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Application of Subsurface Mapping to the Interpretation of Paleozoic Structures from Lineament Analysis of High-Resolution Aeromagnetic Data in the Chatham Sag, Southwestern Ontario

2020

ONTARIO GEOLOGICAL SURVEY

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by

C. Béland Otis

2020

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Abstract

The Chatham Sag is a major regional depression in southwestern Ontario with Paleozoic strata up to 1400 m thick. It is located between the Michigan Basin and Appalachian Basin and separates the Findlay Arch, to the south-southwest, and the Algonquin Arch, to the northeast. In 2014, the Ontario Geological Survey contracted TerraNotes Ltd. to produce a lineament analysis study of the high-resolution aeromagnetic survey flown over this area in 2009. The lineament analysis only distinguishes features in the Grenvillian basement, because the overlying Paleozoic rocks are largely non-magnetic. The TerraNotes Ltd. study delineated various lineaments within 2 Grenville Province domains and their connecting margin: 1) the Huron Domain, comprising 8 linear features and a circular feature, a block faulting feature, and the Can-Am "structure" (circular feature); 2) the Kent Domain, comprising 6 linear features, 1 circular feature and a Z-folding feature; and 3) the Kent–Huron domains boundary.

The goal of this study is to evaluate the utility of lineament analysis in Precambrian bedrock beneath the Phanerozoic geology. To achieve this evaluation, well records of Paleozoic sedimentary strata from the Ontario Petroleum Data System (OPDS) were used to produce regional and local bedrock surface elevation maps. Regional elevation maps, in the form of coloured dot maps that cover the entire study area, were produced for all stratigraphic units of formation rank within the OPDS in the area. Such maps assist in distinguishing the delineation and timing of geological structure formation (e.g., Chatham Sag, Algonquin Arch) and highlight the regional dip of the sedimentary strata. In contrast, local maps focus on a single or small group of TerraNotes Ltd. features. With these smaller scale dot maps, vertical offsets in the various Paleozoic strata can be identified and possibly linked to TerraNotes Ltd. lineaments, suggesting Paleozoic faults with Precambrian origins.

This study did not result in the discovery of new lineaments or faults. However, major Paleozoic structures of the area (e.g., the Electric and Dawn faults) are associated with TerraNotes Ltd. lineaments or segments of them. Also, some Silurian pinnacles and salt dissolution features are aligned along Precambrian lineaments, suggesting some link between formational fluids and deep Grenvillian structures. Finally, a lineament analysis for a different region with fewer available well records may be a helpful tool to identify potential Paleozoic structures. However, these would need to be confirmed by acquiring additional geological information.

Application of Subsurface Mapping to the Interpretation of Paleozoic Structures from Lineament Analysis of High-Resolution Aeromagnetic Data in the Chatham Sag, Southwestern Ontario

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Open File Report 6362
2020

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Introduction

The Chatham Sag is a major structural depression located in southwestern Ontario and is characterized by the thickest Paleozoic sedimentary succession in Ontario, up to 1400 m thick (Johnson et al. 1992; Armstrong and Carter 2010). It is located between the Michigan Basin and the Appalachian Basin and separates the Findlay Arch (to the south-southwest) and the Algonquin Arch—a northeast-trending Precambrian structure that occurs in southwestern Ontario.

Historically, the Chatham Sag has been an area of high interest for oil and gas exploration (Carter, Clark et al. 2016; Carter, Hamilton et al. 2016; Phillips 2019). Since the mid 1850s, several types of hydrocarbon reservoirs within Devonian, Silurian, Ordovician and Cambrian strata have been identified and exploited within this structural feature. It has been suggested that the position of some of these reservoirs is spatially associated with deep crustal structures within the Precambrian basement (Carter, Trevail and Easton 1996).

In 2009, the Ontario Geological Survey (OGS) published Geophysical Data Set 1065 (Ontario Geological Survey 2009), which provides the magnetic and electromagnetic data from an airborne survey flown earlier that year over the Chatham area. This data set is accompanied by a series of residual magnetic field and first vertical derivative maps. Initially, the OGS did not perform any interpretation of the survey data, but, in 2013, it was decided that a lineament analysis of the Chatham aeromagnetic survey would be contracted to TerraNotes Ltd. (Ontario Geological Survey 2014). The company identified lineaments in the underlying Precambrian Grenville Province basement rocks. The Paleozoic sedimentary rocks of southwestern Ontario are non-magnetic and, therefore, provide no magnetic signatures (Ontario Geological Survey 2009).

The main purpose of this study is to investigate whether the lineaments identified by TerraNotes Ltd. in the Precambrian basement reflect any displacement of the overlying Paleozoic strata (Ontario Geological Survey 2014). The locations of some Paleozoic faults, hydrocarbon reservoirs, pinnacle alignments and salt dissolution features appear to be influenced by deeper Precambrian structures (Tanglis 1995; Armstrong and Dodge 2007; Armstrong and Carter 2010).

The main source of data used in this study is the geological information (formation top and bottom picks) in the Ontario Petroleum Data System (OPDS). Within the study area, which encompasses the aeromagnetic survey area plus an additional 10 km buffer zone, the database maintains information on more than 10 000 wells. The Ontario Oil, Gas and Salt Resources Library (OGSRL), in London, stores additional information for the study area in different forms: drill cuttings are available for 5565 wells, and geophysical logs are accessible for 2982 wells; however, only 298 drilled cores are available. Criteria used for selecting wells used for this project are described in “Method”. In recent years, staff from the OGSRL and the Ministry of Natural Resources and Forestry (MNRF) have improved digital access and undertaken QA/QC analyses of the database. This has resulted in an update of the lithostratigraphic chart used for southern Ontario (Brunton et al. 2017; Carter et al. 2017). Also, the location of hydrocarbon pools and previously mapped faults will be compared to those of TerraNotes Ltd. lineaments.

GEOGRAPHIC AREA

The high-resolution aeromagnetic survey flown in 2009 is located over the Chatham Sag area and covers 10 789 km^2 (Figure 1; Ontario Geological Survey 2009). The greater part of the survey is located over land, but also extends over Lake Erie, Lake Huron and Lake St. Clair. The 2 main urban centres in the survey area are the City of Sarnia and the Municipality of Chatham-Kent. The study area for this project covers the extent of the 2009 survey with the addition of a 10 km buffer zone around its boundary.

PREVIOUS WORK

Initial subsurface mapping of the Paleozoic strata in the study area was undertaken by Stauffer (1915), who focussed on the Devonian rocks of southwestern Ontario. Later, Caley (1943, 1946) mapped all rocks located west of London area and his work was updated by Sanford and Brady (1955) and Caley and Liberty (1957). Subsequently, various geological maps have been produced that cover all or part of the study area. Maps produced by OGS staff include Telford and Russell (1981), Ontario Geological Survey (1991) and Armstrong and Dodge (2007). The Geological Survey of Canada also published a few additional maps (Sanford 1969a; Sanford and Baer 1983).

Various stratigraphic studies were done on the multiple Paleozoic units found in the study area. Major stratigraphic compilations include Caley and Liberty (1957), Winder (1961), Beards (1967), Carter (1990), Johnson et al. (1992), Sanford (1993a, 1993b, 1993c) and Armstrong and Carter (2006a, 2006b, 2010). Also, a lithostratigraphic compilation of Phanerozoic bedrock units and a three-dimensional (3-D) geological model of southern Ontario has been developed (Carter, Brunton, Clark, De Kemp et al. 2016; Carter, Brunton et al. 2017, 2019; Brunton et al. 2017; Russell et al. 2015).

Key studies concerning the Precambrian geology of southwestern Ontario include Carter and Easton (1990), Easton and Carter (1991, 1994, 1995), Easton (1992), Easton, Carter and DiPrisco (1990), DiPrisco and Springer (1991), Harper et al. (1995) and Carter, Trevail and Easton (1996). Some of these publications also discuss the possible relationship between Precambrian and Paleozoic structures (i.e., faults, lineaments, basement grabens and topographic highs).

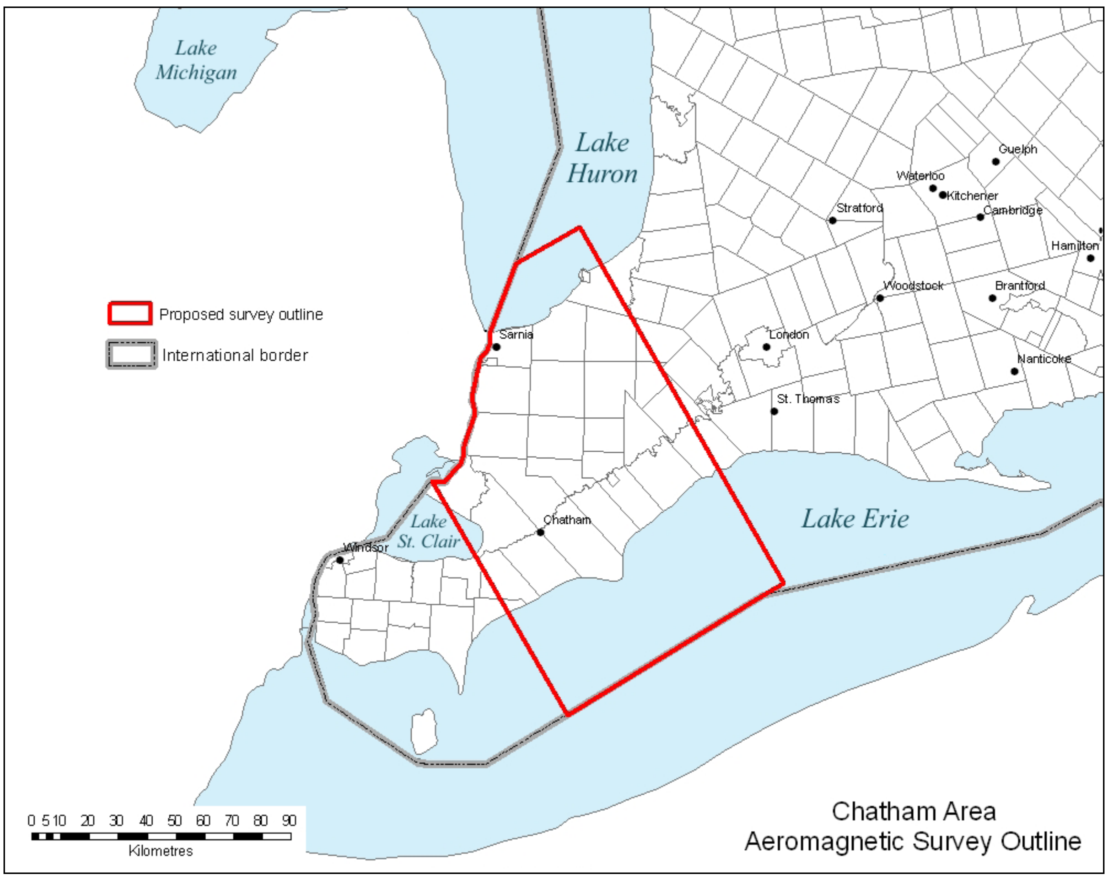

Figure 1. Outline of the area (delineated by red line) covered by the airborne magnetic and electromagnetic survey of the Chatham area in southwestern Ontario (Ontario Geological Survey 2009).

