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The Southern Extension and Reactivations of the Clarendon-Linden Fault System
Le prolongement vers le sud du réseau de failles de Clarendon-Linden et sa réactivation
Die südliche Ausdehnung des Verwerfungssystems von Clarendon-Linden und seine Reaktivier-ungen

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Résumé de l'article

Des dégagements gazeux survenus près de Pike (État de New York), à l'emplacement supposé de la faille centrale du réseau de Clarendon-Linden (RCL), se sont produits pendant ou aussitôt après le séisme de 1988, au Saguenay. Les analyses du gaz démontrent que les fuites proviennent d'une source de shale dévonien aussi profonde que 330 m. Les fractures du RCL, atteignant plus de 300 m de profondeur, se sont vraisemblablement ouvertes en réponse au séisme du Saguenay, permettant ainsi au gaz de se dégager. Les données publiées montrent que le RCL s'étend du lac Ontario jusqu'au sud de Pike, mais on n'a pu déterminer jusqu'à maintenant si le réseau se poursuit plus au sud. Les levés sur la détection de gaz dans le sol et les analyses de données des puits indiquent que le RCL se poursuit dans le comté d'Allegany, qui borde la Pennsylvanie. À partir d'indices tirés de puits très rapprochés, on croit que la faille centrale du réseau consiste probablement en une série de failles en gradin, même dans les unités au-dessus de la section d'évaporite du Silurien, bien qu'un monoclinal ne puisse être rejeté. La géométrie de la croissance des failles montre que le RCL s'est déplacé au cours des orogénies laconique et acadienne. Les cartes d'isopaques, ainsi que la trajectoire présumée vers le sud du RCL, indique le RCL a enregistré le passage de l'axe de l'avant-bassin appalachien au cours du Dévonien supérieur.

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THE SOUTHERN EXTENSION AND REACTIVATIONS OF THE CLARENDON-LINDEN FAULT SYSTEM

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ABSTRACT Gas seeps located near Pike, New York, on the inferred location of the central fault of the Clarendon-Linden Fault System (CLF), were initiated during, or slightly after, the Saguenay earthquake, 1988. Analyses of the gas show that the gas seeps have a Devonian shale source, and a nearby well suggests that the source may be as deep as 330 m. Thus, CLF fractures extending to depths possibly as great as 300+ m were probably opened as a local response to the Saguenay event, allowing the gas to be vented. Published data show that the CLF extends from Lake Ontario to slightly south of Pike. Previously, there were insufficient data available to enable investigators to determine if the fault system continued farther south. Our soil gas survey and analyses of well logs indicate the CLF continues south into Allegany County, which borders the state of Pennsylvania. Closely-spaced wells suggest that the central fault of the CLF is probably a series of step faults, even in units above the Silurian evaporite section, although a monocline cannot be ruled out. Growth-fault geometries of the CLF suggest that the CLF experienced motion during the Taconic and Acadian orogenies. Isopach maps, coupled with the proposed southward extrapolation of the CLF, suggest that in Late Devonian times the CLF motion history recorded the passage of the Appalachian foreland basin axis across the CLF.

RÉSUMÉ *Le prolongement vers le sud du réseau de failles de Clarendon-Linden et sa réactivation.* Des dégagements gazeux survenus près de Pike (État de New York), à l'emplacement supposé de la faille centrale du réseau de Clarendon-Linden (RCL), se sont produits pendant ou aussitôt après le séisme de 1988, au Saguenay. Les analyses du gaz démontrent que les fuites proviennent d'une source de shale dévonien aussi profonde que 330 m. Les fractures du RCL, atteignant plus de 300 m de profondeur, se sont vraisemblablement ouvertes en réponse au séisme du Saguenay, permettant ainsi au gaz de se dégager. Les données publiées montrent que le RCL s'étend du lac Ontario jusqu'au sud de Pike, mais on n'a pu déterminer jusqu'à maintenant si le réseau se poursuit plus au sud. Les levés sur la détection de gaz dans le sol et les analyses de données des puits indiquent que le RCL se poursuit dans le comté d'Allegany, qui borde la Pennsylvanie. À partir d'indices tirés de puits très rapprochés, on croit que la faille centrale du réseau consiste probablement en une série de failles en gradin, même dans les unités au-dessus de la section d'évaporite du Silurien, bien qu'un monoclinal ne puisse être rejeté. La géométrie de la croissance des failles montre que le RCL s'est déplacé au cours des orogénies taconique et acadienne. Les cartes d'isopaques, ainsi que la trajectoire présumée vers le sud du RCL, indique le RCL a enregistré le passage de l'axe de l'avant-bassin appalachien au cours du Dévonien supérieur.

ZUSAMMENFASSUNG *Die südliche Ausdehnung des Verwerfungssystems von Clarendon-Linden und seine Reaktivierungen.* Das Entweichen von Gas in der Nähe von Pike, New York, an der Stelle, die man für den zentralen Bruch des Clarendon-Linden Verwerfungssystems hält (CLV), hat 1988, während oder kurz nach dem Erdbeben von Saguenay begonnen. Analysen des Gases zeigen, daß das entwichene Gas aus einer Tonschieferquelle des Devon stammt, und ein nahegelegener Brunnen läßt vermuten, daß die Quelle 330 m tief sein könnte. So haben sich wohl CLV-Brüche, die möglicherweise bis zu 300+ m tief sind, als lokale Reaktion auf das Saguenay-Ereignis geöffnet und haben so das Gas freigelassen. Die veröffentlichten Daten zeigen, daß das CLV sich vom Ontario-See bis etwas südlich von Pike ausdehnt. Zuvor waren nicht genügend Daten verfügbar, mit denen die Forscher bestimmen konnten, ob das Verwerfungssystem sich weiter südlich ausdehnte. Aus Erhebungen über Erdgas und Untersuchungen von Angaben aus Brunnen ergibt sich, daß das CLV sich bis in die Grafschaft Allegany fortsetzt, die an Pennsylvanien grenzt. Dicht aufeinan-derfolgende Brunnen lassen darauf schließen, daß der zentrale Bruch des CLV wahrscheinlich aus einer Serie von abgestuften Verwerfungen besteht, selbst in Einheiten oberhalb des Evaporationsabschnittes aus dem Silur, wenn auch ein Monoklinal nicht ausgeschlossen werden kann. Die Wachstumsgeometrie der Brüche des CLV legt nahe, daß das CLV sich während der takonischen und akadischen Orogenese bewegt hat. Isopach-Karten sowie die mutmaßliche Südwartsbewegung des CLV zeigen, daß die Bewegungsgeschichte des CLV im späten Devon den Durchzug der Appalachen-Vorlandbeckenachse durch das CLV aufgezeichent hat.

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INTRODUCTION

During, or immediately after, the Saguenay earthquake of 1988, vigorous gas seeps were initiated about 800 km southwest of the epicenter, near Pike, New York (Fig. 1). These seeps appeared to be located near the Clarendon-Linden Fault System (CLF), which stretches from Lake Ontario south to near Pike, where the CLF is terminated on previously published maps because of a lack of data (Figs. 1-3).

The CLF has been called the "longest (?) and oldest (?) active fault system in eastern United States" (Fakundiny *et al.*, 1978a). However, very little is known about the location, southern extent and number of component faults of the system. There is also uncertainty about the cumulative displacement and Phanerozoic movement history along the CLF, the expression of the CLF above the Silurian evaporites and which of the component faults are seismically active.

This paper provides a review of published information on the CLF and presents the results of work undertaken in southern Wyoming and northern Allegany Counties, New York State. Included among the results are: 1) gas seeps tapping "deep" Devonian gas were initiated along the CLF during, or shortly after, the 1988 Saguenay earthquake; 2) the CLF extends farther south than previously known; and 3) each time the continental plate was under relatively high stress, the CLF was reactivated as documented by the existing sedimentary record.

PREVIOUS STUDIES OF THE CLARENDON-LINDEN FAULT SYSTEM

SEISMICITY

The CLF has been the site of both historic and recent seismic activity (Fig. 3; Smith, 1966; Pomeroy and Fakundiny, 1976; Fletcher and Sykes, 1977) including the second largest earthquake in New York State. That earthquake, which occurred in 1929, toppled chimneys in Attica and was assigned a Modified Mercalli Intensity of VIII with a $m_b = \sim 5.2$ (Street and Turcotte, 1977). The imprecise location and felt area of the earthquake has allowed several interpretations to be made of the causative fault, including the SW-trending "Attica" splay of the CLF (R.H. Fakundiny, pers. comm.), a NW-trending fault initially recognized by Van Tyne (1975) that intersects the CLF in the Attica area (Pearce, 1990), and the main faults of the CLF (*e.g.*, McWhorter *et al.*, 1986). A search of historical accounts by Tuttle (1992) revealed that an aftershock of the 1929 Attica earthquake occurred east of Attica near a rupture associated with the mainshock, and near the western fault of the CLF. These data suggest that the 1929 Attica earthquake occurred on the main faults of the CLF (Tuttle, in prep). Since the Attica earthquake, numerous smaller seismic events with magnitudes ranging from 2.7 to 4.7 have occurred in the Attica area, including events in 1955, 1966, 1967, 1968, 1971 and 1973 (Fig. 3, Fletcher and Sykes, 1977). Hypocentral depths and fault plane solutions for the 1966 and 1967 events (Hermann, 1978) show that they occurred at focal depths of 2 and 3 km, respectively, and both have NNE and WNW nodal planes. The NNE trend is consistent with the main faults of the CLF, as determined by Van Tyne (1975).

Induced seismic activity occurred in 1970 when the Texas Brine Corporation began high pressure injection for hydraulic mining of salt at Dale, New York (Fig. 3). Coincident with this injection was a dramatic increase of seismic events, from about 1 event per month to as many as 80 per day (Fletcher and Sykes, 1977). When the injection ceased, so did the seismic activity. The base of the injection well was located only about 50 m from the central fault of the CLF. The timing of seismic activity and the location of the injection well suggest that the injected fluids lubricated the central fault of the CLF. Since that time smaller episodes of seismic activity have been recorded at Dale, such as those in 1974 and 1975. Fault-plane solutions for those events show roughly east-west thrusting with the strike and dip of one of the nodal planes consistent with that of the CLF main faults (Fletcher and Sykes, 1977; Van Tyne, 1975).

More recently, the November 25, 1988, $m_b = 6.5$ Saguenay earthquake in Québec (*e.g.*, Basham and Adams, 1989; Friberg *et al.*, 1989) apparently reopened CLF fractures north of Allegany County. Shortly after the Saguenay earthquake several vigourous gas seeps were initiated near Pike. The timing of their formation, and their location along the inferred trand of the CLF, suggest that seismic waves from the Saguenay earthquake may have reactivated CLF fractures (Jacobi and Fountain, 1989). In Allegany County there has been no known seismic activity in historic times along the CLF; rather, all known activity appears to have been restricted to the area north of about Warsaw (Fig. 3, *e.g.*, Fakundiny *et al.*, 1978b).

SURFACE GEOLOGY

The CLF was first recognized by Chadwick (1920), who postulated its probable existence from the generalized outcrop patterns of various units between Clarendon and Linden, New York (Figs. 2 and 3). Near Clarendon, the map pattern of the Silurian Lockport Formation (which forms the caprock of the Niagara Escarpment) exhibits a prominent bend or "dogleg"; farther south near Batavia, the map pattern of the Middle Devonian Onondaga Limestone (which forms the caprock of the Onondaga Escarpment) displays a similar dogleg. Still farther south near Linden, the Upper Devonian units in the interval from the Genundewa Limestone to Nunda Sandstone (Figs. 4 and 5) are apparently offset across a north-south valley. Chadwick (1920) postulated that not less than a 30 m offset (down-on-the-west) was required along a generally north-striking fault to generate these outcrop patterns and stratigraphic offsets.

Later field work by Chadwick (1932) led him to suggest that the "fault" is actually a monocline in the Upper Devonian shales near Linden, whereas farther north, the CLF is indeed a fault affecting units below the Silurian evaporites. Studies in the Batavia quadrangle by Sutton (1951) and by Pepper *et al.* (1975) supported the Chadwick hypothesis that the vertical displacement along the CLF was accommodated by folding in units above the Silurian shale and evaporites.

