glauconite, fine to coarse-grained, subrounded, thickest sandstone bed is 12.7 cm, cross-bedding

	(<10°), bioturbation, soft-sediment deformation, stylolites. (N3 to N7 Dark Gray to Light Gray)
9653.2-9653.8	**Sandstone:** fossiliferous, quartz arenite, 5%>> glauconite, very fine to fine-grained, rounded, well sorted, stylolites, much fossil debris (*Lingula*? and/or trilobite), specks of iron staining. (5Y 8/1 Yellowish Gray)
9653.8-9662.5	**Sandstone:** quartz arenite, 5%> glauconite, fine-grained, well sorted, rounded, minor clay shale laminations, crossbedding (15°), occasional fossil debris, specks of iron staining, occasional pyrite. (5Y 8/1 Yellowish Gray)
9662.5-9665.3	**Clay Shale and Sandstone:** interlaminated, fissile clay shale dominates, sandstone mostly quartz arenite, 5%> glauconite, fine grained, rounded, well sorted, thickest sandstone bed is 1.4 cm, bioturbation and dewatering structures. (5YR 8/1 to 5GY 2/1 Pinkish Gray to Greenish Black)
9665.3-9682.5	**Sandstone:** quartz arenite, 5%>> glauconite, fine to coarse-grained, subrounded to rounded, well indurated, soft-sediment deformation, stylolites, specks of iron staining, bioturbation. (5Y 8/1 Yellowish Gray)
9682.5-9695	**Granitic Gneiss:** brown mica and chlorite-rich 'vein' at 9685', weathered/altered zones at 9682.5', 9684.5', 9687.5' and 9691.5', less than 20 cm of the interval which contains the contact between the Precambrian and overlying unit, seems to be absent, the color of the overlying sandstone grades into the light-coloring of the weathered Precambrian zone.

NDGS #6749
Shell Oil Company
Gilbertson 33X-3
Renville County, North Dakota
NW SE Sec. 3, T163N, R87W
Intervals: 9290' to 9349'

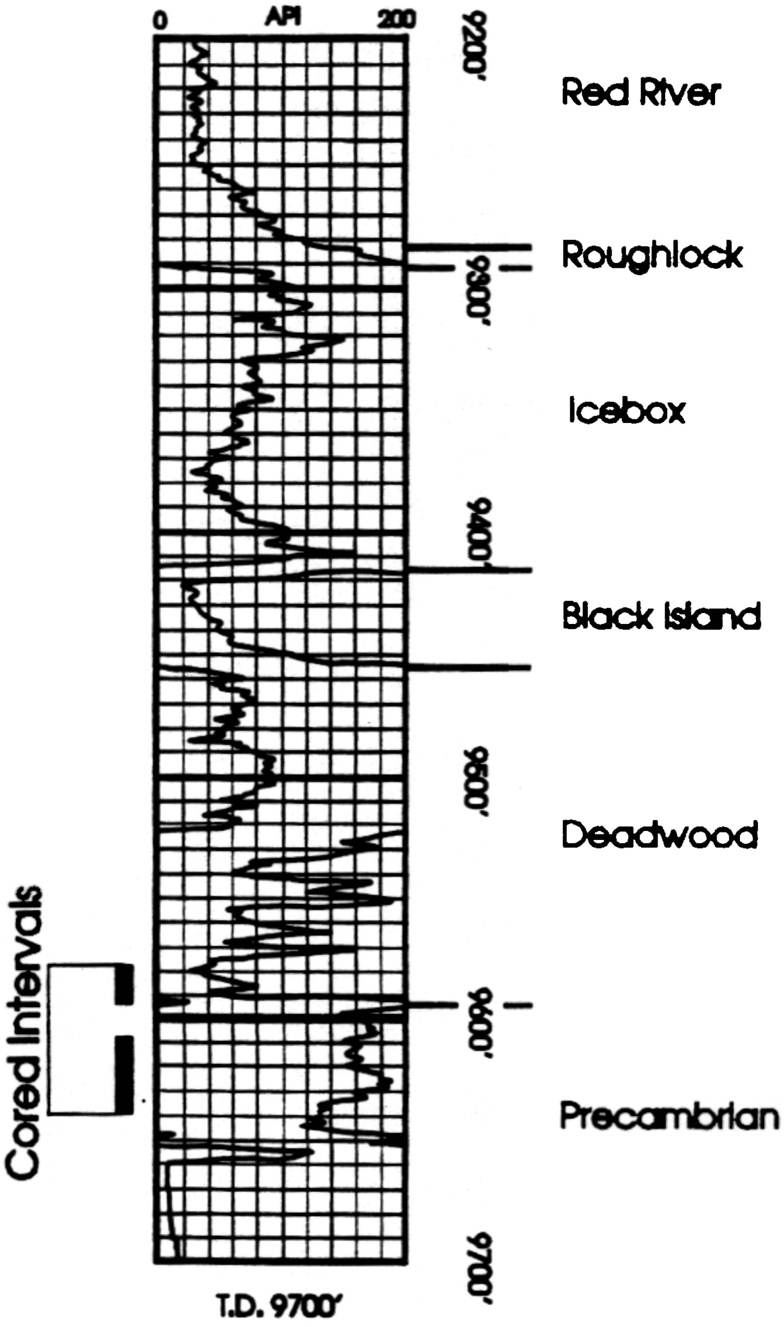
Depth	Description
9290-9349	**Greenschist:** Precambrian basement, of 'lower' grade metamorphism than that found in the bottom of Larson 23X-9 core, some gneissic banding, slightly schistose, metasomatized quartz and feldspars, calcite-filled fractures, slickensides at 9300.7', brecciated or intervals at 9290'-9295', 9305'-9316', and 9327'-9345'; 9300' to 9308' shows intense fracturing and faulting; open, crystal-lined (calcite) vugs at 9295'; brecciation seems 'sporatic' with intervals between exhibiting some fracturing and faulting; serpentine-rich with occasional olivine crystals, zoned vein-like bands of pyroxene, biotite, serpentine and quartz, appears to be slightly more mafic (hornblende?) with depth; breccia seems 'tighter' than that found in Mott 14-34, but resembles lower breccia in that well. (5G 2/1 Greenish Black)

