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Late Quaternary faulting in the Rouge River Valley, southern Ontario: Seismotectonic or glaciotectonic?

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ABSTRACT

A GSC team examined exposures of folded and faulted bedrock and Quaternary sediments in the Rouge River Valley of metropolitan Toronto, reported to exhibit evidence for neotectonic faulting (Mohajer et al., 1992; *Geology*, v. 20, p. 1003–1006). While the published descriptions are basically sound, we consider their interpretation to be open to dispute. From an examination of mechanisms which could account for the folding and faulting, we believe that glaciotectonic processes are sufficient to explain the observed features, in which case they have no seismotectonic implications. If, in the unlikely case they represent seismogenic faulting, their antiquity suggests that they have little relevance for determining the likelihood of future large earthquakes in the region.

RÉSUMÉ

Une équipe de la CGC a examiné des affleurements de substratum rocheux plissé et faillé et de sédiments quaternaires dans la vallée de la rivière Rouge, dans la région métropolitaine de Toronto, endroit où l'on aurais récemment relevé des indices de déformation néotectonique (Mohajer et al., 1992; *Geology*, v. 20, pp. 1003-1006). Bien que les descriptions publiées soient, pour la plupart, exactes, leur interprétation demeure contestée. Après avoir examiné les mécanismes qui auraient pu créer de tels plissements et de telles failles, les auteurs croient que des processus glaciotectoniques suffisent à expliquer les déformations observées et que, par conséquent, ces déformations n'ont aucune importance séismo-tectonique. Même si elles représentaient une fracturation séismogène, leur très grand âge porte à croire qu'elles n'aideront pas à déterminer l'éventualité de grands séismes dans la région.

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INTRODUCTION

In 1991 and early 1992 A. Mohajer of Seismican Geophysical Ltd in Toronto, and his colleagues at the Scarborough Campus of the University of Toronto reported faulting from the Rouge River at several meetings. In October 1992, prior to a MAGNEC (Multi-Agency Group for Neotectonics in Eastern Canada) meeting at Scarborough, C. Fenton, an author of this report, participated in a half-day field trip to the sites. In November 1992 a paper appeared in the journal *Geology* (Mohajer et al., 1992, referred to hereinafter as MER92) that described the faulting and concluded that although the origin of the faults was not yet well established "their development in the recent geological past has important implications for regional seismic hazard assessment, because they occur within 7 km of the Pickering nuclear power plant". The basic thrust (though carefully worded) of the MER92 paper is that the faults were produced by one or more prehistoric earthquakes of major significance to an evaluation of contemporary seismic hazard.

The publication of the scientific paper was accompanied by press attention (e.g., Ottawa Citizen, 1 November 1992, page A1) suggesting that the seismic hazard of southern Ontario had been underestimated and that the safety of the Pickering Nuclear plant was threatened (Fig. 1).

In response to the MER92 paper and the concern expressed by the media, GSC scientists decided to use their expertize to evaluate the exposures and their implications for earthquake hazard. A field visit was arranged quickly, and was necessarily brief because of the time of year (December). Our observations and interpretations are made chiefly in the context of the MER92 paper.

FIELD VISIT ON 1 DECEMBER 1992.

GSC Participants: J. Adams, (Geophysics Division), L. Dredge (Terrain Sciences Division), C. Fenton (GD), D. Grant (TSD), W. Shilts (Mineral Resources Division), B. Todd (TSD), J. Wu (Continental Geoscience Division).

Additional scientists present during the field visit: P. Karrow (University of Waterloo), A. Mohajer (Seismican, Toronto), N. Eyles, C. Rogojina, and A. Pugin (all Scarborough College, University of Toronto).

The GSC members spent half a day at the sites, half an hour at Site 10 on the Little Rouge River (without Shilts), and the remainder of the afternoon at the Rouge River sections (Site 1, Site A, and Site 3; see Fig. 2) with Shilts and the non-GSC participants. The weather during the work was bright overcast, with a temperature around 0°C, and occasional snow flurries. The river was low enough to permit it to be waded in rubber knee boots.

OBSERVATIONS

We looked at four sections, Site 10 on the Little Rouge River, and Sites 1, A, and 3 on the Rouge River (see Fig. 2). Bedrock is exposed discontinuously along the Rouge and Little Rouge rivers (see Map 2077 in Karrow, 1967, and Fig. 2)[1]. The general impression is that the bedrock surface is gently undulating and that the rivers have intersected this surface at different elevations at different places and have cut down into it to varying depths. Site 10 is one of the higher-elevation exposures, with 3 m of bedrock exposed. At Site 3 (discussed below) bedrock is only exposed in the lower 0.5 m of the section.

Site 10 – Bedrock fractures

At Site 10 (Fig. 2) the Little Rouge River has cut down through more than 20 m of Quaternary gravel and till (exposed at river level at the upstream end of the outcrop) and a further 3 m into bedrock. The bedrock is a black shale of the Lower Paleozoic Whitby Formation. The shale is fissile, relatively poorly lithified (but not plastic), contains rare concretions, and is well bedded, but lacks distinctive marker horizons except for a few very thin, light-coloured silt laminae.

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[1] **Note: site numbers refer to our Figure 2.** There appears to be an error in the MER92 paper. On the inset of MER92's figure 2, Site 3, which is extensively referred to in the text, is shown as forming the left (or northeast) bank of the river and representing bedrock exposure only. Our field visit determined that their "Site 3" is actually the one on the right (or south) bank labelled "2" which includes both Quaternary sediments and exposed bedrock (see our annotations on Fig. 2). Note, therefore that the dashed line on Figure 2 inset does not join the two outcrops that show faulting. MER92's figure 2 also does not show a large Quaternary exposure on the right bank, 200 m downstream of the Twyn Rivers Drive bridge and 100 m upstream from Site 3; this we have termed Site A in the following text and on our Figure 2.

The shale is cut by a number of steeply-dipping to vertical fractures striking between 110° and 120°, and there is a very poorly developed, conjugate, nearly orthogonal set. The prominent joints are variably spaced, but on average 2–3 m apart. The joint surfaces are generally iron-stained and without evidence of significant movement, except for one joint that offset a silt marker horizon by about 10 mm, up to the south. Minor joints with a slightly more northward strike occur close (100 mm) to the main joints. These joints converge toward the adjacent main joint; at the point of convergence a new minor joint begins 100 mm from the main joint and also converges on the main joint.

Thin, 1–2-mm-wide, calcite veins fill some of the joints. Crystal alignment, indicating growth direction within the calcite infilling, is perpendicular to the joint walls, suggesting tensional stress acting normal to the joint walls during calcite deposition. The visible crystallinity suggests that the calcite was not deposited very close to the surface. There is no evidence for shear displacement along any of these fractures. The main joints can be traced continuously to the top of the bedrock outcrop, but, in two shallow pits which had been excavated before our arrival in the silty till and overlying gravel above the trend of one prominent joint, we could not determine whether the joints continued into the till.

Site 1 – Faulting of Quaternary deposits

Site 1 is just upstream of the Twyn Rivers Drive bridge over the Rouge River (Fig. 2). This section was first described by Karrow (1967, section F138). It is a 25-m-high, near-vertical cutbank kept fairly well exposed by undercutting, slope wash, and gullying. Four Quaternary formations are exposed over bedrock (which Eyles said crops out in the river bed but was not seen at the time of our visit): at river level, Don Formation, an organic silt of last interglacial age; from river level to halfway up the section, Scarborough Formation, a proglacial lacustrine sand; making up most of the top half of the section and thickening downstream, Halton Till of Late Wisconsinan age; and as a surface cover, postglacial sand and gravel deposited in Glacial Lake Iroquois. The last unit is not shown on figure 3 of MER92, but we have added it schematically to a copy of their figure (Fig. 3).

At the time of our visit, vegetation and slope-wash deposits partly obscured the section compared to its relatively good exposure during the summer of 1992 and the October 1992 MAGNEC visit. Nonetheless, differential erosion revealed the faults shown in MER92. In addition, other fractures at the south end of the exposure were visible in the lower Scarborough Formation as sharp, sub-vertical narrow grooves on the surface of the outcrop. The amounts of vertical displacement on some of the faults could be determined from offsets of the silty layers in the Scarborough Formation which, because of their moisture content, were accentuated by bands of moss and other vegetation. The continuity of the faults and fractures and the vertical displacements could be easily seen from our distant vantage point on the far side of the river. We did not inspect this section from the near bank.

We were told that Figure 3 was constructed by cutting steps in the sloping outcrop and marking the position of the faults. MER92 reports that the faults strike east-west to west-northwest, that is to say, approximately perpendicular to the exposure. In our opinion, the figure could have been reliably drawn by tracing the features from a series of photographs (standard practice in Quaternary geology), supplemented by examination of certain parts of the outcrop to establish the amount of offset and the strike of the faults. Nonetheless, we judge Figure 3 to be a good representation of most of the faults present in the exposure.

We could observe that the base of the Halton Till lacked any fault offsets comparable to those in the Scarborough Formation, and were told that none of the faults extends into the Halton Till or into the overlying postglacial sediments. The base of the Halton Till is an erosional unconformity which truncates the Scarborough Formation. The faulting is thus inferred to have been produced before the final deposition of the Halton Till. We were further informed that the displacement along individual faults is constant throughout their total vertical extent within the Scarborough Formation. Eyles told Shilts there are sand dykes or volcanoes in the Scarborough Formation at this site, which he felt may indicate that the faulting was abrupt, and told Adams that sand from the underlying Don Formation had been injected up some of the faults.

Site A – Folding and Faulting of Quaternary deposits

Site A, the downstream end of which is immediately upstream of Site 3 (Fig. 2), is a ≈100-m-long, ≈20-m-high cutbank with Don Formation at the base and chiefly Scarborough Formation above. Karrow (1967, section F137) described 'Leaside Till' (≈Halton Till, see later discussion) at the top of the section. At the time of Karrow's examination the lower 8 m of the section was covered; when we visited the site, the upper part of the section was covered. The Don Formation is an indurated, blocky, dark grey, silty sand and mud which here, as elsewhere, closely resembles the shale bedrock, from which it is partly derived. At this exposure, the lower part of the Scarborough Formation, in contrast, is a compact, indurated dark-brown mud with a good horizontal stratification and bedding-plane fissility. Higher in the section, and elsewhere in the Toronto area, the Scarborough Formation is sandier.

During our visit[2] much of the section was obscured by slope debris, but at the downstream end of the exposure, where the river had cleaned off the lower few metres, it was possible to see: 1) several thrust faults within the Don Formation at the base of the outcrop (these indicate movement to the east or northeast); and 2) a large fold in the Scarborough Formation. The amplitude of the fold decreases downwards, but it apparently also involves the underlying Don Formation as those beds are higher above river level in the core of the fold than in exposures upstream or downstream. Bedrock was not seen, but based on the thinness of the Don Formation nearby, is thought to be only a little below river level.

In about 1980, Floyd Rutledge (a geologist working for Ontario Hydro) discovered a large fold with an axial trend of about 120^0 , involving thrusting towards the northeast, in the upstream part of the Site A exposure (J. Bowlby, pers. comm. to Adams, 1981/02/17). This second fold is now obscured by slope debris, though the thickness of slumped material is thin enough that the structure could be excavated and mapped (P. Karrow, pers. comm. 1992). The fold was seen by John Bowlby, Joe Wallach, Owen White, and Paul Karrow at various times in the early 1980s (and by Adams in 1981). At the time, it was thought possible that the fold could be a glaciotectonic feature or a deeply-buried stress-relief pop-up, but there was no consensus (P. Karrow, pers. comm. 1992). In 1981 Wallach gave Adams copies of photographic slides showing bedrock dragged up into the Quaternary sequence on the sole of a thrust in the core of the fold (Fig. 4). Although superficially similar to the overlying Don Formation, this material is identified as contorted shale by its characteristic red-brown (subaerial) weathering (see below).

Interpretation. That deformation decreases downwards is not definitive of the causal mechanism because both glacial loading effects and stress-relief features, such as pop-ups, attenuate in amplitude downwards. However, the large amount of shortening in the folds (estimated to be at ≥5–10 m, or >20%) rules out an origin by bedrock stress relief. Eyles was of the opinion that the deformation was caused by glaciotectonic ice-push. Those of the GSC team familiar with such structures share this interpretation.

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[2] Although the exposures at Site A and Site 3 were not continuous at the time of our December 1992 visit, being separated by tree-covered slumped debris, subsequent erosion in March 1993 uncovered the obscured segment between the two, and they are now one continuous exposure. Our report was completed before this new exposure was revealed.

Site 3 – Bedrock and Quaternary faulting

Site 3 (Fig. 2) is the most important exposure because faults offset both the Paleozoic Whitby Shale, which is exposed at and slightly above river level, and part of the Quaternary sequence. The youngest material affected by the faults is the Scarborough Formation. Unfaulted postglacial stream gravels cap the section and truncate both the underlying Scarborough Formation and the faults. The overall structure is that of a series of grabens with bounding faults striking 110° (Fig. 5). Despite the downfaulting, the bedrock is higher at this site than it is upstream. Although the shale bedrock and the overlying Don Formation are similar in colour, stratification, and degree of induration, the upper part of the shale bedrock characteristically has blocky fractures with reddish-orange colouration (due to subaerial weathering prior to the deposition of the Don Formation), whereas the Don Formation contains lignite blebs and wood fragments, together with a few Precambrian glacial erratics near its base.

The exposure at the time of our visit was essentially as depicted in MER92, except that the upper part of the exposure at the northeast (downstream) end was obscured by thin slope deposits and that bedrock was newly exposed toward the upstream end of the outcrop (as annotated in our Fig. 5). The lower part of the Quaternary sequence is clearly displaced against the bedrock. The faults mapped by MER92 could be identified, and the sense and amounts of offset roughly confirmed. If the fault strikes recorded in MER92 are representative, the faults cut the exposure at an angle of about 45°. This could be confirmed in a few cases where river erosion had plucked off one side of the fault. We did not, however, attempt to verify the strikes, because it would have required considerable excavation to expose the fracture planes for a sufficient depth into the face to get reliable measurements of attitude.

The faults are sharp, with abrupt offsets and no adjacent plastic deformation, even within the clayey parts of the Scarborough Formation. Offset is of the order of 5–10 cm on individual faults (the overall offset was not measured nor mentioned by any of the MER92 authors during the fieldtrip). One fault (the third major fault from the left side of Fig. 5) is shown by MER92 as having downward-decreasing offset, inconsistent with faulting from below, but we realized this only after our return to Ottawa and were unable to verify it. The fault planes are generally clean and without gouge, slickensides or brecciation, although it was noted that several of the faults had a thin coating of yellowish-brown iron hydroxide, which is typically produced by subaerial weathering. In bedrock, the normal faults were observed to terminate against open fractures striking 210^0 to 220^0, presumably fractures belonging to the conjugate joint set. This implies the joint surfaces acted as transfer faults, and their opening suggests the extensional deformation acted in a direction slightly oblique to NNE.

SUMMARY OF OBSERVATIONS

The faulting:

- **affects both bedrock and Quaternary sediments**
- **is sharp** (without brecciation, slickensides or other fault textures)
- **in bedrock is dominantly normal**
- **involves a large amount of extension in the NNE direction**
- **has constant throw from bottom to top** (except as shown on Fig. 5)
- **shows no evidence for more than one episode**
- **pre-dates the end of the last glacial advance**
- **trends roughly WNW-ESE**
- **occurs in two outcrops 300 m apart** (and on a WNW trend)
- **is in close proximity to Site A, which shows glaciotectonic thrusting of bedrock and folding and faulting of Quaternary sediments**

INTERPRETATION

Age of faulting

The age of the faulting can be bracketed to sometime during or after the deposition of the Scarborough Formation and before deposition of the upper part of the Halton Till. The lower bound is inferred from the fact that the faults cut the whole of the exposed Scarborough Formation at Sites 1 and 3, although it must be noted that at both sites the upper part of the formation is missing because the top contact is an erosional surface. At Site 1, where the greatest thickness of Scarborough Formation is exposed, the faults are said to have constant offset from base to top (Eyles, pers. comm., 1992). The top of the Scarborough Formation has been eroded, and therefore the age of the faulting is late-Scarborough or younger. [It may be important to note that glacial erratics of Precambrian lithology in the laminated sediments at the base of the Don Formation indicate the occurrence of an older glaciation prior to the faulting.] The minimum age for faulting is inferred from the fact that the faults at Site 1 do not extend into the Halton Till (or the overlying sediments). The faulting may have occurred during deposition of the lower part of the Halton Till and then been obliterated by glacial remobilization of the till mass, but in any case it must have been completed prior to the deposition of the upper part of the Halton Till.

In 1967, Karrow mapped upper and lower layers of a sandy till he called the 'Leaside Till'. The name is now no longer used, but Karrow (1967, p. 40 and p. 48) correlated the upper member of the 'Leaside Till' to the Halton Till (a more clay-rich till found west of Toronto), and the lower member of the 'Leaside Till' to earlier Late Wisconsinan tills in the area. By his correlation, the 'Leaside Till' corresponds to the period 25–13 ka, whereas the Halton Till proper was deposited towards the end of this period, with an estimated age $\approx$13 ka. Figure 6 summarizes our understanding of the stratigraphic relationships of these tills and the older strata discussed below.