Brigham and Winder (1966) and Brigham (1971) provided the first regional structural studies in southwestern Ontario. Subsequently, Sanford, Thompson and McFall (1985) proposed a conceptual fracture framework model for southwestern Ontario. During this same period, Bailey Geological Services Ltd. and Cochrane (1984a, 1984b, 1985, 1986, 1990) produced various structural and isopach maps for southwestern and eastern Ontario.

Only a limited number of previous studies addressed the correlation between Precambrian lineaments and Paleozoic faulting (e.g., Morris et al. 1998; Boyce and Morris 2002). These studies involved lineament mapping across southwestern Ontario based upon previously published aeromagnetic and gravity data sets (Gupta 1991a, 1991b).

Economic potential in the area includes salt mining, hydrocarbon production, and limestone and building stone extraction. Salts found in southwestern Ontario were studied by Hewitt (1962), Sanford (1977) and Smith (1992). Specifically, timing of salt dissolution, which has some importance for this study has been investigated by Brigham (1971), Dutton (1985), Hamilton and Coniglio (1990), Coniglio and Frape (1992) and Sanford (1993c).

The Chatham Sag area has a long history of hydrocarbon exploration and multiple work has been done in the region. The most prominent studies include Hutt, MacDougal and Sharp (1973), Bailey (1986, 1999), Carter (1991), Carter, Trevail and Smith (1994), Colquhoun (1991, 2012), McMurray (1985), Bailey Geological Services Ltd. and Cochrane (1984a, 1984b, 1985, 1986, 1990), Obermajer et al. (1996), Obermajer, Fowler and Snowdon (1999), Osadetz et al. (1996), Dorland (2001), Coniglio, Zheng and Carter (2003) and Hamblin (2006). Also, Lazorek and Carter (2008), Carter, Clark et al. (2016), Carter, Hamilton et al. (2016), Dorland et al. (2016) and Philips et al. (2016) provide overviews of the most important hydrocarbon plays from southern Ontario.

Some hydrocarbon accumulations in southern Ontario have been known to be related to the dolomitization of limestone by fluids moving upward along deep-seated faults. These “hydrothermal dolomites” located in Ontario have been studied by Coniglio et al. (1994), Trevail, Carter and McFarland (2004) and Golder Associates Ltd. (2005).

Finally, studies focussing on the limestone and building stone industry include Goudge (1938), Hewitt (1960, 1964), Hewitt and Vos (1972), Bezys and Johnson (1988) and Derry Michener Booth and Wahl and Ontario Geological Survey (1989a, 1989b).

Geological Settings

The regional depression associated with the Chatham Sag area has resulted in the preferential preservation of the thickest sequence of Paleozoic rocks in southern Ontario. However, the youngest deposits found in the Chatham Sag are Quaternary and are mainly composed of clayey to silty till and glaciomarine deposits (Ontario Geological Survey 2000). These sediments overlie Early Carboniferous (Mississippian Subperiod) and Devonian rocks. Subcropping units within the Chatham Sag area include the Devonian Kettle Point, Dundee and Lucas formations (Figure 2). The youngest sedimentary rocks of southern Ontario, the Mississippian Port Lambton Group, are found along the St. Clair River, just south of Sarnia.

REGIONAL TECTONIC SETTING

The Chatham Sag was first mentioned by Kay (1942) who identified a thickening of Black River Group and Trenton Group strata in Kent and Lambton counties. It is now recognized as a structural depression in which the thickest succession of southern Ontario Paleozoic rocks is found, through more than 1400 m of

Cambrian to Mississippian strata (Figure 3; Brunton et al. 2017; Armstrong and Carter 2010). Brigham (1971) suggested that the Chatham Sag had only limited influence on sedimentation until the Late Silurian.

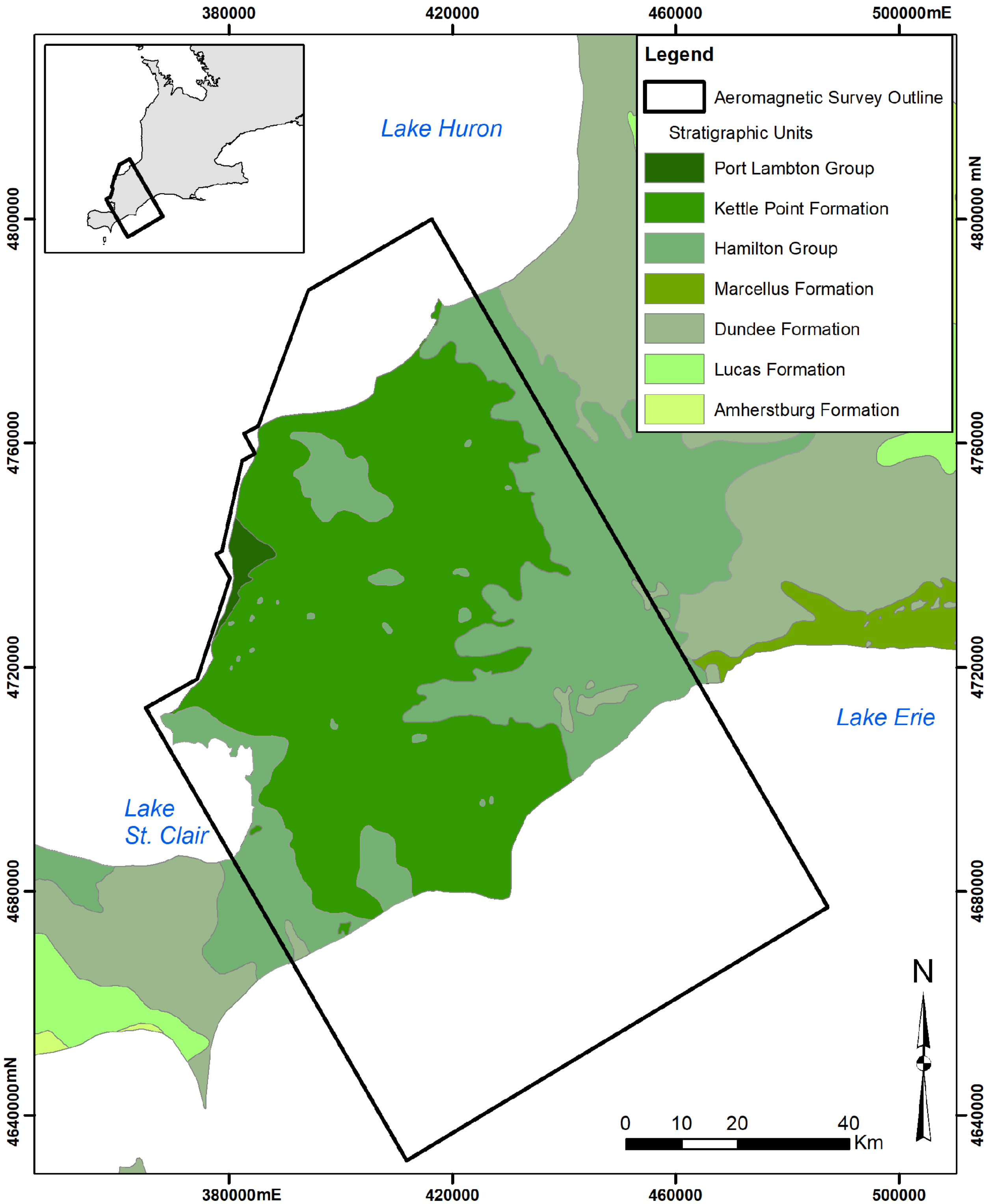

Figure 2. Paleozoic geology of the study area (*after* Armstrong and Dodge 2007), with the aeromagnetic survey area shown.

The Chatham Sag separates the Findlay Arch (Ohio), to the south-southwest, from the Algonquin Arch (southwestern Ontario) to the northeast (Figure 4; Carter, Trevail and Easton 1996; Armstrong and Carter 2010). Both arches delineate the margin between the Michigan Basin and the Appalachian Basin. Another important structural feature in the area is the Midcontinent Rift, although its exact position and relationship with the Chatham Sag and other basement structures have yet to be studied (Easton and Carter 1995; *see* Figure 4).

The Appalachian Basin developed because of sediment loading from the Appalachian Orogen, which involved various collisions with terranes and/or continents (Ettensohn 2008). The basin extends south from Lake Ontario to Alabama (Quinlan and Beaumont 1984; Ettensohn 2008). In jurisdictions situated closer to the Appalachian Mountains, Paleozoic strata are usually highly deformed and can reach thicknesses greater than 8 km (Ryder et al. 2012). In Ontario, sediments are approximately 1350 m thick and Paleozoic strata were mostly unaffected by the various orogenies as they were deposited on a tectonically stable, shallow shelf (Johnson et al. 1992; Armstrong and Carter 2010). The Appalachian Basin is characterized by a dominance of clastic sediments, mostly eroded from the Appalachian orogenic belt.