APPENDIX B

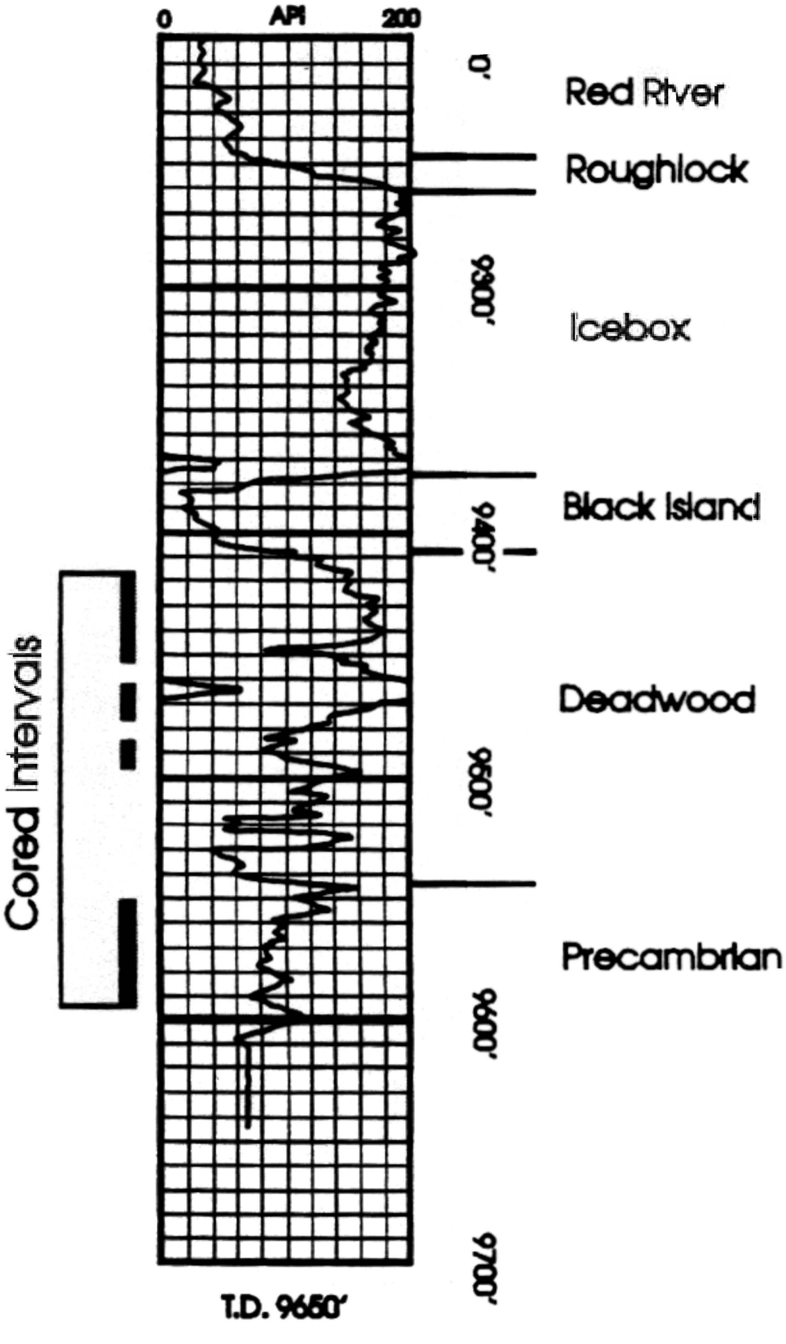
REPRODUCTION OF GAMMA RAY LOGS AND FORMATION TOPS

Wireline logs are arranged alphabetically by their Shell Oil Company name. All depths are those found on original wireline logs. These depths are all in feet have not been corrected for the depths given on core or core boxes. Cored intervals are indicated approximately. Core and wireline log depths correlated well, and seemingly not differ by more than five feet for any of the Newporte wells

