for Yearbook

THE LAST CRUISE OF THE R.V. CONRAD - A MULTICHANNEL SEISMIC EXPERIMENT IN THE HUDSON RIVER

by

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In early April 1989, the R.V. CONRAD made her last scientific cruise, successfully completing the first multichannel reflection profile ever attempted in the Hudson River. The acquisition of this profile was the first phase of a two year NSF supported project that is designed to probe the deep structure of the Appalachian Orogenic Belt. The profile extends from the open ocean, just beyond the mouth of the river, to Albany, crossing most of the major geological structures of the eastern seaboard and the Applalchian mountain system. The seismic experiment also included deployment of portable seismic recording instruments along the bank of the Hudson River near Newburgh. These instruments recorded the seismic signals generated by the ship in the river, providing additional information on the crustal structure.

Over the next two years, the reflection data and the portable array data will be processed and interpreted by members of the geology, seismology and multichannel groups. We expect that the results will shed new light on the geological evolution of Appalachian mountain belt and also will have an important role in developing multichannel seismic profiling in rivers as a new tool for imaging the deep structure of continental lithosphere.

SCIENTIFIC OBJECTIVES OF THE EXPERIMENT

Imaging The Deeply Buried, Pre-Atlantic Continental Margin

One of the large-scale crustal structures that we hoped to image seismically is a pre-Atlantic passive continental margin that formed between 600 and 450 million years ago. This margin, called the Iapetus margin, contains rocks and rifted structures much like those observed along the margins of the modern Atlantic ocean. Some of these rocks and structures can be observed today along the Hudson River between Newburgh (location E, Fig. 2) and Ramapo (location D, Fig. 2). Most of this ancient margin, however, lies deeply buried by younger rocks and, consequently, its precise location and its evolution are poorly understood.

One of the objectives of the experiment was "see" the rocks and structures of this pre-Atlantic margin in the deep subsurface and learn more about its size, origin and the degree to which it was involved in subsequent phases of the evolution of eastern North America. It is possible that fragments of the ancient margin will be seismically imaged at deep levels along most of the river profile, but the best data probably will be obtained in the upper portion north of location D (Fig. 2).

Probing The Deep Structure Of Accreted Terranes In The Appalachian Mountain System

Between about 450 and 200 million years ago, complex motions of the earth's lithospheric plates resulted in a protracted history of collisions between the ancient Iapetus margin and fragments of oceanic islands and continental masses. This long convergent history culminated in a major collision between North America and Africa. The collisions destroyed the ancient Iapetus margin and formed large, west-directed folds and thrust faults. Classical exposures of these structures occur along the profile. Some of the largest faults mark the boundary between North America and slices of exotic continental materials that may have travelled thousands of kilometers before colliding with the Iapetus margin. The profile crossed one of these major boundaries or sutures that lies along Cameron's Line (location C, Fig. 2). This boundary separates North American continental rocks on the north side from the Dunnage Terrane to the south. The Dunnage Terrane thought to be composed of slices of volcanic islands and oceanic rocks that were swept aganist the Iapetus margin during the Taconic Orogeny over 400 million years ago.

While the structures formed by these collisional events are reasonably well known at the surface, their geometry at deeper crustal levels remains elusive, not only in this mountain belt but in most mountain systems of the world. This lack of knowledge at deep crustal levels is a major obstacle to understanding how collisional processes work, how large masses of rock are transported tens or even hundreds of kilometers horizontally and how the continental lithosphere bends in response to the great weight of overthrust crustal material. Moreover, the nature of boundaries at depth between the exotic terranes and North America is especially crucial in understanding how large crustal masses are accreted to continents and the role this process plays in continental growth. The profile crossed the collisional structures of the Appalachian system along nearly its entire length, including the classic Taconic thrust front (between locations A and E, Fig. 2), thereby potentially providing a wealth of new subsurface information that can address these problems within some of the best known structural complexes of the Appalachians.

A highly generalized cross-section of the southeastern United States (Fig. 3) exemplifies the spatial relation of the rocks and structures that formed during the three major phases of deformation in eastern North America described in the preceding sections. Although this cross-section portrays the sub-surface geology well to the south of our profile, it is representative of the predicted deep crustal structures along the Hudson River that are the targets of the seismic experiment.