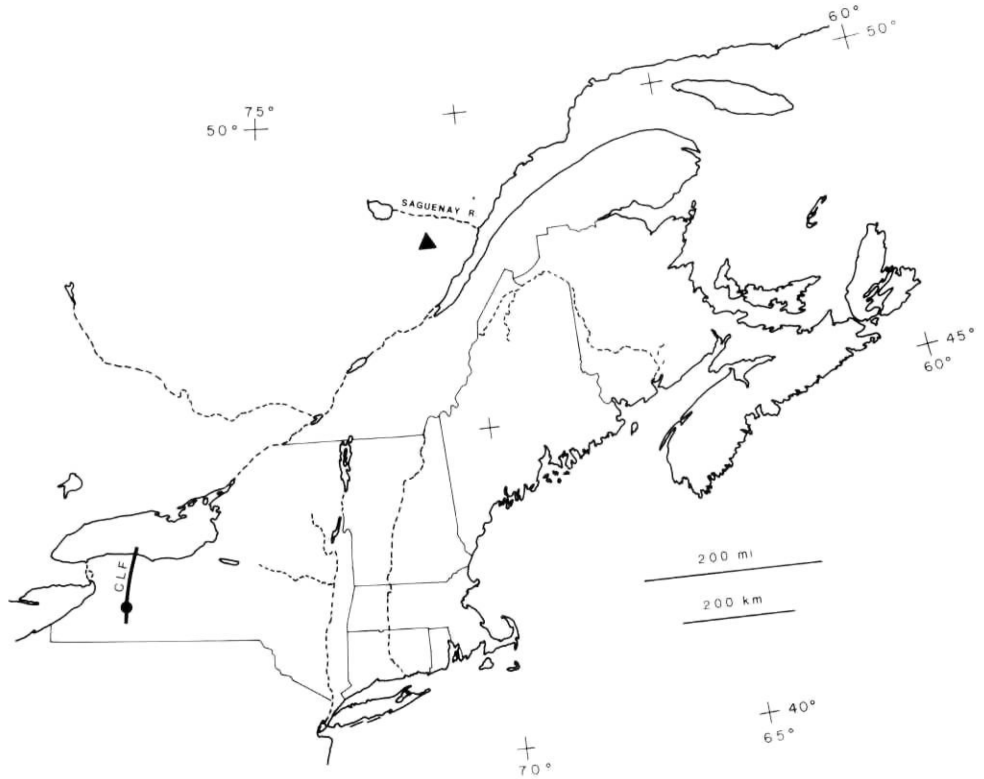


FIGURE 1. Northeastern USA and southeastern Canada. Solid triangle denotes location of the 1988 Saguenay earthquake; solid dot in New York State indicates location of the Pike gas seep; solid line labeled CLF indicated location of the Clarendon-Linden Fault System.

Nord-est des États-Unis et sud-est du Canada. Le triangle situe la source du séisme de 1988, au Saguenay; le point noir donne la localisatiom du dégagement de gaz, à Pike, dans l'État de New York; le trait noir identifie le réseau de failles de Clarendon-Linden (CFL).

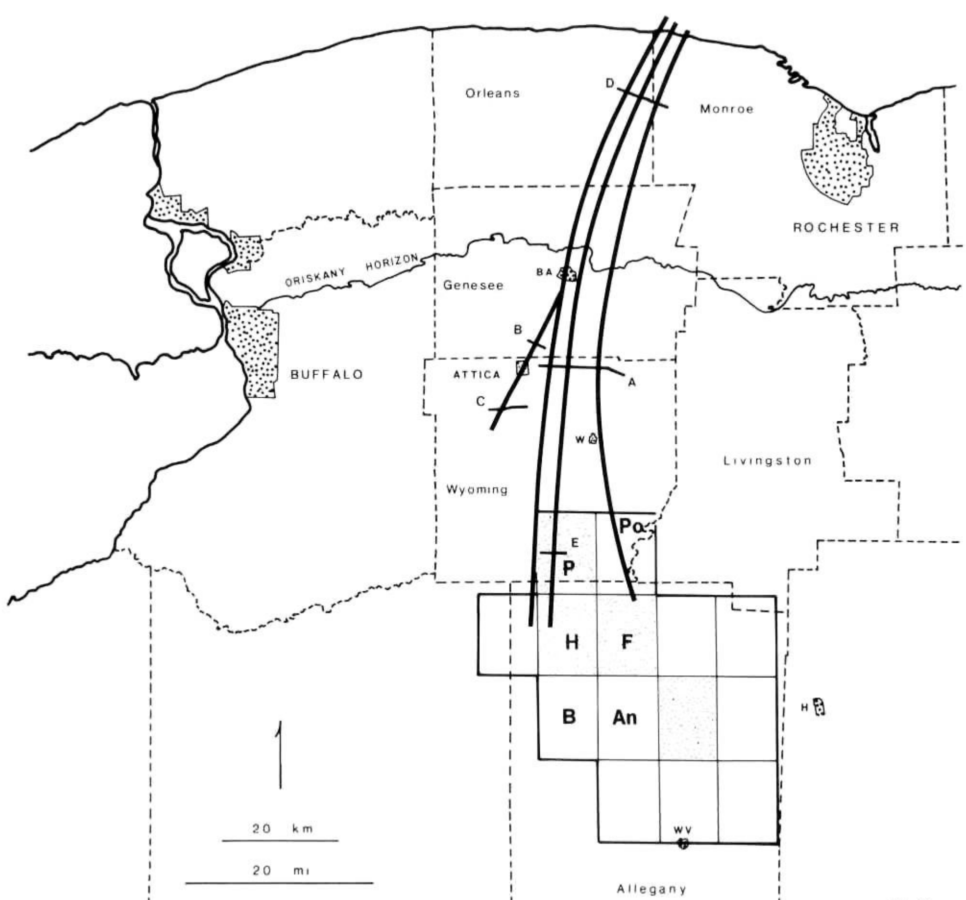


FIGURE 2. Main faults of the CLF (Van Tyne, 1975). Labeled bars across the faults (A-E) indicate locations of NYS seismic lines (Fakundiny *et al.*, 1978b). The 14-box area denotes the 7 1/2′ quadrangles in which well-log analyses were conducted: An = Angelica quadrangle, B = Black Creek quadrangle, F = Fillmore quadrangle, H = Houghton quadrangle, P = Pike quadrangle, Po = Portageville quadrangle. Stippled 7 1/2′ quadrangles indicates region in which the soil gas survey was undertaken. The Pike gas seep is located immediately northeast of the intersection of seismic line E with the fault. BA = Batavia, H = Hornell, W = Warsaw, and WV = Wellsville. Figure after Fakundiny *et al.* (1978b).

Principales failles du réseau Clarendon-Linden (RCL) (Van Tyne, 1975). Les traits transversaux au réseau (A-E) localisent les lignes sismiques dans l'État de New York (Fakundiny et al., 1978a). Les 14 quadrilatères identifient les sites où ont été menées les analyses des puits: An = Angelica, B = Black Creek, F = Fillmore, H = Houghton, P = Pike, Po = Portageville. Le dégagement de gaz a eu lieu à Pike, situé immédiatement au nord-est de l'intersection de la ligne sismique E et de la faille. BA = Batavia, H = Hornell, W = Warsaw, WV = Wellsville. Figure selon Fakundiny et al. *(1978b).*

The most complete study of the northern segment of the CLF was performed by Fakundiny *et al.* (1978a, b). Part of their research was focused on documenting faults observed in bedrock and glacial sediments, however they could not unequivocally relate any of the faults to the CLF. They also measured over 6,000 joint orientations in 47 topographic quadrangles in the vicinity of the CLF, and found the joints to be predominantly NW and NE. Similar joint orientations have been reported in more recent studies of joints in New York State (*e.g.*, Engelder, 1979, 1982, 1985; Gross and Engelder, 1991) and the adjacent Niagara Peninsula, Ontario (*e.g.* Sanford *et al.*, 1985; Williams *et al.*, 1985). Fakundiny *et al.* (1978b) stated that they did not find "an easily understood relationship between joint rose diagrams and the geometry of the Clarendon-Linden fault system". However, Gross and Engelder (1991) showed that in a quarry at Clarendon, close to the main faults of the CLF, the dominant joint orientation is NNE, which is parallel to the assumed trace of the CLF. Similarly, ongoing structural studies in Allegany County show a highly variable density of N-S fractures, the spatial variation presumably related to distance from CLF faults (Zhao and Jacobi, 1993).

Fakundiny *et al.* (1978b) also investigated 87 pop-ups in 63 quadrangles in western New York, including the CLF region. A few of these pop-ups are located along, and parallel to, the CLF. In all phases of the aforementioned studies, the underlying assumption was that only those features that

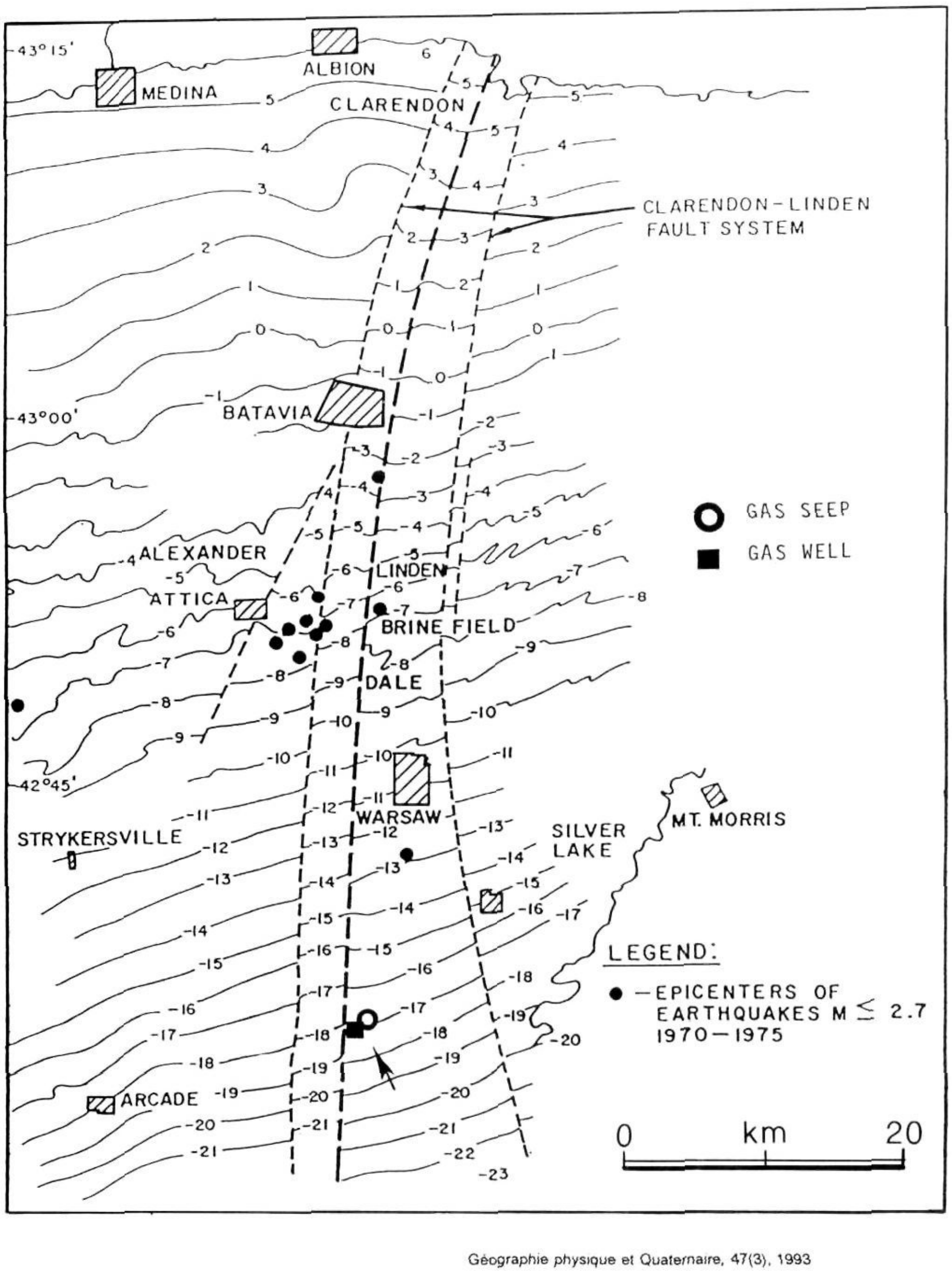


FIGURE 3. Structure contour map of the Medina Formation displaying the CLF. Contours are in hundreds of feet; datum is mean sea level. "Gas seep" indicated by an arrow is the Pike seep that commenced flow during, or immediately after, the Saguenay earthquake. Earthquake epicenters are exclusive of the Dale brine field events. Map after Fletcher and Sykes (1977); faults and contours from Van Tyne (1975).