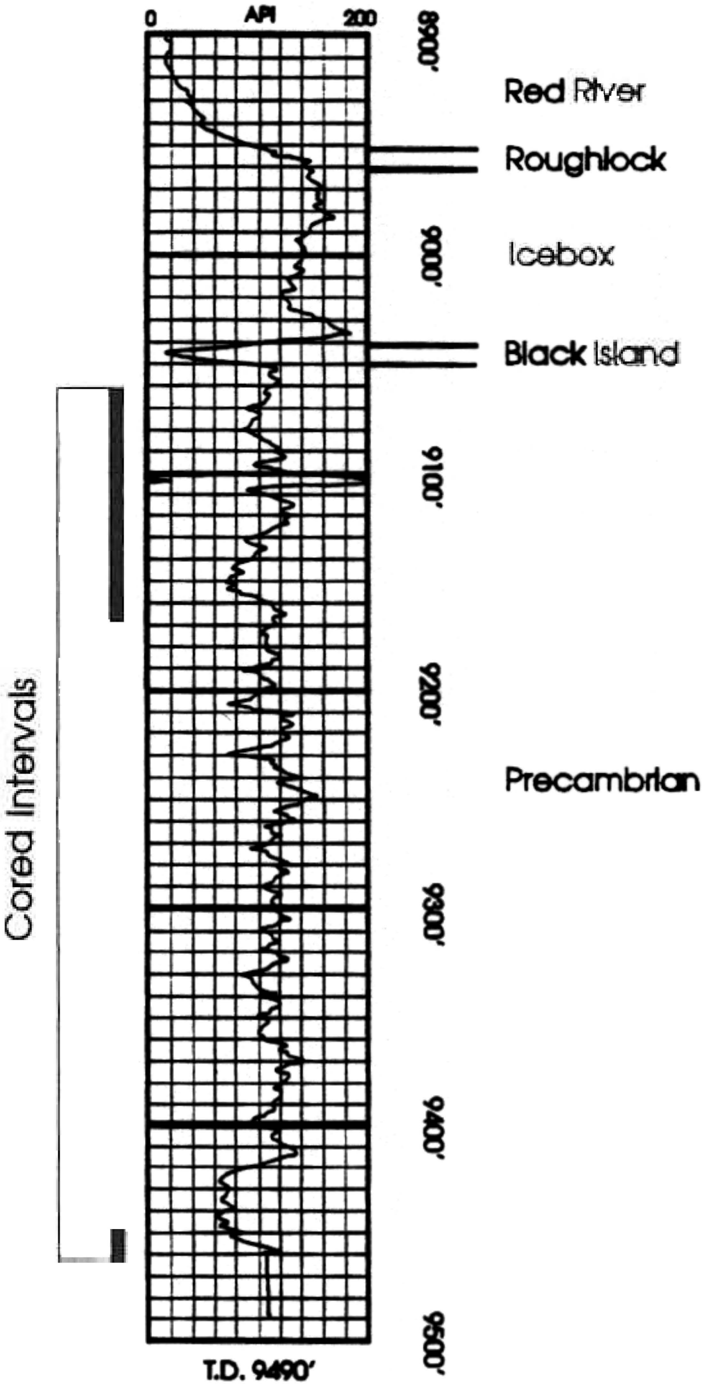
Shell Larson 23X-9



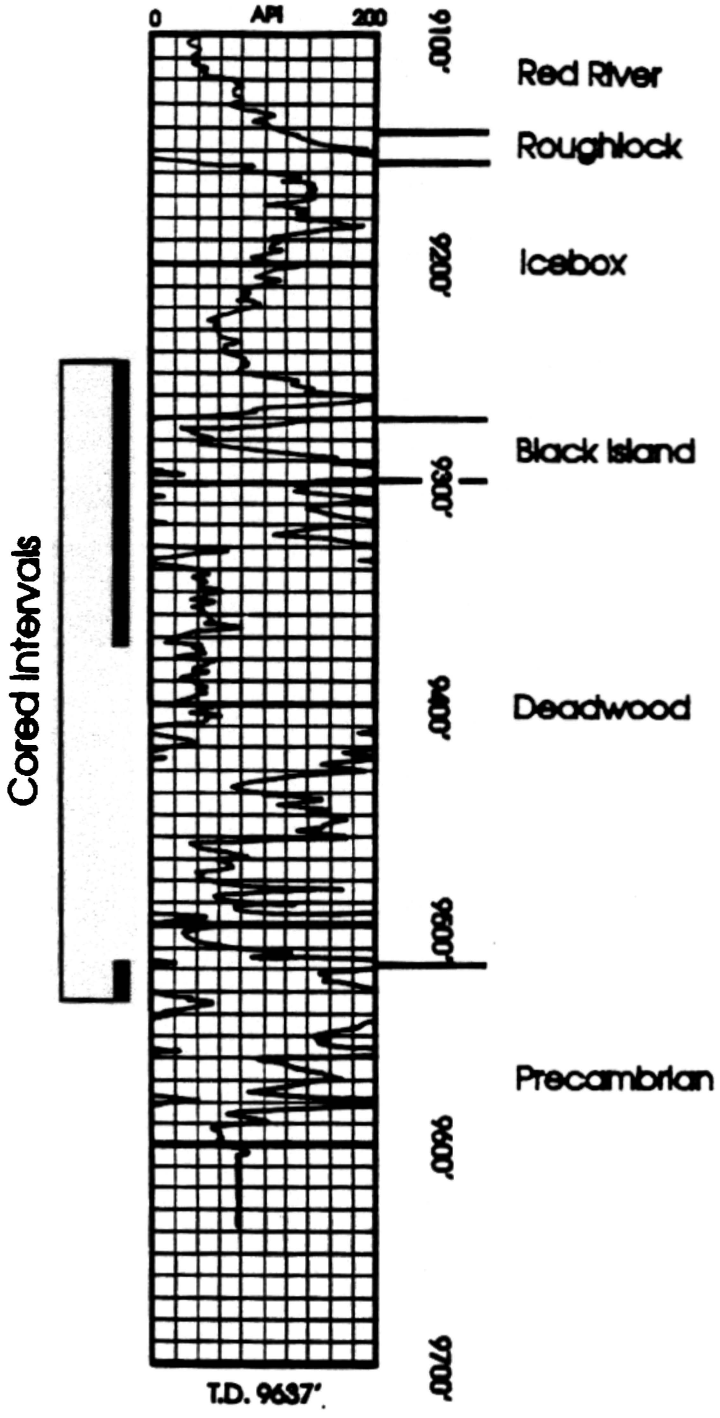
Shell Duerre 43-5

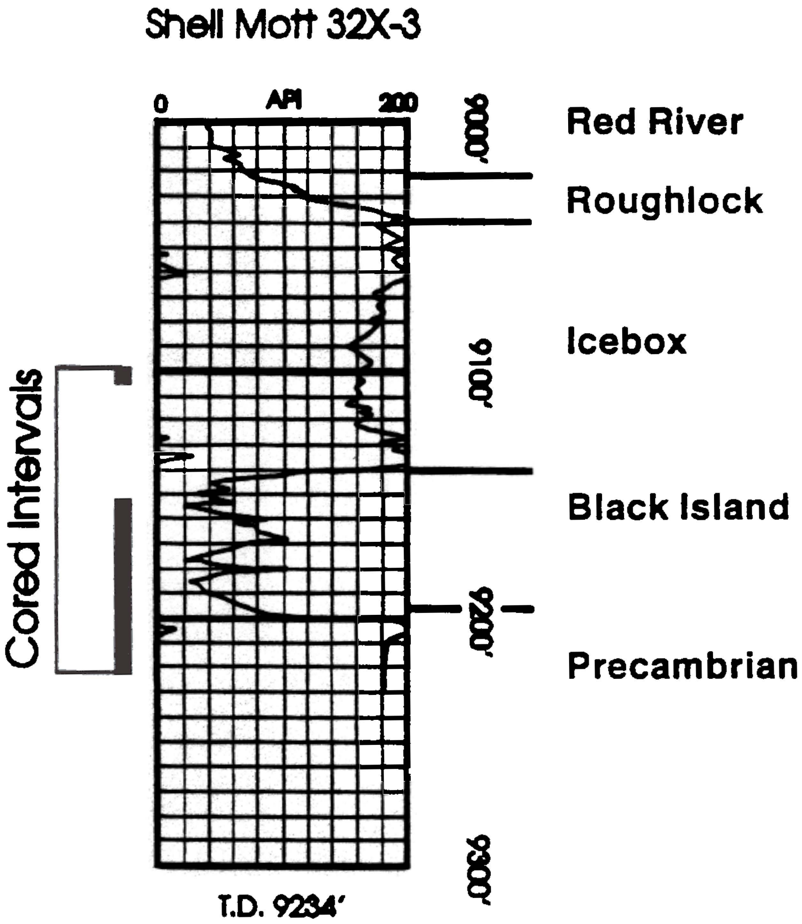


Shell Mott 4-34

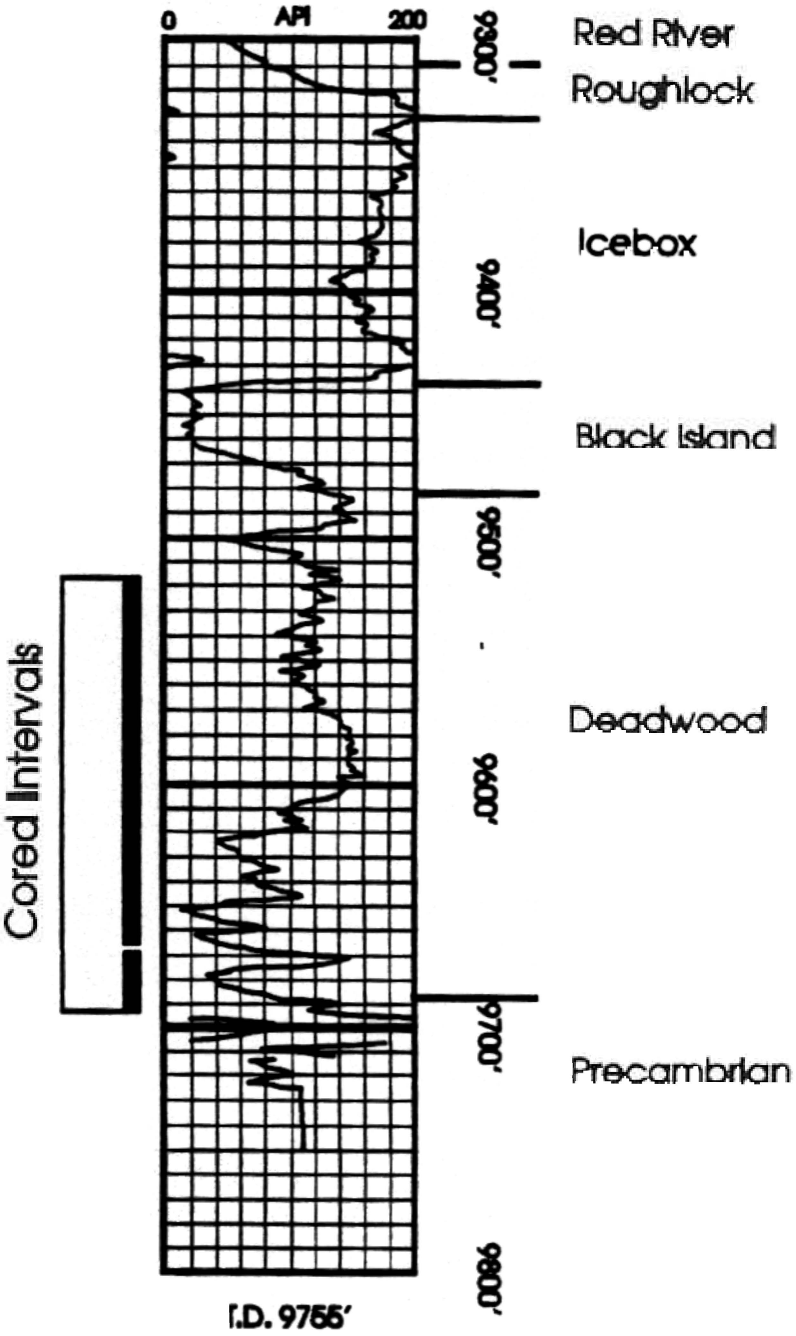


Shell Wisdahl 23-10

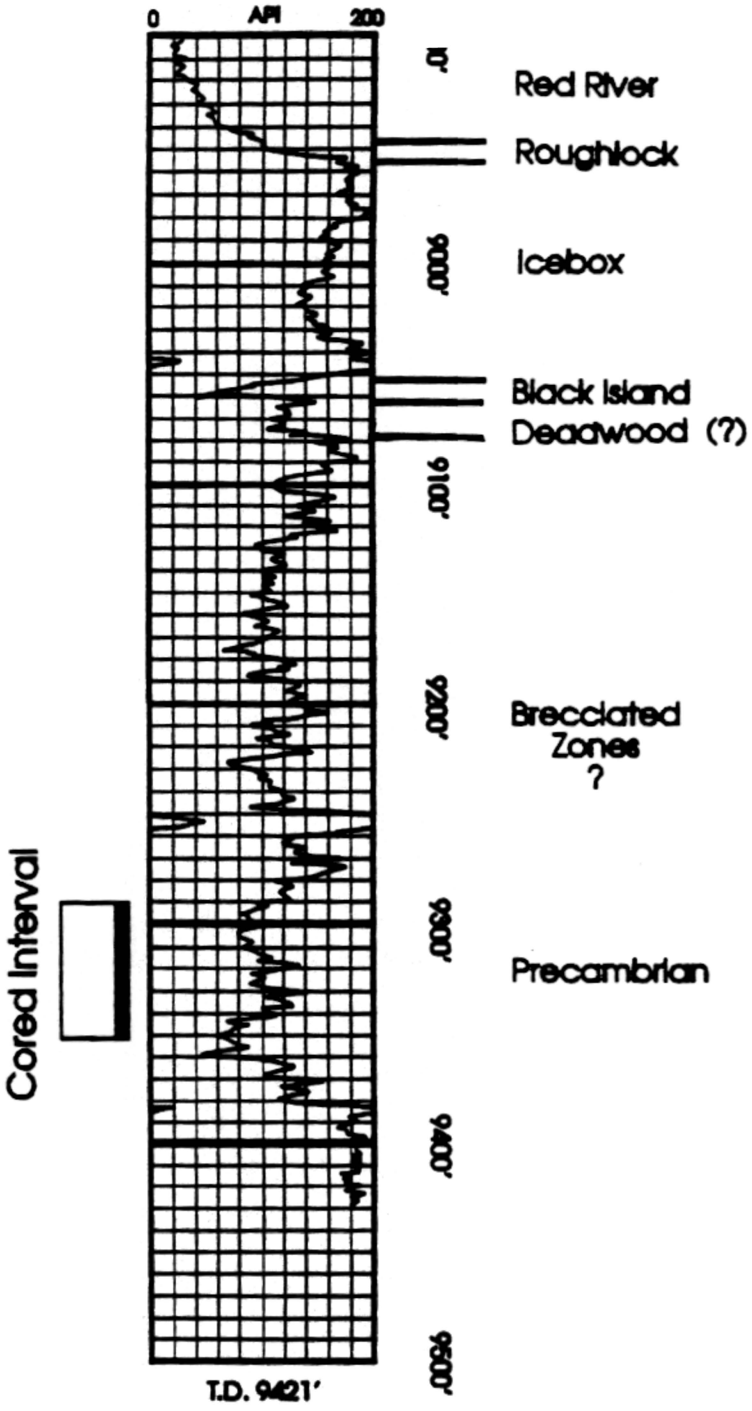



Shell Mott 32X-3
0
API
200
9000'
9100'
9200'
9300'
Red River
Roughlock
Icebox
Black Island
Precambrian
Cored Intervals
T.D. 9234'

Shell Lindblad 4 X- 6



Shell Gilbertson 33X-3



References Cited

Alexopoulos, J.S., Grieve, R.A.F., and Robertson, P.B., 1988, Microscopic lamellar deformation features in quartz: discriminative characteristics of shock-generated varieties: Geology, v. 16, p. 796-799.

