Géographie physique et Quaternaire

Pop-Up Structures and the Fracture Pattern in the Balsam Lake Area, Southern Ontario
Les structures de soulèvement (pop-ups) ef le réseau de fissures dans la région de Balsam Lake, au sud de l’Ontario
Hebungsstrukturen und Bruchmuster im Gebiet des Balsam Lake, südliches Ontario

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La néotectonique de la région des Grands Lacs
Neotectonics of the Great Lakes area

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Résumé de l'article

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POP-UP STRUCTURES AND THE FRACTURE PATTERN IN THE BALSAM LAKE AREA, SOUTHERN ONTARIO

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ABSTRACT An examination of topographic lineaments detectable in Landsat TM images and measurement of joints in outcrop in the Balsam Lake area reveals a systematic bedrock fracture pattern with three principal sets oriented 091°, 027°, and 152°. The 027° trend is parallel to a major aeromagnetic anomaly, the Niagara-Pickering Linear Zone (NPLZ), which underlies the Balsam Lake area and is thought to mark the sub-Paleozoic continuation of the Proterozoic Central Metasedimentary Belt Boundary Zone (CMBBZ). Possible origins of the main joint sets due to Acadian (091° set), Alleghanian (152° set) and St. Lawrence rift system tectonics (091° and 027° sets) are discussed. En-echelon pop-up structures have a mean principal trend of 118°. They displace Lake Algonquin paleobeaches, suggesting formation less than 12,500 years ago. The orientation of the pop-up structures is subnormal to the current in situ maximum horizontal stress direction, S_{Hmax} (020°), and is parallel to members of the 091° joint set, indicating possible nucleation on favourably-oriented pre-existing joints. These pop-ups are the only features in the Balsam Lake area with strong evidence for a neotectonic age.

RÉSUMÉ *Les structures de soulèvement* (pop-ups) *et le réseau de fissures dans la région de Balsam Lake, au sud de l'Ontario.* L'examen des linéaments topographiques repérables sur les images Landsat (TM) et la mesure des diaclases dans un affleurement de la région de Balsam Lake révèle la présence d'un réseau de fractures dont l'orientation des trois principaux ensembles est 091°, 027° et 152°. La direction 027° est parallèle à une anomalie aéromagnétique majeure, la zone linéaire Niagara-Pickering, présente sous la région de Balsam Lake; on croit qu'elle identifie le prolongement subpaléozoïque de l'aire limite de la zone métasédimentaire centrale protérozoïque. On traite des origines possibles des principaux ensembles de fractures attribuables aux systèmes acadien (091°), alléghanien (152°) et du rift du Saint-Laurent (091°et 027°). La direction des structures de soulèvement en échelon est de 118°. Elles ont déplacé des paléo-plages du Lac Algonquin, indiquant ainsi une formation postérieure à 12 500 ans. L'orientation des structures de soulèvement est subnormale à la direction de la contrainte horizontale maximale actuelle, S_{Hmax} (020°), et est parallèle à des éléments de l'ensemble des fractures de direction 091°, montrant ainsi leur formation possible dans des fractures existantes bien orientées. Ces structures de soulèvement sont les seuls éléments de la région démontrant un âge néotectonique.

ZUSAMMENFASSUNG *Hebungsstrukturen und Bruchmuster im Gebiet des Balsam Lake, südliches Ontario.* Eine Untersuchung der topographischen Lineamente die in Landsat TM-Bildern nachweisbar sind und Messungen der Fugen in den Aufschlüssen des Balsam Lake-Gebiets lassen ein systematisches Bruchmuster des anstehenden Gesteins erkennen mit drei nach 091°, 027° und 152° ausgerichteten Haupteinheiten. Die Ausrichtung nach 027° ist parallel zu einer wichtigen aeromagnetischen Anomalie, der linearen Zone von Niagara-Pickering, die unter dem Balsam Lake-Gebiet liegt; man halt sie für eine subpaläozoische Fortführung des Grenzbereichs der proterozoischen zentralen metasedimentären Gürtel-zone. Man diskutiert mögliche Ursprünge der Hauptfugensysteme, die auf die akadische (091° System), alleghanische (152° System) und Sankt-Lorenz-Spaltensystem Tektonik (091° und 027° System) zurückgeführt werden. Die gestaffelten Hebungsstrukturen haben eine durchschnittliche Hauptrichtung von 118°. Sie haben Paläo-Strände vom Lake Algonquin versetzt, und weisen so auf eine Bildung vor weniger als 12,500 Jahren. Die Orientierung der Hebungsstrukturen ist subnormal zu der gegenwärtigen maximalen horizontalen Stressrichtung, S_{Hmax} (020°) und parallel zu Elementen des 091° Fugensystems, was auf ihre mögliche Bildung auf günstig orientierten schon vorhandenen Fugen weist. Diese Hebungen sind die einzigen Strukturen im Balsm Lake-Gebiet, welche deutlich ein neotektonisches Alter belegen.

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INTRODUCTION

Historically, the interior of the North American craton has been viewed as stable, but evidence from Paleozoic and Mesozoic strata, recent seismicity and studies of intracratonic basins suggests that the craton is not stable (Armstrong, 1992) and current research has begun to focus on paleoseismic studies and other geological studies for hazards mapping (Basham and Adams, 1989; Wallach and Mohajer, 1990b; Wallach *et al.*, in press). Linear zones of modern seismicity, such as occurs along the Clarendon-Linden fault zone in New York state (Fakundiny *et al.*, 1978) and its possible extension into Prince Edward County, Ontario (McFall and Allam, 1991), provide evidence of post-Paleozoic reactivation of Precambrian basement faults (McFall and Allam, 1991). Aeromagnetic data (Gupta, 1991) indicate that a similar Precambrian basement structure, the Central Metasedimentary Belt Boundary Zone (CMBBZ) exposed within the Grenville Province of southern Ontario (Fig. 1), continues southward beneath flat-lying Paleozoic cover sequences (Wallach and Mohajer, 1990b). Wallach and Mohajer (1990a) have suggested that this Precambrian structure may also have been reactivated.