Tracing The Structures Of The Modern Atlantic Margin Into The Deep Crust

Between about 200 and 170 million years ago, the eastern seaboard of the United States underwent a new phase of deformation consisting of multiple episodes of lithospheric extension and rifting. This phase of deformation was superimposed on the pre-existing structures, possibly reactivating many of them. The new structural regime produced crustal-scale normal faults and deep sedimentary basins, such as the Newark Basin (Fig. 2), some of which are major exploration objectives for oil and gas. This period of deformation terminated in rupture of the entire continental lithosphere, resulting in the separation of North America from Africa and initiation of a new ocean, the modern Atlantic Ocean.

From the Ramapo Fault (location D, Fig. 1) to south of Long Island, the seismic profile crossed some of the classic rift structures that formed during this last phase of major structural deformation in eastern North America. The results from this segment of the profile will address unresolved questions about the geometry of crustal-scale rift structures at depth. A major issue is whether the fault planes become horizontal detachments at deep crustal levels (5 to 10 kilometers), an issue that is crucial to understanding the depth and thermal history of potential hydrocarbon source beds as well as the rifting process itself.

Understanding The Cause of Seismicity In the Hudson River Valley

Although the major phases of deformation of the eastern seaboard ceased over 100 million years ago, minor, yet significant structural events have occurred in recent times. These events consist of faulting and earthquakes which tend to be concentrated in narrow zones roughly parallel to major structures of the Appalachian mountain system and continental margin. Some of the earthquakes have been relatively large, registering > 4 on the Richter scale. The seismic hazards resulting from present-day deformation in the eastern United States is not insignificant. In the western United States much of the seismicity is clearly related to movement along lithospheric plate boundaries and can be interpreted and predicted to some degree in terms of plate tectonic theories. In marked contrast, the east coast seismicity occurs entirely within the North American plate, and plate tectonic theories provide no simple basis for predicting the locations and magnitudes of seismic hazards in some of the most populated areas of the United States.

The profile crossed distinct zones of seismicity that have been identified in the New York-New Jersey area by the Lamont seismic network

(Fig. 4). A hypothesis proposed recently for the east coast seismicity implies that the earthquakes result from reactivation of faults that formed much earlier during the major phases of extensional and compressional deformation in eastern North America. Subsurface data that was gathered by the profiling potentially will help test this hypothesis if faults can be imaged within the zones of seismicity, hopefully establishing the distribution of faults at depth in relation to the pattern of seismicity and determining if there has been recent movement along them.

THE CRUISE NARRATIVE

Data acquisition for the Hudson River MCS profiling project represented a technical challenge of considerable magnitude, since seismic profiling in such a narrow body of shallow water (as little as 30 feet in some places) had never been attempted before. The answers to several important questions were unknown, though educated guesses had encouraged proceeding with the project. Would it be possible to keep the digital hydrophone streamer afloat in fresh water? Would the streamer follow the ship's track around corners, or would it foul itself on the river bank and tear apart? Would it be possible to keep the airguns, which normally tow at about 40 feet, shallow enough for effective firing?

On the 6th of April, 1989, CONRAD left Piermont to begin the first leg of the profile. Word of the experiment had already attracted the attention of the media, and she was carrying a CNN news team comprising a cameraman, sound technician, and reporter David Monsees. Upon reaching the channel, CONRAD proceeded northward while single channel seismic (SCS) gear was readied. North of the Tappan Zee bridge, the CONRAD reversed course, headed south, and SCS recording started soon thereafter. The CNN crew were offloaded near Yonkers, and their film appeared on the air a day or two later. SCS acquisition continued without incident until it was ended in the vicinity of Ambrose. In preparation for the next leg of the profile, the SCS gear was recovered, and deployment of the 96 x 25m channel MCS array began. This took nearly 18 hours. All lead weights were removed, floats and birds installed, and oil injected in order to lighten the streamer as much as possible. Approximately 125 gallons of streamer oil were used, exhausting the supply on board. Norwegian buoys were Attached to the outer 8 airguns on 25' tethers, so-as to constrain towing depth in the river channel.