Anderson, D.B., 1988, Stratigraphy and depositional history of the Deadwood Formation (Upper Cambrian and Lower Ordovician), Williston Basin, North Dakota: Grand Forks, University of North Dakota, M.S. Thesis, 330 p.

Ballard, F.V., 1963, Structural and stratigraphic relationships in the upper Paleozoic rocks of eastern North Dakota: North Dakota Geological Survey, Bulletin 40, 42 p.

Beals, C.S., 1960, A probable meteorite crater of Precambrian age at Holleford, Ontario: Dominion Observatory, Ottawa, v. XXIV, no. 6, 142 p.

Bluemle, J.P., Anderson, S.B., and Carlson, C.G., 1981, Williston Basin stratigraphic nomenclature chart: North Dakota Geological Survey Miscellaneous Series 61 1 sheet.

Bluemle, J.P., Anderson, S.B., Andrew, J.A., Fischer, D.A., and LeFever, J.A., 1986, North Dakota Stratigraphic Column: North Dakota Geological Survey Miscellaneous Series 66, 1 sheet.

Branco, W. and Fraas, E., 1905, Das kryptovulkanische Becken von Steinheim: Abhandlungen Preuss. Akademie der Wissenschaften Klasse (Berlin), p. 1-64.

Brenan, R.L., Peterson, B.L. and Smith, H.J., 1975, The origin of Red Wing Creek structure: McKenzie County, North Dakota: The Wyoming Geological Association Earth Science Bulletin, v. 8, no. 3, 41 p.

Bridges, L.W. Dan, 1978, Red Wing Creek field, North Dakota: a concentricline of structural origin: *in* Williston Basin Symposium: Billings, Montana Geological Society, p. 315-322.

Bridges, L.W. Dan, 1987, Red Wing Creek field, North Dakota: a growth faulted or meteoritic impact structure?: *in* Longman, M.W., ed., Williston Basin: anatomy of a cratonic oil province: Denver, Rocky Mountain Association of Geologists, p. 433-440.

Bucher, W.H., 1936, Cryptovolcanic structures in the United States: 16th International Geological Congress, United States 1933, v. 2, p. 1055-1084.

Bucher, W.H., 1963, Cryptoexplosion structures caused from without or from within the Earth? ('astroblemes' or 'geoblemes?'): American Journal of Science, v. 261, p 597-649.

