responsible for many of these landslides are still active today and consequently most landslides areas are presently active (Christiansen, 1983; Sauer, 1983).

One of the most extensive areas of landslides within the region, and perhaps anywhere in Canada, occurs along the Manitoba Escarpment which rises in places 300 m in 10 km. Evidence of slumping is present along much of the escarpment but it is best displayed along the east and northeast side of Porcupine Hills (Wickenden, 1945; Scott and Brooker, 1968; Fig. 12.14). The disturbed zone is estimated to be 200 km^2 and appears to consist of four separate landslides. Individual landslides are typically 5 km wide across the slip planes and 10 km parallel to them. The upper one-third to one-half of each landslide consists of a series of parallel grabens, commonly containing long narrow lakes. The lower parts of the slides are hummocky and comprise mixed black Cretaceous shale and Pleistocene sediments. Cretaceous shales of the Favel and Vermilion River Formations, both containing layers of bentonite, occur along the base of the escarpment. Springs and seepage zones were observed in the toe area of minor slope failures that had occurred along valley walls of creeks that drain the northern part of the slide area (Scott and Brooker, 1968). The age and specific cause of the landslides are not known. The toe of the failure truncates the lower Campbell Beach of glacial Lake Agassiz, however, and thus a maximum age of 9.3 ka can be assigned to the failure. It is possible that the presence of bentonite seams and groundwater discharge may have contributed to instability. In addition, drawdown of water levels associated with the early Holocene draining of Lake Agassiz, may have been a significant triggering factor.

Flood hazards

Spring snowmelt is the main source of runoff and erosion in the Prairie region except for local, intense thunderstorms during summer months. Flooding is not a general problem because of the topographic configuration largely developed in response to Quaternary processes and events. Most large rivers are deeply incised and many areas are dotted with undrained sloughs which maximize groundwater recharge and minimize overland runoff. Risk of flooding, however, occurs in valley bottoms and in the lowlands of Manitoba where Red and Assiniboine rivers drain across the flat-floored Lake Agassiz Basin. Past floods in this basin have caused millions of dollars damage and loss of life. Flood risk potential is greatest during the spring and depends upon winter snow accumulation, rate of snowmelt, and precipitation during the snowmelt period. Governments have spent millions of dollars on the construction and maintenance of dykes, dams, and flood control programs.

The most impressive flood diversion project to date has been the Red River Floodway. It was excavated to carry floodwater around the city of Winnipeg and back into Red River near Lockport. The channel is 56.7 km long and construction involved moving 764×10^6 m^3 of material. The floodway is designed to carry a flow of 850 m^3/s which should protect Winnipeg from floods with a recurrence frequency of 1 in 160 years (Table 12.5). Since the beginning of operational use of the floodway in 1968 flood damage to the City of Winnipeg has been eliminated.

The Lake Agassiz plain has been further protected by a floodway between Assiniboine River and Lake Manitoba. This protects the city of Portage La Prairie, several villages, and a 90 km strip of flat farmland between Portage La Prairie and Winnipeg.

The Federal and Provincial Governments, in 1975, initiated a flood damage reduction program aimed at identifying flood risk areas and discouraging further development in areas subjected to periodic flooding. The program involves mapping of flood risk areas, flood forecasting systems, land use planning, works to control flows, and acquisition of property or easements to control further development in flood risk areas.

Solution collapse

Solution collapse is a potential hazard over wide areas of the Prairies that are underlain by evaporites. For example, southern Saskatchewan is underlain by about 250 000 km^2 of Devonian salt which is up to 200 m thick (Pearson, 1963). Dissolution of these salt beds has been a continuous process since their deposition, resulting in the formation of collapsed structures in overlying beds (Gendzwill and Hajnal, 1971). Crater Lake in southeastern Saskatchewan, the youngest known collapse structure, dates possibly at 13.6 ka (Christiansen, 1971). The lack of abundant collapse structures in the present surface suggests that this process does not pose a significant hazard.

GEOLOGICAL HAZARDS IN CENTRAL AND EASTERN CANADA

Jacques Locat and Jean-Yves Chagnon

Quaternary geology finds similar applications to civil engineering, mining, and hydrology in Ontario, Quebec, and the Atlantic Provinces as it does in the Prairies. Differing physiography and Quaternary histories, especially during the Late Wisconsinan glaciation, however, make for divergent geological hazards between these two regions. It is the management of these hazards that is emphasized in the following discussion of Quaternary geology and planning in eastern Canada.