MCS acquisition began south of Long Island, with 10 airguns firing at 2000 psi, with a 25 sec rep.rate. The tuned airgun array consisted of one each, 350, 385, 420, 466, 500, 540, 585, 640, 700, and 760 cu. in. BOLT 1500-C airguns constituting a total of 5346 cubic inches of compressed air. Despite gale warnings that had previously been posted, the CONRAD proceeded towards NY Harbor in the gloom of a raw, cold night. Luckily, the gale warnings proved unfounded. After passing under the Verrazano Narrows bridge, a container ship inexplicably crossed the streamer about 5:30 in the morning, and severed it at can # 2, chopping off 8 sections and the tail buoy. This occurred despite the fact that the pilots on the two ships were in voice contact at the time, and CONRAD had two chase boats in the vicinity of the tail buoy. A gap of about 7.4 km in MCS coverage resulted, as the system was revived and the damage assessed.

After considering traffic and location, a decision was made to restart the DSS240 system and continue recording data, monitoring the streamer towing depths closely. It soon became apparent that the last 1/3rd of the streamer, which had been towing deep before the collision, was getting even deeper, occasionally touching the bottom. It eventually became necessary to start streamer recovery while moving northward in the vicinity of midtown Manhattan. A few hours later, the streamer was aboard, and CONRAD headed downriver at full speed, picking up C.B.Raleigh, L. Johnson, and two Journal-News reporters on the way. Deployment of a shortened, 64-channel streamer was begun in the vicinity of Ellis Island, as the ship slowly steamed north. All remaining floats were applied to the streamer, and the remaining gallon or two of oil injected. The compass sections were removed, on account of their weight and their tendency to pull apart under excessive towing stress. Finally, the streamer was fully deployed, the gun array was redeployed, and recording began just north of the George Washington Bridge. Unfortunately, modifying and redeploying the streamer caused a gap of about 13km in MCS coverage off of mid-and-uptown Manhattan. Raleigh, Johnson, and the two reporters debarked in the vicinity of Piermont.

CONRAD continued northward, acquiring 64 channel MCS data with 10 airguns, moving through the water at the relatively high speed required to keep the streamer at 20ft towing depth. At nightfall, the ship entered the dredged channel at north Haverstraw, and transited without incident. After passing West Point, the USCG auxiliary at Highland Falls contacted the CONRAD on the behalf of the USMA security office. Apparently, the airgun source array was powerful enough to set off alarms on the military reservation. All went well until the next morning, when a passing tanker crowded CONRAD to the inside of a curve and the tail buoy snagged a channel marker. The buoy broke up, and pulled the plug out of the end of the streamer. The CONRAD was within a mile or two of the point at which the streamer was to be retrieved however, and MCS operations were terminated. The total length of MCS profile acquired, based on the pitlog readings was 357km.

After taking on fresh water, and bidding farewell to Bernie Gallagher and Anne Holmes aboard our faithful chase boat, CONRAD departed Albany, with Walter Sullivan of the New York Times aboard, and deployed the single channel seismic gear once again. The ship was running so far ahead of schedule that SCS profiling was continued beyond the planned termination point at Piermont, extending down to about 79th St, Manhattan and then back up to the north until just before reaching Piermont. A total of about 357km MCS, and 322km of SCS data were acquired, along with 926km of 3.5KHz echo sounder and total track.

The successful collection of 94% of the planned MCS mileage despite the unique and difficult circumstances of RC3005 reflects great credit on the scientific and ship's crew. Every single member did his (or her) utmost to complete the necessary work at all times without complaint. Capt. Peterlin, particularly, worked long and hard hours, adapting his skills to the tasks at hand in a flexible and effective fashion.

A PRELIMINARY LOOK AT THE DATA

Work is now underway on processing the SCS and MCS records. This time-consuming step must be completed before the seismic data can be interpreted geologically, and it probably will require close to a year. A preliminary phase of the processing has been completed, however, and the results provide tantalizing suggestions of what we may learn from the experiment.