Courbes de niveau structurales de la Formation de Medina montrant le RCL (courbes en centaines de pieds à partir du niveau moyen de la mer). Le cercle situe le dégagement de gaz de Pike, survenu pendant ou immédiatement après le séisme du Saguenay. Les épicentres ne comprennent pas les séismes survenus à Dale. Carte de Fletcher et Sykes (1977); failles et courbes de niveau de Van Tyne (1975).

SYSTEM	SERIES	GROUP	UNIT	LITHOLOGY	THICKNESS (ft)
Penn.		Pottsville	Olean	Ss, Cgl	75-100
Miss.		Pocono	Knapp	Ss, Cgl	50-100
Devonian	Upper	Conewango		Sh, Ss, Cgl	700
		Conneaut	Chadakoin	Sh, Ss	700
		Canadaway	Undiff.	Sh, Ss	1100-1400
			Perrysburg	Sh, Ss	
		West Falls	Java	Sh,Ss	375-1250
			Nunda	Sh, Ss	
			Rhinestreet	Sh, Ss	
		Sonyea	Middlesex	Sh	0-400
		Genesee		Sh	0-450
	Middle		Tully	Ls	0-50
		Hamilton	Moscow	Sh	200-600
			Ludlowville	Sh	
			Skaneateles	Sh	
			Marcellus	Sh	
			Onondaga	Ls	30-235
	Lower	Tristates	Oriskany	Ss	0-40
		Helderberg	Manlius	Ls	0-10
			Rondout	Dol	
Silurian	Upper		Akron	Dol	0-15
		Salina	Camillus	Sh, Gyp	450-1850
			Syracuse	Dol, Sh, Salt	
			Vernon	Sh, Salt	
		Lockport	Lockport	Dol	150-250
		Clinton	Rochester	Sh	125
			Irondequoit	Ls	
	Lower		Sodus	Sh	75
			Reynales	Ls	
			Thorold	Ss	2-8
		Medina	Grimsby	Sh, Ss	75-160
			Whirlpool	Ss	0-25
Ordovician	Upper		Queenston	Sh	1100-1500
			Oswego	Ss	
			Lorraine	Sh	900-1000
			Utica	Sh	
	Middle	Trenton-Black River	Trenton	Ls	425-625
			Black River	Ls	225-550
	Lower	Beekmantown	Tribes Hill/Chuctanunda	Ls	0-550
Cambrian	Upper		Little Falls	Dol	0-350
			Galway (Theresa)	Dol, Ss	575-1350
			Potsdam	Ss, Dol	75-500
Precambrian				Meta. Rx.	

FIGURE 4. Generalized Paleozoic stratigraphic section for southwestern New York (Van Tyne and Foster, 1979).

Stratigraphie paléozoïque généralisée du sud-ouest de l'État de New York (Van Tyne and Foster, 1979).

parallel the north-trending CLF are related to the CLF. However, structures such as secondary and tertiary splays, would not be expected to parallel the fault system.

SUBSURFACE GEOLOGY

Well log data

Documentation of the possible continuation of the CLF, south and north of the segment between Clarendon and Linden, has relied primarily on geophysical methods because glacial debris covers much of the projected trace south of Linden, and glacial lake clays and Lake Ontario cover the fault trace north of Clarendon. Several studies of well logs in the vicinity of the CLF and its possible southern extension support the premise that a fault, or series of faults, extends south from the escarpments to at least the Allegany County border (Rickard, 1973; Van Tyne, 1975; Van Tyne and Foster, 1979; Van Tyne et al., 1980a, b; Murphy, 1981, Beinkafner, 1983; Harth, 1984). However, all of these studies have been severely hampered by the lack of closely-spaced deep wells in northern Allegany County. For example, Van Tyne and Foster's (1979) database for the northern third of Allegany County consisted of a total of eight wells, with only two located near the projected trace of the central fault. With the exception of a well penetrating a fault, as evidenced by missing or repeated stratigraphic section, the detection of faults from well-log data requires closely-spaced wells so that fold hypotheses can be eliminated. Thus, the paucity of well-logs in northern Allegany County meant that it would be unlikely that these studies would have detected any faults present in this area.

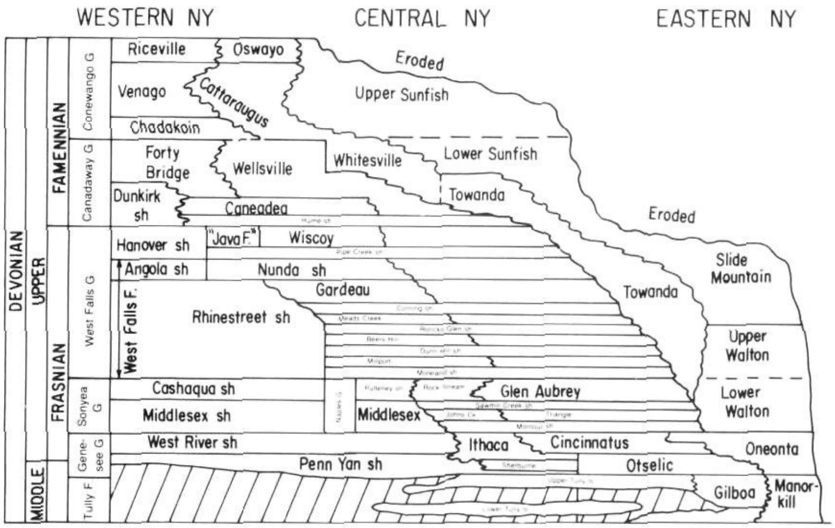
All previous researchers discussed the amount of movement along the CLF in terms of dip-slip motion that was determined from stratigraphic offset (*e.g.*, Fakundiny *et al.*, 1978b). However, there are no data that can contradict a strike-slip component, or a predominately strike-slip motion, along the fault (*e.g.*, Chadwick, 1920). If the offset on the fault is primarily strike slip, total movement would have to be on the order of five kilometers, with the net movement dextral (right lateral, or west-side to the north). The fault probably has actually experienced some sort of combination of dip-slip and strike-slip motion ("oblique slip"), thus the net displacement probably exceeds the apparent stratigraphic offset.

The first comprehensive well-log study of the CLF was published by Van Tyne (1975), who constructed three structure contour maps on the tops of the Galway (Theresa), the Trenton, and the Medina formations (Figs. 3-5). He was able to identify the CLF with some degree of confidence from Clarendon to Warsaw, New York (Fig. 3), but the faults were poorly constrained from Warsaw southward to northernmost Allegany County, where they are terminated due to a lack of data. Van Tyne (1975) had sufficient data in the north to suggest that a central fault is flanked by two subsidiary faults (Fig. 3). Individually, these faults display various stratigraphic offsets along their length, but the overall displacement is approximately 30 m, down-on-the-west (Fig. 3).

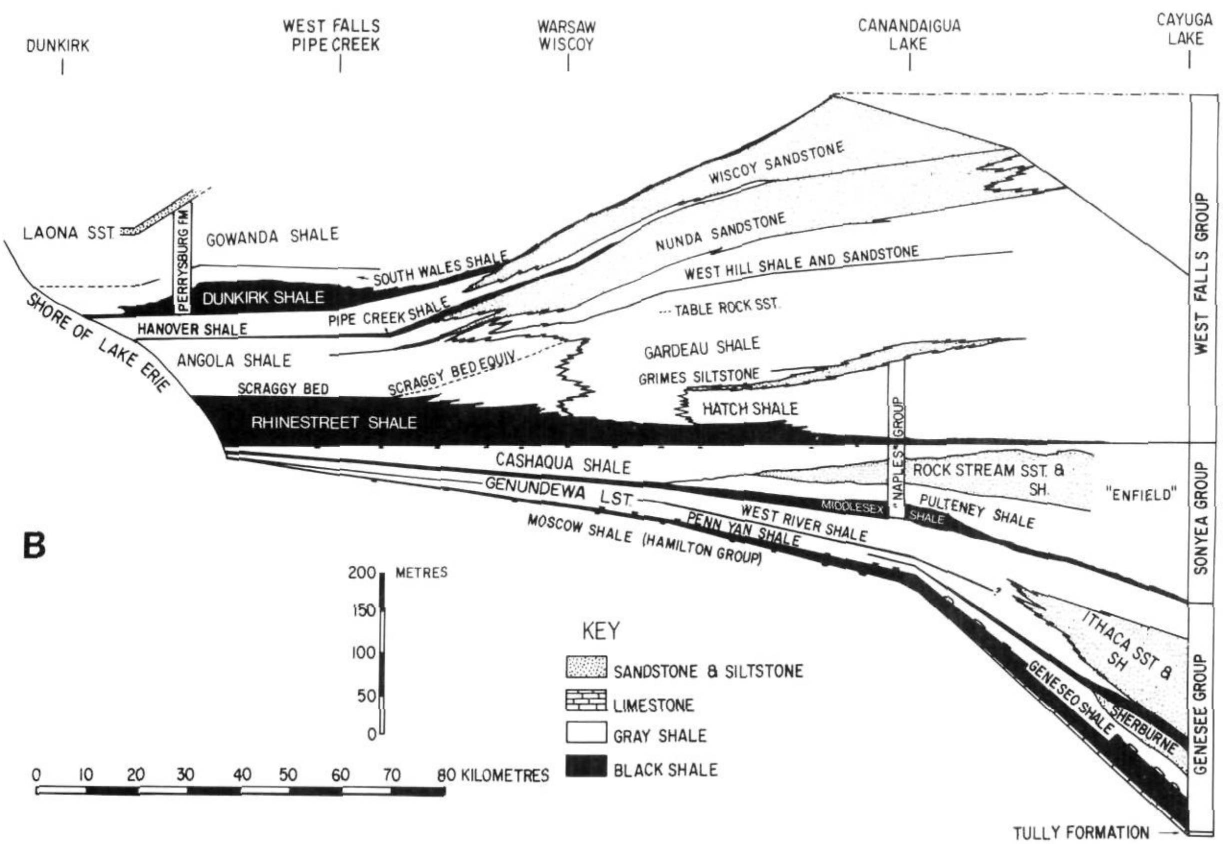
The general locations, offsets, and southern extent of Van Tyne's (1975) three main CLF faults were supported by Murphy's (1981) examination of over 1800 well logs in south central New York, including seven wells in northern Allegany County that intersected the Lockport Formation. Structure contour maps of various units in the Upper Silurian Salina Group also show these same faults, although the well log control is only four wells. Van Tyne's (1975) and Murphy's (1981) fault locations and offsets were also supported by Beinkafner's (1983) structure contour maps of the tops of the Grimsby Sandstone (part of the Medina Group), the Lockport Group, and the Onondaga and Tully formations, and by Harth's (1984) assembly of well-log data for Allegany, Wyoming, Orleans and Genesee counties.

Van Tyne and Foster (1979) assembled all the well log data for Allegany and Cattaraugus counties, and produced a series of structure contour maps for various units from the Precambrian to Upper Devonian. However, because of the lack of deep wells in the area, structure contours on the deeper units are not well defined. For example no wells penetrated the Precambrian in Allegany County and only two wells reached the Precambrian in Cattaraugus County. This lack of well control has resulted in only very generalized contours that cannot be used to determine the presence or absence of any faults, including the CLF, in northern Allegany County.

Van Tyne *et al.*'s (1980a-e) structure contour maps drawn on the surfaces of various Upper Devonian units consistently show between 30 and 61 m of structural relief in the form of



A



B

FIGURE 5. A) Detailed stratigraphic correlation diagram for the Upper Devonian of New York State (from Sevon and Woodrow, 1985). Rocks of the Perrysburg Formation are included in the Dunkirk shale. B) Detailed facies diagram of the Upper Devonian in western and central New York (from Kirchgasser and House, 1981; Johnson *et al.* 1985).