The time spans represented by the Don and Scarborough formations are not precisely known, but they have estimated ages of $\approx$125 ka and $\approx$100–70 ka (Karrow, 1989, p. 345). Between the Scarborough Formation and the Halton Till there is thus a large erosional hiatus in the Rouge River area which is represented elsewhere in the central Toronto area by the Sunnybrook Till (estimated age $\approx$63 ka) and a package of Middle Wisconsinan deposits representing stream and lake deposition and glacial advances in the period >53 ka to 30 ka (the Lower Thorncliffe Member, Seminary Till, Middle Thorncliffe Member, Meadowcliffe Till, Upper

Thorncliffe Member; ages from Karrow, 1989). In the Scarborough area, Karrow (1967) mapped both the Halton Till (then termed the 'Leaside Till') and the earlier Sunnybrook Till, indicating that since deposition of the Scarborough Formation the area was covered by the Lake Ontario ice lobe at least twice, and likely four times, if events were the same as in central Toronto.

The Scarborough Formation is a lacustrine deposit with a flora and fauna indicating a sub-arctic climate near the northern limit of a boreal forest. It is thus inferred to have been deposited in a proglacial lake which was created in the Lake Ontario Basin when ice blocked the St. Lawrence drainage system at the end of the Early Wisconsinan Nicolet Stade. The lake level stood at least 46 m higher than present Lake Ontario. The faults that cut these glaciolacustrine sediments must therefore have developed after the end of the last interglaciation, that is to say during or after the beginning of the last glaciation when ice was in the St. Lawrence – Lake Ontario lowland. From Scarborough times until the end of the last glaciation, ice blocked the St. Lawrence drainage and so the site has been either under water (during minor ice retreats) or under ice. In either case, it is unlikely that the sediments were frozen because the necessary subaerial exposure did not occur.

Style of faulting

The dominant sense of bedrock deformation is extensional, represented in the outcrop by normal faulting, based on both MER92's diagrams for Sites 1 and 3 and our observations at Site 3. At Site 3 the faults generally have moderate dips, but when examined in detail, can be seen to be curved planes, both vertically in the plane of the exposure and horizontally into the exposure. The curvatures seen were fairly strong, amounting to up to 30^0 over less than a metre. This means that an attitude measurement at a single point would not be representative of a given fault surface as a whole. The curved nature of the planes is not evident in the stereonet of fault plane attitudes (MER92, their figure 3, right-hand stereonet) which shows poles tightly-clustered about a NNE direction.

Given that the faults are curviplanar within the relatively small extent of the exposure, it is entirely possible that they flatten with depth and become listric. Although we did not see roll-over, there may be an opportunity to compute the depth of flattening by a detailed geometric analysis.

The amount of extension due to the faulting can be calculated for Sites 1 and 3. The faults at Site 3 represent a large amount of extension in the 33 m length of the section, despite the fact that they are tight. From Figure 5 we have measured the continuous horizons on the left-hand side of the exposure and compute 2.3–2.6 m of extension (≈20% of the faulted outcrop width). For the exposure as a whole, and using the Don/Scarborough contact as datum, the extension is either 12.5 m (65%) assuming this contact has been completely severed by the grabens, or 7.8 m (41%) assuming the contact is immediately below the exposed section. These are, respectively, absolute maximum and minimum values of extension, referenced to the plane of the section, which is at 40^0–60^0 to the average strike of the faults. The amount of extension perpendicular to the faults would be about 30% less, or about 5–8 m. At Site 1, the normal faults record 0.7–0.9 m extension, or about 3% of the width of the faulted outcrop (but only 1.5% of the total outcrop width). There is therefore a six-fold difference in the amount of extension between Sites 1 and 3.

For contrast, some idea of the scale of tectonic normal faulting can be taken from the surface rupture caused by the 1983 magnitude (M) 7.3 Borah Peak, Idaho, earthquake which had a net throw of 2.5–2.7 m (Crone et al., 1987). From both field observations and geodetic modelling (Stein and Barrientos, 1985), the extension is of the order of 1.33–1.47 m. In some places the extension occurred over a number of antithetic and synthetic faults in a 25- to 50-m-wide zone (Fig. 7); here the extension amounts to 2–3% of the faulted outcrop width. Similar extension has been noted for both the 1959 Hegben Lake (M7.3) and Fairview Peak (M7.2) earthquakes. If the offsets at the Rouge River Site 3 formed during an earthquake, the amount of extension (neglecting for the moment the required depth and length extent of the seismogenic fault) would imply an earthquake of magnitude considerably greater than M7.2, perhaps not much less than M8. Normal faulting sometimes accompanies thrust or reverse faulting, occurring on the crest of the hanging-wall block. A good example is El Asnam, Algeria (Yielding et al., 1981), where substantial scarps (but representing only a small amount of extension) were formed (Fig. 8).

Mechanisms that could explain the observed faulting

At least nine possible mechanisms could have produced the faulting observed in the Rouge River sections. A few of the nine, we admit, are speculative and unlikely; however, the neotectonic faulting hypothesis proposed by MER92 (including the earthquake faulting hypothesis implied by their mention of seismic hazard) should be seen as only one of several plausible hypotheses and, we would argue, not the most likely one.

Landsliding. Deep-seated slumps and valley wall sags (Fig. 9), especially ones with a small amounts of movement, might, near the head-scarp, yield faulting like that observed at Rouge River. Uplift and extensional faulting could also occur locally near the compressional toe of a slump (Fig. 9). Neither explanation seems likely for the Rouge River, as the lower topography needed to drive the movement is lacking, unless there is a deep buried valley nearby. In addition, the exposures of bedrock appear for the most part competent and undisturbed (excluding deformation interpreted as glaciotectonic) elsewhere in the valley.

Valley-floor uplift. Valley-floor uplift refers to the up-arching of valley floors (Fig. 10) following erosion of the valley and consequent removal of the confining stress formerly provided by the eroded rock (see for example, Ferguson, 1967). In Canada, diapirism and uparching of river beds and lake bottoms due to removal of overburden by erosion or landsliding has occurred in the Samson River Valley, Quebec (Shilts, 1978, 1981), and in Lake Timiskaming (Shilts, 1984). Postglacial erosion of the Rouge River Valley has been insufficient to trigger valley-floor uplift of the scale envisaged (because the Halton Till is not offset), and it is unclear whether greater topographic stresses (thicker Quaternary deposits and/or deeper valleys) existed in pre-Halton times.

Valley-floor uplift would be one explanation for the lower stratigraphic levels exposed above river level that are found at Sites 3 and A. Valley-floor uplift is primarily a squeezing process, but the up-arching could produce extensional cracking at the centre of the valley. Minor extension, such as that seen at Site 1 might occur above the crest of such an uplift and, while tensional cracking and extension would be expected in a brittle material such as limestone, it is possible that extension would be accomodated in shale by normal faulting. Nonetheless, it seems highly unlikely that this mechanism could explain the large amount of extension at Site 3, and the large folds at Site A were certainly not caused by this mechanism.

Stress relief. Large-scale stress-relief phenomena called 'pop-ups' are quite widely found in southern Ontario, primarily in flat-lying limestone and dolomite (White and Russell, 1982; Fig. 11). Typically these are elongate, up-arched, brittle folds up to several metres high and hundreds of metres to more than a kilometre long. They are generated by decoupling of the topmost few metres of the flat-lying sedimentary rock along some bedding plane or shale layer (a décollement), in response to the ambient horizontal stresses of 5–10 MPa found in the surface bedrock throughout the region. These stresses exceed the bending strength of the rock. The origin of pop-ups is similar to that of valley-floor uplifts, except that the latter are localized in deep valleys in high-relief terrain, whereas pop-ups generally occur at the surface in flat terrain. In many pop-ups found in open country in southern Ontario, it is not clear that removal of restraining overburden has played any role in triggering the failure, though similar features are often formed on quarry floors during excavation ('quarry-floor buckles': White et al., 1974; Adams, 1982; Wallach and Chagnon, 1990). The deformation in a pop-up and the involvement of its décollement surface is not dissimilar to that caused by a listric thrust fault (Fig. 12) or a valley-floor uplift, and the extension seen in the Rouge River could be explained in a similar manner.

Where small pop-ups are seen in section, the deformation often ceases abruptly a few metres down, at a shale layer décollement. The underlying undeformed strata confirm that the pop-ups are not caused by deformation from below. Karrow and some others (P. Karrow, pers. comm. 1992) originally considered the upstream fold at Site A to be a buried bedrock pop-up affecting the cover sediments, a hypothesis consistent with the amount of deformation increasing upwards and also with the presence of "buried pop-ups" in the region (Fig. 11). However, the extremely deep burial of the fold distinguishes it from other examples known to the authors.

Near-surface release of glacially-induced stresses. Although the present stress regime in southern Ontario is dominantly northeast to east-northeast compression (Sbar and Sykes, 1973; Adams and Bell, 1991), many authors have inferred that during deglacial unloading, the upper crust experienced very large transient stresses due to flexure, at times resulting in extension of the crust under areas of previous ice loading (e.g., Bostrom, 1984), and at other times applying compression. As evidence of these stresses, Adams (1989) suggested that both northeast-trending pop-ups and small-scale (typically millimetre to decimetre), steeply-dipping, reverse offsets of glaciated surfaces (colloquially-termed 'postglacial faults') represent the shallow release of these glacially-induced stresses. Whether these stress releases were sudden (seismic) or progressive is uncertain. In any event, the small throws and short exposed lengths suggest that the energy release was small. Nonetheless, the offsets are commonly very closely spaced, and the cumulative throw over a few metres can be substantial (Fig. 13). For example, the postglacial faults with '1 inch' throw in steeply-dipping slates at St Evariste, Quebec (Oliver et al., 1970) were found upon re-examination to have throws of up to 100 mm; over the 13 m outcrop width, the throw totals 0.56 m (J. Adams, unpub. field notes, 1980). This example illustrates that, although the typical stress-relief faulting is often considered to be in the millimetre scale, larger offsets do exist.

Crustal stresses caused by glacial loading and unloading during the advance and retreat of continental ice sheets are sufficient to cause bedrock rupture. All offsets and pop-ups seen today are inferred to have formed during or after the last deglaciation, since most disrupt glaciated surfaces and otherwise would have been obliterated by glacial erosion. Features related to previous deglacial periods could also be preserved if buried and not later excavated by ice. Whereas deglacial faults are typically reverse in sense, it is assumed that faults related to the advance phase of glaciation would be extensional and normal in sense. Hence, in connection with the Rouge River features, the ice advance which brought Lake Scarborough to an end could have produced bedrock normal faults and these could have extended into the overlying Quaternary Don and Scarborough formations. Indeed, the orientation of the Rouge River Valley faults is roughly east-west, that is to say parallel to the hypothetical ice front, and thus not inconsistent with a possible advance-phase origin. Moreover, the observed throw on the faults at Site 1 and perhaps also at Site 3 is not completely out of scale with such a hypothesis. However, the gentle fault dips at Site 3 indicate an amount of extension that is unreasonable considering the generally small amount of shortening across the reverse faults.

Hydrostatic jacking of bedrock blocks. A freezing front propagating downward through a rock/sediment mass with saturated fracture porosity, coupled with the effects of ice-volume increase and fracture sealing, can lead to fluid overpressuring sufficient to cause bedrock heave and frost bursting (Michaud et al. 1989). Extensional features are commonly associated with this kind of disruption. Moreover, substantial vertical displacements can occur if the 'active' layer is relatively deep (Dyke, 1984).

On a larger scale, the same process involving similarly high fluid pressures can occur beneath a wet-based ice sheet where the pressure-melting point is exceeded (Zotikov, 1986). Basal meltwater movement into the underlying fractured crust can increase fracture fluid pressure by a value up to the equivalent of that imposed by the glacier load. If not relieved, this could lead to fluid overpressuring during and after deglaciation to depths equivalent to one third of the former ice sheet thickness, possibly resulting in 'jacking' or 'lifting' of the bedrock, and generating substantial vertical displacements (Talbot, 1990; Fenton, 1992). Such dilational delamination of the shallow crust would most probably be accompanied by vertical faulting, together with complementary compressional and extensional faulting at the leading and trailing edges of the block (Fig. 14).

The glacially-transported blocks can be a few metres to several tens of metres in thickness and of the order of hundreds of metres to over a kilometre in length (e.g., Schroeder et al., 1986). They can show remarkably little internal deformation and rotation of strata away from the horizontal even when transported for considerable distances (Fig. 15). Comparable transport of mechanically-weak argillaceous bedrock ('rafts' of mudstone and clays up to 10 m thick and 100 m across) have been reported from the East Midlands of England (Rice, 1981; Rice and Douglas, 1991). Even larger (25m thick and more than 4 km long) rafts of Cretaceous shale are known from the Prairie provinces (Stalker, 1976). A recently discovered example from New Brunswick (Broster and Seaman, 1991) indicates that even friable weathered granite can be moved in coherent slabs 10 m long by 0.3–2 m thick. Even coherent sand bodies can be rafted if frozen at the time (Broster and Clague, 1987).

High pore pressures undoubtedly aid the detachment of bedrock slabs like those described above, slabs that are subsequently moved and deformed by glacial action (see next section). However, the jacking process itself is a mechanism for deformation if subglacial detritus enters the void created under the detached bedrock block (Fig. 14). Upon deglaciation (or when the hydrostatic head decreases), the fluid pressure under the block decreases, leading to differential settling of the block over the irregularly distributed and poorly-sorted glacial detritus. From Figure 14 it is seen that this can lead to zones of either compressional or tensional deformation. These are in addition to deformation arising from transportation of the block. It should be noted that the zones of tension (normal faulting) are associated with bedrock 'highs'.

The lack of faulting of the Halton Till shows that this process did not act during the last deglaciation, however, multiple ice advances and retreats have occurred in the Rouge River Valley, and conditions during one of them may have been favourable.

Glaciotectonism (ice-push). The deformation in the Rouge River Valley could be due to glacial shear on the relatively incompetent bedrock and surficial sediments, as is ubiquitous in the vicinity. In the course of detailed mapping of the Quaternary geology of the area, Karrow (1967) described 167 sections along the Rouge River, Little Rouge River, West Dufferin and Highland creeks, and the Scarborough Bluffs of Lake Ontario. He noted faulting in 10 of these sections and contorted or folded sediment in a further 47 sections. Section F138 is Site 1 of MER92, which Karrow described as containing "Stratified grey, buff, and orange fine sand and silt with peaty layers. Faulted and contorted." and "Dark-grey faulted clayey silt". However, Karrow's description of site

F137 (our Site A) does not mention the large folds and the thrust structures, and, although he mapped bedrock outcrop at Site 3, there is no description of the faulted stratigraphy, perhaps because neither outcrop was well exposed at that time. Karrow did not invoke glacial tectonism to explain the deformation, although the process had been widely implicated then and subsequently for the area:

- "countless numbers of small faults and folds at the base of till layers indicating drag" exposed in the Scarborough Bluffs (Karrow, 1967).
- sandy shear planes and tension fractures in Sunnybrook Till and Scarborough Formation along the Scarborough Bluffs (Hicock and Dreimanis, 1989).
- contortions, folds and faults in Ordovician shale between Toronto and Burlington. Disturbance decreases with depth, suggesting deformation from overriding ice (Karrow, 1963) [some of these might today be interpreted as stress relief features].
- folds, tension fractures, shear planes and sediment injection in Quaternary sections along the Humber Valley, Toronto (Hicock and Dreimanis, 1985).

A summary of Canadian glaciotectonic features is given by Dredge and Prégent (1993). Figure 16 shows those sites near the Rouge River.

MER92 discounted glaciotectonism as an explanation for the Rouge River faults on the basis that "glaciotectonic features are overwhelmingly compressive". While it may be true that glaciotectonic features are commonly compressional, we find no justification for their implicit assumption that the presence of extensional features rules out glaciotectonism. This assumption influences their arguments.

Sub-vertical, curving fissures in lodgement till have been described by Derbyshire and Jones (1980), who ascribed them to tensional failure of a frozen till surface by compressional loading. In reaching this conclusion, they rejected hypotheses of stress-relief, dessication, frost action, direct ice push, ice-core meltout, substrate compaction, shear failure, propagation of bedrock joints following deglaciation, and tectonic faulting, all hypotheses relevant to the Rouge River sections. Figure 17 (ascribed to Boulton, 1972) indicates a plausible model for the Rouge River deformation, with a large amount of extension (Site 3) at the rear of the entrained block, and the minor extension (Site 1) on the upper surface.

Extensional features are not only predicted from theory, in which compression is accompanied by extension over short distances due to movement of material, but also have been widely noted in glaciotectonized terrains in Canada and abroad (Netherlands, Denmark, Germany, e.g., Figs 18 and 19). Extensional features are especially common over the hinges of folds and the crest regions of thrust structures (e.g. Durand and Ballivy, 1974; Schroeder et al., 1986; Croot, 1988; Fig. 20), and within thrust-front surge or collapse zones (Coward, 1982; Croot, 1987; Yin and Kelty, 1991). The best example in the vicinity of the Rouge River area is from nearby Scarborough Bluffs where the Scarborough Formation has extensional fractures (Fig. 21) linked with glaciotectonic deformation by early Wisconsinan till (Hicock and Dreimanis, 1992).

Dramatic examples of glaciotectonic extension occur in the Montréal area where caves measuring decimetres to metres across have been created in otherwise undeformed limestone bedrock by extension across pre-existing joints (Schroeder et al., 1986; Figs. 22 and 23). As the detachment occurred along bedding planes and stepped upwards on the joints, there was little or no rotation or deformation of the strata.