This paper presents remote sensing and field-based observations of the fracture (undifferentiated joints and faults) pattern and related pop-up structures within the Paleozoic bedrock of the Balsam Lake area which overlies the aeromagnetic expression of the NNE-trending CMBBZ in south-central Ontario (Fig. 1). Outcrop-scale measurements of joints (planar fractures with no observed displacement) were related to the fracture pattern inferred from lineaments observed at the airphoto (1:10,000) to Landsat imagery (1:250,000) scale. By comparison to more regional studies (*e.g.* Parker, 1942; Gross *et al.*, 1992) in New York State we suggest that the bedrock fracture pattern contains elements formed during phases of the Appalachian orogeny as well as an undated event which reactivated the CMBBZ. This event may be related to the opening of the Atlantic and formation of the St. Lawrence rift system in the Cretaceous. Pop-up structures in the area, inferred to be neotectonic, are perpendicular to the current maximum horizontal stress direction but appear to have nucleated on favourably oriented, older fractures.

GEOLOGICAL SETTING

In southeast Ontario the CMBBZ occurs beneath the Paleozoic and Quaternary cover as a prominent NNE-trending aeromagnetic anomaly, which was named the Niagara-Pickering Linear Zone (NPLZ) by Wallach and Mohajer (1990b; see also Gupta, 1991) (Fig. 1). North of the Paleozoic/Precambrian unconformity (Fig. 1), the CMBBZ is defined as a shear zone separating the Central Gneiss and Central Metasedimentary Belts of the Grenville Province (Easton, 1992) and its magnetic expression is less well-defined. The NPLZ underlies Lake Ontario and may connect with the Akron Magnetic Boundary in Ohio, an approximately 50 km long NNE-trending feature which is thought to mark a Precambrian fault separating two different lithologies (Seeber and Armbruster, 1989; Wallach, 1990). Shallowly east-dipping (15°-30°) seismic reflectors within the crystalline basement across the CMBBZ/NPLZ below Lake Ontario have been interpreted as ductile thrust faults (Milkereit *et al.*, 1992). Brittle faulting in Precambrian rock and vertical displacements of upper Middle Ordovician rocks along major NNE-oriented lineaments within the CMBBZ provide evidence of post-upper Middle Ordovician reactivation of the CMBBZ (Wallach and Mohajer, 1990a; Wallach, 1991; Sanford, 1993). However, seismic data collected across the NPLZ below Lake Ontario indicate that a shale-limestone marker is undisturbed at the data resolution scale and that this zone has been relatively stable since the Ordovician period (Milkereit *et al.*, 1992).

The Balsam Lake area (Figs. 1 and 2) overlies the surface projection of the CMBBZ/NPLZ and is located 15 to 20 km south of the Paleozoic/Precambrian unconformity. The area

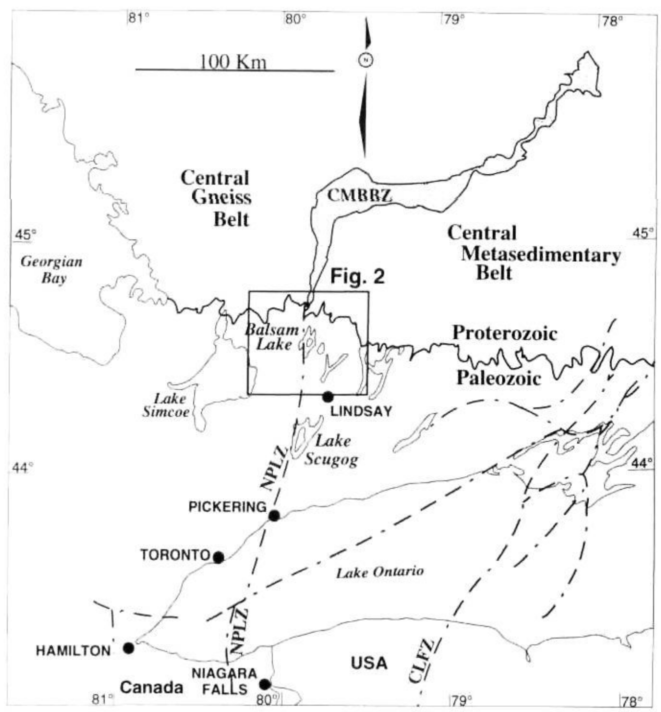

FIGURE 1. Location map showing the area covered in Figure 2 (rectangular box) and the aeromagnetic lineament (NPLZ) which is interpreted to be the subsurface continuation of the Grenvillian Central Metasedimentary Belt Boundary Zone (CMBBZ). Dash-dotted lines represent aeromagnetic lineaments and mapped faults. Dotted area is the Central Metasedimentary Belt Boundary Zone as mapped from surficial geology. Dark solid line is the Paleozoic/Proterozoic unconformity (adapted from the bedrock geology map of southern Ontario, Ontario Geological Survey, 1991).