Carlson, C.G. and Anderson, S.B., 1965, Sedimentary and tectonic history of the North Dakota part of the Williston Basin: American Association of Petroleum Geologists Bulletin, v. 49, no. 11, p. 1833-1846.

Carlson C.G. and Thompson, S.C., 1987, Stratigraphy of the Deadwood Formation and Winnipeg Group in the Williston Basin: *in* Longman, M.W., ed., Williston Basin: anatomy of a cratonic oil province: Denver, Rocky Mountain Association of Geologists, p. 71-81.

Castano, J.R., Clement, J.H., Kuykendall, M.D. and Sharpton, V.L., 1994, Source rock potential of impact craters [abs.]: American Association of Petroleum Geologists National Convention, Denver, June 1994.

Clement, J.H. and Mayhew, T.E., 1979, Newporte discovery opens new pay: Oil and Gas Journal, v. 77, p. 165-172.

Corel Corporation, 1992, CorelDRAW computer graphics software program version 3.0: Ottawa, Houghton Mifflin Company.

Cummings, D., 1968, Shock deformation of biotite around a nuclear explosion: *in* French, B.M. and Short, N.M., eds., Proceedings of the first conference on shock metamorphism of natural materials, NASA Goddard Space Flight Center: Baltimore, Mono Book Corporation, p. 211-218.

Dence, M.R., Innes, M.J.S. and Robertson, P.B., 1968, Recent geological and geophysical studies of Canadian craters: *in* French, B.M. and Short, N.M., eds., Proceedings of the first conference on shock metamorphism of natural materials, NASA Goddard Space Flight Center: Baltimore, Mono Book Corporation, p. 339-362.

Dence, M.R., 1968, Shock zoning at Canadian craters: petrography and structural implications: *in* French, B.M. and Short, N.M., eds., Proceedings of the first conference on shock metamorphism of natural materials, NASA Goddard Space Flight Center: Baltimore, Mono Book Corporation, p. 169-184.

Donofrio, R.R., 1981, Impact craters: implications for basement hydrocarbon production: Journal of Petroleum Geology, v. 3, no. 3, p. 279-302.

French, B.M. and Short, N.M., eds., 1968, Proceedings of the first conference on shock metamorphism of natural materials, NASA Goddard Space Flight Center: Baltimore, Mono Book Corporation, 644 p.

Gerhard, L.C., Anderson, S.B., LeFever, J.A., and Carlson, C.G., 1982, Geological development, origin, and energy mineral resources of the Williston Basin, North Dakota: American Association of Petroleum Geologists, v. 66, no. 8, p. 989-1020.

Gilbert, C.M., 1954, Sedimentary rocks, *in* Williams, H., Turner, F.J., and Gilbert, C.M., Petrography: an introduction to the study of rocks in thin section: San Francisco, W.H. Freeman and Company, p. 251-384

Gilbert, G.K., 1896, The origin of hypotheses, illustrated by the discussion of a topographic problem: Science, v. 3, p. 1-13.

Goddard, E.N., Trask, P.D., DeFord, R.K., Rove, O.N., Singewald, J.T., Jr., and Overbeck, R.M., 1948, Rock-color chart: Boulder, Colorado, Geological Society of America.

Goguel, J. 1963, A hypothesis on the origin of the 'cryptovolcanic structures' of the central platform of North America: American Journal of Science, v. 261, p 665-667.

Golden Software Incorporated, 1990, SURFER version 4.15: Golden, Colorado.

Grieve, R.A.F., Wood, C.A., Garvin, J.B., McLaughlin, G and McHone, J.F., 1988, Astronaut's Guide to Terrestrial Impact Craters: Houston, Lunar and Planetary Institute Technical Report 88-03, 89 p

Hargraves, R.B., Cullicott, C.E., Deffeyes, K.S., Hougen, S., Christiansen, P.P., and Fiske, P.S., 1990, Shatter cones and shocked rocks in southwestern Montana: the

Beaverhead impact structure: Geology, v. 18, p. 332-334.

Kirschner, C.E., Grantz, A., and Mullen, M.W., 1992, Impact origin of the Avak structure, Arctic Alaska, and genesis of the Barrow gas fields: American Association of Petroleum Geologists Bulletin, v. 76, p. 651-679.

Laird, W.M., 1956, The Williston Basin - a backward look with a view to the future: *in* First International Williston Basin Symposium: Bismarck, Conrad Publishing, p. 14-22.

LeFever, R.D., Thompson, S.C., and Anderson, D.B., 1987, Earliest Paleozoic history of the Williston Basin in North Dakota: *in* Carlson, C.G., and Christopher, J.E., eds., Fifth International Williston Basin Symposium: Saskatchewan Geological Society, Special Publication 9, p. 22-36.

LOG-M software, Geophysical microcomputer applications product: Calgary, Alberta.