A) Diagramme de corrélation détaillé du Dévonien supérieur dans l'État de New York (de Sevon et Woodrow, 1985). Les roches de la Formation de Perrysburg sont comprises dans le shale de Dunkirk. B) Diagramme du faciès détaillé du Dévonien supérieur de l'ouest et du centre de l'État de New York (de Kirchgasser et House, 1981; Johnson et al., *1985).*

a broad anticline across the CLF in Wyoming County. This anticlinal interpretation for Upper Devonian units is consistent with the hypothesis (*e.g.* Chadwick, 1932) that the units above the Silurian evaporite section are flexed, not faulted. Van Tyne *et al.* (1980a-e) showed the CLF anticline gradually diminishing in structural relief to the south in southernmost Wyoming County and northern Allegany County, but the lack of well control (two wells in northwest Allegany County) makes any interpretation non-definitive. In contrast to the fold hypothesis, Murphy (1981) showed three CLF faults on the structure contour map of the Middle Devonian Onondaga Formation, but the well control is not shown.

Well control is slightly better in southern and central Allegany County, with the result that structure contours on the Tully and overlying Upper Devonian units display northeast-trending faults (Van Tyne and Foster, 1989; Van Tyne et *al.*, 1980a-e). These faults are thought to be "Alleghanian" ("Appalachian") in origin and timing, because of their trend, and their effect on the Upper Devonian units in western New York. These faults are generally up-on-the-west, although two minor graben structures are shown in southeastern and south-central Allegany County. Typical offsets on these faults vary from 6 to 61 m.

Seismic Reflection

Seismic reflection profiles across the CLF south of Lake Ontario that are in the public domain include about 38 km of New York State Geological Survey lines (NYSGS lines, Fig. 2) and about 40 km of Consolidated Gas Supply Corporation lines (CGS lines) (Pomeroy *et al.*, 1977; Fakundiny *et al.*, 1978b; Harth, 1984). Nine CGS lines cross the trace of the central fault from north of Attica to north of Line E; an additional four lines were shot between the central and eastern faults (Pomeroy *et al.*, 1977). These seismic studies show that the main CLF is a complex fault zone typically 5-15 km wide (Pomeroy *et al.*, 1977; Fakundiny *et al.*, 1978b), containing numerous individual faults with a total offset of about 30 meters down-on-the-west (*e.g.*, Fletcher and Sykes, 1977). Because the resolution of the vibroseis studies was approximately 30 m, faults with smaller offsets could not be resolved (Pomeroy *et al.*, 1977).

Up to six distinct, steeply-dipping fractures can be identified in the NYS seismic sections across the main CLF at the latitude of Attica. The central, or main, fault of Van Tyne (1975) consists of two east-dipping fractures; the more westerly of the two fractures is a reverse fault displaying the maximum throw observed on faults along the seismic line (77 m at the stratigraphic level of the Trenton). This amount of offset is based on an observed 0.015 s (one-way travel time) offset of the Trenton reflector, and a velocity of about 5,148 m/sec for the Trenton, computed from an average of seven interval velocities for the Trenton reported in Beinkafner (1983). In contrast, the eastern of the two faults has a net, apparent stratigraphic offset of 0.0075 s (39 m) down-to-the-east. The result is that the central "fault" of Van Tyne (1975) actually consists of two faults that form a horst.

The eastern fault of Van Tyne (1975) also appears to be at least two faults. The more easterly of the two is a west-dipping normal fault with little offset in the interpreted section of Pomeroy *et al.* (1977) and Fakundiny *et al.* (1978b). The more westerly fault also has little offset, but dips east. However, other interpretations are possible from the uninterpreted data (Pomeroy *et al.*, 1977). For example, a west-dipping fault could be located just east of their more easterly fault (at approximately vibration point 127, their Fig. 6). If the apparent offset is not a processing artifact, the offset is about 0.03 s ($\approx$77 m), down-on-the east at the Lockport-Medina level, and 0 s at the Trenton level. Between the central and eastern fault sets are several fractures that have minimal offset on line A.

The western fault of Van Tyne (1975) dips steeply west, and is a high-angle reverse fault. At deeper horizons, the fault appears to be monoclinal with about 0.02 s ($\approx$52 m) of structural relief, but at the top of the Lockport-Medina reflector, there appears to be an actual break, but with less offset. None of the seismic lines show any reflectors above the Lockport-Medina horizon, so that conclusions concerning the monocline vs faults in the section above the Silurian Salina Group are not possible.

Fakundiny *et al.* (1978b) pointed out that "a noteworthy feature of the fault system is the consistency in faulting density, spacing and dips from north to south along the main part of the system for a distance of approximately 77 km, and along the southwest branching zone for approximately 26 km". However, the offset across the fault zone is not uniform along the lenght of the zone, as evidenced by, for example, the interpreted NYSGS sections (Pomeroy *et al.*, 1977). On line D (Fig. 2), the western fault of the central fault zone displays about 0.03 s (77 m) offset on basement, and nearly none on the Trenton. In contrast, on line A (the Attica line), the Trenton has about 0.03 s offset, and basement has less offset (0.015 s or 39 m); on a proprietary line across the CLF at Warsaw (about 10 km south of Attica), the basement to Trenton section is clearly offset by an east-dipping reverse fault, with an offset of 0.07 s (approximately 180 m). On line E at Pike, the basement shows little offset, but the Trenton shows more offset than on any other NYSGS line across the central fault zone: 0.05 s (128 m). On the CGS lines the offset on the Trenton varies from 50 to 91 m (Pomeroy *et al.*, 1977). The apparent variable offset along the faults has several different explanations, including: 1) strike-slip motion displacing variable-thickness units that have a component of variation parallel to the CLF; 2) fault "scissoring" through time; 3) segmented faults, with the segments behaving in a semi-independent manner through time; 4) faults are miscorrelated between seismic lines.

A dramatic decrease in the number of faults above the Silurian shales and evaporites, as compared to that beneath this interval, has been postulated by Van Tyne (1975) Fakundiny *et al.* (1978b) and Harth (1984). These researchers suggested that the decrease results from a decoupling across the Silurian units when stress was relieved by deformation in the evaporites and shales. Pomeroy *et al.* (1977), in evaluating the CGS data, believed that the reflector representing the Middle Devonian Onondaga Formation exhibits only gentle warping even though the underlying units have been displaced by large offsets (*e.g.*, CGS line 2). However, the Onondaga reflector on other lines (*e.g.*, CGS line 11) is sufficiently ambiguous to make interpretation equivocal. Additionaly, the absence of relectors above the Lockport-Medina on NYSGS lines makes recognition of faults impossible in this interval.

GRAVITY AND MAGNETICS

In north-central New York the CLF is located along the "western flank of a series of magnetic and gravity highs" (Revetta *et al.*, 1978, p. 82; Fakundiny *et al.*, 1978a, b, 1981; Revetta *et al.*, 1979) which are thought to be due to Precambrian bodies (Revetta *et al.*, 1978, 1979). Fakundiny *et al.* (1978b) suggested that a Precambrian fault along the present CLF trend offset these mafic bodies. The gravity and magnetic anomalies continue south into Pennsylvania (Fakundiny *et al.*, 1978a,b, 1981; Revetta *et al.*, 1978, 1979).

If the CLF is a cover rock manifestation of this ancient crustal inhomogeneity, then the CLF also extends into northern Pennsylvania (Fakundiny *et al.*, 1978a, b; Revetta *et al.*, 1978, 1979; Fakundiny, 1981). Culotta *et al.* (1990) named these magnetic anomalies the "Amish anomaly". By tracing these magnetic anomalies and gravity anomalies southward to deep seismic reflection lines and northward to seismic lines and exposed Precambrian rocks, Culotta *et al.* (1990) suggested that the CLF in the Paleozoic cover rocks is actually a reactivated fault along an earlier intra-Grenvillian province suture zone.

The continuation of the CLF northward, in some form beneath Lake Ontario along the Scotch Bonnet Rise and into the province of Ontario, is suggested from seismic, gravity and magnetic data (Diment *et al.*, 1974; Anderson and Lewis, 1975; Van Tyne, 1975; Pomeroy and Fakundiny, 1976; Fakundiny *et al.*, 1978a, b; Hutchinson *et al.*, 1979; Revetta *et al.*, 1979). Anderson and Lewis (1975) showed an apparent 18 m bedrock offset across the Scotch Bonnet Rise. Hutchinson *et al.* (1979) did not observe offset reflectors and, therefore, concluded that if a fault did exist along the Scotch Bonnet Rise, then its movement must have predated the glacial and younger sediments represented in Hutchinson *et al.*'s (1979) data. However, Bowlby (pers. comm.) stated that offsets in glacial sediments are observable on unpublished high resolution seismic ("echo-sounding") lines near the proposed CLF extension in Lake Ontario. North of Lake Ontario, Hutchinson *et al.* (1979) found that the trend of the proposed CLF extension is coincident with magnetic and gravity anomalies, as well as with faults previously mapped by Kay (1937). Some of these faults were mapped at the surface, where post-Middle Jurassic horizontal slickensides imply strike-slip motion (McFall, 1990a, b). Thus, the fault system continues at least 150 km north of New York State and, perhaps, an additional 100 km beyond that.

RESULTS OF OUR ONGOING INVESTIGATION

GEOCHEMICAL ANALYSES OF THE PIKE GAS SEEP

A few days after the Saguenay earthquake of November 25, 1988, several large, energetic, gas seeps were discovered in a swamp near Pike, New York (Figs. 2 and 3), about 800 km southwest of the Saguenay earthquake. The seeps are located near the main central fault of the CLF (Fig. 3); their location and timing of formation suggest that they were caused by reactivation of the CLF system due to the Saguenay earthquake. The seeps initially expelled gas with sufficient energy to spatter the tops of the surrounding 5 m-high trees with mud. The mud spattering, photographed by the landowner, proves that the seeps were initiated shortly before discovery, otherwise the mud would have washed off the trees. In December, 1988 the gas produced a flare about 0.3 m long and, at the time of our first visit in March, 1989, the flare had grown to 1 m. As of May, 1993 the gas was still producing a flare which varied in length from less than 0.3 m to more than 1 m.

Since the seep is in a swamp, the gas may have been biogenic in origin (swamp gas). Biogenic gas can be differentiated from thermal (deep) gas because biogenic gas contains only methane, whereas thermal gas contains both methane and ethane (Rice and Claypool, 1981; Whiticar, 1986). Several samples from the Pike gas seep show that this gas was about 90% methane and 10% ethane (Table I); thus, it is evident that the Pike gas seep is thermal gas (Jacobi and Fountain, 1989). This conclusion is supported by the carbon isotopic composition of the methane from the seep. Gas compositions point to a Devonian source for the ejected gas, because gas from deeper units has a different composition (Table I). Drillers' logs from a gas well in a neighboring farm indicate gas was encountered at a depth of about 310 m. Well-logs show a very large temperature perturbation at this same depth, indicating a large flow of gas. These data suggest that there is a gas reservoir in fractured Devonian shales at this depth and that local ground motion from the Saguenay earthquake reopened fractures that tapped this reservoir.

SOIL-GAS SURVEY

Formation of the large gas-seep on the trend of the central fault of the CLF near Pike suggested the use of a soil-gas survey as a method of tracing the fault system farther south than the limited well-logs had previously allowed (*e.g.*, Van Tyne, 1975). A soil-gas survey involves analysis of gas from within the soil layer. If the underlying bedrock is fractured and contains natural gas, then the overlying soil will contain anomalously high values of methane in the vicinity of the fractures because fractures provide a path for gas to migrate to the surface. Devonian shales, which underlie the entire study area, are known to contain natural gas. Thus, even though nonfractured Devonian shale has a very low permeability, if the CLF extends from its known location near Pike south into Allegany County, fractures within the system should produce detectable soil-gas anomalies. Soil-gas surveys have been widely used by the petroleum industry (Horvitz, 1969, 1985; Jones and Drozd, 1983; Richers et al., 1982, 1986) and have shown a clear correlation between large soil-gas anomalies and faults.

Design of The Soil-Gas Survey

Previously only those faults with offsets in excess of 30 m were resolvable in the seismic data from southern Wyoming

TABLE I

Gas Compositions

Sample	Methane/Total hydrocarbons	Delta 13C
Pike gas seep		
Sample #1	0.87	
Sample #2	0.86	−50.3
Sample #3	0.85	
Biogenic gas	> 0.97	−55 to −90
Devonian shale gas	0.78-0.86	−41 to −49
(Average of 6 samples)	0.82	−47
Silurian Medina gas	0.86-0.92	−35 to −41
(Average of 10 samples)	0.90	−37

Pike analyses by Global Geochemistry Corp.

Biogenic gas data from Tissot and Welte (1984)

Devonian shale gas and Medina gas analyses from New York DEC; also analyzed by Global Geochemistry Corp.