Carte de localisation montrant l'aire couverte par la figure 2 (rectangle) et le linéament aéromagnétique (NPLZ) interprété comme étant le prolongement en subsurface de l'aire limite de la zone métasédimentaire centrale grenvillienne (CMBBZ). Les lignes en traits-points représentent les linéaments aéromagnétiques et les failles cartographiées. La trame en pointillé représente l'aire limite de la zone métasédimentaire centrale déterminée par la géologie des formations superficielles. Le trait sinueux gras identifie la discordance entre le Paléozoïque et le Protérozoïque (adapté de la carte de géologie structurale du sud de l'Ontario de la Commission géologique de l'Ontario, 1991).

was originally chosen for study after a regional lineament analysis using Landsat imagery identifed a lineament intersection and a relatively high lineament density in the vicinity of Balsam Lake. Furthermore, the Quaternary cover is relatively thin to absent (Armstrong and Anastas, 1992), allowing for a good definition of the fracture pattern within the subhorizontal Ordovician strata (Bobcaygeon and Verulam Formations; Liberty, 1952; 1969) which underlie the area.

LINEAMENT ANALYSIS

SATELLITE IMAGERY

A detailed analysis of satellite imagery along the CMBBZ/NPLZ between Lake Ontario to 190 km N of the Paleozoic/Precambrian boundary is reported elsewhere (Rutty and Cruden, 1993; manuscript in preparation). In the area south of the Precambrian/Paleozoic boundary, around Balsam Lake, the major topographic lineament trends, summarized in Table I, are as follows: 023°, 155° 132°, and 070° (see Fig. 3). These linear topographic features correspond to wooded, low-lying areas, marshes, muck and alluvial deposits, straight lake edges, rock escarpments and ridges. They are differentiated from lineaments defined by constructional land forms (*e.g.* drumlins, eskers, and the depositional contacts between glacial sand, till and moraine deposits) which are not reported here. The 023°, 155°, and 070° trending lineaments are also present in the Precambrian north of the unconformity. The 023° lineament trend, which dominates the satellite imagery for this area, is parallel to the CMBBZ/NPLZ. However, further work is required to establish whether this trend is restricted to a zone overlying the CMBBZ/NPLZ or is part of a more regionally occurring lineament set.

AERIAL PHOTOGRAPHS

Aerial photographs of the Balsam Lake area were examined and linear features were compared with published geological and topographic data. Features that were not anthropogenic or obviously glacial in origin were considered for field examination. Of particular interest are a number of sharp contrast, white-with-dark-edge lineaments which match with three pop-up structures mapped by Finamore and Bajc (1983) and three previously unreported pop-up sets in the area (Fig. 2).

FIELD INVESTIGATION

JOINTS

The orientations of systematic joints (see Nickelsen and Hough, 1967 for a definition) were measured at one outcrop (near location A on Fig. 2) of Paleozoic bedrock in the Balsam Lake area (Fig. 4). These joints are planar, vertical to subvertical, and open with no visible slickenside lineations on their surfaces. Coarse grains of clear white calcite infill some of the joints. The joints cut through, and are also terminated by, bedding planes. No clear cross-cutting relationships, giving the relative ages of the joints, are discernible. The principal joint trend, determined statistically using a circular counting routine (Robin and Jowett, 1986), is 091°. The secondary trends are 027° and 152°, corresponding to the orientations of topographic lineaments (Table I, Fig. 3). It appears that the

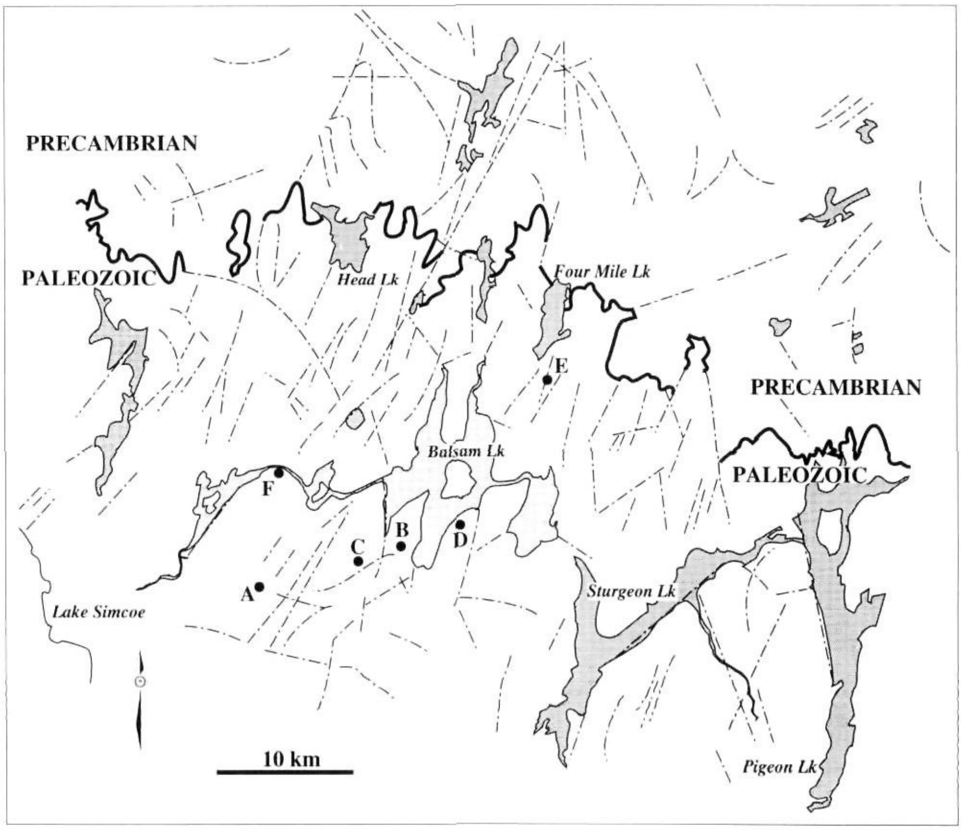

FIGURE 2. Lineament interpretation map of the area around Balsam Lake. Note the strong NNE trend of linear features. Location of pop-up structures discussed in the text are as follows: A) Eldon pop-ups; B) Cawker-Williams pop-ups; C) Curly pop-ups; D) Camp Kagawong pop-ups; E) Baddow pop-ups; F) Kirkfield pop-ups.