On the opposite side of the arches, the circular intracratonic Michigan Basin is mainly composed of Paleozoic carbonates, evaporites and craton-derived clastic sediments (Johnson et al. 1992; Armstrong 1992). Strata generally dip about 1° toward the depocentre located over the Michigan Peninsula, where the thickness of Cambrian to Mesozoic sediments can reach 4800 m (Gillespie, Harrison and Grammer 2007). The basin is found over the eastern extension of the Midcontinent Rift, although their structural relationship is not fully understood. The thickest Paleozoic sequence is found on the Michigan Basin side of the Chatham Sag.

The Algonquin and Findlay arches are southwest-trending structures that divide both basins (*see* Figure 4). Strata north of the arches exhibit a 6 to 9 m/km northwestern dip toward the Michigan Basin depocentre, whereas strata located south of the structure show a general southeastern dip of 6 m/km dip

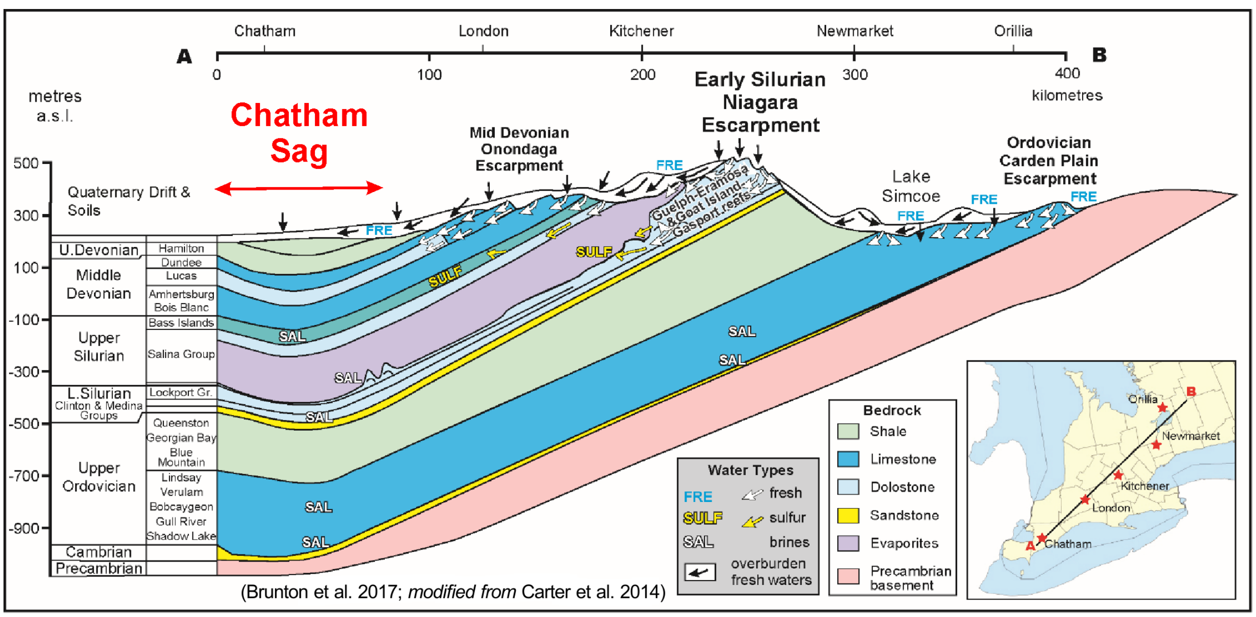

Figure 3. Generalized southwest ("A") to northeast ("B") cross section of Phanerozoic strata across southern Ontario (Brunton et al. 2017; *modified from* Carter et al. 2014). The depression at the southwestern extent of the cross section corresponds to the Chatham Sag.

toward the Appalachian Orogen and strata along the crest of the arches dip toward the Chatham Sag (Winder and Sanford 1972; Johnson et al. 1992; Armstrong and Carter 2010). Various vertical and lateral movements of the arches occurred, mainly in response to various tectonic events during the Paleozoic (Quinlan and Beaumont 1984; Armstrong and Carter 2010). Accompanied by the eustatic sea-level changes, these variations resulted in complex sedimentary facies and development of both local and regional unconformities, generally adjacent to the arches (Johnson et al. 1992).

PRECAMBRIAN BASEMENT GEOLOGY

With the exception of Manitoulin Island, basement rocks underlying Paleozoic strata in southern Ontario are part of the Grenville Province (Figure 5). These Proterozoic crystalline basement rocks are highly deformed as a result of the continent–continent collision known as the Grenville Orogeny and form the core of the Grenvillian mountains, representing several tens of kilometres of rocks (Easton 1992). Current low-relief topography of the Precambrian basement is the result of a minimum of 500 million years of erosion before Cambrian deposition (Carter, Trevail and Easton 1996).

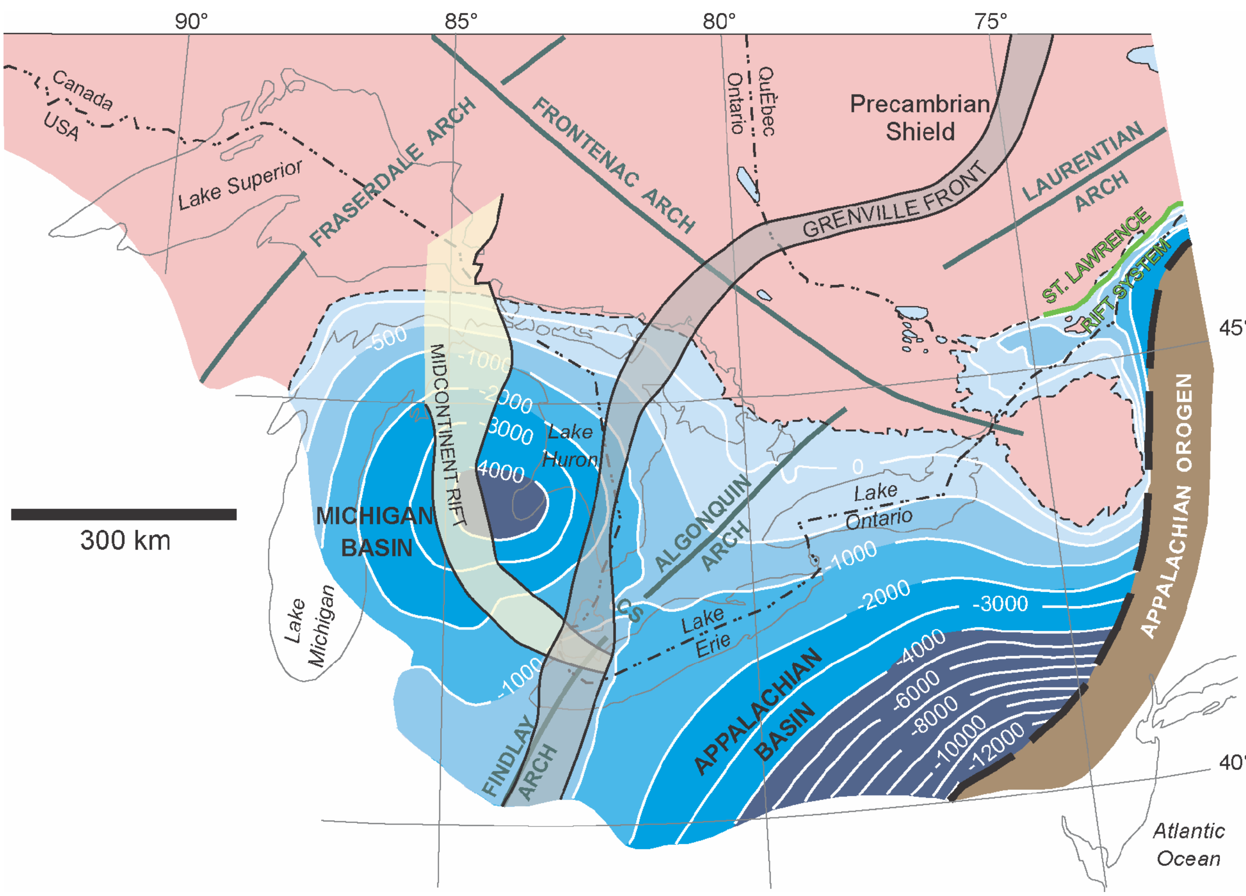

Figure 4. Major tectonic elements affecting Paleozoic sedimentation in southern Ontario (*after* Johnson et al. 1992; *modified from* Armstrong and Carter 2010), including the Michigan and Appalachian sedimentary basins (blue), Algonquin and Findlay basement arches (green) and the Chatham Sag (CS). Contour lines (white) indicate elevation of the top of Precambrian basement in metres below mean sea level. The extents of the Proterozoic Midcontinent Rift (yellow) and Grenville Front tectonic zone (grey) are shown, with the southernmost extents being estimated locations. The location of the Appalachian orogenic belt (brown) is shown, with the westward extent of thrusting indicated (thick, long black dashed line). The present-day erosional edge of Paleozoic rocks (thin, short black dashed line) is also indicated.

The Grenville Province has been subdivided into terranes, domains and boundary zones (*see* Figure 5; Easton and Carter 1991, 1995; Carter and Easton 1990). Most of the study area is covered by the Kent and Huron domains of the Central Gneiss Belt (Easton 1992). The boundary between these 2 domains, as mapped by Easton and Carter (1991), trends west, approximately halfway through the study area and corresponds approximately with that identified by TerraNotes Ltd. (Figures 5 and 6; Ontario Geological Survey 2014). The Huron Domain, located in the northern half of the study area, is mostly composed of gneissic quartzofeldspathic rocks and is characterized by low magnetic intensity (Easton and Carter 1995). In contrast, the Kent Domain shows high magnetic intensity and, thus, relief on the aeromagnetic survey. The associated rocks mostly have a granitic composition with some granodioritic and tonalitic components. To the west of the aeromagnetic survey area, and a few kilometres west of the Detroit River, the Grenville Front trends north-northeast (Carter and Easton 1995). A major shear zone, referred to as the Grenville Front tectonic zone (*see* Figure 5) and distinguished by highly deformed rocks, is located 30 to 50 km east of the Grenville Front (Carter and Easton 1990; Easton and Carter 1995).