A geological hazard is defined as a possible event or unpredicted geological condition that is unwanted or undesired. It excludes such things as foundation settlement problems, disposal of toxic wastes, or groundwater supply problems. Natural hazards encountered in Ontario, Quebec, and the Atlantic Provinces are predominantly related to crustal deformation, mass movement, flooding, and erosion. Submarine processes, such as iceberg scour and coastal erosion, are considered in Volume 2 of the Geology of Canada (Keen and Williams, 1989).

Pertinent Quaternary events

In eastern Canada, many geological hazards are directly related to the Quaternary geological history of the area. The preglacial physiography and the processes of glaciation have

Locat, J. and Chagnon, J-Y.
1989: Geological hazards in central and eastern Canada; in Chapter 12 of Quaternary Geology of Canada and Greenland, R.J. Fulton (ed.); Geological Survey of Canada, Geology of Canada, no. 1 (also Geological Society of America, The Geology of North America, v. K-1).

controlled the emplacement of the Quaternary deposits and these play a large role in determining the location of many hazards.

The downwarping of the crust, caused by the weight of the Laurentide Ice Sheet, depressed areas such as St. Lawrence and lower Ottawa valleys below sea level so that upon retreat of the ice they were submerged by the sea. Ice damming and differential uplift during glacier retreat resulted in development of many large glacial lakes (e.g., lakes Iroquois, Algonquin, Ojibway). These basins were the loci of fine grained sedimentation. Crustal unloading initiated isostatic uplift (Quinlan, 1984) as evidenced by the emergence above sea level of most coastal areas of eastern Canada, and St. Lawrence and lower Ottawa valleys. Isostatic uplift of lake and marine basins led to stream incision of fine grained marine and lacustrine sediments, which in turn has triggered landsliding (Locat, 1977). Even where these deposits have not been incised, they remain metastable and create problems for the engineering of buildings and road foundations (Smalley, 1979; Quigley, 1980; Torrance, 1983; Locat et al., 1984).

Vertical movement has also caused faulting of Quaternary sediments and a reactivation of ancient vertical faults (Adams, 1981). In some areas, such as the Hudson Bay Lowland (Hardy, 1976; Andrews and Peltier, 1989) crustal uplift continues today.

Table 12.5. Maximum discharge and return period for the fifteen greatest floods on record on Red River at Winnipeg

Date of maximum discharge	Estimated maximum discharge at Redwood Bridge (1000 m³/s)	Probable return period (years)
1826 May 21	6.37 E	667
1852 May 21	4.67 E	147
1861 May 8	3.54 E	45
1979 May 10	3.00 *	26
1950 May 19	2.93	23
1974 April 24	2.93 *	23
1966 April 14	2.50	14
1970 May 3	2.26 *	10
1882 May 3	2.26	10
1969 May 1	2.17 *	9
1916 April 22	2.02	8
1948 April 30	1.95	7
1956 April 27	1.95	7
1904 April 24	1.87	6
1897 April 27	1.83	

E - Estimated
* computed natural flow without existing control works

Tectonic activity and seismicity

Earthquakes are frequent in eastern Canada (Leblanc, 1981; Basham and Adams, 1984). Major ones were noted as early as 1534-1535 (Smith, 1962) and tremors of greater than magnitude 7 on the Richter scale have occurred periodically during the last 300 years. A well known example is the Grand Banks Earthquake of 1929 (Basham and Adams, 1982; Keen et al., 1989) which triggered an enormous landslide on the continental slope off Newfoundland. Table 12.6 lists recent major earthquakes in eastern Canada and Figure 12.15 shows locations of seismic activity. Additional information on zones of intense earthquake activity such as