Carte interprétative des linéaments de la région autour de Balsam Lake. Noter la prédominance de la direction NNE. Les structures de soulèvement dont on parle dans le texte sont les suivants: A) Eldon; B) Cawker-Williams; C) Curly; D) Camp Kagawong; E) Baddow; F) Kirkfield.

TABLE I

Summary of Tectonic Features in the Balsam Lake Area

Features	Trend	Interpreted Tectonic Significance
Topographic lineaments south of the Precambrian/ Paleozoic Boundary	i) 023°	i) drainage features, muck, parallel to a set of bedrock joints in the Paleozoic
	ii) 155°	ii) parallel to a set of bedrock joints in the Paleozoic
	iii) 132°	iii) unknown
	iv) 070°	iv) may be part of a regional bedrock joint trend to the south (Rogojina, 1993)
Joints	i) 091°	i) possibly related to Acadian age E-W loading (Gross *et al.*, 1992) or the middle Mesozoic Ottawa-Bonnechere-Nipissing rift system (Kumarapeli and Saull, 1966; Kumarapeli, 1985; Stesky and Bailey-Kryklywy, unpublished)
	ii) 027°	ii) parallel, and possibly related, to the CMBBZ/NPLZ as well as the opening of the Atlantic in the Mesozoic
	iii) 152°	iii) possibly related to Alleghanian age cross-fold joints (Gross *et al.*, 1992)
Pop-ups	i) 118°	i) normal to S_{Hmax} (020°), nucleated on part of the 091° bedrock joint set
	ii) 073°	ii) composed of the "curly pop-ups" only and not considered a significant trend in the Balsam Lake area

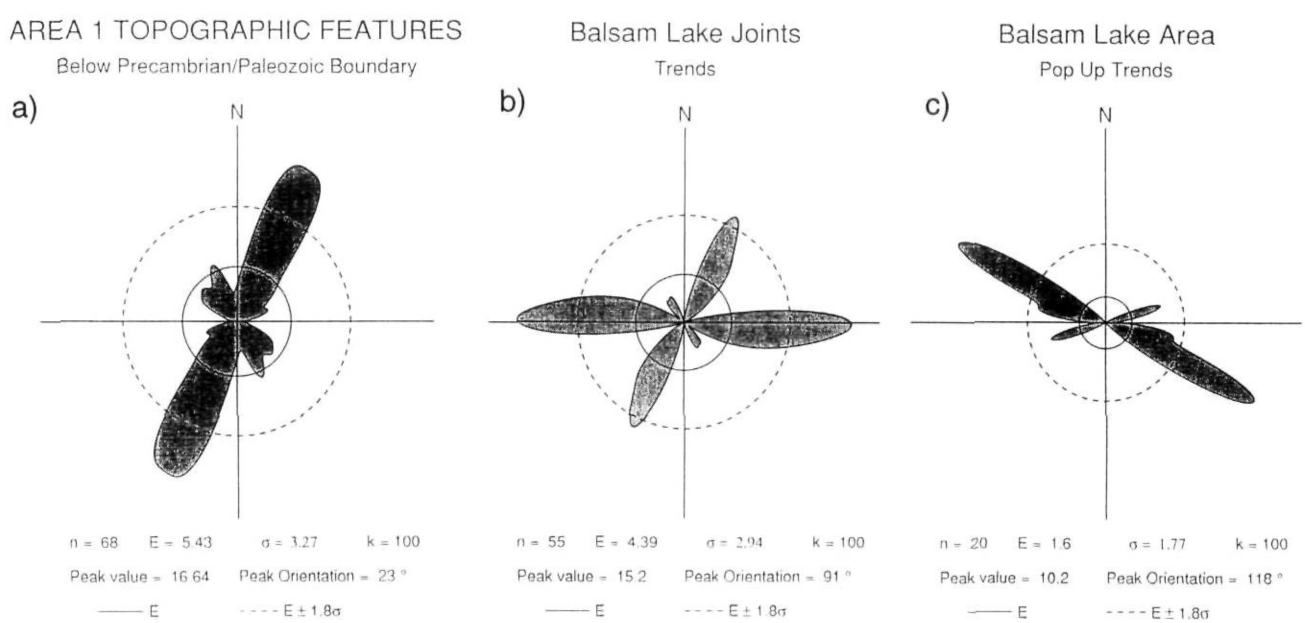

FIGURE 3. Orientation data displayed using the "propeller diagram" program developed by P.-Y. Robin, R. Stesky and F. Fueten (University of Toronto): a) Landsat TM topographic lineaments south of the Precambrian/Paleozoic boundary; b) Balsam Lake Area Joints; c) Balsam Lake Area Pop-ups.

Données d'orientation sur diagrammes en forme d'« hélice », un programme élaboré par P.-Y. Robin, R. Stesky et F. Fueten (University of Toronto). a) Linéaments topographiques au sud de la limite Précambrien-Paléozoïque déterminés par Landsat TM; b) diaclases de la région de Balsam Lake; c) structures de soulèvement de la région de Balsam Lake.