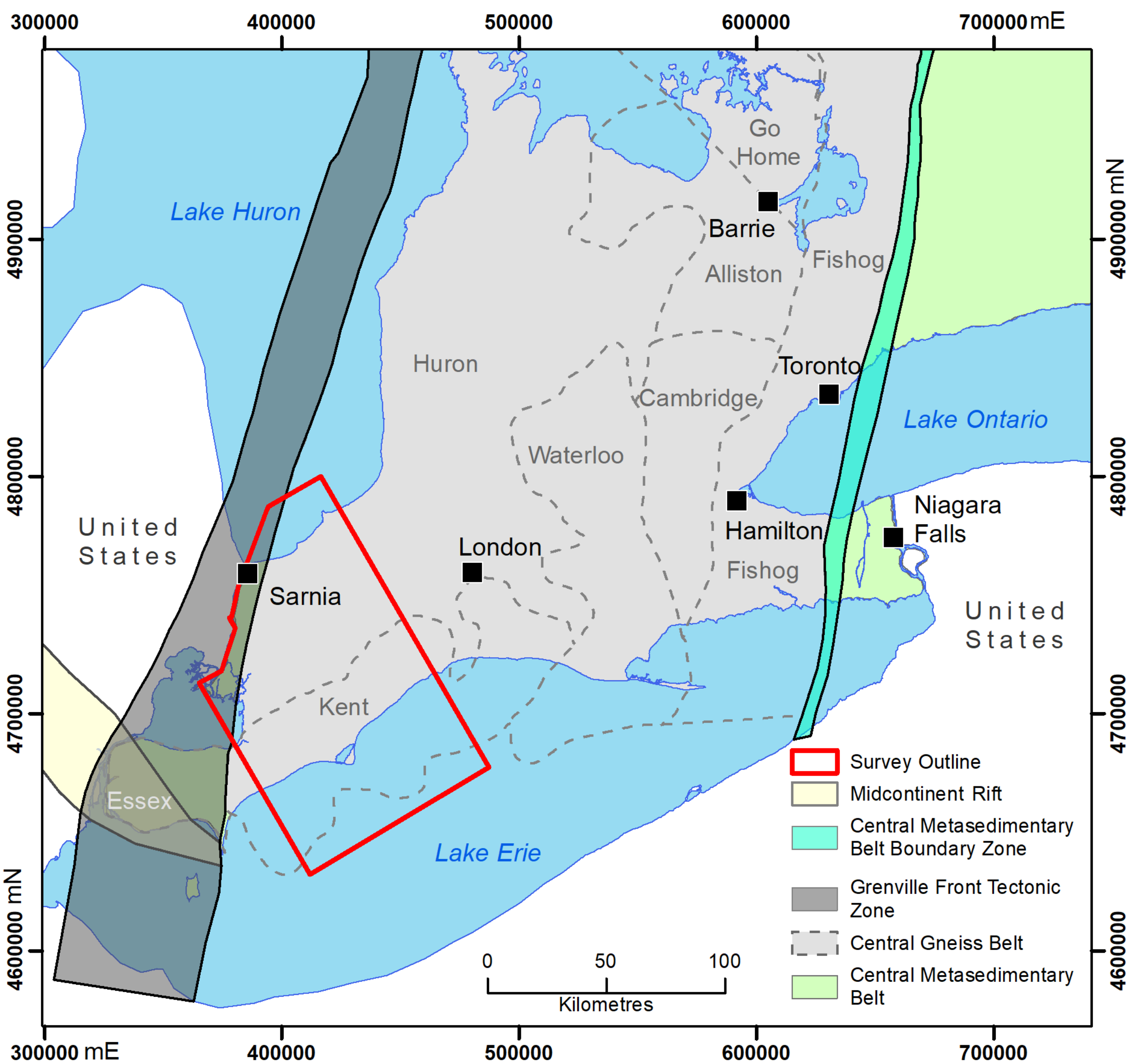

Figure 5. Principal geological subdivisions (domains, terranes and boundaries) of the Precambrian rocks of southwestern Ontario (*modified from* Armstrong and Carter (2010), Easton (1992) and Carter and Easton (1990)). Abbreviations: CMBBZ, Central Metasedimentary Belt boundary zone; GFTZ, Grenville Front tectonic zone; CMB, Central Metasedimentary Belt; MCR, Midcontinent Rift. Domain names are shown on the figure in grey or white.

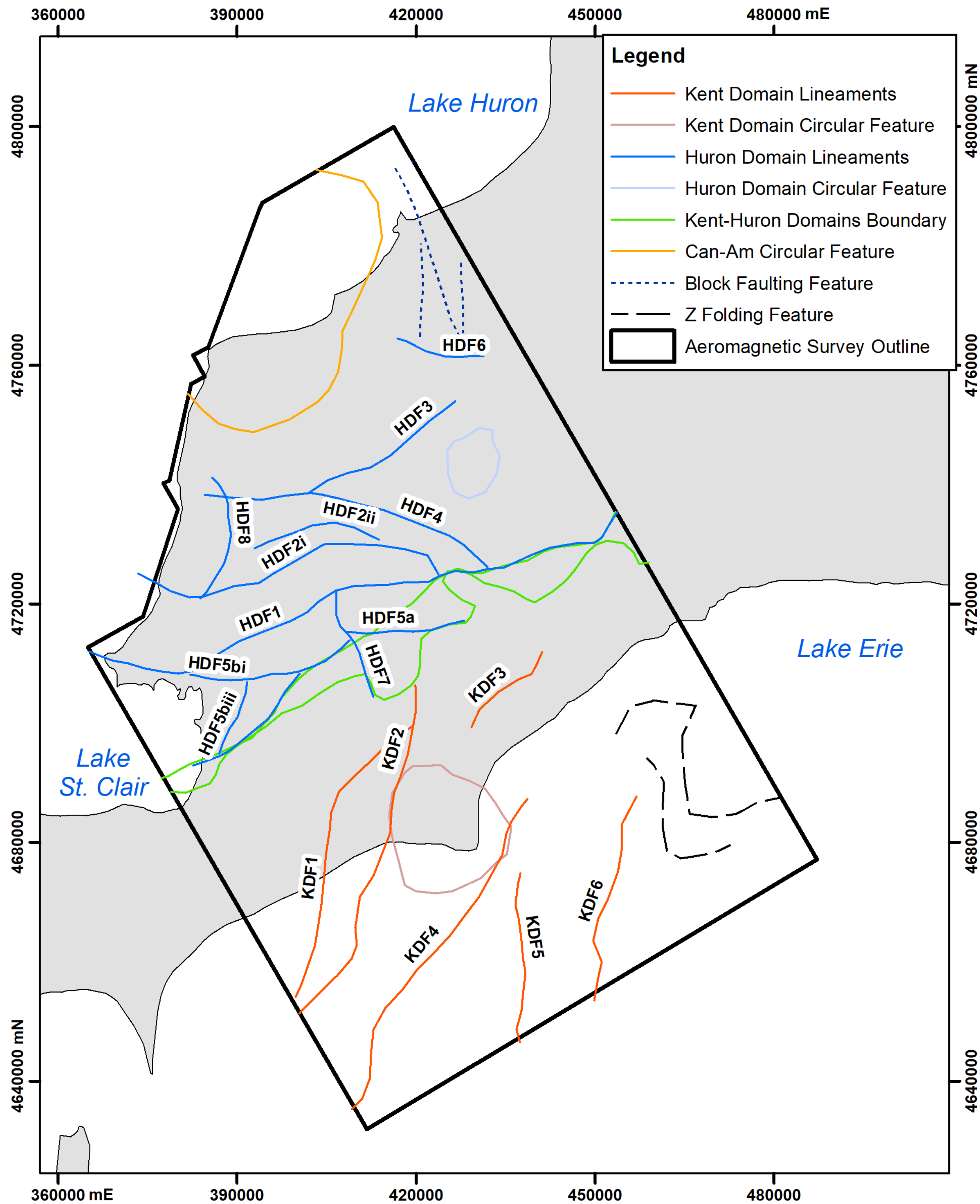

Figure 6. Extent of the Chatham area aeromagnetic survey and lineaments identified by TerraNotes Ltd. (*modified from* Ontario Geological Survey 2009, 2014). All lineaments are listed in Table 1.

The eastern extension of the Midcontinent Rift terminates near the eastern limit of the Grenville Front tectonic zone in Essex County, just southwest of the study area (*see* Figure 5; Armstrong and Carter 2010). These buried igneous rocks are highly magnetized and generate a positive anomaly on aeromagnetic surveys, although the exact position of the Midcontinent Rift in southwestern Ontario is still unclear (Easton and Carter 1995; Stein et al. 2018). Also, the possible relationship between this structure and the Chatham Sag has yet to be studied. Neither the Grenville Front tectonic zone nor the Midcontinent Rift were discussed by TerraNotes Ltd. for this study area (Ontario Geological Survey 2014).

Also, a major, deep circular feature was identified on a previous aeromagnetic survey over Lake Huron (Forsyth et al. 1990). The authors proposed the name "Can-Am" for this circular feature because of its proximity to the Canada–United States border, and further suggested that its origin was an impact crater after the Grenville Orogeny, but prior to Paleozoic sedimentation. Subsequently, this structure has been identified by Boyce and Morris (2002) and TerraNotes Ltd. (Ontario Geological Survey 2014) on different aeromagnetic surveys, but its origin and influence on Paleozoic rocks have yet to be confirmed (Forsyth et al. 1991).

PALEOZOIC GEOLOGY

The Paleozoic strata are mainly composed of Cambrian to possibly Mississippian marine sediments deposited at tropical latitudes. The Paleozoic sedimentation was largely influenced by siliciclastic input of the Appalachian Orogeny, eustatic sea-level changes and lateral movements of the Algonquin and Findlay arches (Armstrong and Carter 2010). Within the study area, these rocks are overlain by up to 75 m of unconsolidated Quaternary sediments (not discussed herein; for further information, *see* Armstrong and Carter (2010)). This study uses the *circa* 2017 lithostratigraphic chart used by the OGSRL and the OPDS (Figure 7; Brunton et al. 2017).