The Single and Multichannel Data

The Portable Array Data

Data from the portable array are expected to constrain the velocity structure of the lithosphere along the profile, which is not measured accurately by MCS. The array consisted of twenty three-component, digital seismometers, located on a twenty km long line parallel to the Hudson River, from Newburgh to Kingston (Fig. 2). This is an area of thrust-faulted sediments that includes a north-south oriented exposure of quartzite that forms a high ridge called Marlborough Mountain. The array produced a high-quality recording of the CONRAD'S airguns out to ranges of about 30 km. This range was shorter than was anticipated, and the airgun signal proved too weak to investigate deep crustal and mantle structures, which requires measurements in the 100 km range. Nevertheless, the data from a criss-cross pattern of rays along Marlborough Mountain, and should provide a detailed picture of the geologic structure of this feature. Preliminary velocity analysis indicates that the compressional velocity increases from 5.5 km/s at the surface to about 6.5 km/s at 12 km depth, with an interesting inversion of velocity at about 4 km depth (Fig.)

HUDSON RIVER

The Single and Multichannel Data

The computer processing of the single and multichannel data to make appropriate displays for geological interpretation presents a difficult challenge. The offshore portions represent a more typical working environment, similar to several previous continental shelf studies. Here the sequence of required processing steps is reasonable well established. The profile lines are straight and so for the multichannel portion we can use two-dimensional techniques. In the Hudson River, in contrast, the ship, air guns and streamer are confined to the narrow and shallow channel. The River's cross-sectional shape changes the source pulse character through reverberation in the water column. The steep, hard rock channel walls in the Hudson Highlands around Bear Mountain and West Point contribute additional echoes. Although the Hudson lacks the sinuosity of the Mississippi, for example, the ship's track is not straight and so the multichannel data will require a more complicated three-dimensional analysis.

We are only at the beginning stages of processing, but some of the anticipated data difficulties such as reverberation are already apparent. We will need to experiment with various techniques before we generate final profile sections.

An example of a portion of the single channel watergun data is shown in Figure 5.

FIGURE CAPTIONS

Figure 1 - ship

Figure 2 - Generalized map of the Hudson River and adjacent offshore area. Heavy line shows the profile. Ancient crystalline basement of North America shown by random dash pattern. Rift basins formed during rifting of modern Atlantic Ocean are stippled. A = Albany; B = New York Bight basin in offshore subsurface; C = New York City; D = Ramapo Fault and seismic zone at Indian Point Nuclear Reactor; E = Newburgh; F = Gander/Avalon terrane boundary inferred from areomagnetic data; G = Cameron's line at seismic zone in New York City area; H = Kingston.

Figure 3 - Schematic representation of the collage of structures that have formed during the evolution of the Atlantic continental margin and Appalachian mountain belt. This cross-section is based on the central Appalachians in Virginia and Tennessee, but is representative of the general section in the New Jersey-New York area as well. The youngest rift structures that formed during rifting of the modern Atlantic margin 200 to 170 million years ago occur in the Augusta thrust sheet; below this lies the overthrust complexes resulting from Taconic and younger collisional events between 200 and 450 million years ago. Below these thrusts lies the intact remnants of the Iapetus passive margin that formed between 600 and 450 million years ago. Below this, the unpatterned part of the section is the Grenville crystalline basement with diagrammatic fault blocks that formed during the rifting of the Iapetus margin. The upward step in M (Moho) is the inferred position of crustal thinning of the ancient Iapetus margin. The crustal thinning associated with the younger, modern Atlantic margin lies out of the section to the right.

Figure 4 - Map of the distribution of earthquakes in the greater New York City area between 1734 and 1983. The earthquakes tend to be

concentrated in two belts , one along Cameron's Line and the other along and north of the Ramapo Fault. Both belts appear to be related to major structures that formed during the evolution of the eastern seaboard. The HUDRISE line will cross both belts.route

Figure 5 - SCS and MCS records

Figure 6. Record section for a shot south of the portable array that was placed along the Hudson River on Marlborough Ridge near Newburgh. Note that the first arriving compressional wave is shadowed at about 18 km distance, indicating a low velocity zone at a shallow level (2 to 4 km) in the crust.