Table 12.6. Major earthquakes of eastern Canada

Date	Epicentre	Intensity	Magnitude	Remarks
1534-1535	Les Éboulements	IX-X		
June 1638	St. Lawrence Valley	IX		Near mouth of Saguenay River
Feb. 1663	La Malbaie	X		Greatest ground shaking episode recorded in Quebec
Sept. 1732	Montréal	VIII	5.6-6.0	Resulted in one death and damage or destruction of 300 homes
Dec. 1791	Baie-St-Paul	VIII		
Oct. 1860	Rivière-Ouelle	VIII-IX		Vibrations felt over an area of 1.8×10^6 km²
Oct. 1870	Baie-St-Paul	IX		
28 Feb. 1925	La Malbaie	IX		Caused considerable damage in Québec, Trois-Rivières, and Shawinigan
18 Nov. 1929	Grand Banks		7	
9 Jan. 1982	Miramichi		5.7	

the Mount Tremblant and Miramichi areas are available in Horner et al. (1979) and Basham and Adams (1984), respectively. These earthquakes are expressions of tectonic activity believed to be partly related to plate tectonic movements and possibly also to vertical uplift resulting from the stress relief caused by the melting of the last ice sheet. This strain energy appears to be dissipating in zones of crustal weakness. For example, the Charlevoix area of Quebec was the locus of a meteorite impact 350 Ma ago (Rondot, 1968; Roy and Duberger, 1983). The strain energy imparted by this impact is coupled with the regional tectonic stress to induce in situ principal stress ratios greater than 1 ($\sigma h/\sigma v$, $v<1$) in many areas. These deviatoric stresses can exceed the shear strength of the rock, resulting in popouts (White et al., 1974; Durand and Ballivy, 1974). Compilations of seismicity and neotectonism in eastern Canada have been made by Adams (1981) and Chagnon and Locat (1984), and a new compilation is being prepared by Adams for the neotectonics volume of the Geological Society of America's Geology of North America series.

Mass movement

Many landslides have occurred and will continue to occur in the fine grained sediments of eastern Canada. The most recent major ones are listed in Table 12.7. Loss of life has resulted in many cases from these mass movements. In the last two decades major studies were undertaken to shed more light on the causes of landslides and to attempt some measure of prediction (Chagnon, 1968; Tavenas et al., 1971; Mitchell and Markell, 1974; Quigley, 1980; Lebuis et al., 1983; Locat et al., 1984; Lefebvre, 1984). Natural mass movements are not entirely restricted to Quaternary sediments but also occur locally in rock materials (Dionne, 1969a).

Landslides in soft clay

Landslides of more than one type occur in soft sediments (Fig. 12.16-12.18). Depending on soil properties, deposit stratigraphy, and underlying topography, failures can be a simple block rotation or a large earthflow. Stability analysis of the first rupture can be carried out easily as a routine measure (Lefebvre, 1981), but much remains to be done in the prediction of landslides in time and space (Locat et al., 1984). Mapping techniques for areas prone to landslide failure have been developed for Ontario (Klugman and Chung, 1976) and Quebec (Lebuis et al., 1983). Carson and Bovis (1989) also discuss flowslides in marine clay in another part of this volume.

The major landslides of eastern Canada are found in the so-called sensitive clays located primarily in St. Lawrence, lower Ottawa, and adjacent tributary valleys.