Cambrian Units

The Cambrian rocks are deposited directly on the Precambrian basement. Within the study area, they comprise feldspathic arenite to arkose, sandy dolomite and dolomitic sandstone (Trevail 1990; Armstrong and Carter 2010). There is a general upward decrease in sand coincident with an increase in carbonate content, although variations are observed within the strata (Bailey 2005). Various authors have proposed that these sediments probably covered all of southwestern Ontario, but various eustatic variations and/or progression of the forebulge of the Taconic Orogen resulted in subaerial exposure and erosion of the Cambrian rocks over its crest, as well as the overlying Lower Ordovician strata that have been completely eroded (Sanford and Quillian 1959; Bailey Geological Services Ltd. and Cochrane 1984b; Trevail 1990; Johnson et al. 1992; Carter, Trevail and Easton 1996; Bailey 2005; Armstrong and Carter 2010). This major erosion event is referred to as the Knox unconformity (Johnson et al. 1992).

The basal strata of Cambrian rocks were probably deposited in a near-shore shallow marine and shoreline environment with high-level of energy, whereas upper strata are thought to represent a shallow subtidal to nearshore environment with moderate energy (Hamblin 2011). The internal stratigraphy of Cambrian strata has been studied by Trevail (1990), Bailey (2005) and Hamblin (2011). However, for most wells in the OPDS, Cambrian strata are not subdivided. Therefore, all Paleozoic strata located stratigraphically between the Shadow Lake Formation and the Precambrian basement have been amalgamated. This corresponds with what was done for the 3-D Paleozoic model (Brunton et al. 2017; Carter et al. 2017, 2019).

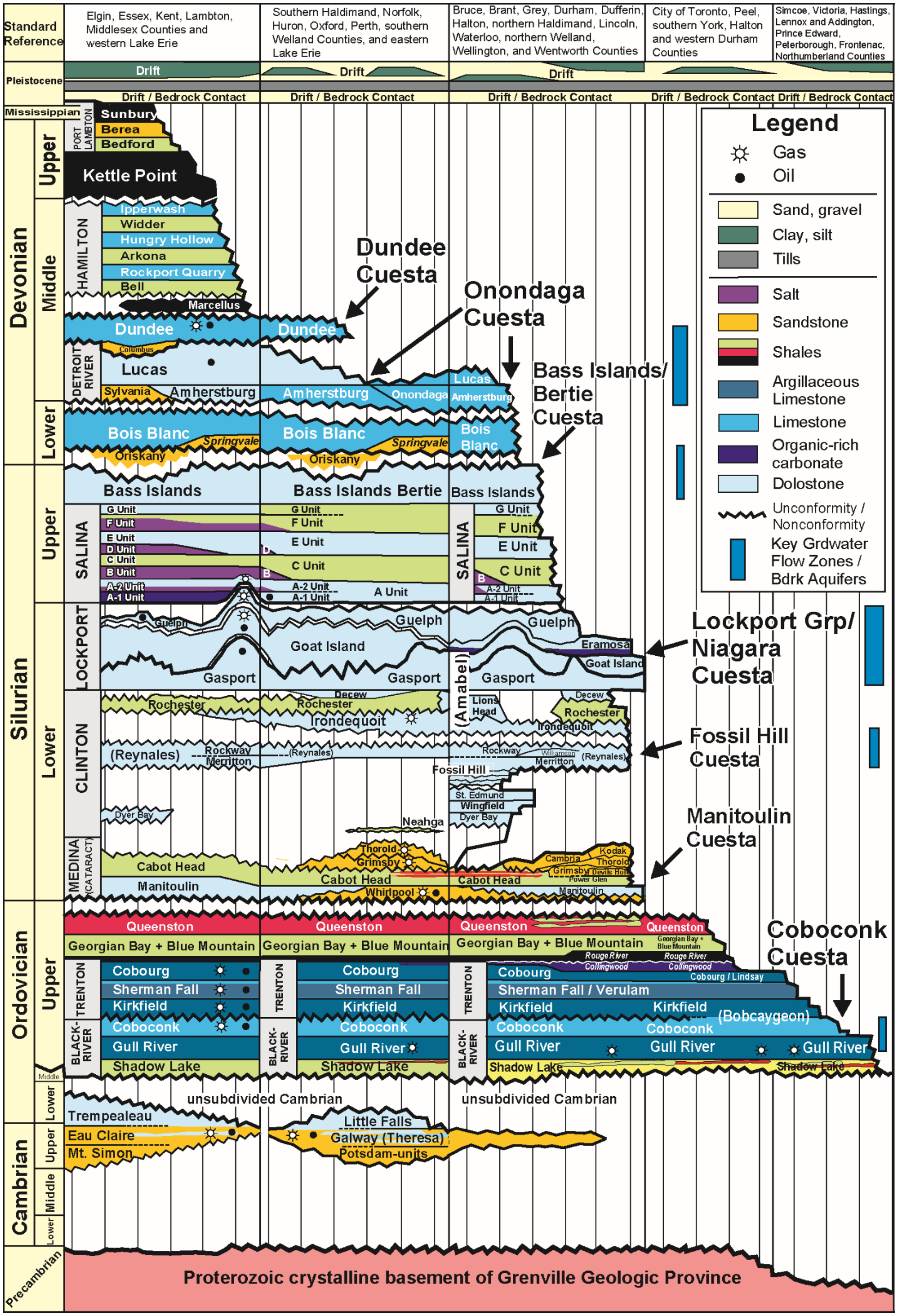

Figure 7. Revised terminology of Paleozoic strata for south-central and southwestern Ontario used by the OGSRL (*circa* 2017) (*modified from* the following references: Winder 1961; Beards 1967; Winder and Sanford 1972; Armstrong and Carter 2010; Brunton et al. 2017; Carter et al. 2017).

The top of the Cambrian succession is easily identified by an upward increase in gamma-ray count reflecting the lithologic change from Cambrian siliciclastic sediments to the overlying Shadow Lake Formation shales. Thickness variation of the Cambrian rocks may be the result of fault movement coeval with or following deposition, but could also result from topographic relief in the Precambrian basement prior to deposition during the Paleozoic.

Ordovician Units

The Ordovician rocks of southern Ontario can be differentiated into 3 sections, which, in ascending order, are the Black River Group, the Trenton Group and the shale succession, referred to as the Simcoe Group in the south-central Ontario outcrop belt (Liberty 1969; Johnson et al. 1992; Armstrong and Dodge 2007). The Black River Group is associated with marine transgression with shallow carbonate deposition (supratidal, lagoonal) (Armstrong and Carter 2010). Deposition of the Trenton Group is associated with the gradational deepening of the shelf accompanied by a general increase in shale (carbonate ramp). The main siliciclastic input from the Appalachian Orogen is recorded by the overlying shale succession, composed of the Georgian Bay, Blue Mountain and Queenston formations (Sanford 1993b).

BLACK RIVER GROUP

The Black River Group comprises, in ascending order, the Shadow Lake, Gull River and Coboconk formations (*see* Figure 7). The Shadow Lake Formation represents the onset of deposition above the Knox unconformity and was deposited either directly on the Precambrian basement or on inferred Cambrian strata (Trevail 1990). It comprises various lithofacies, depending on sediment source, depositional environment, tectonic activity, subaerial exposure and erosional extent (Trevail 1990). It is mainly composed of sandy red and green shales, but can also include argillaceous and arkosic sandstones, sandy argillaceous dolostones and arkosic conglomerates (Armstrong and Carter 2010).

The top of the Shadow Lake Formation is easily picked on geophysical logs because it is associated with a sharp drop in gamma-ray count from shales (Shadow Lake Formation) upward to limestones and dolostones of the Gull River Formation. This pick is one of the most reliable for the deepest Paleozoic units. It has been proposed that the coarser sandy lithofacies are present where the Shadow Lake Formation was being deposited directly on the Precambrian basement, making it difficult in examining geophysical logs to determine with certainty where Cambrian strata are absent (Armstrong and Carter 2010). Also, the thickness of the Shadow Lake Formation is supposedly greater (up to 15 m thick) where it onlaps the Precambrian basement, versus when it overlies the Cambrian (around 2–3 m thick) (Armstrong and Carter 2010; Sanford 1961, Johnson et al. 1992). However, this was not obvious from the OPDS database (Figure 8).

The Gull River Formation gradually overlies the Shadow Lake Formation and is mainly composed of limestone with some dolostone, shale and argillaceous sandstone (Armstrong and Carter 2010). The unit has more argillaceous material than the overlying Coboconk Formation and its upper contact is picked at the last upward gamma-ray spike below the Coboconk Formation.

The Coboconk Formation is composed of bioclastic limestone (wackestone to grainstone) and represents the top of the Black River Group (Armstrong and Carter 2010). It has a low argillaceous material content and correspondingly low gamma-ray profiles. The upper contact with the overlying Kirkfield Formation (basal Trenton Group) is sharp and shows a sharp rise in the gamma-ray count corresponding to an increase in clay mineral content in the Trenton Group limestones. Picking this contact may be complicated in places by the presence of bentonite beds in the upper Coboconk Formation, leading to possibly misinterpretation of the geological contact (*see* discussion in Armstrong and Carter 2010).