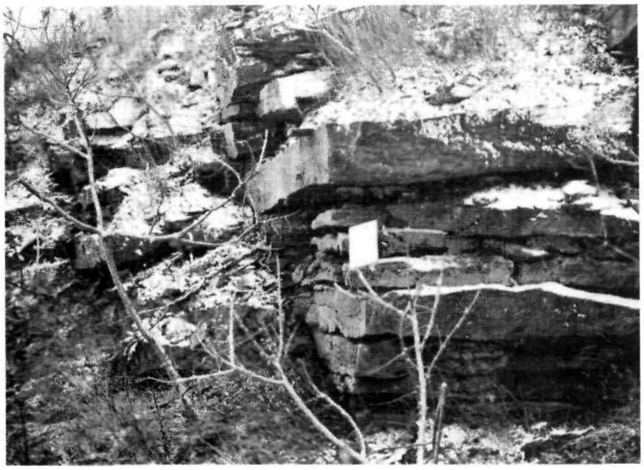

FIGURE 4. Photograph of joint surfaces near the Eldon pop-ups.
Surfaces fracturées, près des structures de soulèvement de Eldon.

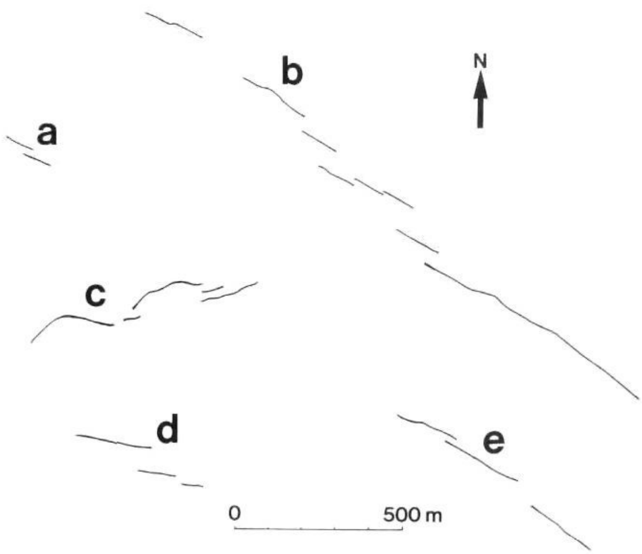

FIGURE 5. Traces of pop-up structures from aerial photographs: A) Eldon pop-ups; B) Cawker-Williams pop-ups; C) "curly" pop-ups; D) Camp Kagawong pop-ups; E) Baddow pop-ups. Scale is the same in each case.

Tracés de structures de soulèvement à partir des photographies aériennes: A) Eldon; B) Cawker-Williams; C) structures de soulèvement ondulées; D) Camp Kagawong; E) Baddow. L'échelle est toujours la même.

principal lineament orientations have been controlled by major bedrock joint trends. The minor 070° lineament trend does not parallel any joint orientation measured in the Balsam Lake area.

POP-UPS

With the exception of the "curly pop-ups" (see Fig. 5 c), all pop-up structures in the Balsam Lake area occur as sets of linear, en-echelon ridges (Fig. 5). The sets vary in length from approximately 156 m to 2 km, and individual pop-up segments measure from 10 m to 275 m long. A characteristic bright blue flower (Blueweed or Viper's bugloss; *Echium vulgare* L.), growing along the crests of the pop-up ridges makes

TABLE II

Balsam Lake Pop-ups

Pop-up	Segment	Height (m)	Length (m)	Width (m)	Orientation
A) Eldon Pop-up SW of Kirfield, E of Eldon	2a	1-1.5	90	6-7	113.5°
	2b	1-1.5	80	6-7	114.0°
B) Cawker-Williams pop-up below West Bay of Balsam Lake	68	1-2.5	185	20-25	114.0°
	69	2-2.5	210	20-25	121.0°
	70	2-2.5	110	20-25	120.0°
	49	2-2.5	120	20-25	115.5°
	50	2-2.5	90	20-25	119.0°
	52	2-2.5	145	20-25	119.5°
	53	2-2.5	76	20-25	119.0°
	50a	2-2.5	10	20-25	120.0°
C) Curvy Pop-up W of Eldon/Fenelon Township line	71	N/A	275	N/A	?
	72	N/A	50	N/A	079.0°
	73	N/A	220	N/A	071.0°
	74	N/A	60	N/A	072.0°
	75	N/A	180	N/A	071.5°
D) Camp Kagawong Pop-up	3	N/A	230	N/A	102.0°
	4	0.5-1	110	15-18	102.0°
	5	0.5	60	N/A	098.0°
E) Baddow Pop-up - E of Hwy 35	1	N/A	190	N/A	100.0°
	2	2	250	15	118.5°
	3	3-4	220	20-25	127.5°
F) Kirkfield Pop-up near locks	N	0.5-1	N/A	8	120°
	S	1.5	N/A	15	N/A

it easy to follow en-echelon pop-up structures in the field. Blueweed has an affinity for limestone soils, has a very deep root and tends to grow in areas with thin soil cover.

The characteristics of the pop-up structures have been compiled in Table II and two pop-up sets will be discussed in detail below. Lengths and orientations were measured from the aerial photographs and each segment was given a separate label.