County but, if the fault zone continues into Allegany County, then numerous smaller fractures would also be expected. To locate them a series of east-west traverses, across the projection of the fault system, was planned to address the following questions: 1) Do any anomalously high soil-gas values occur south of the known extent of the CLF and, if so, are they confined to narrow linear trends, as would be expected if the anomalies are related to a bedrock fracture system? 2) Are the linear anomalies parallel to the CLF? and 3) How far do the anomalies continue to the south?

Implicit in our approach was the interpretation that north-south trending soil-gas anomalies result from the CLF. The trend of an anomaly cannot, however, be unambiguously determined from parallel transects. A row of anomalies which constitute a north-south line across several traverses could be produced by a single north-trending fracture, or by multiple fractures which diagonally cross the traverses. Ideally, a survey should be designed as a series of boxes defined by intersecting north-south and east-west traverses. However, due to the limited time available for this study, it was not possible to run boxes in most cases. Instead we relied on closely spaced traverses, a limited number of north-south traverses and boxes, and associated topographic lineaments to define the trend of the anomalies.

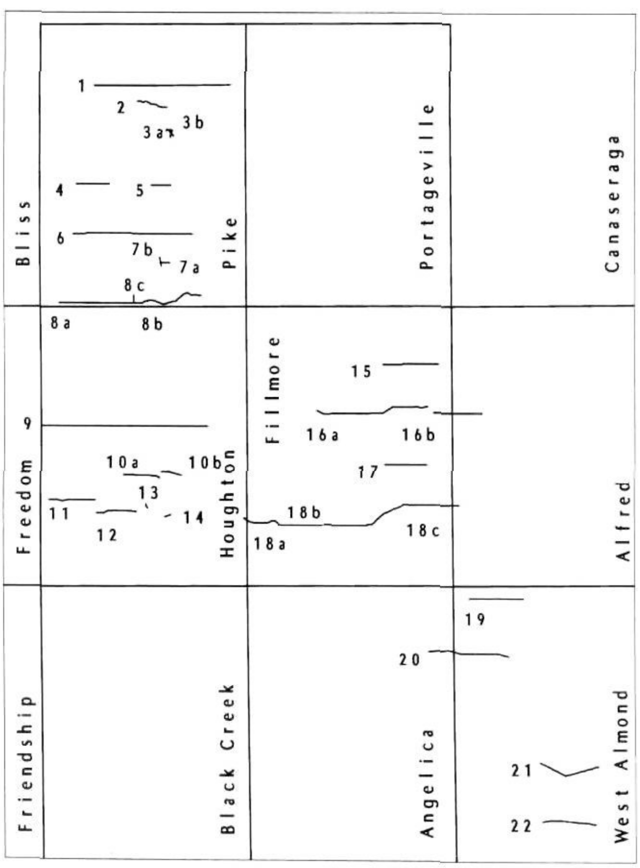


FIGURE 6. Location of soil-gas survey traverses in Allegany and Wyoming Counties. Rectangular outlines are quadrangles shown in Figure 2.

Localisation des transects de détection de gaz dans le sol, dans les comtés d'Allegany et de Wyoming. Les rectangles correspondent aux quadrilatères de la figure 2.

Factors Affecting Soil-Gas Surveys

The primary assumption in interpretation of soil-gas survey data is that a linear band of anomalously high concentrations of natural gas indicates an underlying fracture in the bedrock. Many factors, including permeability and moisture content of the soil, and thickness of surficial deposits, affect the size and distribution of such anomalies. However, none of these factors contradicts the interpretation of an observed anomaly as being an indicator of bedrock fracture. Gas anomalies may, however, be generated by several processes in addition to seepage from fractures, including the decay of organic material, leaking gasoline tanks, discarded solvents and leaking natural gas wells and pipelines (for a detailed review, see Jacobi and Fountain, 1989).

In order to determine if each anomaly was biogenic or thermal in origin, a portable gas chromatograph was utilized (see next section) to determine the methane/ethane ratio of each anomaly. The gas chromatography also could be used to determine if the anomaly were produced by gasoline leaks or spilled solvents, rather than by natural gas. This is because the total concentration of methane plus ethane in a natural gas seep equals the total leak concentration (heavier hydrocarbons comprise less than 5% of natural gas samples), whereas this would not be true for gas from other likely sources. In order to differentiate fracture-related natural gas anomalies from anomalies caused by a leaking gas well or pipeline, reliance was placed upon gas composition and anomaly pattern.

Experimental Method

Gas samples were obtained for analysis with a stainless steel probe from a depth of approximately 1 m (Jacobi and Fountain, 1989). Soil gas enters the probe through a ring of holes that are located approximately 5 cm from the tip and flows from the gas-sampling chamber to the gas chromatograph through a small-diameter teflon tube. In survey mode, the entire sample is run directly to a flame ionization detector and the detector determines the total organic vapor content of the sample. Background values for most areas was 4 parts per million (ppm) total hydrocarbons. If an analysis indicated more than 20 ppm, the instrument was switched to gas chromatograph mode to determine if the gas were biogenic or thermal.

Results

Over 6000 soil-gas analyses were performed along 22 traverses across the projected southern extension of the CLF, and large gas anomalies were found along nearly every traverse (Figs. 6-8). Chromatographic analyses of the anomalies showed that, in every case, the anomalies were caused by thermal gas and not by biogenic gas (swamp gas was found in several isolated locations but these analyses were not mapped as anomalies).

Boxes were surveyed around anomalies near the Allegany-Wyoming County line and in several other locations. Anomalies were found on the north and south segments of each of these boxes, but not on the east or west segments. These data provide strong evidence that, at least in these local areas, the anomalies trend north-south. Further evidence for north-south trending anomalies was found where individual anomalies were followed. In both Pike and Houghton quadrangles, large anomalies were followed along strike (profiles 3a, 3b, 7b, 8c, and 13, Figs. 6 and 8). These traverses were located primarily in the floors of distinctive, narrow "dry valleys"; short segments of the traverses perpendicular to the valleys established the width and trend of the anomalies. In every case, but one, the anomalies were found to define narrow, north-trending structures. The exception trends northwest and is one of a pair of intersecting anomalies that follow dry valleys south of the gas seep at Pike (profile 3a, Figs. 6 and 8). The other anomaly at that site is oriented approximately north-south (profile 3b).

The tendency of the anomalies to occur where north-trending topographic lineaments intersect the traverses was found in several other areas. In both the Pike and Houghton quadrangles, anomalies appeared to follow north-south trending topographic lineaments. These lineaments had been independently identified from topographic maps by Wulforst (pers. comm.). In the Fillmore quadrangle the anomalies are also located at intersections with north or north-northeast-trending topographic lineaments. Similarly, the gas anomalies in the West Almond quadrangle that are on profiles 21 and 22 (Fig. 6) also occur where a north-trending topographic lineament crosses both traverses. Almost without exception, a major gas anomaly was found where the traverses crossed the lineaments. The lineaments define long, continuous north to north-northeast trending structures. The nearly ubiquitous occurrence of gas along the north-south trending lineaments provides additional support for the northerly trend of most anomalies. However, anomalies on the western ends of traverses 18 (18a) and 20 both occur where NE-trending topographic lineaments intersect the traverses, suggesting these anomalies may be related to NE-trending Alleghanian faults.

The regional pattern of anomalies (Fig. 8) suggests that there are several north-trending fractures that continue through the entire length of the study area. In the Pike and Houghton Quadrangles, there are two apparently continuous

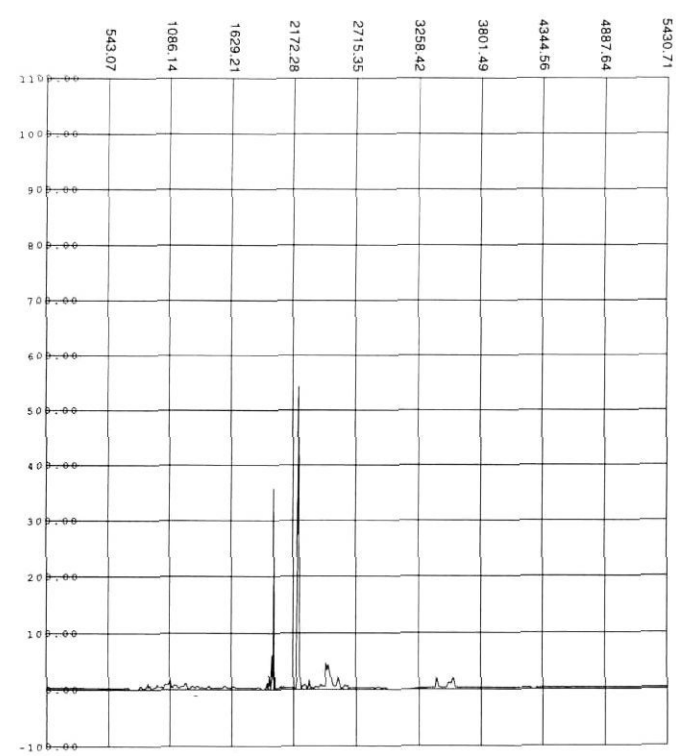


FIGURE 7. Typical soil-gas profile (#2). Vertical scale in ppm of soil-gas; horizontal scale is one box = 165 m. Note the narrow character of the major soil gas anomalies.

Profil caractéristique du gaz dans le sol (n° 2). En ordonnée, gaz en ppm; en abcisse, le carré équivaut à 165 m. Noter l'étroitesse des principales anomalies de gaz.

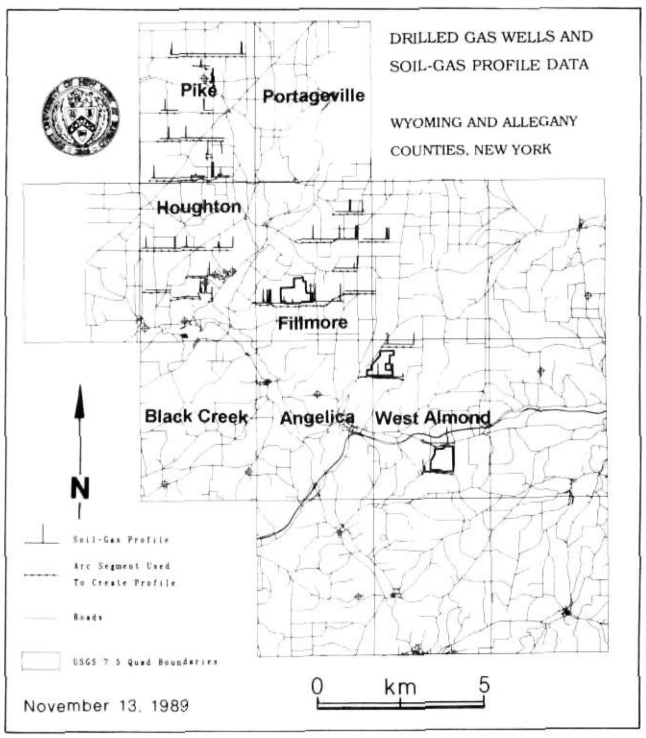


FIGURE 8. Results of soil-gas survey. Beaded lines represent the traverses shown in Figure 6; horizontal lines with narrow vertical spikes display the methane concentrations along the profile (maximum spike height = 1000 ppm). Thin lines are roads. Open circles with cross-hairs symbolize wells utilized in the well-log analysis. Note that north-south gas profiles are rotated to an east-west direction for ease of viewing. The three areas delineated with a heavy line are potential sites for low-level radioactive waste disposal.

Résultats de la détection de gaz dans le sol. Les lignes à points représentent les transects de la figure 6; les lignes verticales montrent les concentrations de méthane le long des profils. Les cercles repères représentent les puits qui ont servi à l'analyse. Noter que les profils de gaz nord-sud ont subi une rotation en direction est-ouest pour faciliter la lecture. Les trois zones soulignées par des traits gras sont des sites potentiels d'enfouissement de déchets à faible radioactivité.

anomalies that extend the lenght of the quadrangles. The more westerly of the two is broad, whereas the more easterly anomaly, which extends south from the gas seep near Pike (adjacent to profile 3b), is very narrow and coincides with the extension of the central fault zone of the CLF. Of particular note are the large anomalies on traverses 13 and 14 (Figs. 6 and 8), which lie exactly on the traces of the two faults determined from well-log data obtained in adjacent wells (see next section). The coincidence of these anomalies and the projected fault trend provide support both for the interpretation of the well-log data and of the soil-gas anomalies.