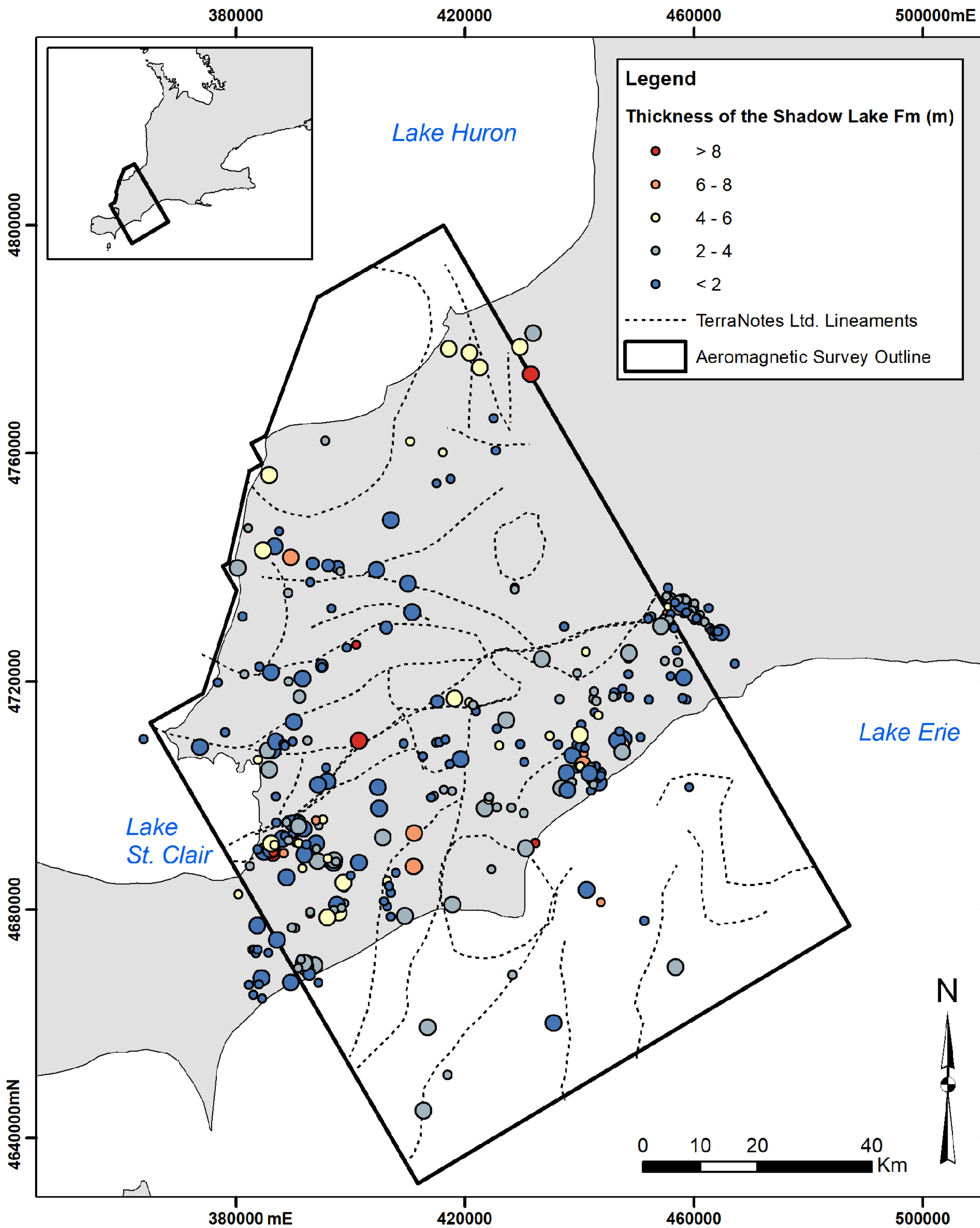

Figure 8. Thickness (in metres) of the Shadow Lake Formation within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: Fm, Formation.

TRENTON GROUP

In the subsurface stratigraphy, the Trenton Group is subdivided into 3 formations, which, in ascending order, are the Kirkfield, Sherman Fall and Cobourg formations. The Kirkfield Formation consists of wackestone, packstone and grainstone with some thin shale interbeds (Armstrong and Carter 2010). On geophysical logs, its upper contact is defined as the top of a less argillaceous interval situated below the higher gamma-ray profile of the Sherman Fall Formation. This contact is not easily picked.

The Sherman Fall Formation is mostly composed of mudstone and wackestone. The upper section of the unit can show a coarser grainstone known as the Sherman Fall Formation "fragmental" unit (Armstrong and Carter 2010). This lower gamma-ray signal is an identifiable marker used in the industry to pick the top of the formation.

The Cobourg Formation shows a general increase in argillaceous content and, thus, gamma-ray count from the coarser grained packstone and grainstone at the base to the finer grained wackestone at the top of the formation. In some areas, the Collingwood Member, a shaly limestone (micrite) unit, is identified at the top of the formation. It varies in thickness throughout southwestern Ontario, but measures generally less than a metre in thickness in the study area (Armstrong and Carter 2010; Béland Otis 2015). On geophysical logs, the top of the Trenton Group is easily identified from the overlying Blue Mountain Formation by a sharp upward increase in the gamma-ray curve (Rancourt 2009; Béland Otis 2015).

SHALE SUCCESSION

The Ordovician shale succession comprises the Blue Mountain, Georgian Bay and Queenston formations. Hamblin (2018) recently suggested the term "Nottawasaga Group" for this shale succession. The units indicate a regressive system from the deposition of a marine shale (Blue Mountain Formation) to shallow marine (Georgian Bay Formation) to a shoreline environment (Queenston Formation) (Hamblin 2018).

The Blue Mountain Formation is a bluish shale unit stratigraphically situated between the underlying Trenton Group and the overlying Georgian Bay Formation. The lowest portion of the unit shows dark shales with higher gamma-ray counts and is associated with the Rouge River Member (Russell and Telford 1983). There is a general upward increase in limestone, sandstone and siltstone within the unit until it reaches the Georgian Bay Formation, which is mainly composed of greenish-grey shale (Armstrong and Carter 2010). The contact between the 2 formations is gradational, which makes it a difficult consistent pick for the top of the Blue Mountain Formation. Therefore, as part of this project, both formations will be combined and named the Georgian Bay–Blue Mountain formations similar to what is registered on most well cards of southern Ontario.

The overlying Queenston Formation is easily recognized by its characteristic red and green shale with varying amounts of limestone, siltstone and sandstone (Armstrong 2001; Armstrong and Carter 2010). On geophysical logs, these strata are characterized by hundreds of metres of elevated gamma-ray values, with some lower values confined to limestone interbeds. The top of the Queenston Formation is associated with a decrease in gamma-ray count resulting from the change in lithology of the overlying Manitoulin Formation dolostones.

Silurian Strata

Within the current OPDS database, Silurian strata are divided into 4 groups and the overlying Bass Islands Formation. In ascending order, the 4 groups are the Medina (Cataract), the Clinton, the Lockport and the Salina groups. Internal stratigraphy of these groups is highly dependant on the location (*see* Figure 7). Only units found within the study area will be discussed.

MEDINA (CATARACT) GROUP

Within the Chatham Sag, the lowest unit of the Medina (Cataract) Group is the Manitoulin Formation, which sharply overlies the Queenston Formation (*see* Figure 7). The Manitoulin Formation is composed of dolostone with varying argillaceous content and is thought to have been deposited in a shallow ramp dipping toward the Appalachian Basin. Because the Manitoulin Formation is overlain by the green to red-maroon shales of the Cabot Head Formation, its upper contact is easily picked on geophysical logs. The Cabot Head Formation shows a slight increase in thickness within the Chatham Sag, accumulating to about 40 m and has been suggested to have been deposited in a shallow, restrictive environment (Brintnell et al. 2009; Armstrong and Carter 2010). Within the OPDS, the overlying stratigraphic unit of the Cabot Head Formation is not constant and, depending upon location, can be the Grimsby, Thorold, Dyer Bay or Reynales formation. The Reynales Formation is the unit with the greatest coverage within the Chatham Sag, whereas the first 3 formations are identified more locally and will not be discussed here (Figures 30 to 33).

CLINTON GROUP

In the western part of southern Ontario, the Clinton Group consists of the Dyer Bay, Reynales (Rockway and Merriton), Irondequoit, Rochester and DeCew formations (*see* Figure 7). The Dyer Bay, Irondequoit and DeCew formations will not be addressed here because their extent, interpreted from the OPDS, is too limited within the study area.

Within the study area, the Reynales Formation is a relatively thin unit and measures around 1 m (Sanford 1969b; Armstrong and Carter 2010). This dolostone is easily recognized on geophysical logs because it is located between 2 shale units: the underlying Cabot Head Formation and the overlying Rochester Formation. Thinning seems to be observed over the Algonquin Arch, suggesting uplift after deposition (Sanford 1969b).

The Rochester Formation of the Clinton Group is characterized by a dark grey to black calcareous shale with varying amounts of calcisiltite and calcarenite (Armstrong and Carter 2010). The Rochester Formation is overlain by the DeCew Formation, where present, or by the Lockport Group (Armstrong and Carter 2010). In the Chatham Sag, the top of the Rochester Formation is easily recognized on geophysical logs by the well-defined upward decrease in gamma-ray values associated with the sharp contact of overlying crinoidal dolostones of the Gasport Formation of the Lockport Group. Also, the Rochester Formation has a relative constant thickness of about 24 m and is associated with deposition in a subtidal environment (Thusu 1972; Brett 1983; Armstrong and Carter 2010). Because of these characteristics, the Rochester Formation is frequently used in the identification of subsurface structural features (Armstrong and Carter 2010).

LOCKPORT GROUP

Within the study area, the Lockport Group is composed of the Gasport, Goat Island and Guelph formations, in ascending order; lithofacies of the Eramosa Formation are not present within the study area (*see* Figure 7; Brunton et al. 2012). The Gasport Formation represents a regional transgressive crinoidal dolostone (Brunton 2009). It is apparent from the OPDS data that some issues are associated with its upper formational contact, although the Gasport Formation shows a characteristic low gamma-ray geophysical signature (Armstrong and Carter 2010; Carter et al. 2019). Also, missing and inconsistent formational picks were found to be a major issue within the OPDS for the overlying finer grained argillaceous encrinites of the Goat Island Formation (Brunton 2009; Brunton et al. 2012; Brunton et al. 2017). The upper section of the Goat Island Formation is a chert-rich dolostone (Brunton 2009).

The Guelph Formation is mainly composed of tan to brown dolostones, can be very fossiliferous in the lower part of the unit and is associated with an open-marine environment (Brunton 2009; Brintnell 2012; Armstrong and Carter 2010; Rowell 2015). Recent stratigraphic work (Brunton and Brintnell 2011; Brintnell 2012) now incorporates the formation into the Lockport Group. The top of the Guelph Formation is a somewhat difficult geophysical pick (Armstrong and Carter 2010). Indeed, the overlying A-0 Carbonate Unit of the Salina Group, a bituminous dolomudstone is usually not differentiated from the underlying Guelph Formation in the OPDS well records. Also, because of karst erosion, the thickness of the formation varies considerably, ranging from zero to more than 100 m thick (Armstrong and Carter 2010; Brunton and Brintnell 2011; Brunton et al. 2012; Brintnell 2012).