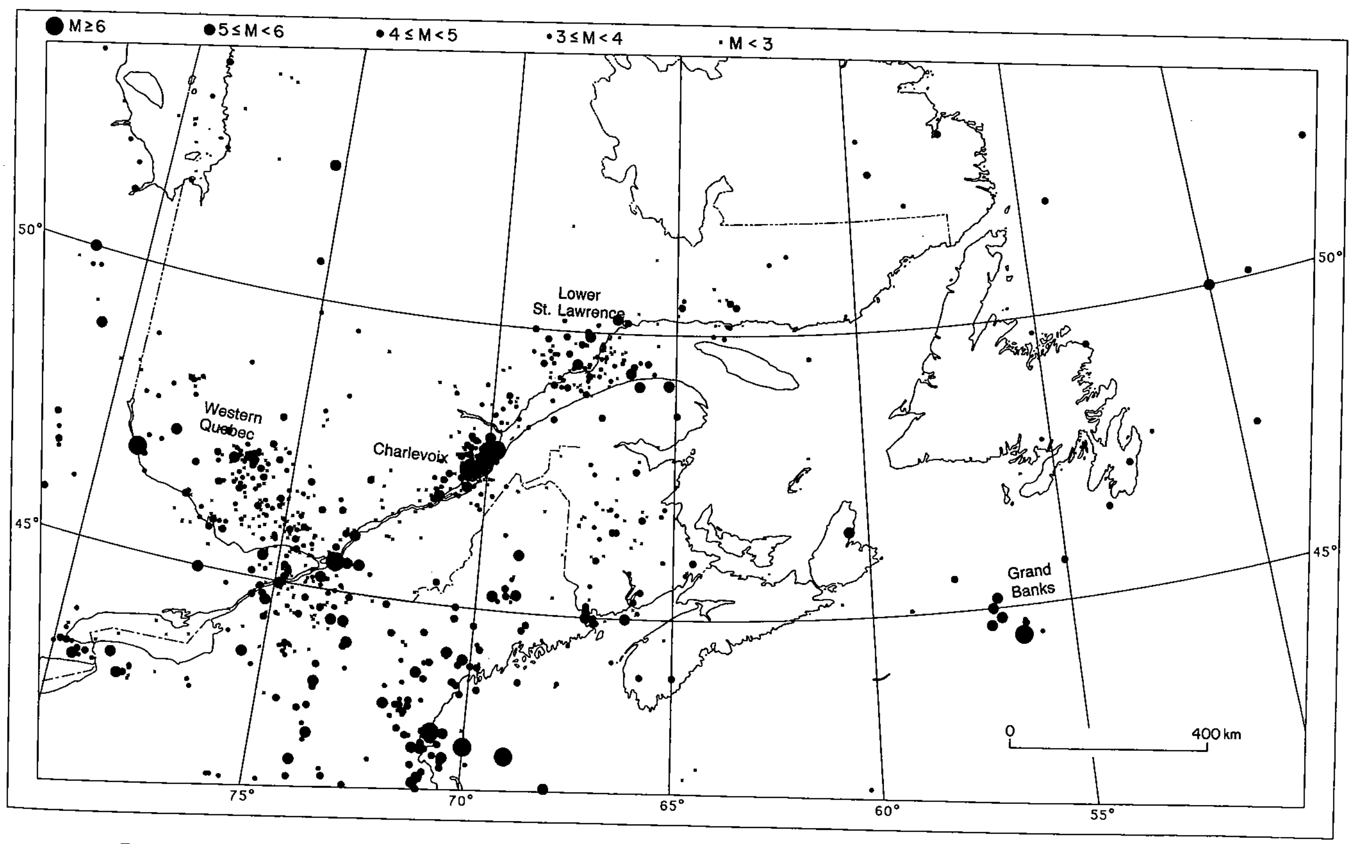

Figure 12.15. Locations of earthquake epicentres and magnitude of earthquakes in eastern Canada and adjacent United States (from Geophysics Division, Geological Survey of Canada).

Quigley (1980) and Torrance (1983) gave a full account of the behaviour of these clays. Torrance (1974), Locat (1982), and Locat and Lefebvre (1986) discussed the role that salts and their leaching play in promoting sensitivity in marine clays. The most sensitive soils are the marine clayey silts (muds) flanking the Canadian Shield. These were deposited from glacial meltwater in brackish waters at a high sedimentation rate. Consequently, these soils are commonly stratified with alternate layers of sandy silts and clayey silts. Stratification aids the leaching process (Donovan and Lajoie, 1979; Locat, 1982) in addition to providing potential zones of high pore pressures. Lowering of the water table by incision related to the glacial isostatic uplift of these areas enhanced leaching of the salts and hence a significant reduction in the liquidity index (or remoulded strength). Mitchell and Klugman (1979) have recently reviewed many aspects of mass instabilities in sensitive clays.

Rock slides and rock avalanches

Rock slides or avalanches are much less frequent than other types of landslides in eastern Canada and are restricted to areas of high relief. An example of a failure of this type occurred near Saint-Fabien-sur-Mer, about 200 km east of Québec, in 1967 (Dionne, 1969a). Many small areas of rock