Extension within the Rouge River fault zones is highly variable, ranging from ≈1.0 m at Site 1 where the faults cut the Don and Scarborough formations to 8–12 m at Site 3 where bedrock is displaced against the Don and Scarborough formations. The latter value greatly exceeds that usually associated with tectonic faulting; normal fault systems only exhibit extension approaching this amount when dips are less than 30^0 and then rarely over such a short outcrop width (Roberts et al., 1991). All the major faults at Site 3 dip 40^0 or more, with two populations at 40^0 and 80^0. Moreover, all strata at Site 3 are essentially horizontal, whereas with this degree of extension (41%–65% of the outcrop width), it is usual to find roll-over within the hanging-wall block. The lack of roll-over presents a major problem of simple geometry in that it is difficult to accommodate the space and volumes if the faults are to be interpreted as tectonic normal faults. From the geometry of the features and the evidence of glaciotectonism from the neighbouring Site A it is plausible to explain these features as being the result of glaciotectonic activity.

The orientation of the normal faults in this local area would be consistent with the northward to northwestward direction of ice advance from the direction of Lake Ontario if the ice front were lobate. Post-Scarborough channelling of ice flow (from which the ice might spread outward to northeast and southwest) might have occurred because of pre-existing valleys in the Scarborough Formation (Karrow, 1967, p. 29). As discussed above, the local ice advance could have formed both WNW-trending folds and WNW-striking extensional features (normal faults).

Melting of glacier blocks or ground ice. Melting of buried ice blocks is a common cause of faulting in outwash deposits (McDonald and Shilts, 1975; Fig. 24). The features produced, such as high-angle reverse faults, invariably represent only a small amount of lateral shortening (compression) because the sediments sag almost vertically into the cavity. Only where slumping, such as into adjacent kettles, is involved does normal faulting become important. To produce the observed faulting in the interglacial beds by this mechanism would require that ice lenses grow in the bedrock some time after the deposition of the Scarborough Formation, perhaps during one of the glaciations not represented by tills in the Rouge Valley. Normal faulting might be produced as the ice lens grew, then collapse and compressional features as it subsequently melted. We view this as a highly unlikely explanation, firstly because of the sharp appearance of the fault planes and their lack of sediment infilling (not what would be expected to follow slow ice melting), secondly because the bedrock shows no sign of flaking or deformation that would have accompanied the growth of deeper ice lenses, and thirdly because the glacial history, as discussed above, makes extensive post-Scarborough freezing of the bedrock unlikely.

Surface faulting due to a large normal-faulting earthquake driven by tectonic or deglacial stresses. This, the favoured explanation of MER92, has no reported parallel anywhere in a glaciated craton, except perhaps the poorly understood 15-m, post-interglacial, throw on Aspy Fault, Nova Scotia (Grant, 1990). If the exposure at Site 3 is taken as the surface expression of a normal fault, then for an extension of 5–8 m the slip ranges from at least 5 m (assuming the lower value for the amount of extension and a zero-dip fault) to possibly 16 m (taking the upper value and assuming a fault dip of 60^0). While offsets of this magnitude have occurred on the largest of the large postglacial faults in intracontinental settings in Sweden and Norway (Lagerbäck, 1990), those examples are reverse faults and have confirmed lengths of tens of kilometres to hundreds of kilometres.

The amount of slip, taken by itself, implies a magnitude 7.4–7.8 earthquake, when magnitude is estimated from surface offset using empirical relations (Bonilla et al., 1984). However, an earthquake of this magnitude requires a fault tens of kilometres to hundreds of kilometres long and extending to depths of 10–20 km. The Rouge River faulting has so far been documented for only 300 m (if indeed the faulting at the two outcrops is the result of the same underlying fault).

Finally, the Rouge River faults occur in a tectonic environment that is presently compressive (Adams and Bell, 1991) and manifested by reverse or strike-slip faulting. Thus, although there might have been a period during the glacial unloading cycle when deviatoric extensional stresses dominated and made normal faulting possible, those stresses do not exist today. Nor has postglacial (or interglacial) normal faulting comparable to that in the Rouge Valley been reported elsewhere from glaciated shields. Thus, the particular geometry and very local development of the Rouge River features strongly suggests they are not in the class of large normal faults.

Hanging-wall faulting above a large reverse faulting earthquake driven by tectonic stresses. This mechanism is considered to be even less likely than the possibility of normal faulting discussed above, for two main reasons. The reported orientation of the features is oblique to the plate-wide compressional stress field, and the observed normal faulting is at variance with almost all contemporary stress indicators in the region (including earthquake focal mechanisms) which indicate thrust or strike-slip faulting. The only possible way to explain the observed (normal) faulting in the Rouge River would be to assume that it is antithetic to a hypothetical underlying thrust fault. This suggestion is based on the fact that the most obvious fault scarps formed by the 1980 El Asnam earthquake (Fig. 8) were not the low-angle thrust scarps, but the steep antithetic normal fault scarps on the hanging-wall block (Yielding et al., 1981; Vita-Finzi, 1986, p. 75–76).

Still, notwithstanding the possibility of a deep thrust fault, the scale of the extension at Site 3 (5–8 m) as a secondary consequence implies an unreasonably large slip during thrust faulting.

ASSESSMENT

We have discussed nine possible explanations for the faults at Rouge River. From the discussion, we rate the hypotheses according to their probability as follows:

Improbable

- Landsliding
- Stress-relief
- Melting of glacier blocks or ground ice
- Surface faulting due to a large normal-faulting earthquake driven by tectonic or deglacial stresses
- Hanging-wall faulting above a large reverse faulting earthquake driven by tectonic stresses

Possible

- Valley-floor uplift
- Near-surface release of glacially-induced stresses
- Hydrostatic jacking of bedrock blocks

Probable

- Glaciotectonism (ice-push)

A CAUTIONARY EXAMPLE

A cautionary example about interpreting Quaternary faulting comes from Fakundiny et al. (1978) regarding an exposure on the south shore of Lake Ontario. Because of the limited distribution of this document, we quote the paragraph in full:

> "The reverse fault exposed in the stratified deposits of the lake shore cliffs, called Devil's Nose, in the Hamlin Quadrangle (Table 1 F11) is situated above the western branch of the Clarendon-Linden fault system and has the relative reverse-movement-sense similar to the subsurface. Here the Hamlin Beach fault cuts stratified sands that are overlain by 2-meter thick till. The fault dies upward before reaching the overlying till and, thus, represents an event that happened during or before the last glacial re-advance. The dip of the fault *shallows downward and becomes a bedding plane thrust* within a few meters of its upper terminous. If this movement represented a surface expression of bedrock fault movement in the subsurface, the dip would be expected to remain the same or steepen rather than shallow as the fault surface is traced downward. Similar features are common where it can be proved that differential movement in ice-contact deposits is the result of ice

> shove of frozen ground or collapse over melting ice blocks. Regardless of the origin of the Devil's Nose fault, it has not moved since the deposition of the overlying till unit, a period of at least 12,000 years before present." (p. 145–146; *italics* added for emphasis).

This occurrence is important for interpreting the Rouge River faults for several reasons:

1. The faulting predates the last till.
2. The fault is close to a geological structure believed, from seismicity, to be active.
3. The sense of faulting in the Quaternary sediments is consistent with the expected reverse-faulting neotectonic activity on the bedrock faults.
4. Nevertheless, the dip of the fault is seen to decrease downwards, thus confirming its non-tectonic origin.

If we seek similarities with the Rouge River examples, points 1 and 2 apply (note MER92 allude to the association between the Rouge faults and geophysical lineaments and microseismicity). However, point 3 does not apply (the normal faulting in the Rouge River sections is not that expected in the contemporary stress field), and point 4 is untested at the Rouge River because of the shallow exposure of bedrock.

In this regard, we note that the upper part of the Scarborough Formation has been removed from the Rouge River sections (especially at Site 3) so that the overall style of deformation (which may have increased or died out upwards) is not known. In addition, bedrock is not exposed at Site 1 and minimally exposed (less than half a metre) at Site 3, so it is unknown whether the observed fault planes might become bedding plane thrusts at shallow depth within the bedrock. We assert that had only the upper part of the Devil's Nose section been exposed, given its location near the Clarendon–Linden fault, it might well have been interpreted in the fashion of MER92.

IMPLICATIONS FOR CONTEMPORARY SEISMIC HAZARD

We give below our conclusions regarding the implications of the Rouge River sections for seismic hazard assessment. We consider there are four outcomes from the nine possible interpretations we considered:

1. IF the faulting is due to glaciotectonism (our preferred interpretation), hydrostatic jacking of bedrock blocks, melting of ice blocks, or landsliding, there are no seismotectonic implications whatsoever.

2. IF the faulting is due to valley-floor uplift or near-surface stress relief, either at present or during early postglacial time, there are no seismotectonic implications.

3a. IF the faulting represents release of seismogenic energy at depth due to crustal loading strains during a post-Scarborough glacier advance, then this is interesting, but has no seismotectonic implications for the present day.

3b. IF the faulting represents release of seismogenic energy due to crustal unloading during a post-Scarborough glacier retreat (especially if during the last deglaciation, though it is unclear why the Halton Till is not then offset), then there are some seismotectonic implications for the present. These, however, are limited because most of the strain would have occurred soon after deglaciation and the residual strains are now accumulating far more slowly. Furthermore, it should be noted that the site has been glacially loaded two to four times since the deposition of the Don Formation, yet there was only one phase of faulting.

4. IF the faulting represents antithetic normal faulting consequent on seismogenic energy release at depth due to the reverse-faulting release of plate-tectonic strains and stresses, then there are some seismotectonic implications for the present day. However, the impact is judged minimal considering that in about the last 125 000 years there has been at most one large event on the structure. Crone et al. (1992) have demonstrated that large surface rupturing earthquakes in cratonic settings are rare worldwide (only 10 in historical times). Moreover, wherever young faulting has been studied, the time since the previous event ('repeat time') appears to be very long, greater than 10^4–10^5 years, and only limiting ages have been placed on the previous ruptures.

Outcomes 1 and 2 have no seismotectonic implications, Outcomes 3a and 3b are mechanisms linked to glacial events and not necessarily active today. Outcome 4, which we consider very unlikely based on the available evidence, is the most relevant for contemporary seismic hazard estimation, but even then its significance is chiefly limited to demonstrating that large earthquakes have happened in the past.

The implications of outcome 4 for future earthquakes are uncertain because:

1. The hypothesis is not the simplest explanation, and is therefore more likely incorrect than correct.
2. The evidence suggests only a single event in ≈125 000 years; hence, even if due to an earthquake, that earthquake is an improbable event. This belies the conclusion that an important active fault may have been identified, as alluded to by MER92.
3. Probabilistic seismic hazard analyses presently being considered by the GSC allow the possibility of a magnitude 7 earthquake in the Lake Ontario — Lake Erie region. The additional contribution of the supposed 'Rouge River earthquake' to seismic hazard assessment is judged to be negligible.

POSSIBLE TESTS OF THE HYPOTHESES

Although we consider glaciotectonism to be a likely cause of the faulting of bedrock outcrops in the Rouge River Valley, we consider that definitive evidence precluding a 'seismic' origin has not been identified, thus that this hypothesis, while not in our view the most likely one, can not be dismissed as an impossibility. We note further that, even if the faulting were proven to have occurred during an earthquake, the single known occurrence only underlines the rarity and great antiquity of the event. Thus, as discussed above, it would not materially change our assessment of contemporary seismic hazard. However, should definitive evidence as to the origin of the deformation be required, we suggest the following tests.

A. Shallow drilling at each end of the Site 3 outcrop. Two vertical holes (≈20 m), and perhaps two inclined holes angled at 45^0 to pass beneath the centre of the outcrop, might be needed. Full coring and real-time logging, together with surveying for levels would be required. The aims would be: 1) to confirm that the bedrock is in place and not a large glacially-transported block bounded by till layers or shear planes at depth; 2) to establish the bedrock stratigraphy at each end of the outcrop and to confirm (or preclude) stratigraphic offset of bedrock at a depth at least equal to the width of the central graben; 3) hence to find the total amount of post-Ordovician offset, perhaps at a deep shale/limestone interface; 4) to identify a moderate-dipping fault plane, if present.

B. A geometric analysis of the faults in order to: 1) confirm that all of the faulting resulted from a single episode and to determine whether or not it is consistent with a deep deformation source; and 2) to identify roll-over and deduce the depth to a detachment.

C. Excavation of the outcrops after construction of two small temporary coffer dams at the foot of Sites 1 and 3 to exclude the river and thereby permit an area of bedrock to be exposed, so as to further investigate the curved geometry of the features. This would also allow direct measurement of bedrock offsets and hence extension, which at Site 3 must be inferred (with large errors) from the absence of the Don Formation in the centre of the graben.

D. Clean, study, and document the folds and fractures at Site A for comparison with the deformation at Sites 1 and 3. This would be conducted in the context of a regional study of glaciotectonism in the Quaternary sequence in order to constrain the time of deformation. [Enviromental constraints in the Rouge Valley may make it difficult to get approval for tests C and D. However, we feel that with careful attention to housekeeping details, the long-term effect of these investigations would be less than that of a major storm, and therefore tolerable given the improvement in understanding that might be gained.]

E. Shallow seismic reflection profiles parallel and perpendicular to the cut bank face at Site 3. The survey lines should intersect the drill holes (Test A) to extend knowledge of the overburden/bedrock contact at least tens of metres from the drill holes.

RELEVANCE OF OUR OBSERVATIONS TO THE DISCUSSION AND CONCLUSIONS IN MER92

From our brief field visit, the team unanimously agrees that bedrock and Quaternary sediment in the Rouge River Valley are faulted. However, we strongly disagree with the certainty of neotectonic origin implied by MER92. We believe that the observations they report can be interpreted in several different ways, particularly when structures in adjacent sections and the regional stratigraphic relations are considered as well. Although the paper is generally carefully worded and aims to make a strong case for neotectonic faulting, we believe it contains important omissions that affect the interpretation:

- It failed to mention some of the previous and relevant literature, notably Karrow (1967) who did both the basic mapping, developed the stratigraphic framework, and described numerous sections, including some which showed Quaternary faults and other deformation, such as at Site 1.
- It did not mention that the stratigraphic sections at Sites 1 and 3 are incomplete, lacking all or most of the tills known to overlie the Scarborough Formation, and that much of the sediment package and its contained structures has been eroded away at Site 3, so the total amount, style and timing of deformation is unknown. The exisiting section may only represent the lower part of a downward-attenuating disturbance.
- It did not acknowledge the reported extent of nearby glaciotectonic deformation, especially at Site A, thereby contributing to a bias against glaciotectonism as a possible mechanism.
- It did not acknowledge that normal faults are common in glaciotectonically disturbed sequences, thereby lending a bias against glaciotectonism as a possible mechanism.
- It did not mention that similar types of faults, in the same formations, have been reported in a number of places nearby, and have been ascribed to glaciotectonic deformation, and that not all of these are aligned with 'seismic lineaments'.
- It did not address the issue of whether the bedrock is indeed in place rather than being a transported block.
- It did not mention that most of the faults are curvilinear and could well be listric, a condition that greatly reduces the value of the stereographic plots and the interpretations made therefrom.
- It reported a maximum fault displacement of 1.25 m which, while true for the Scarborough Formation at Site 3, is not the observed offset in the bedrock.
- It reported the 1.25 m displacement, but did not discuss the 5-8 m of extension at Site 3, which we consider implausibly large for tectonic faulting.
- It claimed that the strata at Sites 1 and 3 "are cut by the same system of normal faults", although the proof of continuity is circumstantial and only plausible if the faulting was tectonic.

Furthermore, MER92 have, in our opinion, overemphasized the relevance of their work to nearby nuclear installations. The choice of wording in the title "*Neotectonic faulting in metropolitan Toronto: Implications for earthquake hazard assessment in the Lake Ontario region*" is a headline grabber. In the abstract, reference to the faults having "*important implications for regional seismic hazard assessment because they occur within 7 km of the Pickering nuclear power plant*" suggests a knowledge of cause and effect that is not demonstrated in the paper. Their concluding phrase (p. 1006, our emphasis added) "*Irrespective of the origin of the Quaternary normal faults, the presence of these faults may have seismotectonic implications for metropolitan Toronto and the nearby nuclear facilities*" is illogical. As we have noted above, there are several plausible explanations for the observed faulting, some of which have absolutely no implications for evaluating contemporary earthquake hazard.

Hopefully this report will promote discussion that will lead to a better understanding of the features observed along the Rouge River Valley and their relevance, or not, for assessing potential seismic hazards in southern Ontario.

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FIGURE CAPTIONS

Figure 1. Press item from page A1 of the Ottawa Citizen, November 1, 1992, the day the MER92 paper was released in the United States.

Figure 2. Rouge River area showing study sites and outcrops of Ordovician shale and Quaternary sediments (modified from MER92, figure 2). Note position of 'Site A', and correct location of Site 3.

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Figure 4. Sketch of the thrust-cored anticline at Site A along the Rouge River (drawn from a photographic slide taken by J. Wallach in 1981). Weathered shale bedrock has been carried up along the thrust plane into the overlying folded Don and Scarborough formations. The axial plane of the anticline dips to the SSW.