SALINA GROUP

The Salina Group is characterized by an evaporitic succession of dolomite, anhydrite, salt, shaly dolomite and dolomitic shale (Armstrong and Carter 2010). Salt deposits are only found in the Michigan Basin and the Chatham Sag (Armstrong and Carter 2010). The group is subdivided in lettered formational rank units, which, from base to top, are A to G (*see* Figure 7).

Because of the high variability of lithofacies in the Salina Group, this study focussed on the salt horizons (A-2 Salt, B Salt and F Salt units) and the uppermost G Unit. Indeed, extent and vertical offsets identified for salt units are indicative of salt dissolution features that influence deposition and thicknesses of overlying strata (Dutton 1985; Hamilton and Coniglio 1990; Coniglio and Frape 1992; Sanford 1993b). Preferably, interpretation of regional faults should be based on the presence of offsets and/or thickness variations in strata older than the Salina Group. Also, the G Unit was selected because it is a reliable geophysical pick in southwestern Ontario associated with an upward increase in gamma-ray values because of its high shale content (Armstrong and Carter 2010). Some additional shaly beds above the G Unit can still be present in the Salina Group. Usually, the G Unit is overlain by the Bass Islands Formation, which is characterized by a low gamma-ray signature.

Interestingly, Sanford, Thompson and McFall (1985) proposed that salt dissolution from the Salina Group was linked to regional tectonics and faults. However, these may only represent fractures permitting either shallow groundwater and/or deep fluid flow to salt beds. Structural movement may not be involved.

BASS ISLANDS FORMATION

Within the OPDS, the Bass Islands Formation is listed jointly with the Bertie Formation of the Niagara Peninsula (Armstrong and Carter 2010; Carter et al. 2019). The Bass Islands Formation, dominated by sabkha facies, is a variably laminated dolomudstone that shows a great range in thickness, especially over salt dissolution depressions where it can reach up to 150 m (Sanford 1969b; Carter et al. 2019). The upper formational contact, which corresponds to the Silurian–Devonian boundary, is not based on geophysical logs, but is based on a lithological break observed in samples.

Devonian and Mississippian Strata

In southern Ontario, the Devonian units range from the Oriskany Formation to the Port Lambton Group, which overlaps the Mississippian. The elevations and thickness of these units are greatly influenced by the underlying salt dissolution of the Salina Group. Therefore, vertical offsets should not be automatically associated with fault movement. Furthermore, many Devonian formational picks are based on samples and should be considered unreliable (Armstrong and Carter 2010).

The Devonian and Mississippian rocks represent the top of bedrock within the study area. For this project, elevation values of the subcropping stratigraphic unit are not reported in the regional or local maps because vertical offsets could be attributed to Quaternary or recent erosion and would not reflect fault movement.

ORISKANY FORMATION

The Oriskany Formation is a marine quartzose sandstone that has only been identified erratically throughout the study area (e.g., Figure 58; Sun 2018; Carter et al. 2019). Its location is determined primarily by the presence of salt dissolution (Bailey Geological Services Ltd. and Cochrane 1985; Sun, Brunton and Jin 2014; Davis 2017). Its low gamma-ray signature is not highly recognizable on geophysical logs.

BOIS BLANC FORMATION

The Bois Blanc Formation consists of fossiliferous, bioturbated, cherty limestone and dolostone deposited in nutrient-rich waters (Sun 2018). Its geophysical signature is not characteristic and, therefore, its upper formational contact is a sample pick (Armstrong and Carter 2010). The Springvale Member is found in the lower section of the Bois Blanc Formation, with a characteristic greenish quartzitic sandstone of possible marine origin (Sun 2018). Within the study area, it is preserved where salt dissolution occurred (Armstrong and Carter 2010; Davis 2017).

DETROIT RIVER GROUP

The Detroit River Group comprises, in ascending order, the Sylvania, Amherstburg, Lucas and Columbus formations. The Sylvania Formation is a quartzose sandstone that occurs exclusively in the Essex County and was only sparsely identified in the study area (Armstrong and Carter 2010).

The Amherstburg Formation is composed of bituminous, fossiliferous limestones and dolostones. Its upper formation contact with the Lucas Formation is an unreliable pick and is based on an ambiguous lithological change observed in sample (Armstrong and Carter 2010).

The Lucas Formation is composed generally of limestone, dolostone and anhydrite of restricted marine origin. Internal subdivision has been proposed by Uyeno, Telford and Sanford (1982), but is not used within the OPDS. The upper contact is considered unreliable when based solely on geophysics (Armstrong and Carter 2010).

The Columbus Formation, previously included in the Lucas Formation, is composed mainly of fossiliferous, bioclastic dolomitic limestones and sandstones (Armstrong and Carter 2010; Birchard, Rutka and Brunton 2004). It does not show as either a uniform distribution within the study area or as a reliable geophysical pick (*see* Figure 64; Armstrong and Carter 2010).

DUNDEE FORMATION

The Dundee Formation is generally composed of fossiliferous limestone deposited in shallow to open-marine conditions (Sun 2018). Chert nodules may be abundant and some dolostone is also present (Armstrong and Carter 2010). The contact between the Dundee Formation and the Hamilton Group is one of the most reliable geophysical picks for Devonian rocks. However, it can become problematic where the

Dundee Formation becomes argillaceous in its uppermost section, underlying the Hamilton Group shales (Armstrong and Carter 2010). Also, the Dundee Formation is present throughout the study area and is the oldest unit cropping out within the study area, close to the Lake Erie shoreline.

MARCELLUS FORMATION

The black organic-rich shales of the Marcellus Formation are easily identified on geophysical logs by a diagnostic high gamma-ray signature (Johnson et al. 1989; Armstrong and Carter 2010). It is composed of organic-rich shales derived from the Appalachian Basin during the Acadian Orogeny (Johnson et al. 1989). The unit is found in the Appalachian Basin and is confined within the Lake Erie area (Johnson et al. 1989). However, within the OPDS, the Marcellus Formation has been identified in the northern extent of the study area, suggesting possible issues within the database (Figure 66). This unit is not used as part of this project.

HAMILTON GROUP

In ascending order, the Hamilton Group is subdivided into the Bell, Rockport Quarry, Arkona, Hungry Hollow, Widder and Ipperwash formations. However, these formations are not recognized separately within the OPDS (Carter et al. 2019). The Hamilton Group is composed of a succession of calcareous shale and carbonates and outcrops within the study area (Armstrong and Carter 2010; *see* Figure 2). Its lower gamma-ray signature is easily recognizable from the overlying organic-rich Kettle Point Formation.

KETTLE POINT FORMATION AND PORT LAMBTON GROUP

The Kettle Point Formation is composed of black organic-rich shales and represents the outcropping bedrock for most of the study area (Armstrong and Carter 2010; *see* Figure 2). Interpretations from this unit can only be made for a limited area along the St. Clair River, where the overlying siliciclastic sediments of the Port Lambton Group are present (Figure 68). Because of the clear lithological break between the 2 units, the geophysical pick of the formational contact is easily recognizable and is reliable.

The Port Lambton Group is not discussed in this report because it represents the uppermost stratigraphic unit and, therefore, all elevation variations of the unit are the result of Quaternary and/or recent erosion.

STRUCTURAL GEOLOGY

Various evidence indicates that the Paleozoic strata are structurally related to the underlying Precambrian basement (Sanford, Thompson and McFall 1985; Easton and Carter 1995; Carter, Trevail and Easton 1996; Boyce and Morris 2002).

One of the most conclusive elements comes from the 2 major faults in the area: the Electric and the Dawn faults (Figure 9). These subvertical normal faults trend generally west, in the centre of the study area, although the exact locations of these faults are difficult to determine because of insufficient control points (Brigham 1971; Carter, Trevail and Easton 1996). Both structures are apparent in the Precambrian surface and their development may be closely associated with the boundary between the Huron and Kent domains (Carter, Trevail and Easton 1996). Authors have also recognized that magnetic strike directions from the Precambrian basement, interpreted from older aeromagnetic surveys, are subparallel to the