Table 12.7. Major landslides of eastern Canada

Date	Place	Area or volume	Victims
April 1840	Maskinongé (Co. Maskinongé, Que.)	35 ha	
27 April 1894	St-Alban (Co. Portneuf, Que.)	650 ha	4
Sept. 1895	St-Luc de Vincennes (Co. Champlain, Que.)	2 ha	5
May 1898	St-Thuribe, Riv. Blance (Co. Portneuf, Que.)	35 ha	1
6 April 1908	N.D. -de-la-Salette (Co. Papineau, Que.)	40 ha	33
April 1925	Portneuf (Co. Portneuf, Que.)	1 ha	
24 July 1935	St-Vallier (Co. Bellechasse, Que.)	6 ha	
Sept. 1938	Ste-Geneviève de Batiscan (Co. Champlain, Que.)	6 ha	
18 May 1945	St-Louis (Co. Richelieu, Que.)	4.5 ha	
12 Nov. 1955	Nicolet (Co. Nicolet, Que.)	190×10^3 m^3	3
23 May 1962	Riv. Toulnustouc (Co. Saguenay, Que.)	3.8×10^6 m^3	8
10 May 1963 11 Dec. 1963	St-Joachim-de-Tourelle (Co. Rimouski, Que.)	6.9×10^3 m^3	
13 June 1964	Desbiens (Co. Lac St-Jean, Que.)	24.5×10^3 m3	4
15 April 1969	Louiseville (Co. Maskinongé, Que).	?	
4 May 1971	St-Jean-Vianney (Co. Chicoutimi, Que.)	32 ha 76 x 109 m^3	31
12 May 1972	South Nation River (Ontario)	?	

instability are found along highways of the Gaspésie (A. Drolet, Ministère des Transports du Québec, personal communication, 1979) and parts of the Maritime Provinces. In addition, local rock avalanches have been a persistent and serious problem. For example, between 1836 and 1889 below the scarp of Cap Diamant, in Québec, more than 100 persons were killed in rock avalanches (Chagnon et al., 1979). No general survey, however, has been made of rock slides and avalanches in eastern Canada.

Erosion and flood hazards

Hazards created by the action of both wind and water are included here. Stream and river flooding occurs particularly during spring snowmelt; wind erosion is a problem in some areas (on Iles-de-la-Madeleine, winds of more than 100 km/h are common); wind can also cause flooding along lake or sea shores where the fetch is long enough to permit buildup of storm tides; and, of course, wind and water combine to cause wave erosion in coastal areas.

Erosion and sedimentation

Shoreline erosion is a common problem in areas of Quaternary sediments throughout the Great Lakes-St. Lawrence system. Land loss due to this process is a particularly severe problem along the shores of Lake Erie (Gelinas, 1974), but it is also a persistant problem throughout the Great Lakes basin (Rukavina, 1976, 1978, 1982). Rivers and streams downcutting in fine grained sediments, and waves and floating ice action erode shore areas, causing bank instabilities (e.g., at the delta of the St. Lawrence near Sorel) in wider reaches of St. Lawrence River (Dionne, 1969b, 1970; Troude et al., 1983). Marine coastal areas exposed to the