Figure 5 - A portion of the single channel data near Lamont-Doherty. Deconvolution and a band-pass filter have removed much of the water column reverberation present on the field data. This record shows variable Recent channel fill as thick as 100 meters. The vertical scale will change appreciably after correction for the non-vertical path from source to receiver.

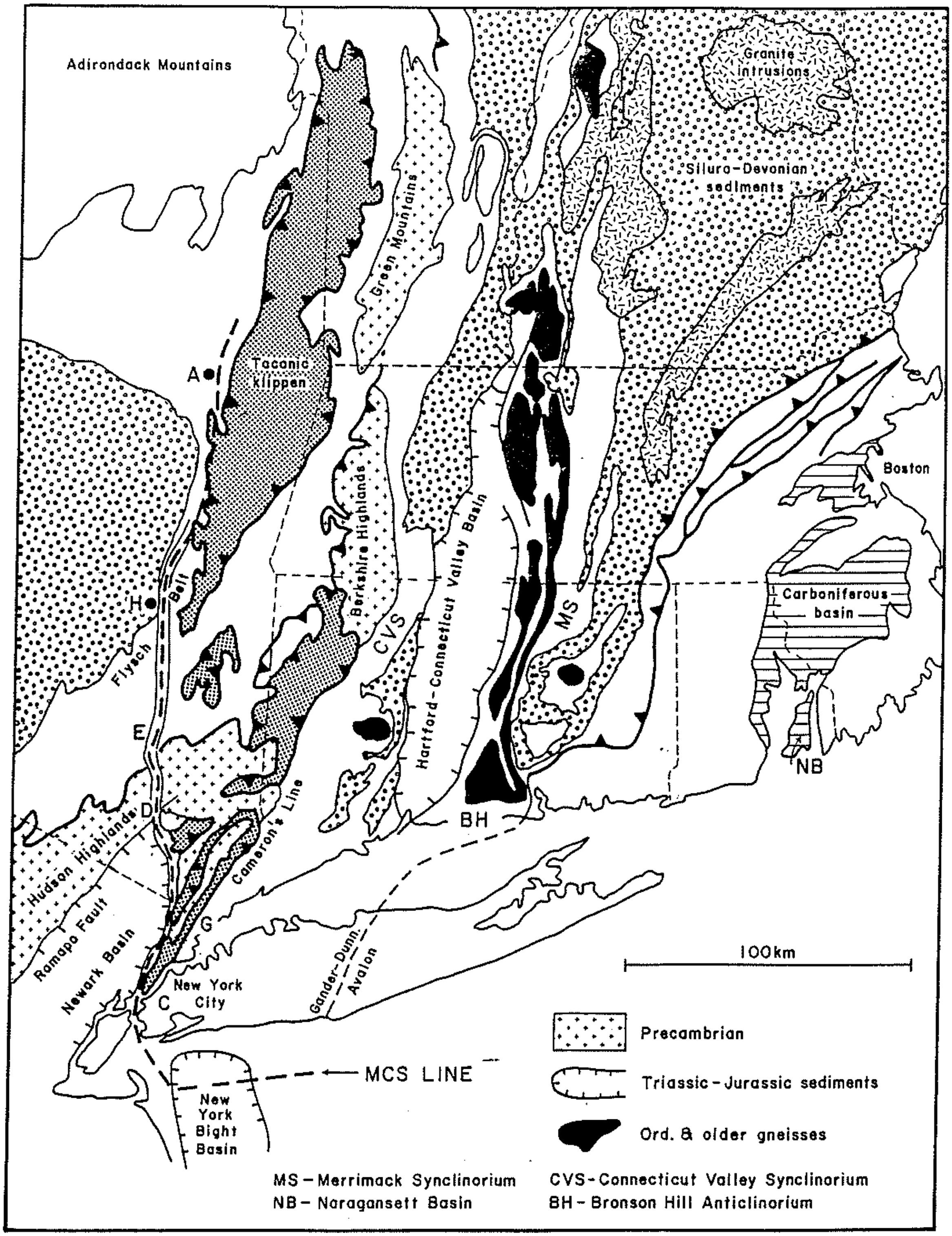


Figure 1. Generalized map of the Hudson River and adjacent offhosre. Heavy dashed line shows the proposed MSC line. Grenville basement massifs are shown by random dash pattern. Mesozoic rift basins are stippled. A = Albany; C = New York City; D = Ramapo Fault; E = Newburgh; G = Cameron's Line (western boundary of the Taconic suture zone and eastern limit of undisputably North American rocks) at seismic line in New York City area; H = Kingston.