In the Fillmore Quadrangle, there are apparently continuous anomalies in the eastern and central parts of the quadrangle (Fig. 8). Due to the limited number of traverses, and the occurrence of an extensive zone of clay-rich soil on traverse 16, the identification of these trends is more tenuous than in the western quadrangles. However, there are enough topographic lineaments and gas anomalies to define the central, north-trending anomaly from traverse 15 to traverse 18b. The anomaly on traverse 15 occurs at the head of a deep north-trending ravine; on the next traverse to the south (profile 16a), a small anomaly occurs due south of the ravine and anomaly on profile 15. This north-south trend projects south to the eastern anomalies observed on profile 17; projected still farther south-southwest along a topographic lineament, the trend crosses profile 18b at a small gas anomaly at the eastern third of the profile. On profile 18c the easternmost anomalies occur where both north and northeast-trending topographic lineaments cross the profile. Thus, because a northeast-trending "Alleghanian" fault determined from well logs (see next section) may pass the eastern end of the traverse. this anomaly may be related to the "Alleghanian" fault system.

The data from the soil-gas survey strongly suggest that a system of north-south trending fractures continues from the area near Pike, where the trend is known to be related to the CLF, south through central Allegany County. Our instrument was capable of measuring concentrations of methane up to 1000 ppm, a value which was commonly exceeded along several prominent anomalies. Such large quantities of gas would be expected only where there are fractures that have been opened by relatively recent reactivation.

WELL LOG ANALYSIS

Well locations were compiled for the 14 quadrangles that straddle the projected trace of the CLF in northern and central Allegany County (Figs. 9 and 10). Available gamma-ray well-logs were analyzed by using Van Tyne and Foster's (1979) gamma ray log example as a model for identifying the formation boundaries. The depths and thicknesses were calculated for two distinctive horizons, the Devonian Onondaga and Tully formations, that appear on most of the logs (Figs. 9 and 10). Faults (or folds) were identified where the observed depth to a unit did not agree with its predicted depth, which was calculated from strike and dip determined from neighboring wells. Although the number of wells in the western part of the study area is not large, we are confident that the data reveal the central fault of the CLF in Allegany County

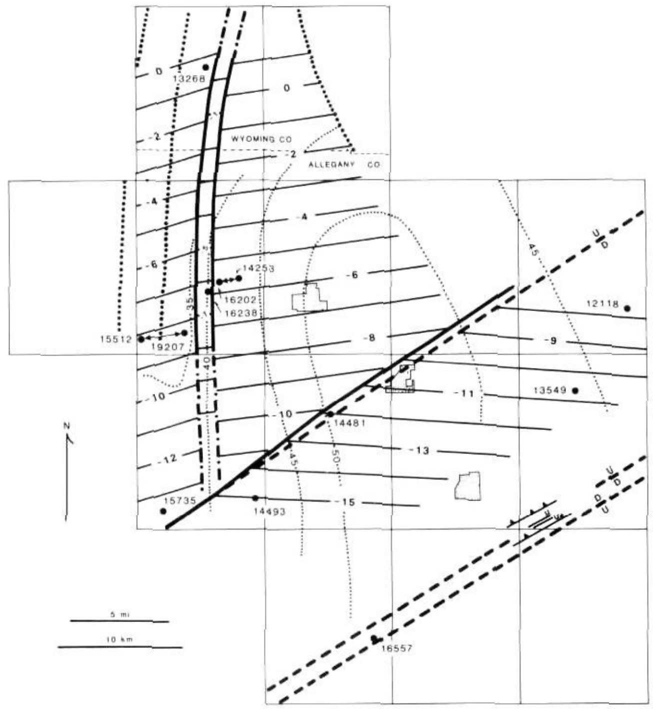


FIGURE 9. Structure contour and isopach maps of the Tully Formation, displaying the CLF. Rectangular boxes indicate 7 1/2' quadrangles which are located in Figure 2. Structure contours based on interpretation of gamma ray logs for wells indicated by the solid circles and identified with the API well number. Faults in the central fault zone of the CLF are shown as thick, solid lines. Extrapolated positions shown as dot-dash patterns. Thick dotted lines indicate fault traces of the CLF as proposed by Murphy (1981). Thick dashed lines indicate approximate position of "Alleghanian" faults as proposed by Van Tyne and Foster (1979). Thin-lined faults in the southeast are from Beinkafner (1983). "U" and "D" signify relative stratigraphic offset, with "D" indicating the "down" side, and "U" indicating the "up" side. Barbs are displayed on the upthrown side of thrust faults. Structure contours on the top of the Tully Formation are shown as solid, annotated lines (depth annotations are in hundreds of feet). Datum is mean sea level. Isopach contours are thin, dotted lines (annotations are in feet). The three candidate sites for the disposal of low-level nuclear waste are portrayed in a dotted pattern. Double arrowed lines denote the locations of the westernmost and easternmost parts of the cross-section displayed in Figure 11.

Carte des courbes structurales et isopaques de la Formation de Tully montrant le RCL. Les rectangles représentent les quadrilatères de la figure 2. Les courbes structurales sont fondées sur les diagrammes de rayonnement gamma faits à partir des puits (cercles noirs) identifiés par un numéro. Les failles situées au centre de la zone de RCL sont en traits gras continus. Les emplacements extrapolés apparaissent en traits et points. Le pointillé gras montre le tracé du RCL proposé par Murphy (1981). Le tireté gras montre le tracé approximatif des failles «alléguaniennes» proposé par Van Tyne et Foster (1979). Les failles en traits fins au sud-est sont de Beinkafner (1983). Les lettres U et D indiquent un déplacement stratigraphique relatif vers le bas (D) ou vers le haut (U)) Les barbules sont du côté déjeté des failles. Les courbes structurales sur le dessus de la Formation de Tully sont continues et accompagnées d'un chiffre (en centaines de pieds à partir du niveau moyen de la mer). Les courbes isopaques sont en pointillé fin. Les trois sites susceptibles de recevoir des déchets de faible radioactivité sont identifiés par une trame à points. Les flèches à double sens montrent les extrémités des coupes de la figure 11.

(see detailed analysis in Jacobi and Fountain, 1989). Well locations allow the central fault to be interpreted either as two closely-spaced north-striking faults, with a total stratigraphic offset of ~43 m down-on-the-west, or as a relatively steep monoclinal warp (Figs. 9,11). Because the cross section (Fig. 11) passes through two soil gas anomalies (indicating open fractures) that are located precisely where needed for the fault interpretation, we believe the fault hypothesis is more tenable. The orientation of the faults cannot be northeast because they pass only through the central part of the cross section, not through the eastern and western offset portions of the cross section as well (Figs. 9,11). The north-south orientation of the fault agrees with 1) the results of the gas survey, 2) the trend of several "dry-valley lineaments", and 3) the trend of the central fault of the CLF in Wyoming County that is also a double fault on seismic lines.

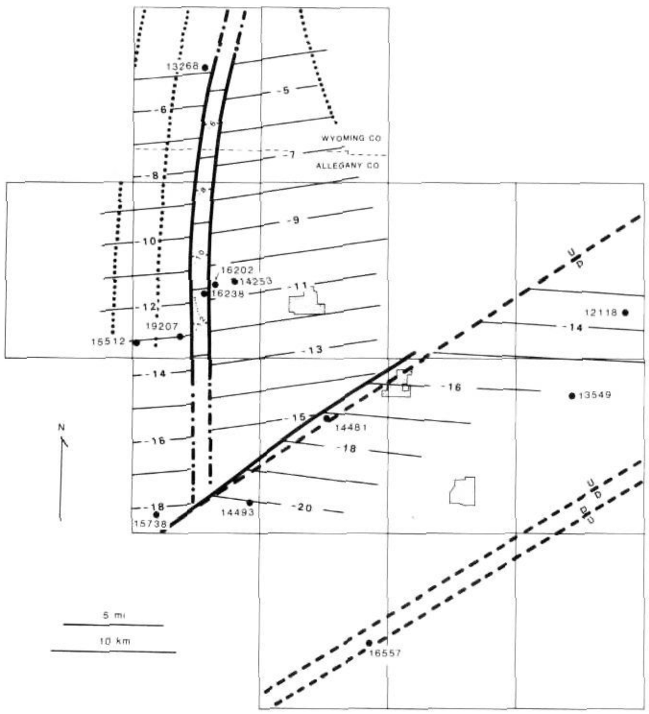


FIGURE 10. Structure contour map of the Onondaga Formation, displaying the CLF. Rectangular boxes indicate 7 1/2′ quadrangles which are located in Figure 2. Structure contours based on interpretation of gamma ray logs for wells indicated by the solid circles and identified with the API well number. Faults in the central fault zone of the CLF are shown as north-trending, thick, solid lines. Extrapolated positions are shown as dot-dash patterns. Thick dotted lines indicate fault traces of the CLF as proposed by Murphy (1981). Thick dashed lines indicate approximate position of "Alleghanian" faults as proposed by Van Tyne and Foster (1979). "U" and "D" signify relative stratigraphic offset, with "D" indicating the "down" side, and "U" indicating the "up" side. Structure contours are shown as solid, annotated lines (depth annotations are in hundreds of feet). Datum is mean sea level. The three candidate sites for the disposal of low-level nuclear waste are portrayed in a dotted pattern. A small, north- northwest trending dotted line between wells 19207 and 16238 shows the location and trend of a soil-gas anomaly and a coincident topographic lineament (a "dry valley").

Courbes structurales de la Formation d'Onondaga montrant le RCL. Les rectangles représentent les quadrilatères de la figure 2. Les courbes structurales sont fondées sur les diagrammes de rayonnement gamma faits à partir des puits (cercles noirs) identifiés par un numéro. Les failles situées au centre de la zone de RCL sont en traits gras continus. Les emplacements extrapolés apparaissent en traits et points. Le pointillé gras montre le tracé du RCL proposé par Murphy (1981). Le tireté gras montre le tracé approximatif des failles « alléguaniennes » proposé par Van Tyne et Foster (1979). Les lettres U et D indiquent un déplacement stratigraphique relatif vers le bas (D) ou vers le haut (U). Les courbes structurales sont continues et accompagnées d'un chiffre (en centaines de pieds à partir du niveau moyen de la mer). Les trois sites susceptibles de recevoir des déchets de faible radioactivité sont identifiés par une trame à points. Un court pointillé orienté NNW, entre les puits 19207 et 16238 montre la localisation et la direction d'une anomalie de gaz dans le sol coïncidant avec un linéament topographique (« vallée sèche »).

The central and eastern parts of Allegany County have insufficient closely-spaced wells to definitively trace the eastern CLF splay. However, the wells do indicate a NE-trending fault, consistent with Van Tyne and Foster's (1979) NE-trending Alleghanian fault (down-on-the-east) that they projected into the area from the west (Fig. 9). The northeast trend is also consistent with the trend of the faults hypothesized from seismic data by Beinkafner (1983) in southeastern Allegany County (Fig. 9). Depths to the Onondaga Formation are consistent with the conclusions drawn from the Tully data (Figs. 10, 11), except that the total stratigraphic offset across the central fault zone is 30 m, down-on-the- west.

MOVEMENT HISTORY ALONG THE CLARENDON-LINDEN FAULT SYSTEM

Culotta *et al.* (1990) suggested that the CLF in the Paleozoic cover rocks is actually a reactivated fault along an intra-Grenvillian province suture zone. Fakundiny *et al.* (1978a) suggested that Precambrian strike-slip movement may have occurred, based on juxtaposition of magnetic anomalies. For Paleozoic CLF movement history, researchers have relied upon evidence of a growth-fault geometry (observed in isopach maps for various units) as an indicator of both CLF movement and the sense of motion (Fig. 12).