Figure 5. Faulted strata at Site 3 along the Rouge River (modified from MER92, figure 3, top). Additional exposure of bedrock was seen in December 1992, as shown. Arrows indicate a fault for which the throw is depicted to decrease downwards.

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Figure 18. Glaciotectonic deformation at Ossenbeck sandpit, Germany. Top: overview of thrust nappes (van der Wateren, 1992, figure 3.10). Lower right: photograph (van der Wateren, 1987, figure 24) and line drawing (van der Wateren, 1992, figure 3.44), both showing extensional faulting within the circle labeled 'fig. 3.44' on the top figure. Lower left: similar deformation elsewhere in the sandpit (van der Wateren, 1987, figure 26).

Figure 19. Extensional faulting of sands under till, coastal cliff at Nygard Hage, Denmark (Jensen, 1985, figures 3 and 4).

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Figure 21. Steeply dipping extensional faults in sand of the Scarborough Formation at Cudia Park, Toronto (Hicock and Dreimanis, 1992, figure 4a).

Figure 22. Regional model (bottom) for glaciotectonic deformation of large limestone sheets in the Montréal area and some details (top) of this deformation (Schroeder et al., 1986, figure 1).

Figure 23. Photographs showing the remarkable hidden extension under thrusted limestone sheets, and the likely extent of the displaced block (Schroeder et al., 1986, figures 5 and 9).

Figure 24. Lake-bottom record of ice-block melt-out (Shilts and Clague, 1992, figure 8).

OTTAWA CITIZEN 1/11/92

Pickering nuclear plant near fault line: scient[illegible]s

BY TOM SPEARS
Citizen environment writer

Newly discovered faults in the Earth near the Pickering nuclear generating station show the area is a potential earthquake zone, say scientists writing in *Geology* magazine.

"It can no longer be assumed that southern Ontario is a region of structural stability and negligible seismic risk," the magazine's November issue says.

There have been four small earthquakes — ranging from 2.2 to 3.5 on the Richter scale — under or near western Lake Ontario since 1987, the article says.

And it records 16 "micro-earthquakes" measuring 1.5 or less on the scale in 1991 alone.

But the big news is the discovery of faults — areas where layers of rock have buckled — exposed by erosion in a river valley seven kilometres from the Pickering nuclear plant.

"It's actual evidence you can go and stand on. It's field evidence of faulting," said co-author Nick Eyles, a professor of geology at the University of Toronto.

"We don't know what their (faults') potential is to generate earthquakes, and the fact that we don't know is the biggest problem," Eyles said.

Ontario Hydro should "put their engineering geologists onto it straightaway and follow it up quite aggressively," he said.

Alex Mohajer, another author of the report, is a seismologist who also teaches at the University of Toronto and does private work.

The faults appear in the Rouge River valley, which runs between Pickering and Scarborough. Eyles said layers of rock show a broken pattern instead of following straight lines.

He likened it to a layer cake that's had slices cut and partly lifted out, so that the layers are uneven.

The faults only show in the river valley because in other areas there's too much soil to see the underlying rock, Eyles said.

The combination of small earthquakes and faults "indicate the presence of sufficient stress magnitude to produce tectonic movements," the article says.

Geology is the monthly magazine of the Geological Society of America.

Mohajer's and Eyles's paper is the second source of questions about how solid is the rock under Pickering.

Two years ago, the Atomic Energy Control Board reported two lines meeting at Pickering where the Earth's magnetic field is different from the field in the surrounding area. A change in magnetic field can indicate a fault in the Earth's crust, AECB geologist Joe Wallach said.

Wallach says the new findings bear out his earlier work. "Now no one can say it's just a magnetic anomaly."

The stress comes as the plate of the Earth's crust that lies under North America slowly drifts west, Eyles said. This causes tension that is released from time to time in earthquakes.

"The big deal is that previous work has been working on these magnetic lineaments . . . You can't obviously see these deeper layers," he said.

A Hydro spokesman says there's no danger to its reactors from "any earthquake that can realistically be expected to occur in that area.

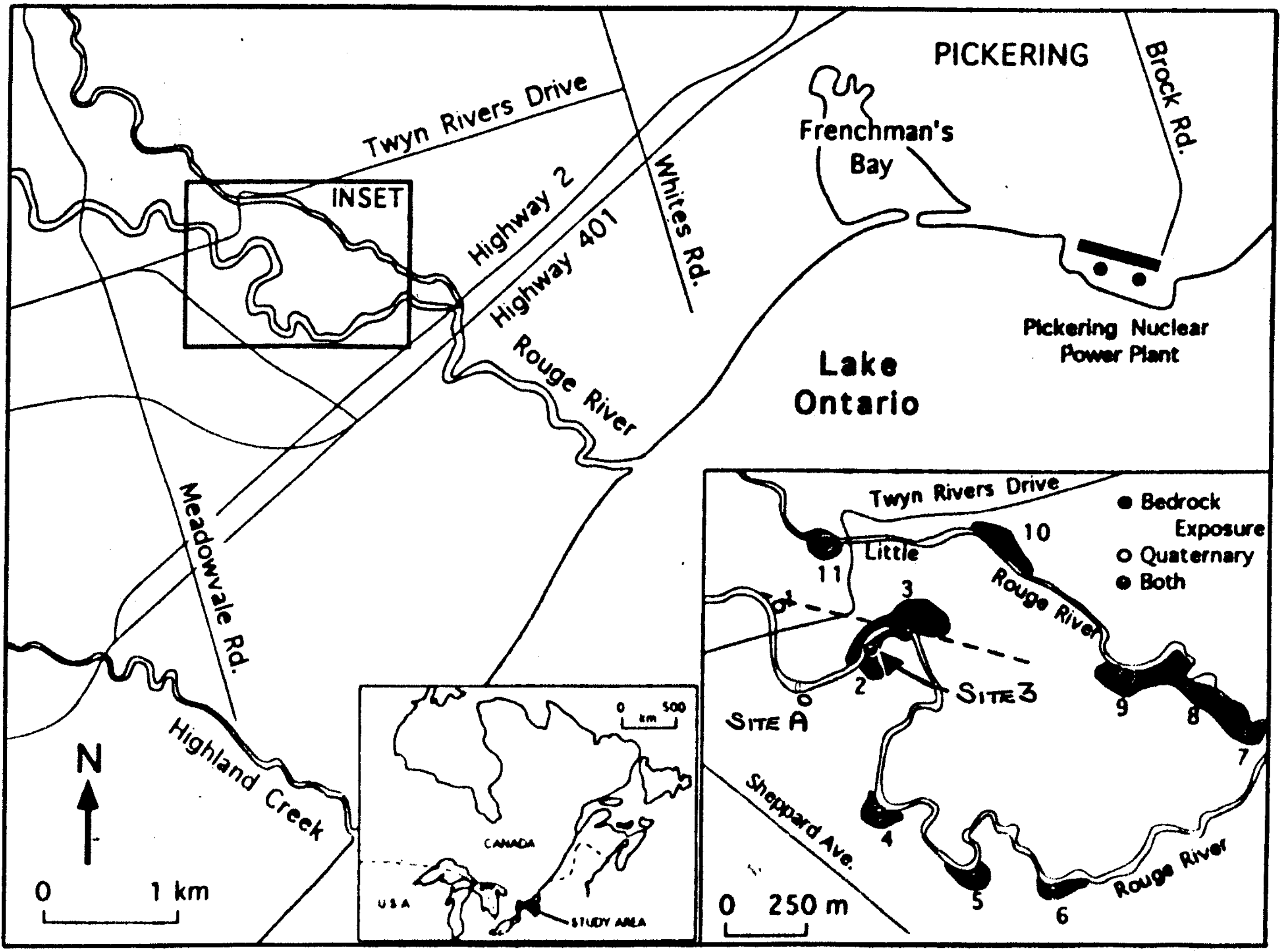
"Hydro designed the stations to withstand any kind of seismic activity" that southern Ontario is likely to have, said utility spokesman Al Manchee. "All the recent study data have not led to any alarm at Hydro."

— Citizen file photo

Fault lines discovered seven kilometres from the Toronto-area plant

■ **ACCIDENT:** Phone system would sound alarm / **A2**

Figure 1. Press item from page A1 of the Ottawa Citizen on November 1, 1992, the day the MER92 paper was released in the United States.



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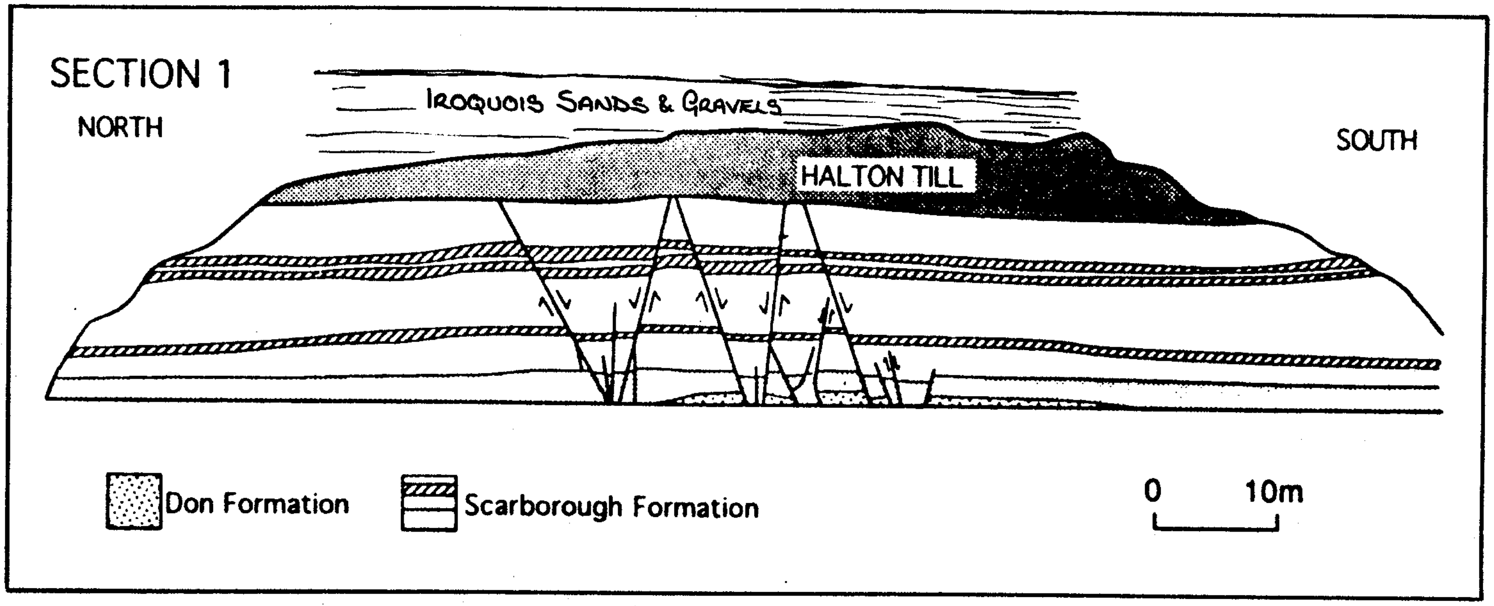

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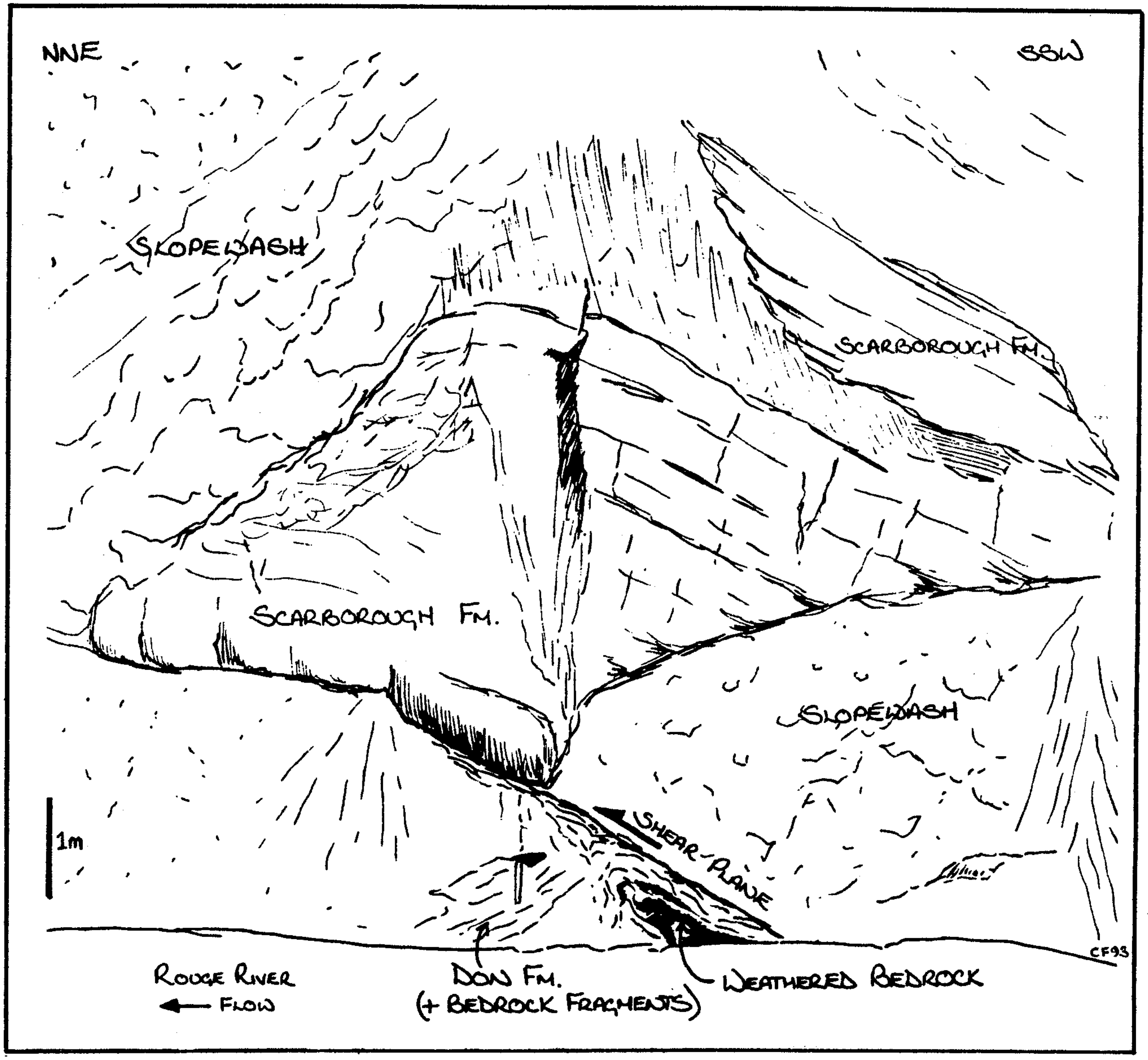