Eldon Area

The Eldon pop-up structures appear as an en-echelon set of distinct, short, white photolineaments, trending 114° (Fig. 6). They are visible in the field as narrow (6-7 m) ridges (Fig. 7) with open fractures located along their crests. A break in vegetation type and density is observed across each of these central fractures. Other 114° trending vegetation breaks, unrelated to pop-up structures, also occur within the Eldon area (Figs. 6 and 8) and are due to sudden changes in soil thickness across inferred faults. Measurements of bedding attitudes across the pop-up structures indicate that they have an asymmetric internal structure (Fig. 9). Bedding is subhorizontal at the crests of the pop-ups but steepens abruptly across the central fracture to a maximum dip of 44° on the south limb of the southern pop-up and on the north limb of the northern pop-up (Fig. 9). The sense of curvature of bedding approaching the central fractures of these two overlapping ridges suggests that the central block has been uplifted or

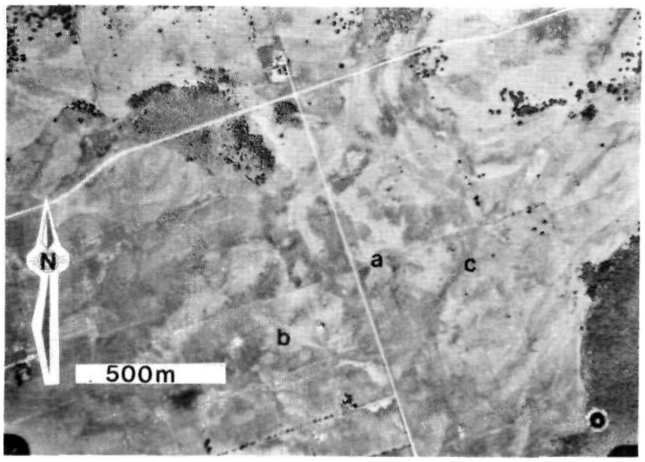

FIGURE 6. Aerial photograph near Eldon, southwest of Kirkfield. Notable features are: a) tonal contrast of vegetation/soil break (dark area = healthy green grasses, light area = well-drained, sparsely vegetated area); b) en echelon pop-up set; c) subtle topographic lineament (which is part of the pattern of NNE-trending drainage and muck band lineaments seen on the satellite imagery).

Photographie aérienne prise près de Eldon, au sud-ouest de Kirkfield. Noter a) les tons contrastés entre la végétation et le sol (en sombre: herbes vertes saines; en clair: zone bien drainée avec peu de végétation); b) ensemble de structures de soulèvement en échelon; c) linéament topographique ténu (qui fait partie de l'ensemble des linéaments de direction NNE sur image-satellite).

FIGURE 7. Photograph of Eldon pop-ups looking NW (Fig. 6b).

Structures de soulèvement de Eldon, vues vers le nord-ouest (fig. 6b)

FIGURE 8. Photograph of vegetation/soil break near Eldon (Fig. 6a), looking NW. In this Fall photograph, the well-vegetated area is seen as light-coloured dead grasses and the well-drained area of thin soil cover appears dark with bedrock and blueweed clearly visible in the field.

Contraste entre le sol et la végétation, près de Eldon (fig. 6a); vue vers le nord-ouest. Sur cette photographie prise à l'automne, la partie plus claire reflète une végétation plus dense, tandis que la partie plus sombre reflète un sol mince bien drainée avec substratum et paturin clairement visibles.

"popped up". We suggest that this is a near-surface stress release phenomenon, facilitated by a bedding parallel décollement at depth as indicated in Figure 9. Further investigation (trenching or shallow seismic surveying) is required to verify this interpretation and determine the depth to the décollement surface.

Cawker-Williams Pop-up Structures

The Cawker-Williams set of eight en-echelon pop-up structures (Figs. 5 and 10) was briefly reported by Finamore and Bajc (1983). Here, the segment lengths vary from 10 to 210 m (Fig. 10) and the ridges are broader (25 m) than those in the Eldon area. One pop-up segment crosses a Lake Algonquin paleobeach near Balsam Lake (Fig. 10). Unfortunately, a barn has been built directly above the intersection between the pop-up and the paleobeach (Fig. 10) obscuring their relationship. However, the barn is located at the highest point in the field and the trace of the paleobeach is deflected toward Balsam Lake at the intersection, indicating that the paleobeach has been displaced upward by the pop-up structure. A pop-up structure near Kirkfield (Fig. 2), which is along strike with the Cawker-Williams set and part of the same orientation pop-up population, also crosses and uplifts a Lake Algonquin paleobeach (Johnston, 1916; Finamore, 1985). These pop-ups are therefore inferred to be younger than the Lake Algonquin beach, which is between 12,500 and 10,500 years old (Finamore, 1985).

A trench dug across one of the Cawker-Williams pop-ups near the turn of the century (Brentnall, pers. comm.) provides a cross-sectional view of its internal structure (Fig. 11). The pop-up displaces beds of massive crystalline limestone and interbedded shale and fossiliferous limestone beds of the upper Middle Ordovician Verulam Formation (Liberty, 1969). A vertical fault is located in the centre of the pop-up structure (Fig. 11). The vertical displacement along this fault must be greater than one metre since shaley beds exposed on the south side of the structure cannot be followed across the approximately one metre high exposure of the fault. As in the Eldon example, this pop-up also has an asymmetric internal structure, with the beds on the SW limb showing moderate dips whereas those on the NE limb are subhorizontal (Fig. 11).

Other Pop-up Structures

The curly pop-up structures (Figs. 2 and 5), first reported by Finamore and Bajc (1983), have the same image charac-

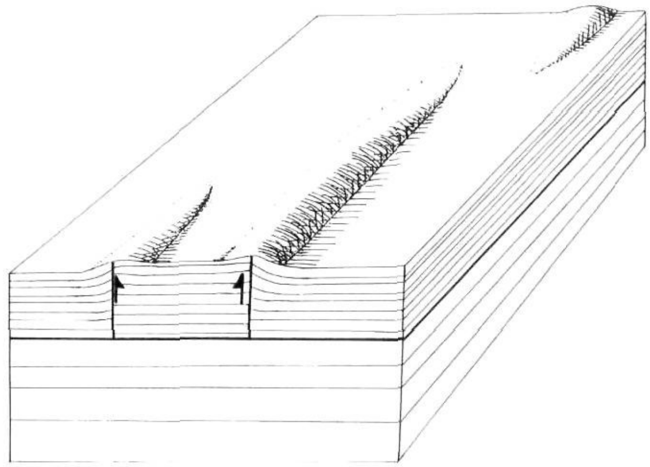

FIGURE 9. The near surface internal structure of the overlapping Eldon pop-up pairs, as inferred from measurements of exposed bedding planes. Structure below the immediate surface is interpreted. Thick horizon = décollement surface.