McCabe, H.R. and Bannatyne, B.B., 1970, Lake St. Martin crypto-explosion crater and geology of the surrounding area: Winnipeg, Manitoba Department of Mines and Natural Resources, Geological Paper 3/70, 79 p.

McHone, J., 1979, Riacho Ring, Brazil: a possible meteorite crater discovered by manned spacecraft: *in* Farouk El-Baz and Warner, D.M., eds., Apollo-Soyuz test project: summary report II, Earth observations and photography, NASA Special Publication 412, p. 193-202.

Melosh, H.J., 1989, Impact cratering: a geologic process New York, Oxford University Press, 245 p.

Merrill, G.P., 1909, On a peculiar form of metamorphism in siliceous sandstone: Proceedings of the United States National Museum, v. XXXII, no. 1546, p. 547-550.

Mescher, P.K. and Pol, J.C, 1985, Sedimentation and tectonic implications of Cambrian-Ordovician clastics, Renville County, North Dakota [abs.]: American Association of Petroleum Geologists Bulletin, v. 69, no. 2, p.288.

North Dakota Industrial Commission (NDIC), 1978, Newporte Field: Proceedings of the North Dakota Industrial Commission July hearing.

Paul, R.W., 1970, The age and origin of the Decaturville structure, Camden and Laclede Counties, Missouri:

Lawrence, University of Kansas, M.S. Thesis, 38 p.

Peterman, Z.E. and Goldich, S.S., 1982, Archean rocks of the Churchill basement, Williston Basin, North Dakota: *in* Christopher, J.E. and Kaldi, J., eds., Fourth International Williston Basin symposium: Regina, Saskatchewan Geological Society, Special Publication 6, p. 11-12.

Petroleum Information, 1980, The Williston Basin: Denver, Petroleum Information, p. 88-89.

Pike, 1977, Size-dependence in the shape of fresh impact craters on the moon: *in* Roddy, D.J., Pepin, R.O. and Merrill, R.B. (eds.), Proceedings of the symposium on planetary cratering mechanics: New York, Pergamnon Press, p. 488-509.

Potter, P.E., Maynard, J.B., and Pryor, W.A., 1980, Sedimentology of shale: New York, Springer-Verlag, 306 p.

Roddy, D.J., 1977, Large-scale impact and explosion craters: comparisons of morphological and structural analogs: Impact and explosion cratering - planetary and terrestrial implications, *in* Roddy, D.J., Pepin, R.O. and Merrill, R.B., eds., Proceedings of the symposium on planetary cratering mechanics: New York, Pergamnon Press, p. 185-246.

Roddy, D.J., Pepin, R.O. and Merrill, R.B., eds., 1977, Impact and explosion cratering - planetary and terrestrial implications: Proceedings of the symposium on planetary cratering mechanics: New York, Pergamnon Press, 1299 p.

Rountree, R., 1977, Prolific discovery in Renville County puts regional spotlight on North Dakota: Western Oil Reporter, v. 34, p. 15-17.

Sawatzky, H.B., 1975, Astroblemes in Williston Basin: American Association of Petroleum Geologists Bulletin v. 59, no. 4, p. 461-480.

Sawatzky, H.B., 1977, Buried impact craters in the Williston Basin and adjacent area: impact and explosion cratering - planetary and terrestrial implications: *in* Roddy, D.J., Pepin, R.O. and Merrill, R.B., eds., Proceedings of the symposium on planetary cratering mechanics: New York, Pergamnon Press, p. 461-480.

Sharpton, V.L. and Grieve, R.A.F., 1990, Meteorite impact cryptoexplosion, and shock metamorphism; A perspective on the evidence at the K/T boundary: *in* Sharpton, V.L. and Ward, P.D., eds., Global catastrophes in Earth history: an interdisciplinary conference on impacts, volcanism, and mass mortality: Geological Society of America Special Paper 247, p. 301-318.

Short, N.M., 1970, Anatomy of a meteorite impact crater: West Hawk Lake, Manitoba, Canada: Geological Society of America Bulletin, v. 81, p. 609-648.

Stearns, R.G., Wilson, C.W. Jr., Tiedmemann, H.A., Wilcox, J.T. and Marsh, P.S., 1968, The Wells Creek structure, Tennessee: *in* French B. and Short, N., eds., Proceedings of the first conference on shock metamorphism of natural materials, NASA Goddard Space Flight Center: Baltimore, Mono Book Corporation, p. 323-338.

Thompson, S.C., 1984, Depositional environments and history of the Winnipeg Group (Ordovician), Williston Basin, North Dakota: Grand Forks, University of North Dakota, M.S. thesis, 210 p.

Williams, G.E., 1986, The Acraman impact structure: source of ejecta in Late Precambrian shales, south Australia: Science, v. 233, p. 200-203.

Wood, C.A., 1973, Moon: central peak heights and crater origins: Icarus, v. 20, p. 503-506.