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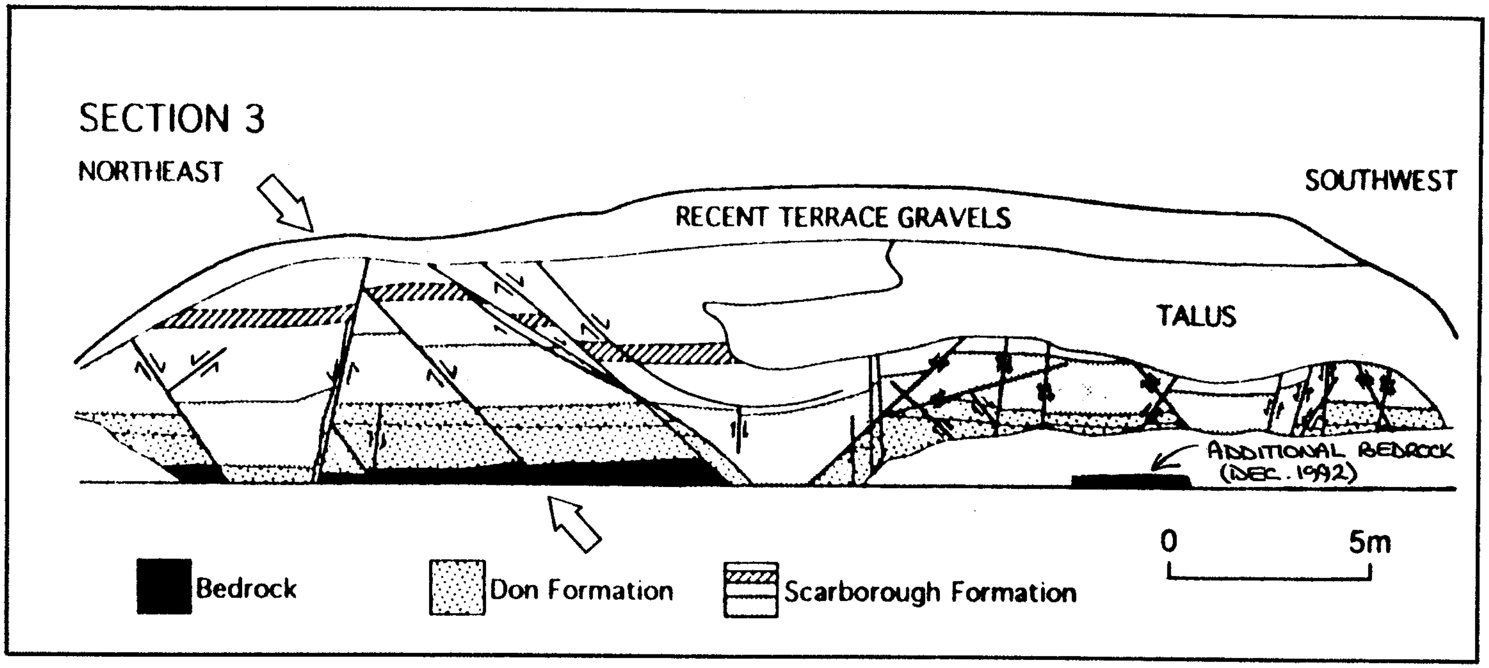
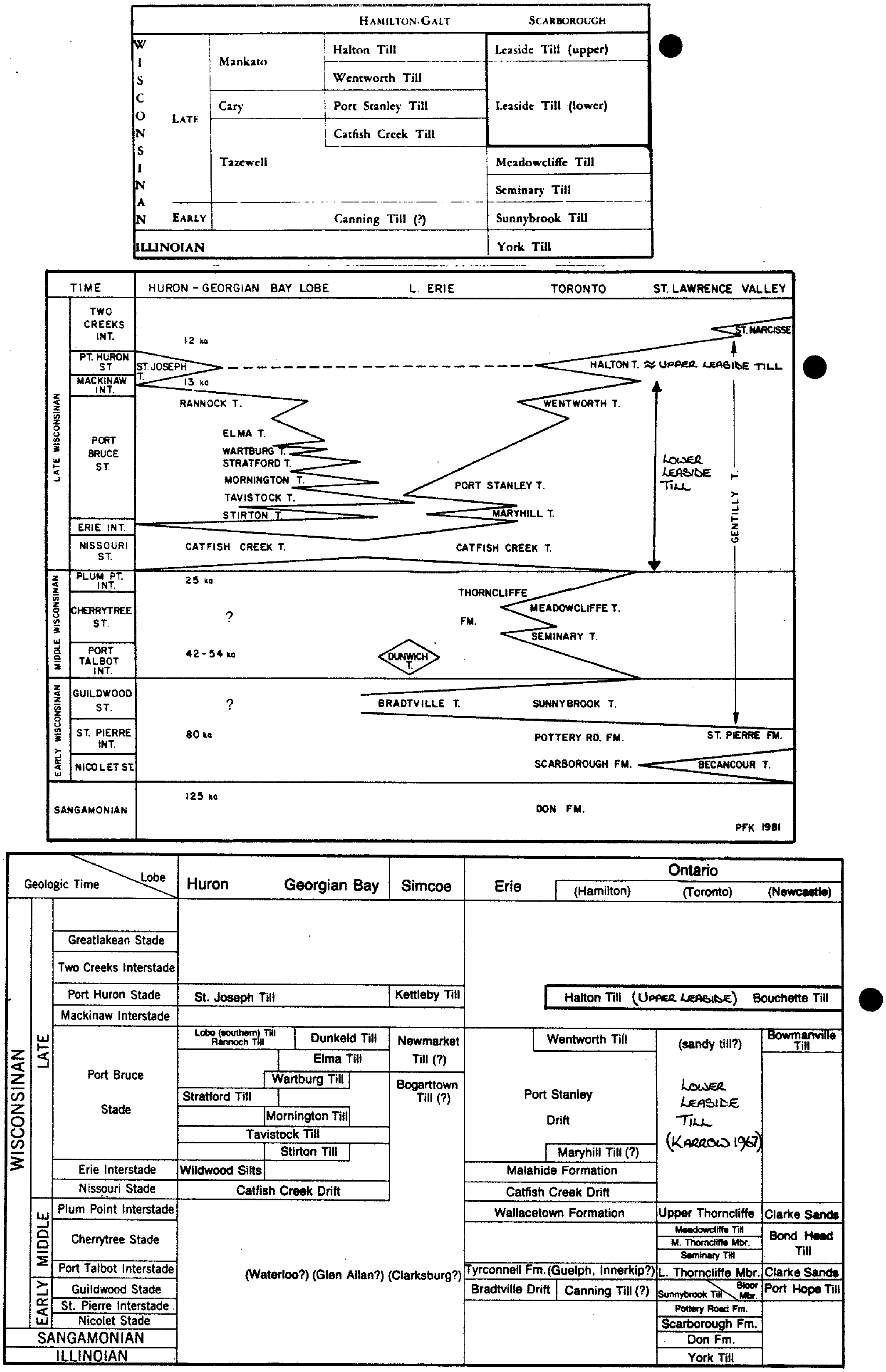


Figure 5. Faulted strata at Site 3 along the Rouge River (modified from MER92, figure 3, top). Additional exposure of bedrock was seen in December, as annotated. Arrows indicate one fault for which the throw is depicted to decrease downwards.



			HAMILTON-GALT	SCARBOROUGH
WISCONSINAN	LATE	Mankato	Halton Till	Leaside Till (upper)
			Wentworth Till	Leaside Till (lower)
		Cary	Port Stanley Till	
		Tazewell	Catfish Creek Till	
				Meadowcliffe Till
				Seminary Till
	EARLY		Canning Till (?)	Sunnybrook Till
ILLINOIAN				York Till

		Geologic Time / Lobe	Huron	Georgian Bay	Simcoe	Erie	Ontario (Hamilton)	Ontario (Toronto)	Ontario (Newcastle)
WISCONSINAN	LATE								
		Greatlakean Stade							
		Two Creeks Interstade							
		Port Huron Stade	St. Joseph Till		Kettleby Till		Halton Till	(Upper Leaside)	Bouchette Till
		Mackinaw Interstade							
		Port Bruce Stade	Lobo (southern) Till Rannoch Till	Dunkeld Till	Newmarket Till (?)	Port Stanley Drift	Wentworth Till	(sandy till?)	Bowmanville Till
				Elma Till				Lower Leaside Till (Karrow 1967)	
				Wartburg Till	Bogarttown Till (?)				
			Stratford Till						
				Mornington Till					
			Tavistock Till						
				Stirton Till			Maryhill Till (?)		
		Erie Interstade	Wildwood Silts			Malahide Formation			
		Nissouri Stade	Catfish Creek Drift			Catfish Creek Drift			
	MIDDLE	Plum Point Interstade				Wallacetown Formation		Upper Thorncliffe	Clarke Sands
		Cherrytree Stade						Meadowcliffe Till M. Thorncliffe Mbr. Seminary Till	Bond Head Till
		Port Talbot Interstade	(Waterloo?) (Glen Allan?) (Clarksburg?)			Tyrconnell Fm. (Guelph, Innerkip?)		L. Thorncliffe Mbr.	Clarke Sands
	EARLY	Guildwood Stade				Bradtville Drift	Canning Till (?)	Sunnybrook Till Bloor Mbr.	Port Hope Till
		St. Pierre Interstade						Pottery Road Fm.	
		Nicolet Stade						Scarborough Fm.	
SANGAMONIAN								Don Fm.	
ILLINOIAN								York Till	

Figure 6. Stratigraphic correlation diagrams (top from Karrow, 1967, middle from Karrow, 1984, and bottom from Karrow, 1989) annotated (black dot) to show the position of Karrow's Upper Leaside Till.

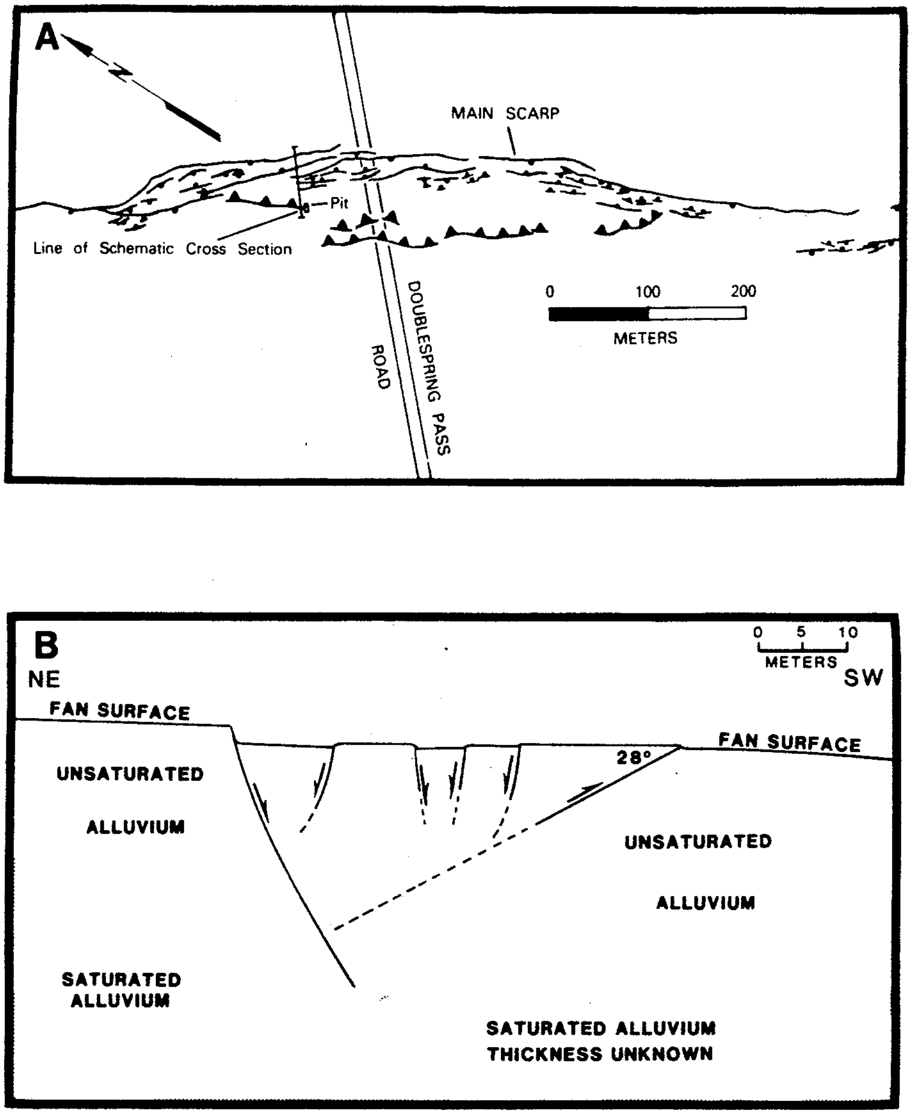


FIG. 10. Detailed map of fault scarps (A) and schematic diagram (B) of thrust faults near Doublespring Pass Road (see Plate 1). (A) Normal faults have ball on downthrown side; thrust faults have barbs on upper plate. Thrust fault exposed in pit dips 28° to the northeast. Note arcuate form of main scarp. (B) Schematic diagram showing geologic relations associated with the thrust faults. Maximum height of thrust faults is about 15 cm. Depth to top of saturated alluvium from Pelton *et al.* (1985).

Figure 7. Antithetic and synthetic faulting at Double-spring Pass Road, Idaho; 1983 Borah Peak earthquake scarp (Crone et al., 1987, figure 10).

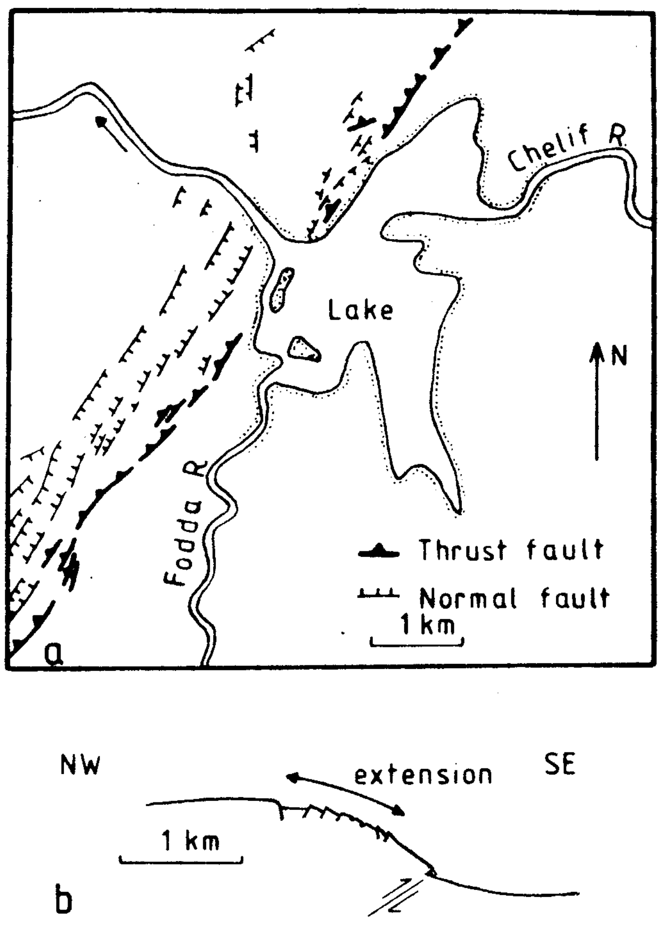
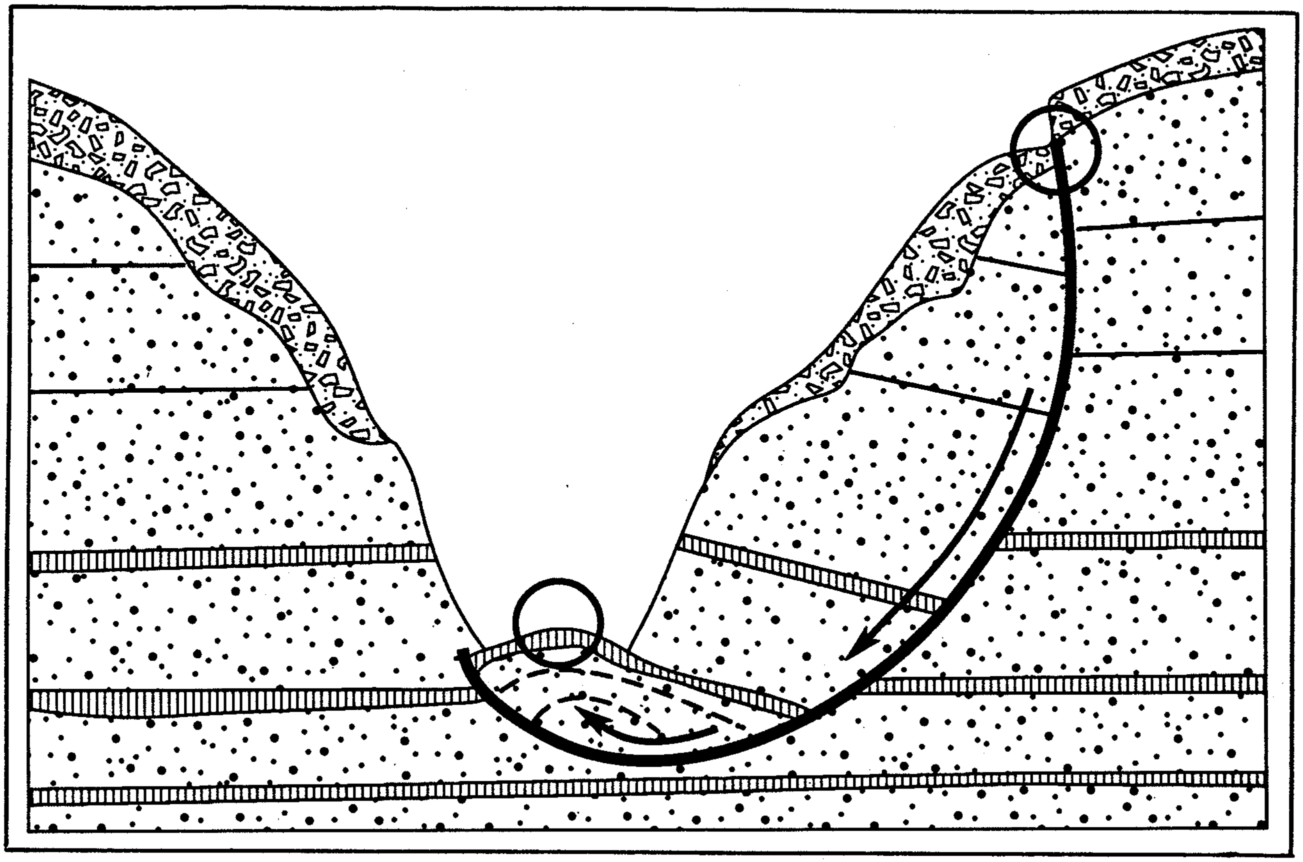


Fig. 8. Part of the surface faulting observed after the El Asnam, Algeria earthquake of 10.10.1980 (adapted from King and Vita-Finzi [88]). The map (a) shows the substantial normal faulting associated with the thrust. The section (b) shows that this extension represents internal deformation of the hanging wall above the thrust plane.

Figure 8. Extensional faulting within the hanging wall block above the 1980 El Asnam, Algeria, thrust fault (Jackson et al., 1982, figure 8).