During a survey of subsurface Cambro-Ordovician units, Rickard (1973) examined 34 well logs in the counties through which the CLF may pass (Orleans, Monroe, Genesee, Wyoming, and Allegany). Isopach maps for the various Cambrian and Lower Ordovician units reveal no thickness variations that can be ascribed to effects of the CLF. However, isopach maps of both the Middle Ordovician Black River and Trenton units imply that these units thicken by 9-15 m immediately east of the CLF (Rickard, 1973). Rickard's (1973) stratigraphic section #5, which passes over the CLF through southern Wyoming County, implies even more thickening on the east side (upwards to about 40 m in the Black River section). Van Tyne (1975) also documented an "abrupt increase in thickness of 38 m on the east side of the major Clarendon-Linden fault" in the Trenton to Galway interval. Van Tyne (1975) believed the increase in thickness was not repeated in units above the Trenton, leading him to suggest that the growth fault was active in Ordovician times, but that it had ceased by Silurian times. Van Tyne (1975) and Fakundiny *et al.* (1978 a, b) have used the thickening to the east to suggest that the CLF was a normal fault during

Taconic times with a down-on-the-east sense of motion. To account for the opposite sense of offset presently observed, Van Tyne (1975) suggested that later reactivation during a compressional event caused a reversal of throw along the early fault. The discussion below suggests that this reversal may have begun in Late Devonian times.

Beinkafner's (1983) well-log study was limited by insufficient data, and so the necessarily generalized contours reveal no effect of the CLF. However, thickness values posted for three closely-spaced wells in northern Allegany County (her Figs. 5-9) suggest that the Queenston thins to the east over the proposed extension of the central trace of the CLF. Such thinning implies motion along the fault in Queenston or later times, with an opposite sense of motion to that in Trenton times.

Beinkafner's (1983) isopach map of the Rondout Formation/Helderberg Group interval displays prominent local thinning over the projected trace of the CLF in Allegany county. In contrast, her isopach maps of the Onondaga Formation, the Hamilton Group, and the Tully Formation show no effect of the CLF. Neither wells nor postings of thicknesses are displayed, so more detailed interpretations are not possible. Van Tyne *et al.*'s (1980f) isopach map of radioactive shale in the Hamilton Group also displays no prominent

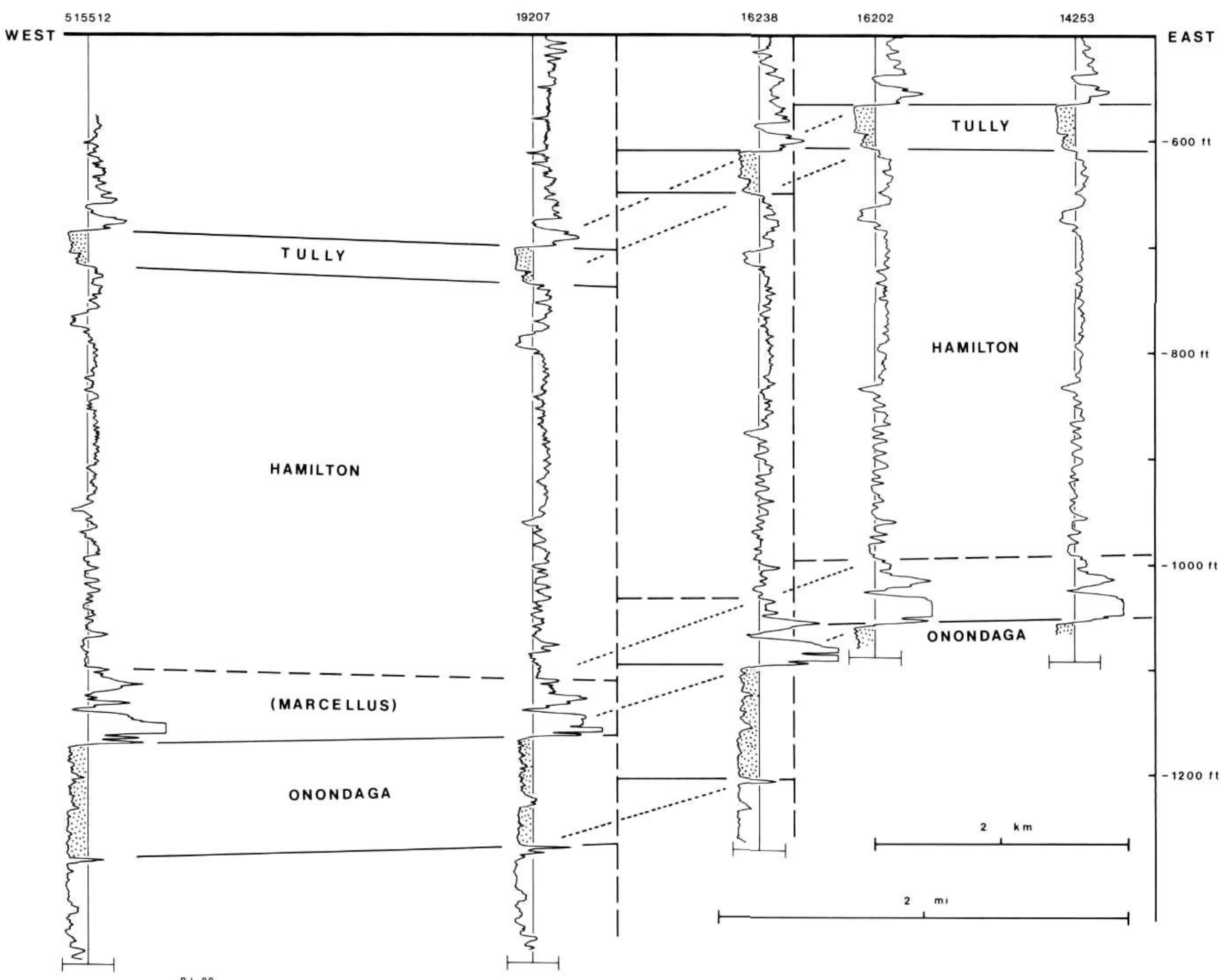


FIGURE 11. Cross section across the main central fault of the CLF. Location of cross-section shown in Figure 9. Identification of units on gamma-ray logs (vertical squigglely lines) based on Van Tyne and Foster (1979). Well API number is at the top of each log. The preferred interpretation is the two step faults in the central fault zone of the CLF (fault locations denoted by vertical dashed lines). The alternative interpretation is that the observed offset is accommodated by a monocline (indicated by the sloping unit boundaries). Exact locations of the faults are based on nearby soil gas anomalies. Datum is mean sea level.

Coupe à travers la faille principale du RCL (localisation à la fig. 9). Identification des unités du diagramme de rayonnement gamma (courbes à la verticale) fondée sur Van Tyne et Foster (1979). Le numéro des puits apparaît au-dessus de chaque courbe. L'interprétation la plus plausible consiste en la présence d'une faille à deux gradins dans la zone centrale du RCL (localisations des failles identifées par les tiretés verticaux). Il est aussi possible que le déplacement observé soit conforme à un monoclinal (identifié par les limites de l'unité en pente). La localisation exacte des failles est fondée sur les anomalies de gaz dans le sol.

PERIOD		GROUP	UNIT		THICKNESS	PRODUCTION	
Penn.		POTTSVILLE	OLEAN	Ss,Cgl	75-100'		
Miss.		POCONO	KNAPP	Ss, Cgl	50-100'		
DEVONIAN	UPPER	CONEWANGO		Sh,Ss,Cgl	700'		
		CONNEAUT	CHADAKOIN	Sh,Ss	700'		
		CANADAWAY	UNDIFF.	Sh, Ss	1100-1400'	Oil,Gas	
			PERRYSBURG	Sh,Ss		Oil,Gas	KVT
		WEST FALLS	JAVA		375-1250'	Oil,Gas	VTKC
			NUNDA	Sh,Ss			? VTKC
			RHINESTREET				
		SONYEA	MIDDLESEX	Sh	0-400'	Gas	VTKC
		GENESEE		Sh	0-450'		VTKC
	? ?		TULLY	Ls	0-50'	Gas	VTF, JF
	MIDDLE	HAMILTON	MOSCOW LUDLOWVILLE SKANEATELES MARCELLUS	Sh Sh Sh Sh	200-600'	Gas	
			ONONDAGA	Ls	30-235'	Gas, Oil	O B
	LOWER	TRISTATES	ORISKANY	Ss	0-40'	Gas	O B
		HELDERBERG	MANLIUS RONDOUT	Ls Dol	0-10'		? B
			AKRON	Dol	0-15'	Gas	
SILURIAN	UPPER	SALINA	CAMILLUS SYRACUSE VERNON	Sh, Gyp. Dol,Sh,Salt Sh, Salt	450-1850'		
		LOCKPORT	LOCKPORT	Dol	150-250'	Gas	
	LOWER	CLINTON	ROCHESTER IRONDEQUOIT	Sh Ls	125'		
			SODUS REYNALES	Sh Ls	75'		
			THOROLD	Ss	2-8'		
		MEDINA	GRIMSBY	Sh,Ss	75-160'	Gas	
			WHIRLPOOL	Ss	0-25'	Gas	
ORDOVICIAN	UPPER		QUEENSTON OSWEGO	Sh Ss	1100-1500'	Gas	B
			LORRAINE UTICA	Sh Sh	900-1000'		
	MIDDLE	TRENTON-BLACK RIVER	TRENTON	Ls	425-625'	Gas	R,VT,F
			BLACK RIVER	Ls	225-550'		
	LOWER	BEEKMAN-TOWN	TRIBES HILL-CHUCTANUNDA	Ls	0-550'		VT
CAMBRIAN	UPPER		LITTLE FALLS	Dol	0-350'		
			GALWAY (THERESA)	Dol,Ss	575-1350'	Gas	
			POTSDAM	Ss, Dol	75-500'	Gas	
PRECAMBRIAN			GNEISS, MARBLE, QUARTZITE, etc.				

FIGURE 12. Columnar section for western New York (Van Tyne and Foster, 1979) showing times of CLF fault movement and sense of motion. Shear arrows at right side of various units show the sense-of-motion on the CLF deduced from growth-fault geometries (0 = no movement detected). Sources of data indicated by letters: B = Beinkafner (1983), F = Fakundiny (1978b), JF = this paper, KVT = Kamakaris and Van Tyne (1980) and Van Tyne *et al.* (1980k), R = Rickard (1973), VT = Van Tyne (1975), VTF = Van Tyne and Foster (1979), and VTKC = Van Tyne *et al.* (1980g-j).

Histoire et cinématique du déplacement du RCL dans l'ouest de l'État de New York (Van Tyne et Foster, 1979). Les demi-flèches à la droite de certaines unités donne la direction des mouvements à partir de la géométrie de l'évolution des failles (0 = aucun mouvement détecté). La source des données est indiquée par les lettres: B = Beinkafner (1983), F = Fakundiny (1978b), JF = présent article, KVT = Kamakaris et Van Tyne (1980) et Van Tyne et al. *(1980k), R = Rickard (1973), VT = Van Tyne (1975), VTF = Van Tyne et Foster (1979), VTKC = Van Tyne* et al. *(1980g-j).*

CLF-related feature. The lack of well logs intersecting the Onondaga in Allegany County prevented us from constructing a useful isopach map for the Hamilton and Onondaga intervals.

For consideration of motion along the CLF during Tully time, an isopach map was constructed based on our well-log analyses (Fig. 9); this map strongly suggests the central fault was active. The Tully is 12-13 m thick in all three wells east of the more westerly central fault, and is consistently 10 m thick in the wells west of the westerly central fault. The abrupt change in thickness across the trace of the more westerly central fault suggests that this westerly fault was active in Tully time, and that its sense of motion was down-on-the-east. The lack of evidence for significant thickening across the more easterly central fault suggests that at this time the easterly central fault was less active than the westerly central fault.