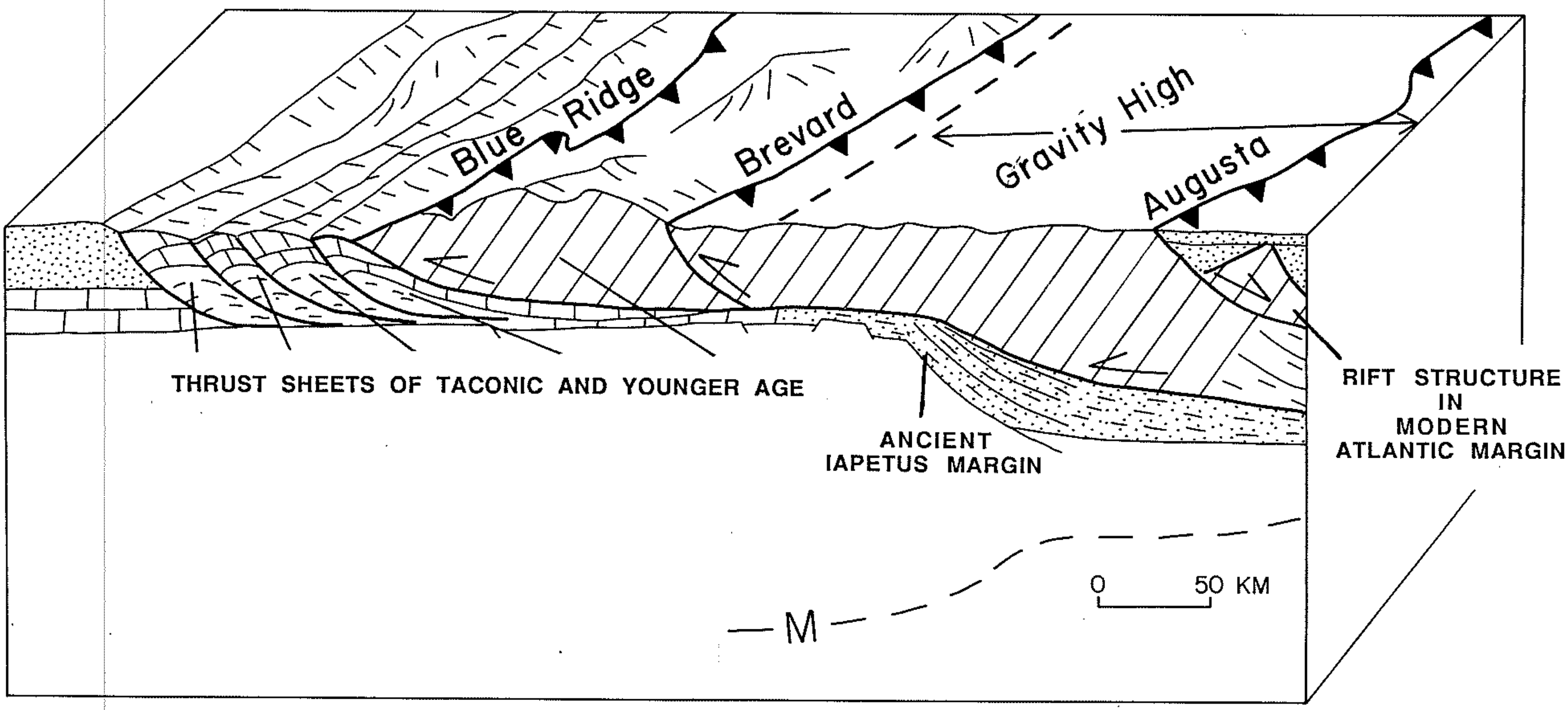


FIGURE 2 Schematic representation of the collage of structures that have formed during the evolution of the Atlantic continental margin and Appalachian mountain belt. This cross-section is based on the central Appalachians in Virginia and Tennessee, but is representative of the general section in the New Jersey-New York area as well. The youngest rift structures that formed during rifting of the modern Atlantic margin 200 to 170 million years ago occur in the Augusta thrust sheet; below this lies the overthrust complexes resulting from Taconic and younger collisional events between 