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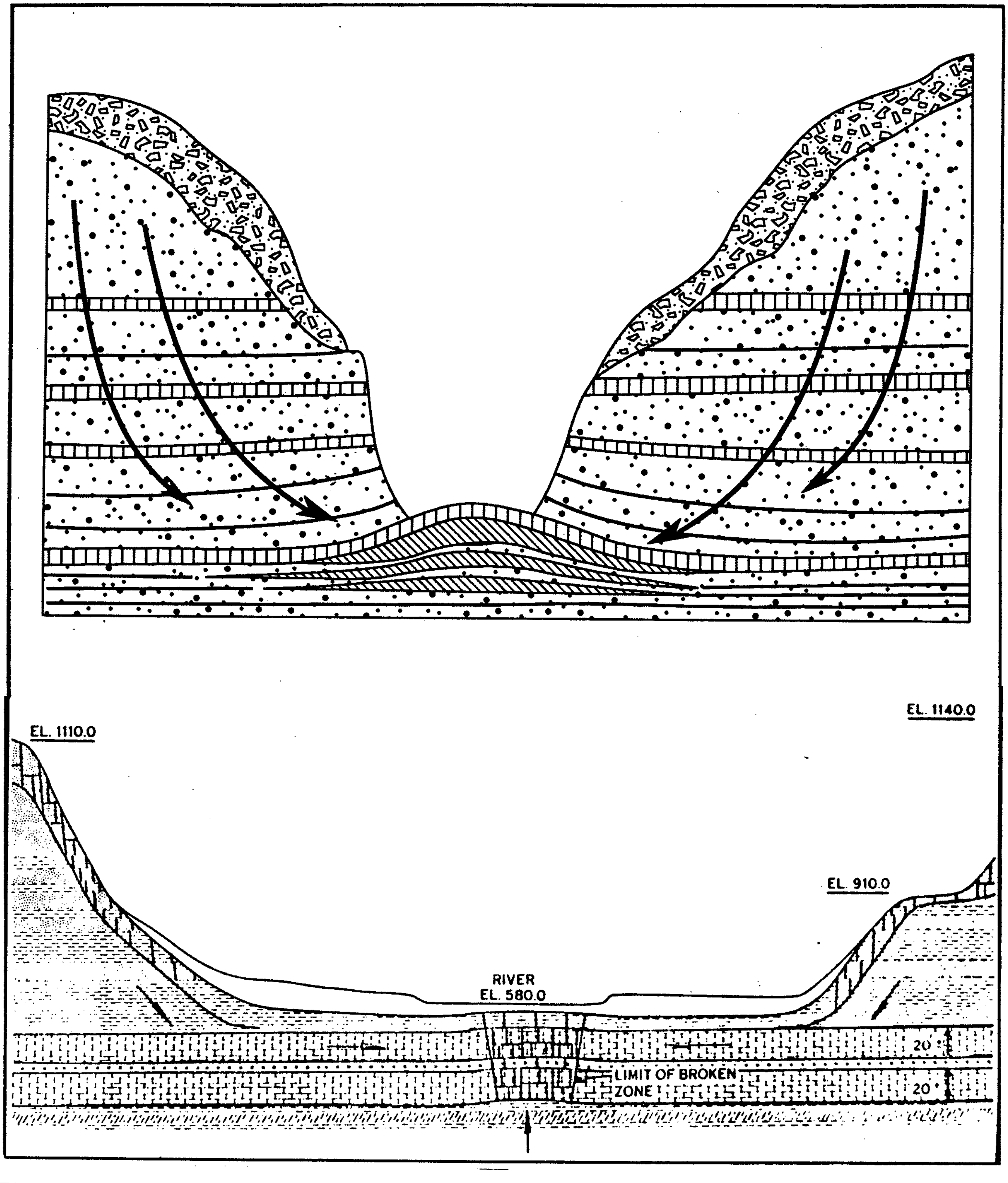

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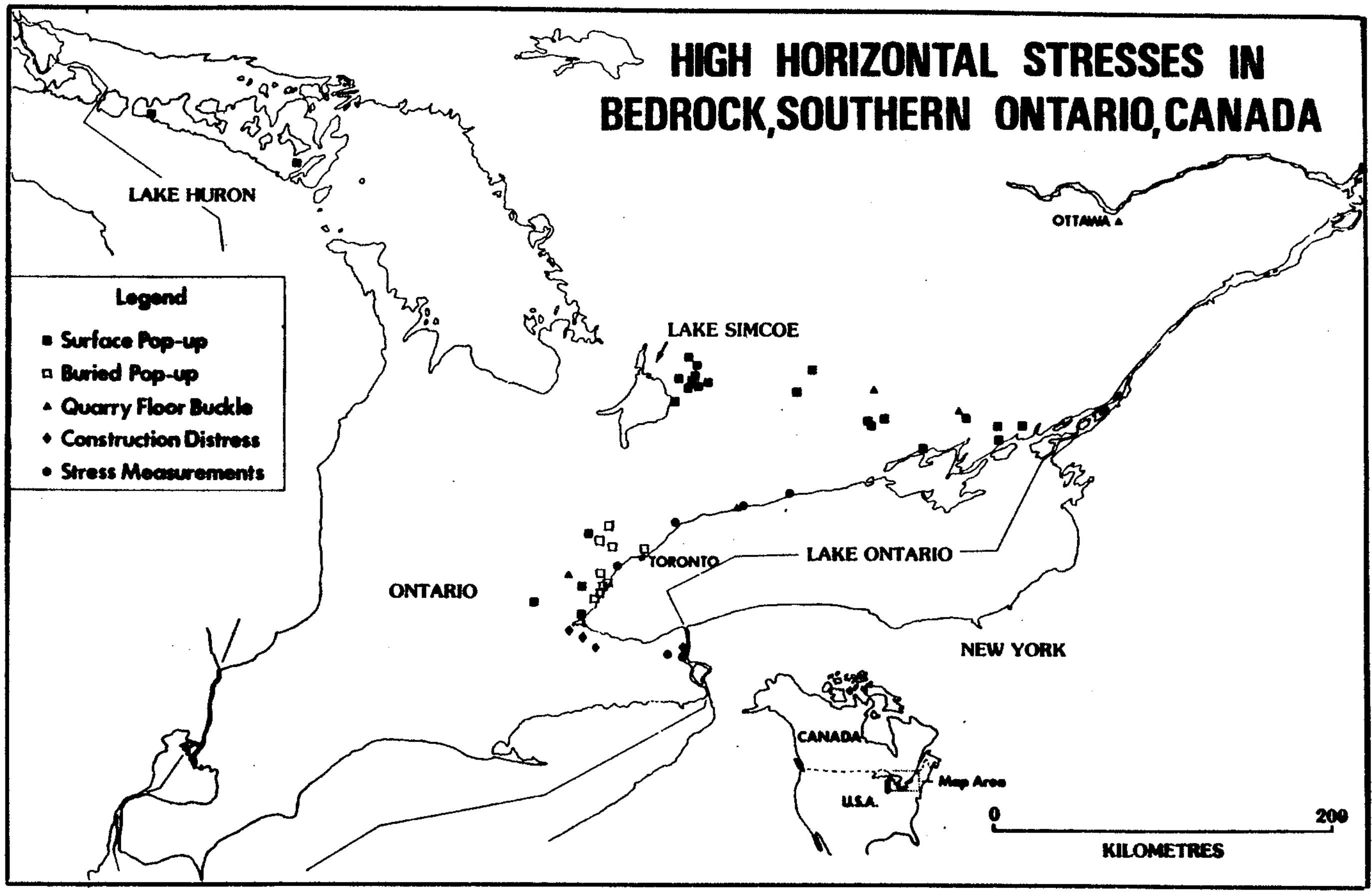

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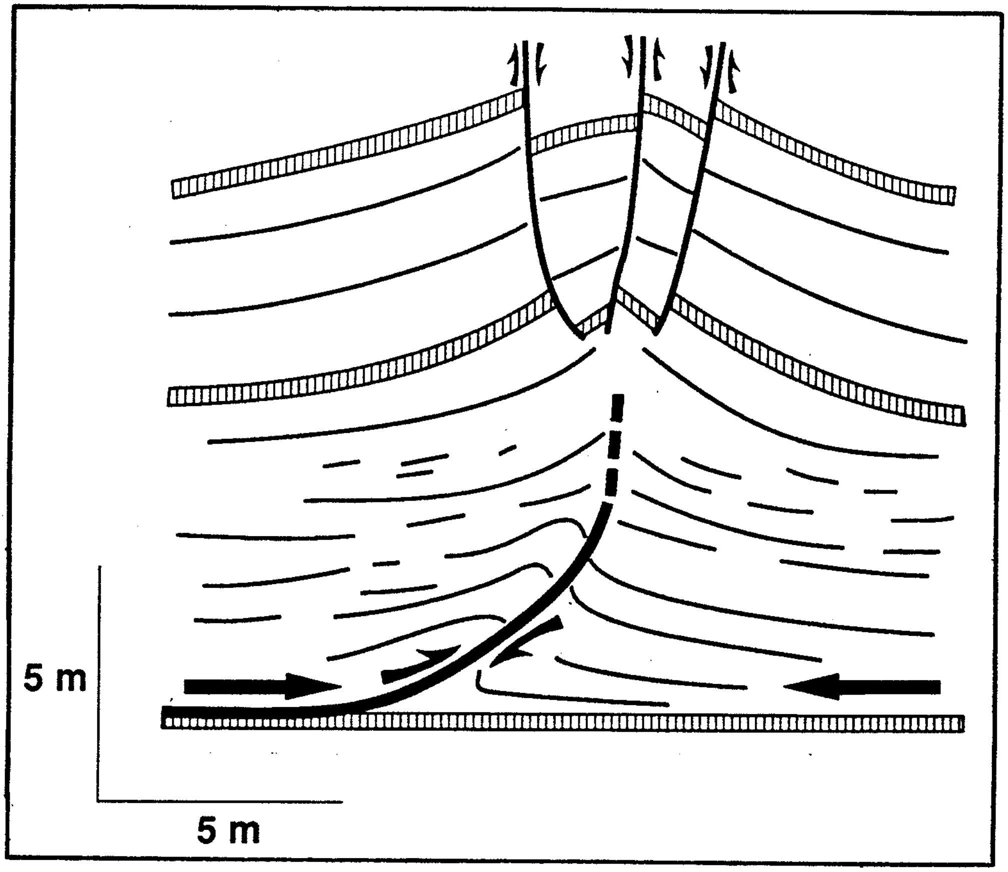

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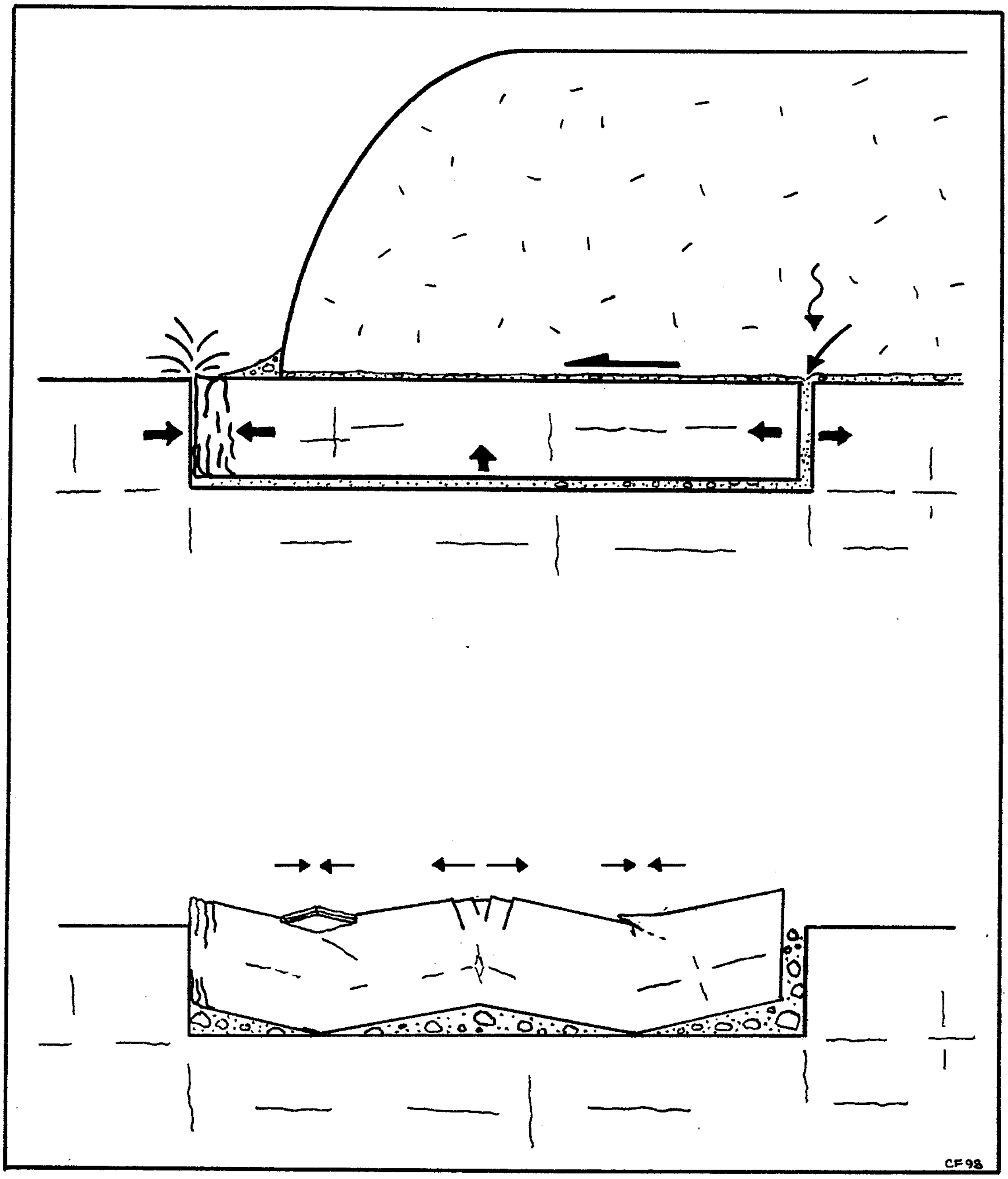
Figure 5.15. Postglacial faulting, Cape Cove, Nova Scotia. A glaciated outcrop of slate is offset along cleavage planes; striations can be traced across the steps. Movement, which is up to the south and exceeds 1 m, occurred during Wisconsinan time. 203673-W

Figure 13. Closely-spaced postglacial faults, Cape Cove, Nova Scotia. Film container is 5 cm high (Grant, 1989, figure 5.15).



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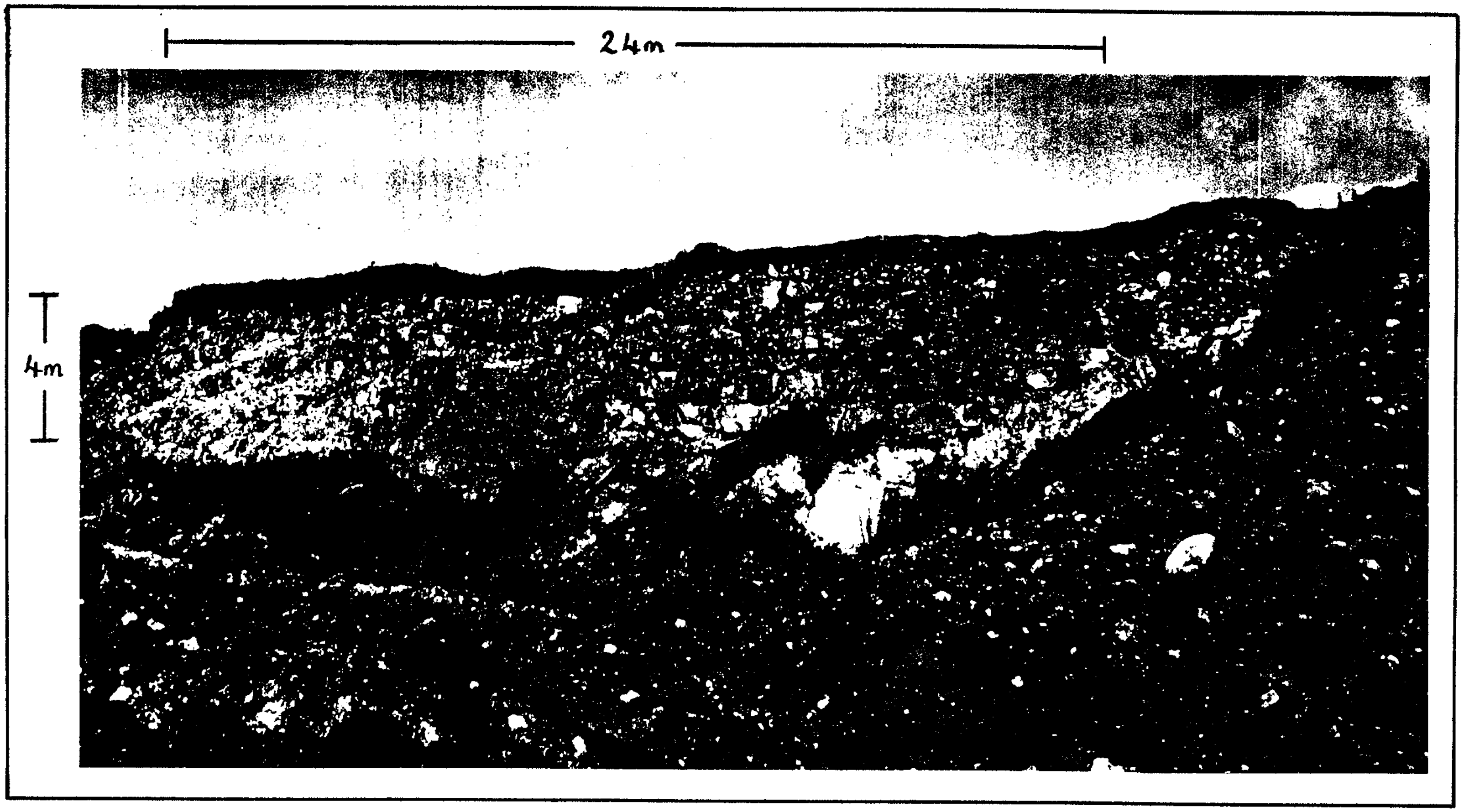


Figure 15. Raft of Carboniferous limestone, 4 m thick and 24 m long, overlying Pleistocene sand at Pollnahallia, Ireland (Coxon and Brown, 1991, plate 39).