Indications of fault activity in the Late Devonian are evident in Van Tyne *et al.*'s (1980 g-j) series of isopach maps (Fig. 13). Widely-spaced, 15 m (50 feet) contour intervals in the original isopach map of the lowest stratigraphic interval analyzed (the Genesee Group) show no effect of a possible CLF. However, inspection of the thickness postings at individual wells in northern Wyoming County reveal that the Genesee Group displays an abrupt increase in thickness across the fault zone. Thickness values increase abruptly to the NE along regional strike from about 22 m to 26 m, an 18% increase. The addition of a supplemental 3-m contour interval, and careful modification of the original 15 m contours, reveal these subtle variations (Fig. 13). The transition to

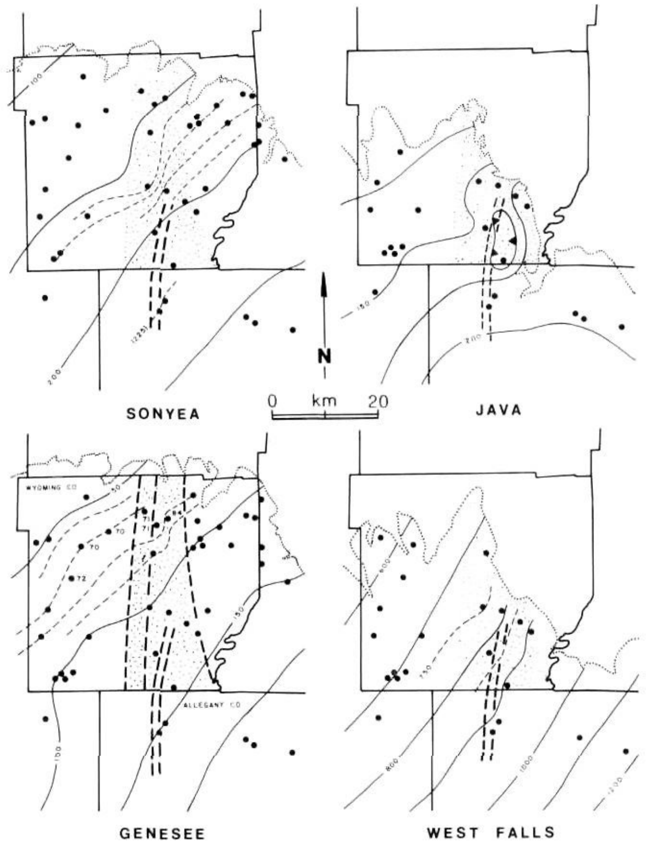


FIGURE 13. Isopach maps of upper Devonian units. Well locations shown as solid circles. Thickness values (in feet) from Van Tyne *et al.* (1980), as are the general trends of the 50′ (≈ 15 m) contours. The 50′ contours are carefully modified in all, but the Java isopach map, to be consistent with the supplemental 10′ (3 m) contours which are from this study. The stippled pattern defines the zone encompassed by Van Tyne's (1975) three CLF faults (shown as dashed lines on the Genesee map). The two closely-spaced lines that extend into Allegany County are the locations of the main central fault zone proposed in this study.

Cartes isopaques des unités du Dévonien supérieur. Les points localisent les puits. Les données sur l'épaisseur sont de Van Tyne et al. *(1980), ainsi que la direction générale des courbes de 50 pieds (15 m). Les courbes de 50 pieds ont été soigneusement modifiées (sauf sur la carte de Java), afin d'être compatibles avec les courbes complémentaires de 10 pieds (3 m) de la présente étude. Les trois tiretés à l'intérieur de la zone tramée à points montrent la localisation des failles du RCL selon Van Tyne (1975). Les tiretés rapprochés qui s'étirent dans le comté d'Allegany montre les localisations de la zone centrale des principales failles proposées dans la présente étude.*

thicker values in the northeast occurs between two wells separated by ≈2.4 km; the location of the step in thickness occurs exactly in the locale of the southern projection of the CLF. The thickening to the east implies that either the fault was active during deposition of the Genesee Group, forming a growth fault, or that movement prior to Genesee time had formed an escarpment. In either case, the implied motion is down-on-the-east.

The original 15 m contour interval on the Sonyea Group isopach map also do not reveal any distinct effects of the CLF. However, wells located in Wyoming County show a thinning of the unit over the CLF, and a thickening of the unit to the east, as can be observed in the added supplemental contours and slightly modified 15 m contours (Fig. 13). The amount of thinning and thickening is on the order of 3-6 m (12.5% of the thickness of the unit).

The 30 m (100 feet) contour interval on isopach maps of the West Falls Group also do not reveal any effect of the CLF. The lack of sufficient data posted on the map restricts interpretations; however, wells in central Wyoming County on the CLF show an anomalously rapid thickening of the unit to the east of the CLF. The amount of increase is difficult to determine, because of the lack of well control, but a conservative estimate is about 8 m, or 3% of the total thickness of the unit.

The isopach map of the Java Formation is the only isopach map that clearly shows an effect of the CLF in the original contours (Fig. 13). The ≈8 m (25 feet) contour interval displays a prominent thinning immediately east of our proposed location of the central fault in southern-most Wyoming County. In contrast to the Upper Devonian intervals below the Java, the Java appears to thin east of the eastern fault of Van Tyne (1975), although the data are sparse (Fig. 13). Total anomalous relief is on the order of 8-9 m, which is 20% of the unit thickness in southern Wyoming County. Such thinning east of the central fault implies a reversal in the relative motion from earlier times: now it is down-on-the-west.

Isopach maps of black shales in the Perrysburg Formation (Van Tyne *et al.*, 1980k; Kamakaris and Van Tyne, 1980) are based on very little well control (eight wells and three wells, respectively, in the northern half of Allegany County), but the postings of thicknesses on Van Tyne *et al.*'s (1980k) map, and the generalized contours on Kamakaris and Van Tyne's (1980) map both suggest that the thickest black shales occur immediately southwest of the proposed extension of the CLF. Thus, the sense of motion along the main central fault in Perrysburg time may have been similar to that in Java time, down-on-the-west.

To summarize, isopach maps and cross sections of various Cambrian to Devonian units suggest that the CLF was active in Taconic times, in Queenston times, possibly in Helderberg times and in Acadian times, with the greatest differential deposition across the fault occurring during the Taconic and Acadian orogenies. Thus, it appears that when the continental plate is under relatively high stress, the CLF is reactivated. That such motion should occur during periods of high stress is to be expected if the deep CLF is actually a major suture of possible crustal dimensions. Other intraplate "deep" faults, such as the Bowling Green fault in Ohio (Onasch and Kahle, 1991), show a similar long-lived movement history. Because the plate is presently under stress, it is then not surprising that the CLF is seismically active.

The apparent reversal in relative sense-of-motion along the CLF during Late Devonian times (Fig. 13) may find an explanation in Figure 14. The black shales (*e.g.*, Geneseo, Rhinestreet) are traditionally viewed as indicating the central portion of the foreland basin. If this supposition is correct, then the basin axis moved west through Late Devonian time (Fig. 14), in response to continued loading by the westward advancing sedimentary wedge (the Catskill delta) and/or the thrusts "behind" (*i.e.*, east of) the sedimentary wedge. Thus, during Genesee Group time, the basin axis was located well east of the CLF, but in Dunkirk Shale time, the axis was located west of the CLF (Fig. 14). If movements along the CLF were in response to basin subsidence, then the relative motions on the fault should have been down-on-the-east in times when the basin lay east of the CLF, and down-to-the-west in times when the basin lay to the west of the CLF. In Figure 14, it is obvious that the observed reversal in motion occurred approximately at the time that the basin axis (as identified by the thickest section of black shale) passed by the CLF. Thus, the motion on the CLF in Late Devonian times appears to have recorded the westward advance of the foreland basin past the CLF.

CONCLUSIONS

Gas seeps located near the central fault of the CLF in southernmost Wyoming County were initiated during, or slightly after, the Saguenay event, 1988. Analyses of the gas demonstrate a Devonian shale source, and a nearby well suggests that the source may be as deep as ≈330 m. Thus, CLF fractures extending to depths of 300+ m were probably opened (or reopened) during the Saguenay event, allowing the gas to be vented.

Published data show that the CLF extends south from Lake Ontario to the Allegany County line. Offset on the fault is as large at the southern end of this section as anywhere else along the line, indicating the fault system does not diminish to the south. South of Pike, in southern Wyoming County, there were insufficient well-log data available for previous investigators to determine if the fault system continued farther south. The soil gas survey and analyses of new well logs indicate the CLF does continue into Allegany County; closely-spaced wells suggest that the central fault of the CLF is most probably a series of step faults, even in units above the Silurian evaporite section (although a monocline cannot be ruled out).

Growth-fault geometries of the CLF, as observed in isopach maps of various Cambrian to Devonian units, suggest that the CLF experienced motion during the Taconic and Acadian orogenies, when stress on the plate was relatively high. Detailed examination of the isopach maps, coupled with the proposed extrapolation of the position of the main central faults of the CLF, suggest that in Late Devonian times the CLF moved in response to foreland basin subsidence, and

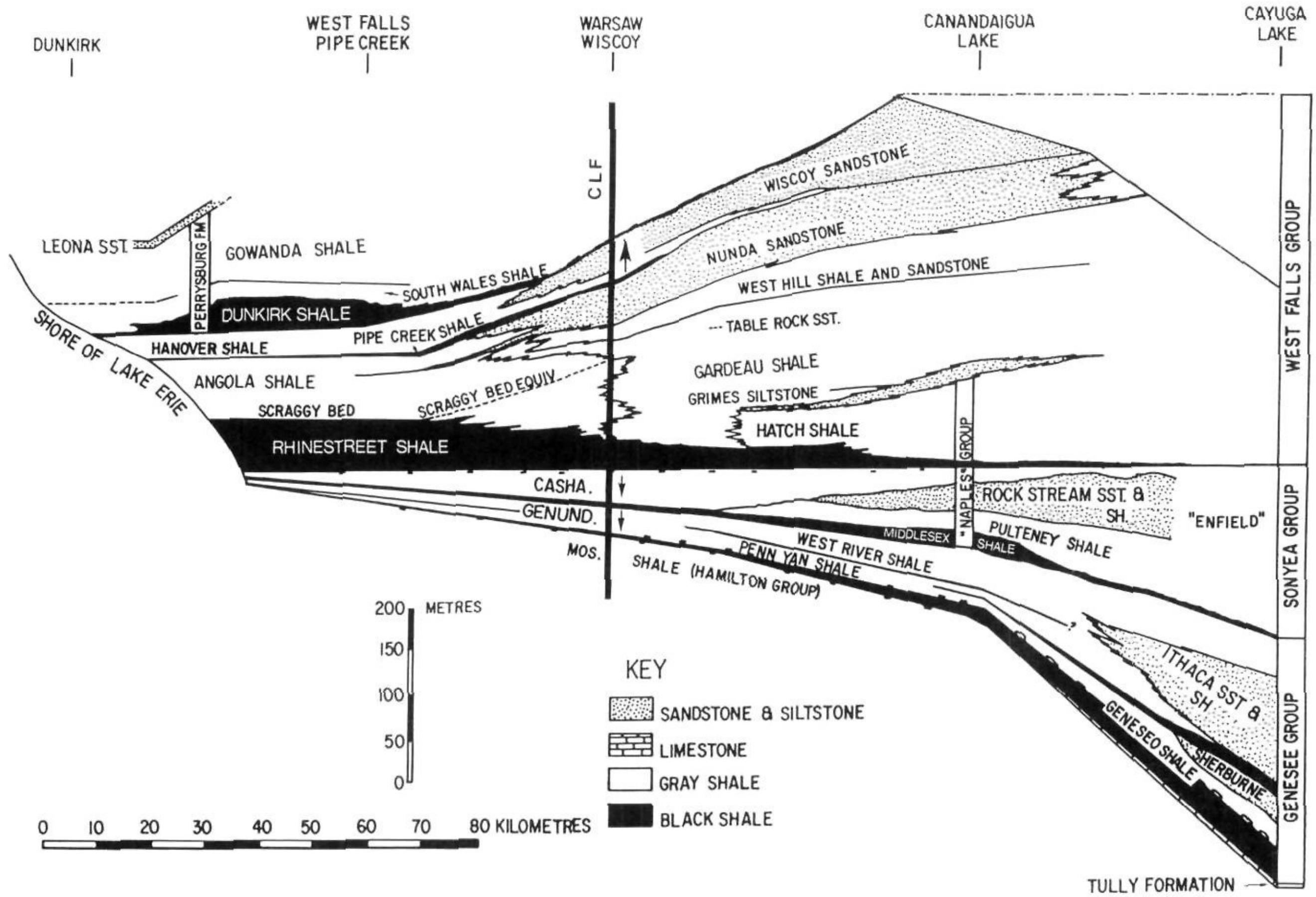


FIGURE 14. Stratigraphic cross-section with sense of motion indicated for the CLF. Arrows along CLF indicate deduced sense of motion for the various units (*e.g.*, a downward pointing arrow indicates a down-on-the-east sense of motion). Stratigraphic cross-section from Kirchgasser and House (1981); Johnson *et al.* (1985).

Coupe stratigraphique et sens du mouvement du RCL. Les flèches donnent le sens du mouvement des différentes unités (tiré de Kirchgasser et House, 1981; Johnson et al.*, 1985).*

that the CLF motion history actually recorded the passage of the foreland basin axis across the CLF. The fact that the CLF has such a long movement history in times of continental plate stress lends support to the supposition that, since the plate is presently under stress, the CLF is presently potentially seismically active.

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