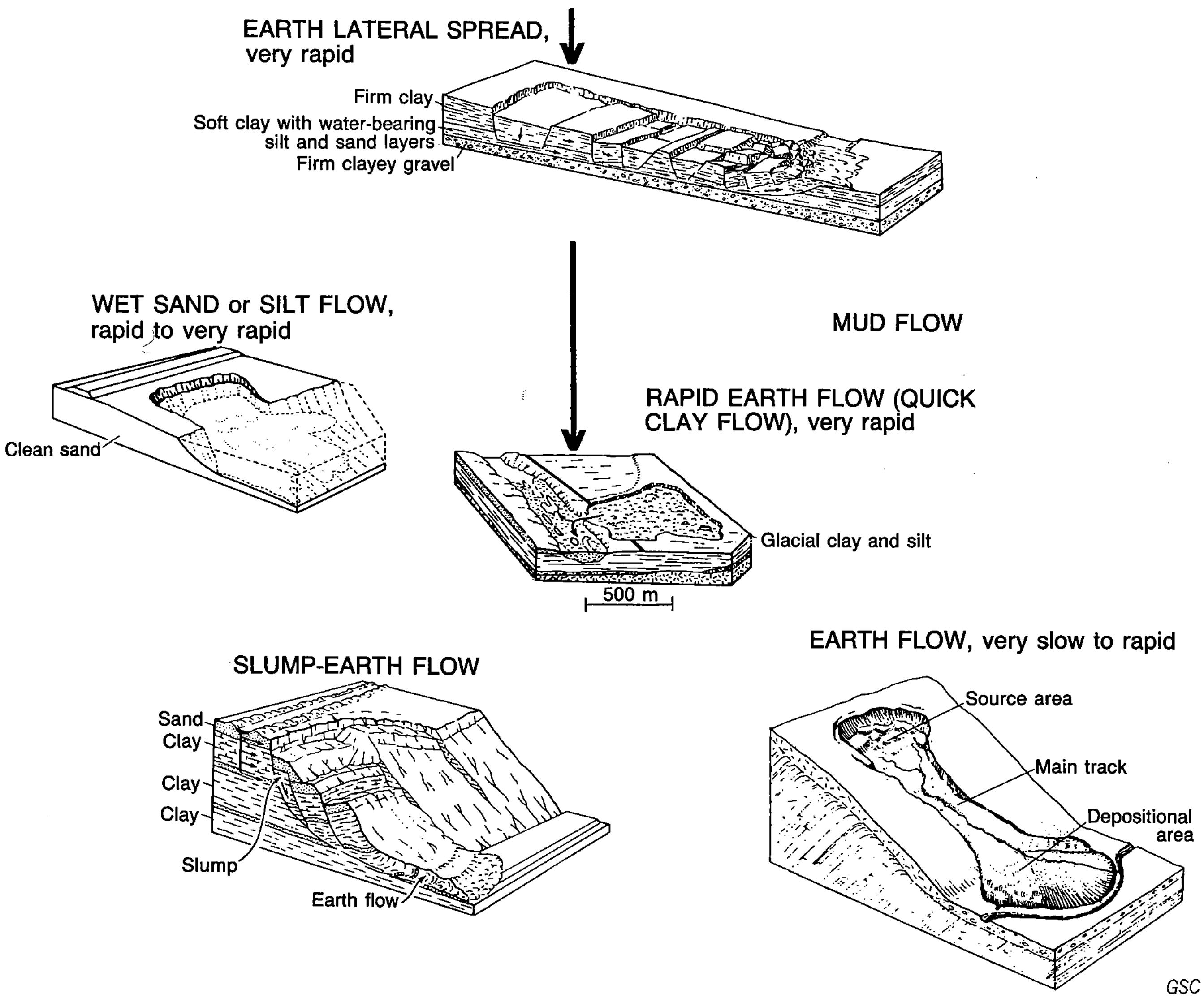

Figure 12.16. Types of landslides occurring in eastern Canada (from Varnes, 1978).

combination of high winds and longshore currents, such as Îles-de-la-Madeleine, Prince Edward Island, and parts of Nova Scotia, suffer extensive erosion and coastal retreat (Owens and Drapeau, 1973). Additional information on coastal erosion, in both marine and fresh water environments, is available in three conference reports (National Research Council, 1979, 1982; McCann, 1980) and is discussed further in a separate volume (no. 2) of this series (Keen and Williams, 1989). In a few areas intense erosion has caused rapid sedimentation in adjacent areas (Greenwood and Davidson-Arnott, 1979; Greenwood and Keay, 1979); for example, at Rivière Pentecôte near Baie-Comeau the intervention of man along the river course has resulted in the siltation of the entire bay which was formerly a deep water port. The material involved is a loose deltaic sand which is common along the north shore of the St. Lawrence estuary and gulf (Dredge and Thom, 1976).

Floods

In local areas of eastern Canada the risk of flood hazard is high. Such areas are subject to periodic torrential rains (occasionally associated with dying hurricanes) and heavy spring rains and snowmelt which commonly occur before breakup of river ice. Floods caused by ice jams on St. Lawrence River during snowmelt are of common occurrence and similar problems plague low-lying areas adjacent to many other rivers and streams. Shipping on the St. Lawrence Seaway helps maintain an open channel and has in part alleviated ice jam problems on St. Lawrence River. Little can be done in other areas prone to this type of flooding, however, other than to control development on floodplains and to attempt to blast ice jams loose when they occur. Small conservation reservoirs built on many streams throughout southern Ontario generally control "normal" flooding but are of little effect during a catastrophic storm, such as that which resulted in 78 deaths through flooding of Holland Marsh north of Toronto in October 1954.