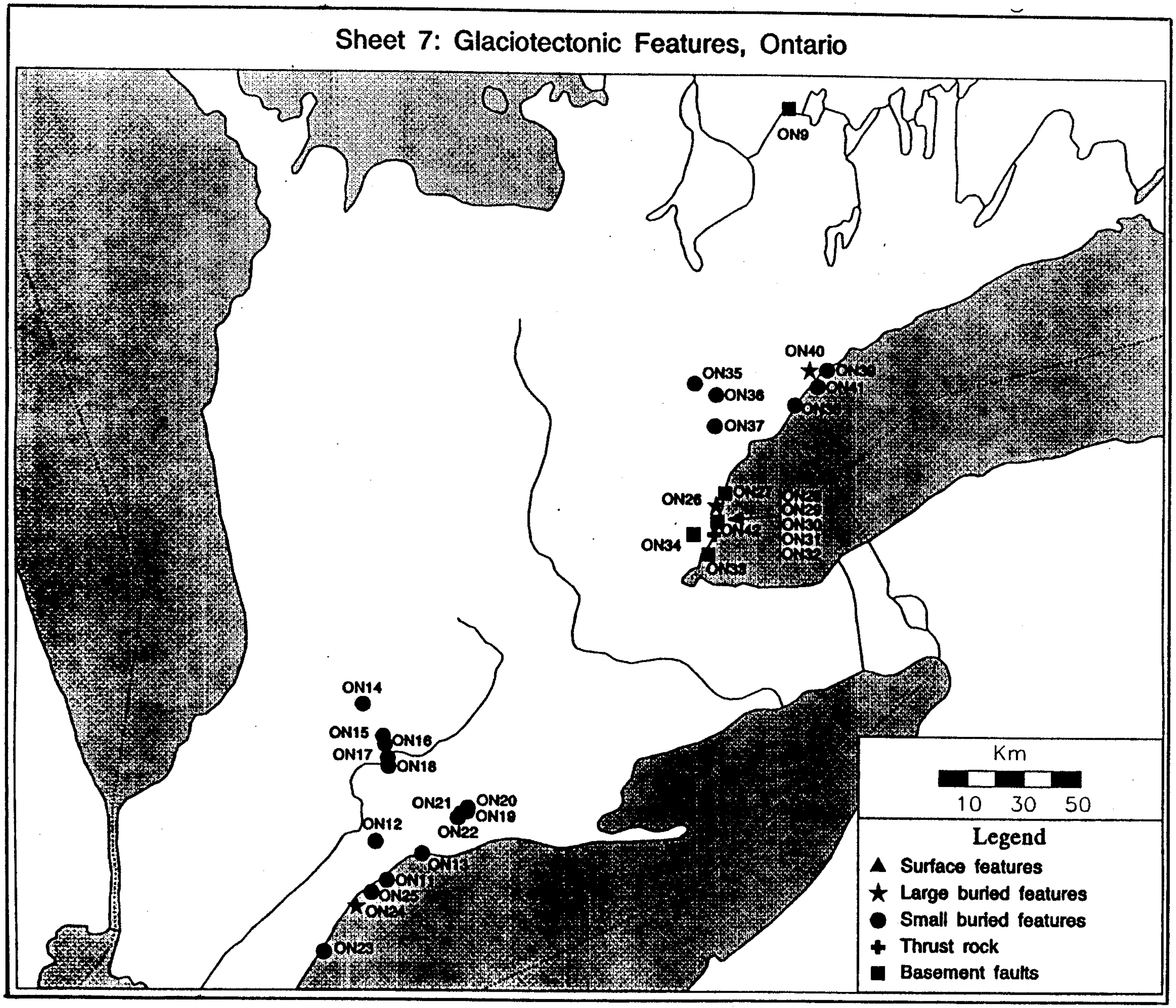
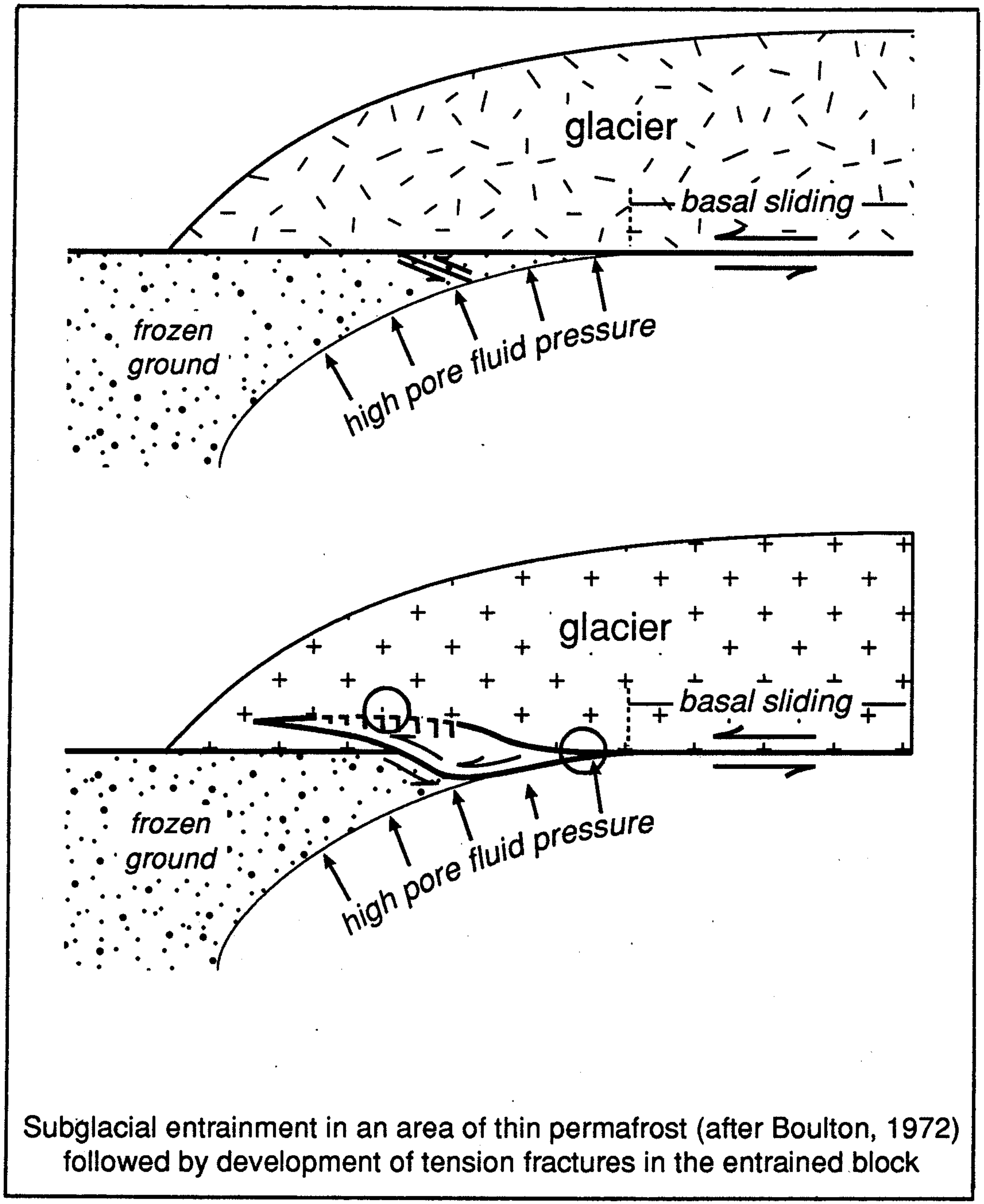
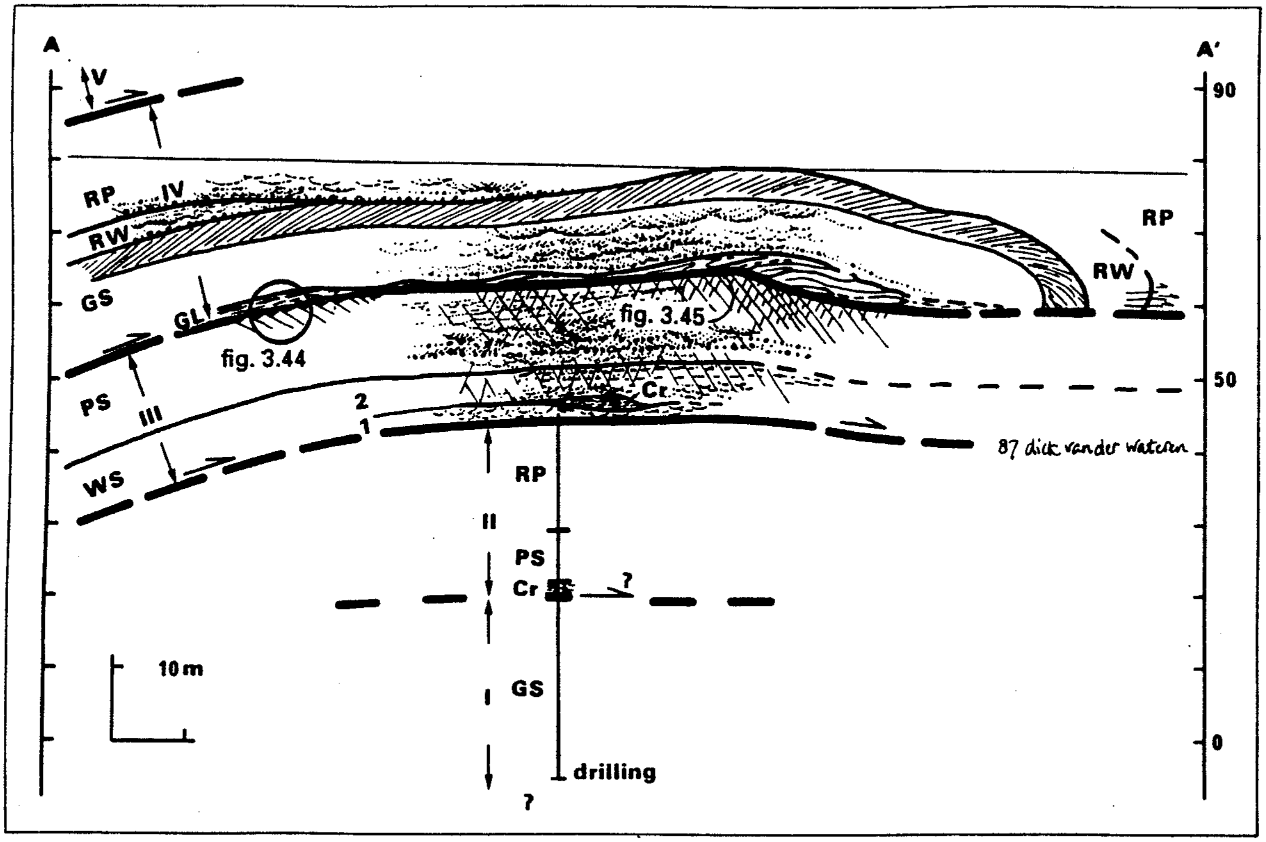


Figure 16. Map of southern Ontario showing the sites of glaciotectonic features as compiled by Dredge and Prégent (1993). The Rouge River sites lie near the star labelled 'ON40'.



Subglacial entrainment in an area of thin permafrost (after Boulton, 1972) followed by development of tension fractures in the entrained block

Figure 17. Model for the entrainment of frozen ground (or perhaps bedrock slabs if the bedrock is fractured and permeable) by an advancing glacier (Derbyshire and Jones, 1980, figure 8). The normal faulting in the Rouge River Valley might correspond to extension at the rear of the block or to extension on the top of the block when the ice melts and the block sags (circles).



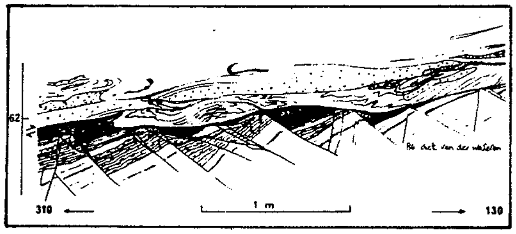


Fig. 26. Layer-parallel extension beneath nappe overthrust (nappe IV) at Ossenbeck. Shear zone material is incorporated in the down-thrown blocks.

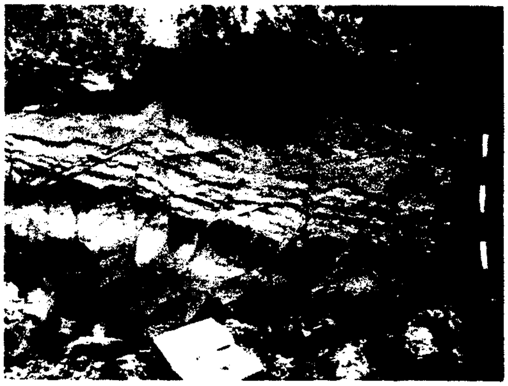


Fig. 24. Overprinting fault sets F1, F2 and F3 (Figs. 25b, c). North is to the right. Scale division 10 cm.

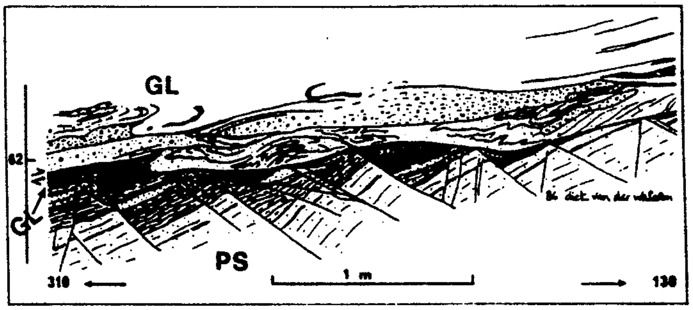


Figure 3.44. **Structural style of the shear zone at the base of nappe 4 at Ossenbeck (fig. 3.10). Normal faults form an asymmetric extensional crenulation typical of a right lateral shear zone. The central part of the shear zone shows an intensely folded and attenuated transposed foliation of GL material mixed with other lithologies.**

Figure 18. Glaciotectonic deformation at Ossenbeck sandpit, Germany. Top: overview of thrust nappes (van der Wateren, 1992, figure 3.10). Lower right: photograph (van der Wateren, 1987, figure 24) and line drawing (van der Wateren, 1992, figure 3.44) both showing extensional faulting within the circle labeled 'fig. 3.44' on the top figure. Lower left: similar deformation elsewhere in the sandpit (van der Wateren, 1987, figure 26).

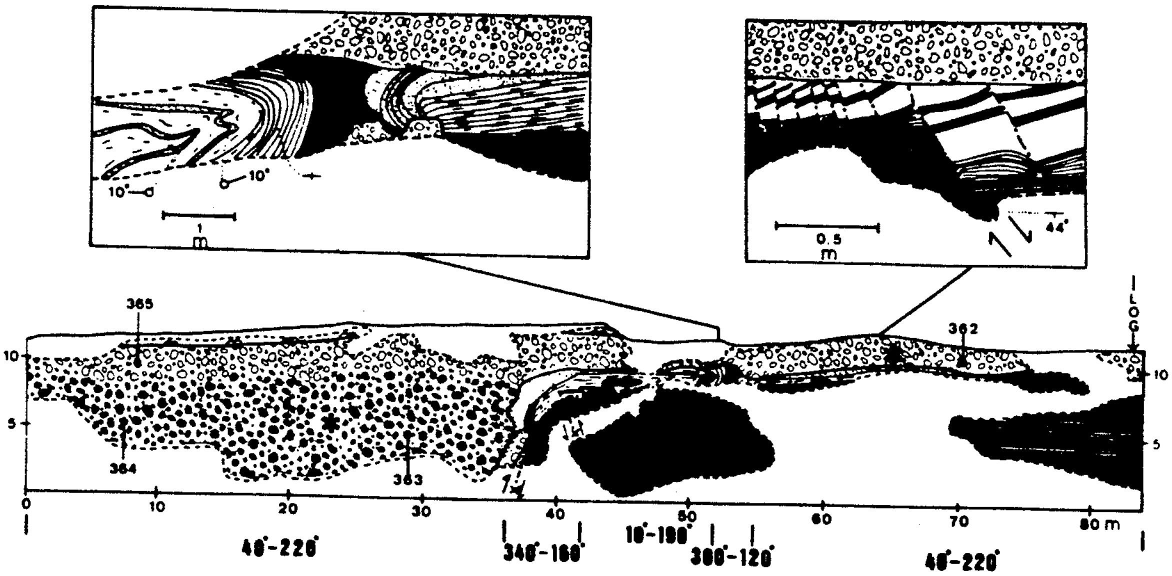


Fig. 4. Mindre forkastninger ved Nygård Hage, antydende isbevægelse fra nord. Se desuden fig. 3.