Structure interne près de la surface des deux structures de soulèvement se chevauchant, établie selon les mesures des plans de stratification mis à nu. La structure immédiatement sous la surface est une interprétation. L'horizon épais est une surface de décollement.

teristics as the other pop-ups but are nonlinear. Closer examination of the aerial photograph and in the field shows that they have the same morphology and vegetation patterns as the other features and are en-echelon pop-up structures with curved links. Pop-up structures and vegetation/soil breaks are also observed near Camp Kagawong (Fig. 2 and 5). These pop-up structures have a lower amplitude than the ones described above. Pop-up structures observed on the Goodhand farm (Lot 21, Conc. 3, Somerville) near Baddow (Figs. 2 and 5) are broad features, similar to the Cawker-Williams examples, with visible bedrock and the characteristic Blueweed growing along them. The Kirkfield pop-up structures (Figs. 2 and 5) do not have an easily detectable aerial photograph signature but one of the pair was reported by Finamore and Bajc (1983).

TECTONIC SIGNIFICANCE OF JOINTS IN THE BALSAM LAKE AREA

It is difficult to compare the joint and lineament trends of this study with those in other areas or with regional data because of the lack of published, reliable joint studies in southern Ontario. However, the 091° joint set may be related to Parker's (1942) Set III joints in New York State and a similar joint set has been associated with the Acadian orogeny by Gross *et al.* (1992). Alternatively, this trend is also favourably oriented to be included with structures related to the Middle Mesozoic Ottawa-Bonnechere-Nipissing rift system (Stesky and Bailey-Kryklywy, unpublished data, University of Toronto), corresponding to the trends of the Ottawa (110°) and Nipissing (095°) grabens (Kumarapeli and Saull, 1966; Kay, 1942). Likewise, the 152° trend may be related to the 150°-180° trending Alleghanian cross-fold joints (Gross *et al.*, 1992) and Parker's (1942) Set I joints. There is no clear 027° joint trend in the New York shale joints of Parker (1942), but

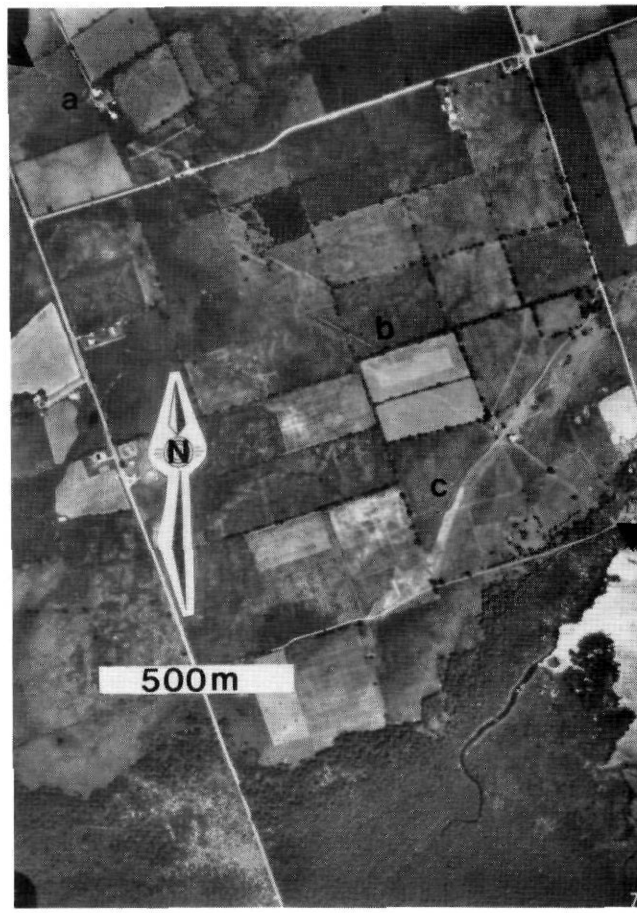

FIGURE 10. Aerial photograph of Cawker-Williams pop-up set. Note locations of a) trench; b) pop-ups (between arrows); c) Lake Algonquin paleobeach. Note the barn on the intersection of a pop-up and the paleobeach.

Photographie aérienne des structures de soulèvement de Cawker-Williams. Noter: a) la tranchée; b) les structures de soulèvement entre les flèches; c) la paléo-plage du Lac Algonquin. Noter la grange, à l'intersection d'une structure de soulèvement et de la paléo-plage.

this orientation is comparable with a N-S bedrock joint trend found around Hamilton and the Niagara River, southern Ontario, that may have a pre-glacial origin (Daniel, 1990). Gross *et al.* (1992) suggested that there is an anomalous N-S fracture orientation in the Lockport dolostone formation in the immediate vicinity of the N-trending Clarendon-Linden fault system. By comparison, the 027° joint trend in the Balsam Lake area may be confined to a zone over the CMBBZ/NPLZ but further studies are required to verify this speculation.