200 and 450 million years ago. Below these thrusts lies the intact remnants of the Iapetus passive margin that formed between 600 and 450 million years ago. Below this, the unpatterned part of the section is the Grenville crystalline basement with diagrammatic fault blocks that formed during the rifting of the Iapetus margin. The upward step in M (Moho) is the inferred position of crustal thinning of the ancient Iapetus margin. The crustal thinning associated with the younger, modern Atlantic margin lies out of the section to the right.

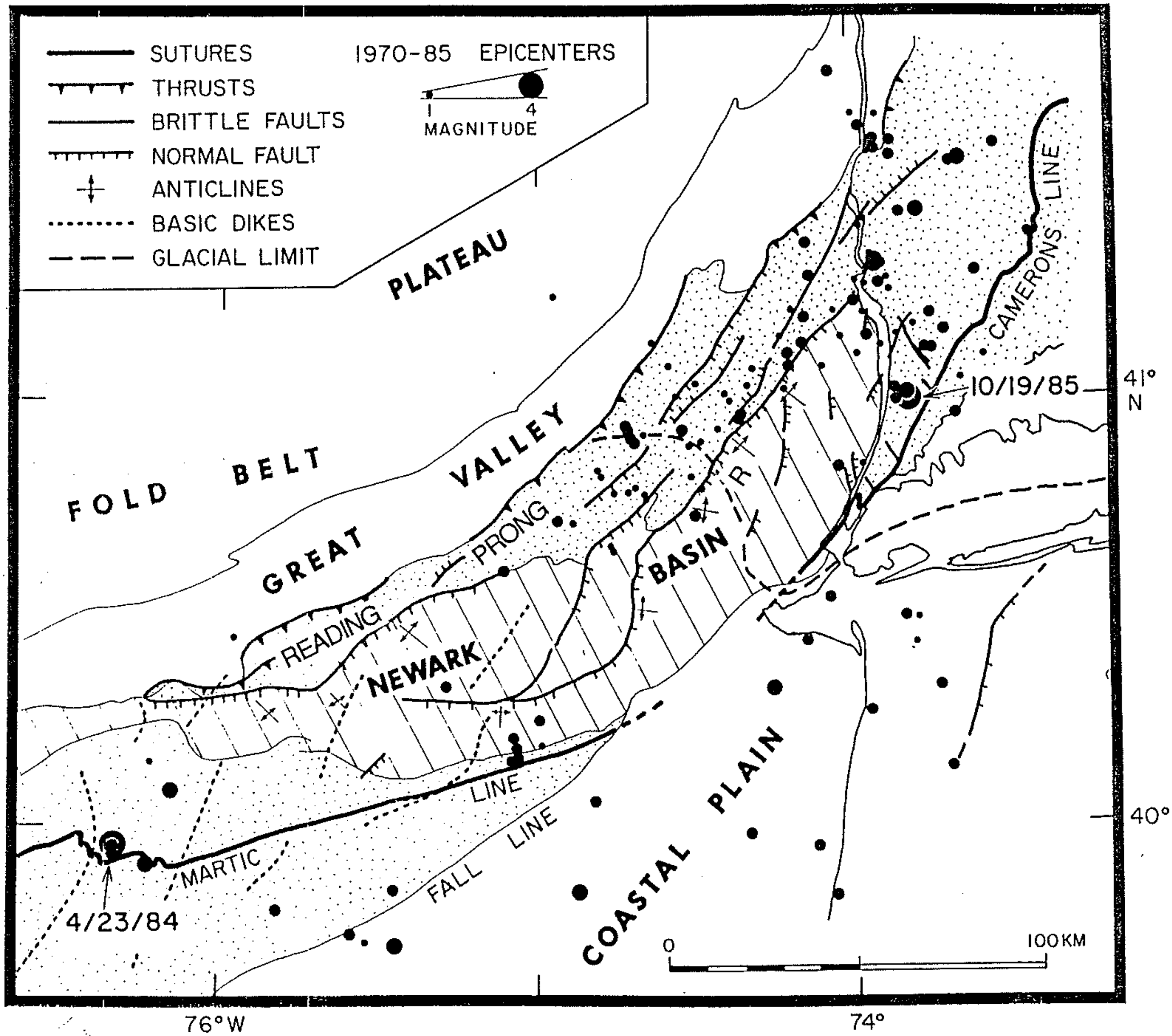
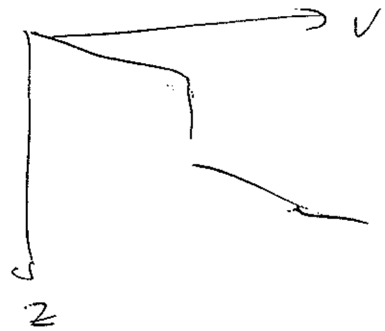