Minor faults at Nygård Hage.

Figure 19. Extensional faulting of sands under till, coastal cliff at Nygard Hage, Denmark (Jensen, 1985, figures 3 and 4).

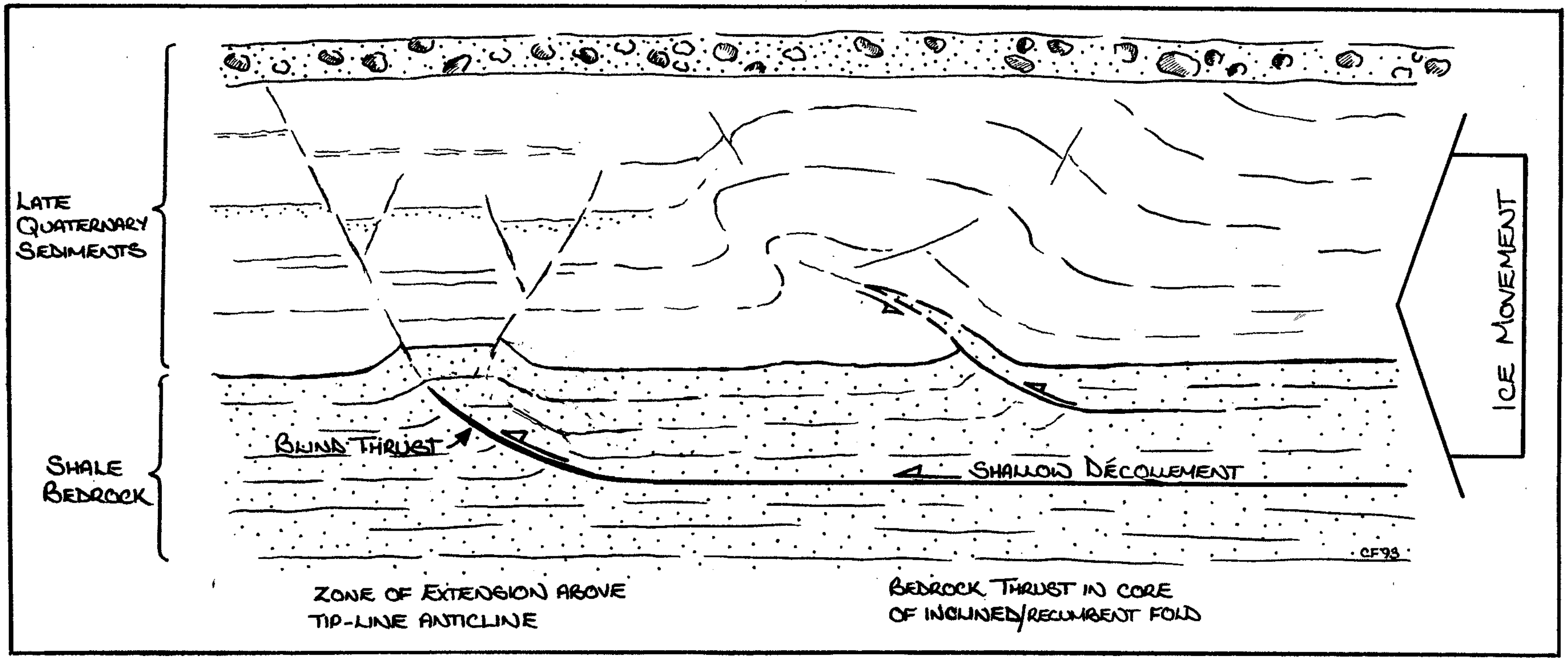
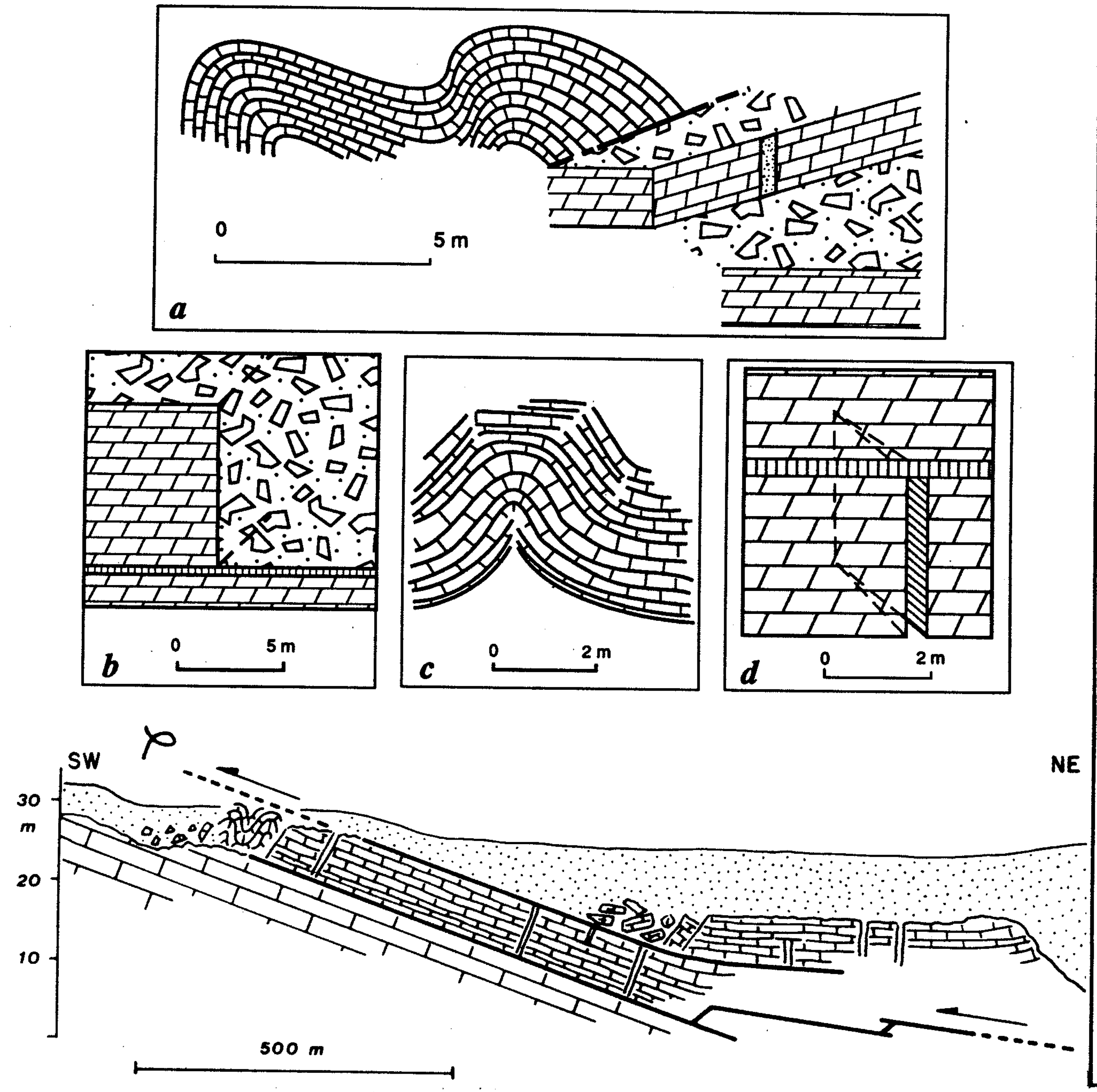


Figure 20. Diagramatic sketch of both compressional and extensional deformation features produced by ice-push, which results in shallow bedrock décollement. This model may explain the deformation observed at Sites 3 and A along the Rouge River.

Figure 21. Steeply dipping extensional faults in sand of the Scarborough Formation at Cudia Park, Toronto (Hicock and Dreimanis, 1992, figure 4a).



Known glaciotectonic features in the bedrock of Montréal area. (*A*) Overlapped and displaced limestone blocks overlying dense till (after Grice 1972). (*B*) Sharp vertical drop related to a joint plane (after Durand and Ballivy 1974). (*C*) Parallel and nearly fan-shaped fold found in the downstream part of a thrust (after Durand and Ballivy 1974). (*D*) Open vertical joint closed at its top by interbedding sliding (after Durand 1978). (*E*) Schematic thrust showing the relationships between previous features (after Durand 1978).

Figure 22. Regional model (bottom) for glaciotectonic deformation of large limestone sheets in the Montréal area and some details (top) of this deformation (Schroeder et al., 1986, figure 1).

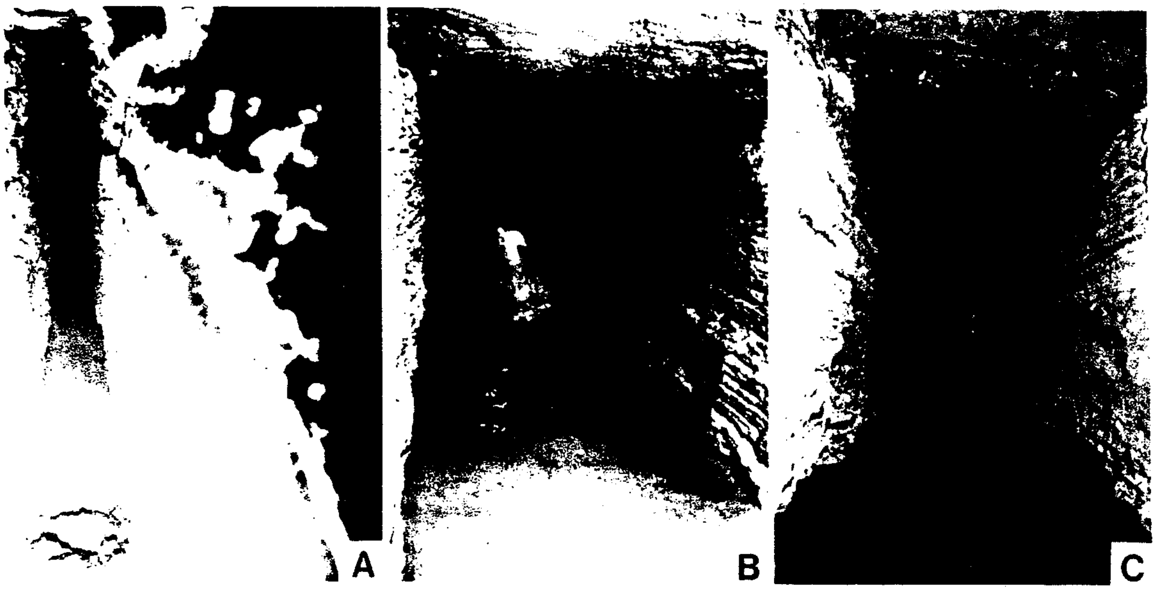


FIG. 5. Three galleries from the newly discovered cave system with fit-feature walls opened by 0.4 m (*A*), 1.4 m (*B*), and 1.9 m (*C*). The flat ceiling corresponds to limestone bed soles.

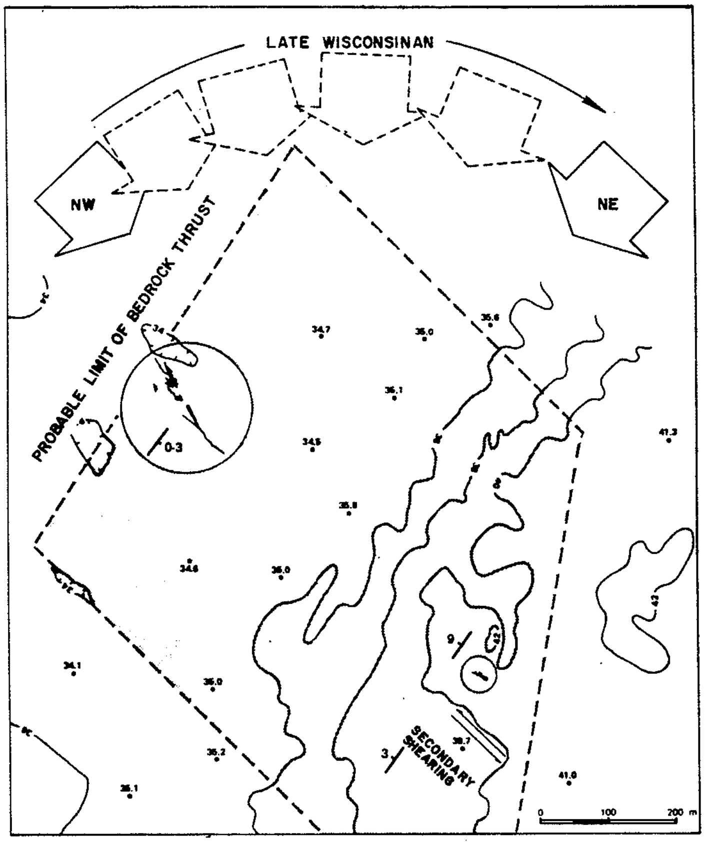


FIG. 9. The topographic features surrounding encircled glaciotectonic caves suggest that a bedrock thrust, shown in grey, is bounded on the upstream side by three closed depressions at 34 m asl and on the downstream side by a rock crest lying between 36 and 42 m asl. The thrust seems to extend on the northeast side, and the upper beds in the southern portion have been truncated by a wrench fault, indicated by arrows. Dips and topography are lower south of this fault. This hypothesis is in good agreement with known ice-movement directions going from northwest to northeast.

Figure 23. Photographs showing the remarkable hidden extension under thrusted limestone sheets, and the likely extent of the displaced block (Schroeder et al., 1986, figures 5 and 9).

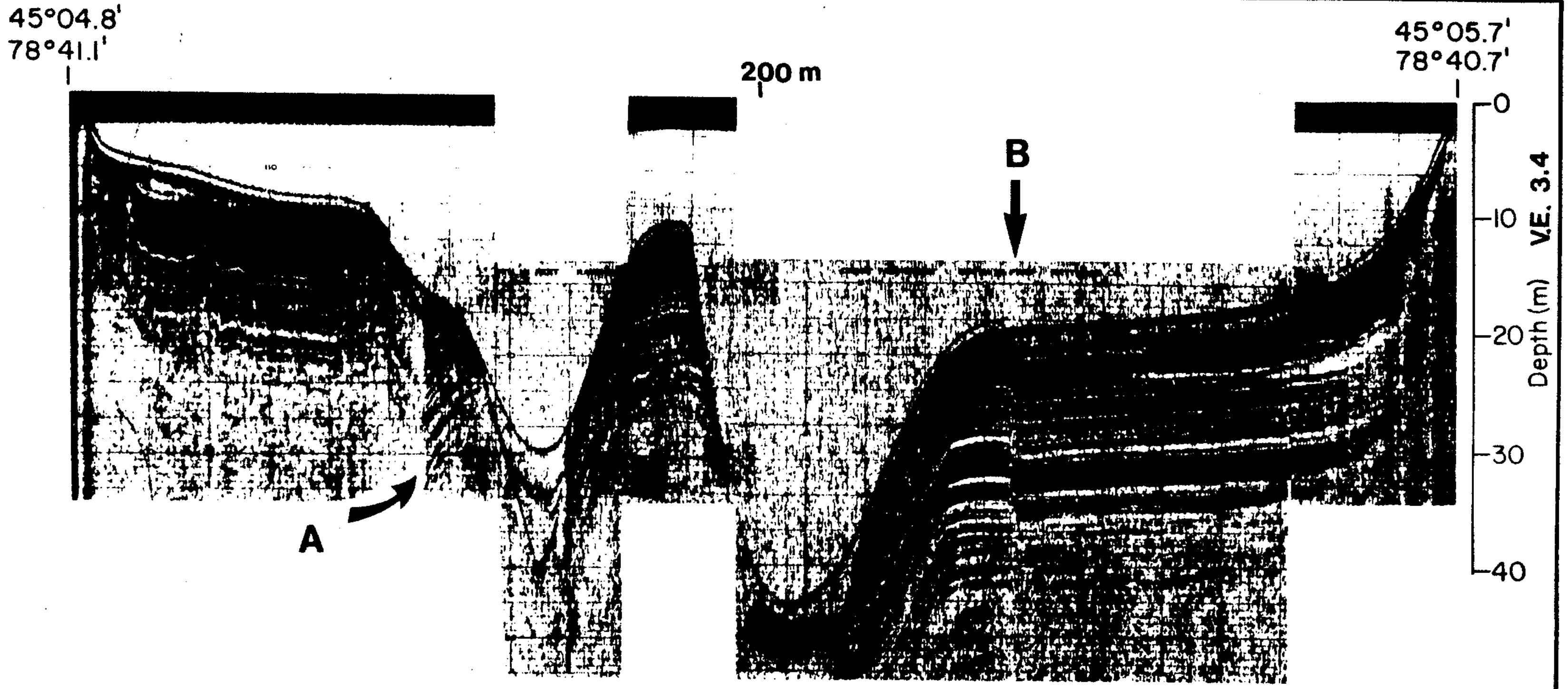


FIG. 8. SAP (RTT-1000) record of ice-block casts and syn- or post-depositional faults, Maple Lake, Ontario. Arrowed fault (A) delineates slump block displaced from a steep ice-contact face after adjacent ice had melted. Arrow B indicates a fault produced by differential lowering of sediment over a melting ice block.

Figure 24. Lake-bottom record of ice-block melt-out (Shilts and Clague, 1992, figure 8).