The age of the N-S joints in the Clarendon-Linden fault zone and 027° trending fractures in the Balsam Lake area is currently unknown. However, they are both sub-parallel to normal faults within the Hudson River-Champlain arm of the St. Lawrence rift system (Kumarapeli and Saull, 1966). Tensional stresses associated with the formation of the St. Lawrence system and the opening of the Atlantic in the Mesozoic (Kumarapeli, 1976), would have provided a favourable tectonic environment for reactivation of the CMBBZ and generation of 027° trending fractures in the overlying cover.

FIGURE 11. Photograph of exposure of the internal structure of the Cawker-Williams pop-up in a trench (Fig. 10a). Note the book measures 19 cm. Southwest is to the left on this photograph. Because the strata exposed on each side of the central fracture cannot be traced across, it is interpreted as a fault with at least 1 m vertical displacement.

Structure interne d'un soulèvement dans une tranchée, à Cawker-Williams (fig. 10a). Le carnet mesure 19 cm. Le sud-ouest est à gauche de la photo. On estime qu'il s'agit d'une faille avec rejet vertical d'au moins 1 m.

ORIGIN AND SIGNIFICANCE OF THE POP-UP STRUCTURES

The average orientation of pop-up structures in the Balsam Lake area is 118° with a secondary trend at 073° (Fig. 3c). The secondary trend is due entirely to the curved segments of the Curly pop-up (Fig. 5c) and is therefore not considered to be regionally significant. The mean orientation of pop-up structures is sub-parallel to that reported by Wallach *et al.* (in press) for all known pop-ups in open fields in southern Ontario. It is also sub-normal to the current in-situ maximum horizontal stress direction ($S_{Hmax} = 020°$) in southern Ontario and northern New York State (Zoback and Zoback, 1980). The pop-up structures reported here are therefore favourably oriented to be interpreted as stress-release features formed under the contemporaneous tectonic stress field in southern Ontario. This interpretation is supported by the kinematics of the overlapping pop-up segments observed at Eldon (Fig. 9) and models proposed by White *et al.* (1973), Fakundiny *et al.* (1978), Roorda *et al.* (1982) and others for both open field pop-up structures and quarry floor buckles in flat-lying sediments.

Uplift of Lake Algonquin paleobeaches by the Cawker-Williams and Kirkfield pop-up structures strongly suggests that they must have formed less than 12,500 years ago. Postglacial ages for other pop-up structures in southern Ontario and New York State have also been reported by Sbar and Sykes (1973), White and Russell (1982) and Wallach and Chagnon (1990). All pop-up structures with bedrock exposure in the Balsam Lake area display a central vertical fracture, located along their crests, which is associated with a soil-vegetation break or a demonstrable vertical displacement. These fractures are parallel to systematic bedrock joints which are part of the 091° set (Fig. 3b), suggesting a possible relationship between them. As noted above, the 091° joint and lineament set most likely formed in response to the Acadian orogeny (410-360 Ma, Sutter *et al.*, 1985; Marshak and Tabor, 1989) or formation of the Ottawa-Bonnechere-Nipissing rift system which initially occurred during the late Hadrynian but was reactivated during the early Cretaceous (Kumarapeli, 1985). On the basis of their postglacial age, occurrence as long en-echelon structures in open fields normal to S_{Hmax}, and association with pre-Cenozoic fractures, we suggest that the pop-up structures formed in order to relieve high near-surface tectonic stresses that were accumulated beneath the Laurentide Ice Sheet. Ice removal is similar to overburden removal in the case of quarry floor buckles and is predicted by Roorda *et al.* (1982) to promote pop-up formation. The pop-up structures appear to have nucleated on favourably oriented (*i.e.* normal to S_{Hmax}) pre-existing joints in the bedrock.

DISCUSSION AND CONCLUSIONS

Examination of remote sensing data and comparison with outcrop observations of joints in the Balsam Lake area reveals the presence of a systematic bedrock fracture pattern with three principal sets oriented 091°, 027°, and 152° (Table I). By comparison with joint data published for northern New York state (Parker, 1942; Gross and Engelder, 1991; Gross *et al.*, 1992) and southern Ontario (Daniel, 1990; Rogojina, 1993) and consideration of the post-Ordovician tectonic history of eastern North America, we propose that all of these fracture trends were formed by the end of the Mesozoic. The presence of a dominant 027° trending fracture set in the area may indicate reactivation of the CMBBZ. This hypothesis remains to be tested by establishing whether the 027° trend is restricted to a zone overlying the CMBBZ or is part of a regional fracture set. By comparison to analogue experiments of basement fault reactivation (Horsfield, 1977), an extensional tectonic regime would be required to reactivate moderately E-dipping basement structures like the CMBBZ to produce systematic open, vertical, tensile joints parallel to the zone in the overlying cover. Such a regime was active during the formation of the Hudson River-Champlain arm of the St. Lawrence system (Kumarapeli and Saull, 1966) to the east in early Cretaceous times (Kumarapeli, 1985). The 060° to 070° trending joints, interpreted as neotectonic, load parallel structures, reported by Gross and Engelder (1991) and Rogojina (1993) for the bedrock exposures in the Niagara Escarpment and Toronto areas have not been observed in the Balsam Lake area at the outcrop or aerial photograph scale and are considered a minor trend in the topographic Landsat TM lineaments (Table I).

The only neotectonic features found in the Balsam Lake area to date are 118° trending en-echelon sets of pop-up structures. They are less than 12,500 years old, but appear to have nucleated on much older structures. They have a common orientation with the bulk of open field pop-up structures observed in southern Ontario (Wallach *et al.*, in press) and are oriented perpendicular to the present day S_{Hmax}. This suggests that it is unlikely that they are genetically related to recent reactivation of the CMBBZ. However, as in the case of the 027° fractures, more regional surveys are required to evaluate any such relationship with confidence.

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