Figure 9a. Seismicity detected by the regional network during the last decade superimposed on structural features associated with the Newark Mesozoic Basin. Seismicity is concentrated in crystalline rocks adjacent to the basin (stippled area) and with the Ramapo fault (R F), the western border fault along the northern part of the basin. But, the basin itself and the subsurface extension of the Ramapo fault below the basin are prominently inactive. The most prominent brittle faults strike northeast, parallel to Appalachian trends. A set of antithetic north to northwest striking faults can also be recognized. Members of this set were the sources of the two most prominent earthquakes in these data (10/19/85, Mb=4.0; 4/23/84, Mb=4.0).



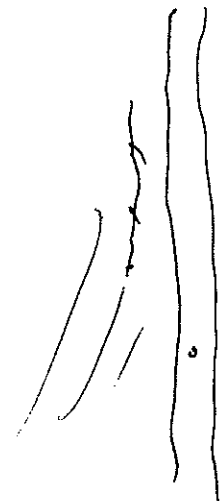
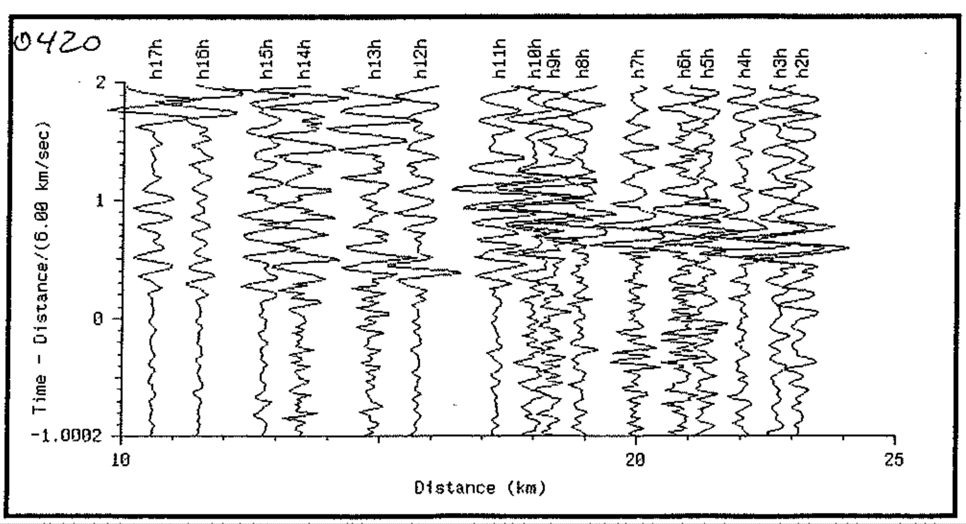


Fig. 6



Screendump in progress ...