Karst

Many areas of eastern Canada are underlain by limestone and several areas are underlain by evaporites in which solution features can be or have been developed (Roberge, 1977). Karst development is well known on Îles-de-la-Madeleine and in some parts of Nova Scotia and Newfoundland. These underground openings, which are difficult to locate, pose a problem to urban and road development. In the Québec city area alone many kilometres of underground passages can be traced, especially in the Boischatel area (Société québécoise de spéléologie, 1980). At Îles-de-la-Madeleine the dissolution of gypsum is observed at the surface by the presence of depressions or dolines. Caverns are also found in parts of Ontario (Cowell and Ford, 1980). Karst features locally pose engineering problems but as active collapse is not occurring today, karst processes do not appear to constitute a significant hazard.

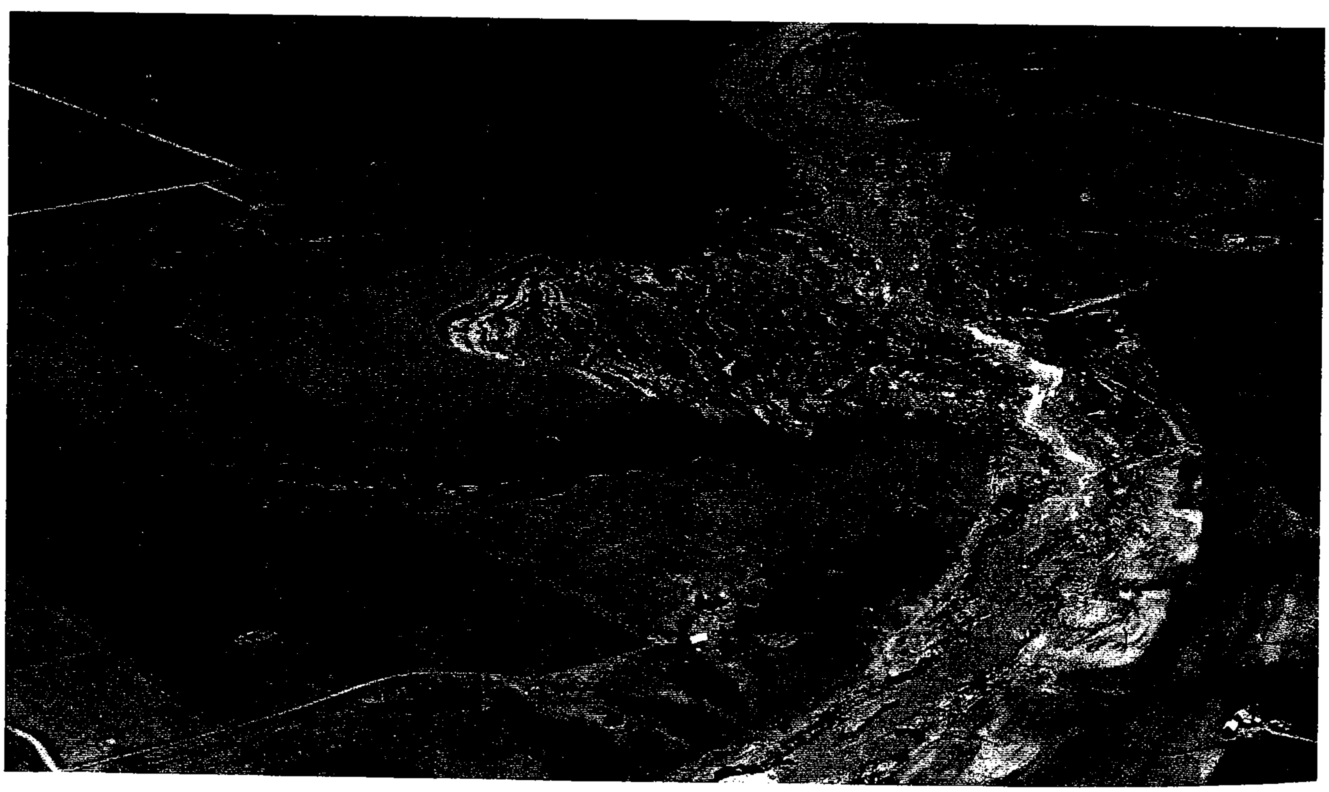

Figure 12.17. The South Nation River Landslide, May 12, 1972. Courtesy of C. Malcolm Photography, Cornwall.