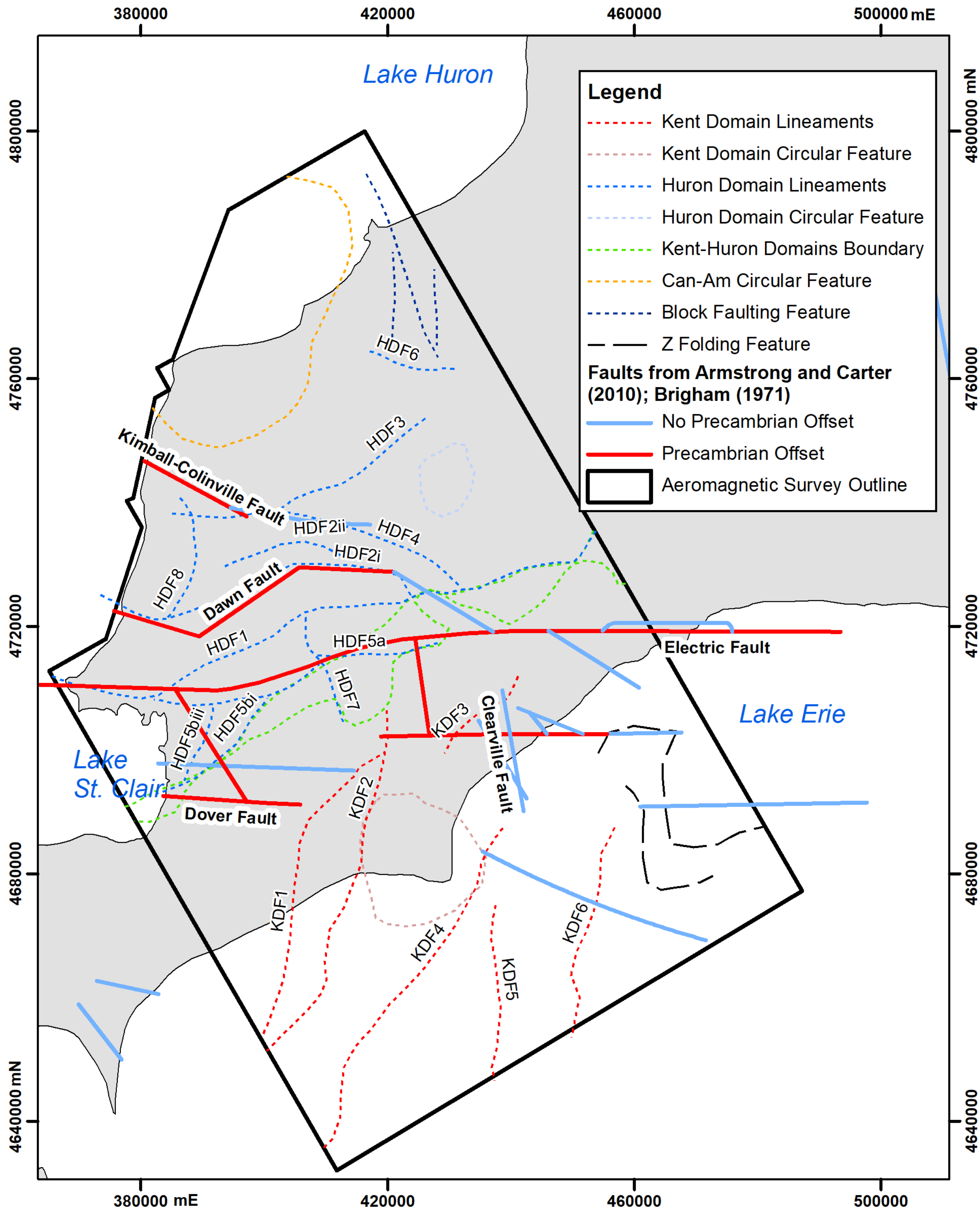

Figure 9. Correspondence between lineaments identified by TerraNotes Ltd. and previously mapped faults (Ontario Geological Survey 2009, 2014; Armstrong and Dodge 2007; Armstrong and Carter 2010; Brigham 1971).

orientation of these major faults (Easton and Carter 1995; Gupta 1991a). The Electric and Dawn faults seem to have major influence on salt dissolution, suggesting vertical fluid flow along the structures (Brigham 1971). The Electric Fault has a maximum vertical displacement of approximately 93 m and is present in both the Huron and Kent domains. The Dawn Fault, located in the Huron Domain, has a maximum vertical displacement of approximately 47 m. The south side is downthrown for both faults (Brigham 1971). Other Precambrian faults have been suggested by Bailey (2005) to explain the location of the northern shore of Lake Erie and the position of the St. Clair River, where thinning of Cambrian rocks is observed.

The Kimball–Colinville fault is another important fault in the Huron Domain (*see* Figure 9). This fault is oriented northwest and may extend west into Michigan, across St. Clair River. Brigham (1971) refers to the "Kimball–Colinville monocline", a narrow Precambrian basement feature showing a maximum displacement of over 40 m down to the southwest. The feature has an onshore east-southeast unnamed extension that apparently does not offset the Grenvillian rocks (*see* Figure 9).

Several previously mapped west- and north-northwest-trending faults are in the Kent Domain. The most important west-trending fault is the Dover fault, which is a structure associated with the Dover pool, and is related to hydrothermal dolomitization of Ordovician carbonates. The northwest- to north-northwest-trending faults (e.g., Clearville fault) seem controlled by the west-trending fault system because they are bound by them. Most of the offshore faults only offset Paleozoic strata and not the Grenvillian basement (*see* Figure 9).

Finally, it has been suggested that deformed magnetite-bearing brittle plutons, associated with magnetic highs, may be the cause of other localized faults (Carter, Trevail and Easton 1996). Industry seismic lines (data not publicly available) show that the Precambrian basement has been offset by faults associated with oil and gas pools in the Essex and Kent domains (Easton and Carter 1995).

Model of Sanford, Thompson and McFall

Sanford, Thompson and McFall (1985) suggested that the locations and orientations of major faults and fractures observed in the Paleozoic strata were controlled by Precambrian basement structures. They also proposed that southwestern Ontario was divided into 2 megablocks that moved independently from each other (Figure 10). The Bruce megablock, located north of the Algonquin Arch, shows relatively simple east-trending structures, whereas the Niagara megablock, located south of the arch, has a more complex pattern. Easton and Carter (1995) identified that the Bruce megablock approximately corresponds to the Grenvillian Huron Domain and that the Huron and Kent domains boundary matches the megablocks boundary, especially in the study area.

More recent work by Morris et al. (1998) and Boyce and Morris (2002) also supports the Sanford, Thompson and McFall (1985) conceptual structural model. They compared that model with their regional basement magnetic trends, which were based on their interpreted aeromagnetic and gravity lineaments based on the data set available at the time (Figure 11). For the Niagara megablock and mostly within the current study area, there is a good correlation between orientations of the proposed Sanford, Thompson and McFall (1985) model and their lineaments. However, the magnetic lineaments do not show the east-trending orientation speculated for the Bruce megablock and the authors suggested a few factors to explain it. There could be a simple lack of control of Precambrian structure in the overlying Paleozoic strata in the Bruce megablock, which could agree with a less tectonically active area, as suggested by Sanford, Thompson and McFall (1985). Also, the apparent simple fracture pattern in the Bruce megablock could be the result of a lower well density, which constrains structural interpretations for that area. Boyce and Morris (2002) also suggested that northeast-trending lineaments are associated with Grenville basement, whereas northwest-trending lineaments represent structures related to the Iapetus Ocean opening. Additional lineaments with east to northeast trends may represent extension of the St. Lawrence rift system into the lower Great Lakes (Adams and Basham 1989; Thomas et al. 1993).

Precambrian Structures and Hydrocarbon Exploration

Most of the subsurface geological information available for southwestern Ontario has been obtained through oil and gas exploration. As such, deep-seated structures affecting both Paleozoic and Precambrian rocks have mostly been studied for their implications in the development of fault traps, dissolution of salt-bearing strata and dolomitization of carbonate strata, all of which can be involved in reservoir development (Brigham 1971; Carter 1991; Carter, Trevail and Easton 1996). Furthermore, fractures and faults can act as hydrocarbon conduits.

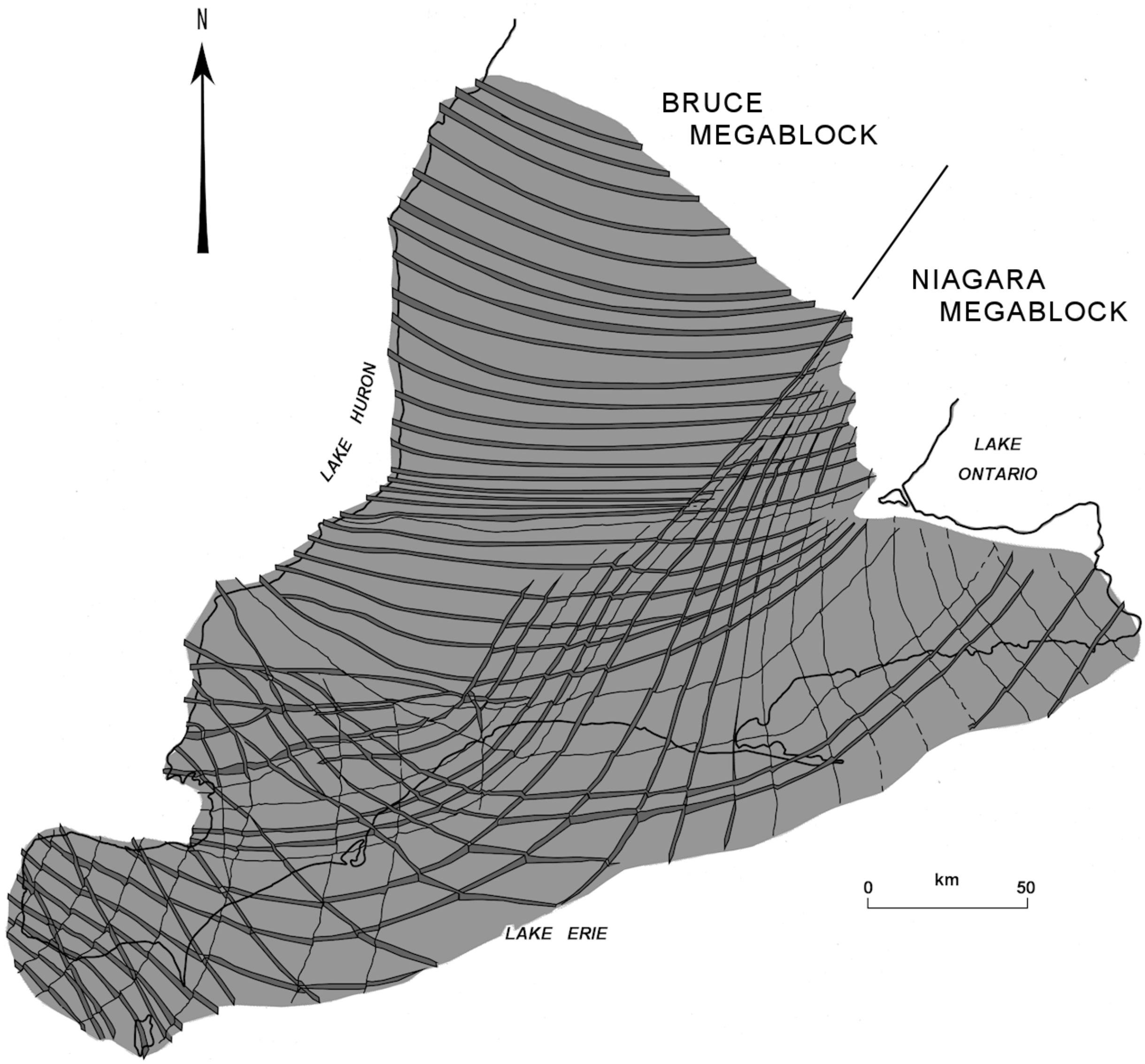

Figure 10. Conceptual fracture–framework model for southwestern Ontario proposed by Sanford, Thompson and McFall (1985).

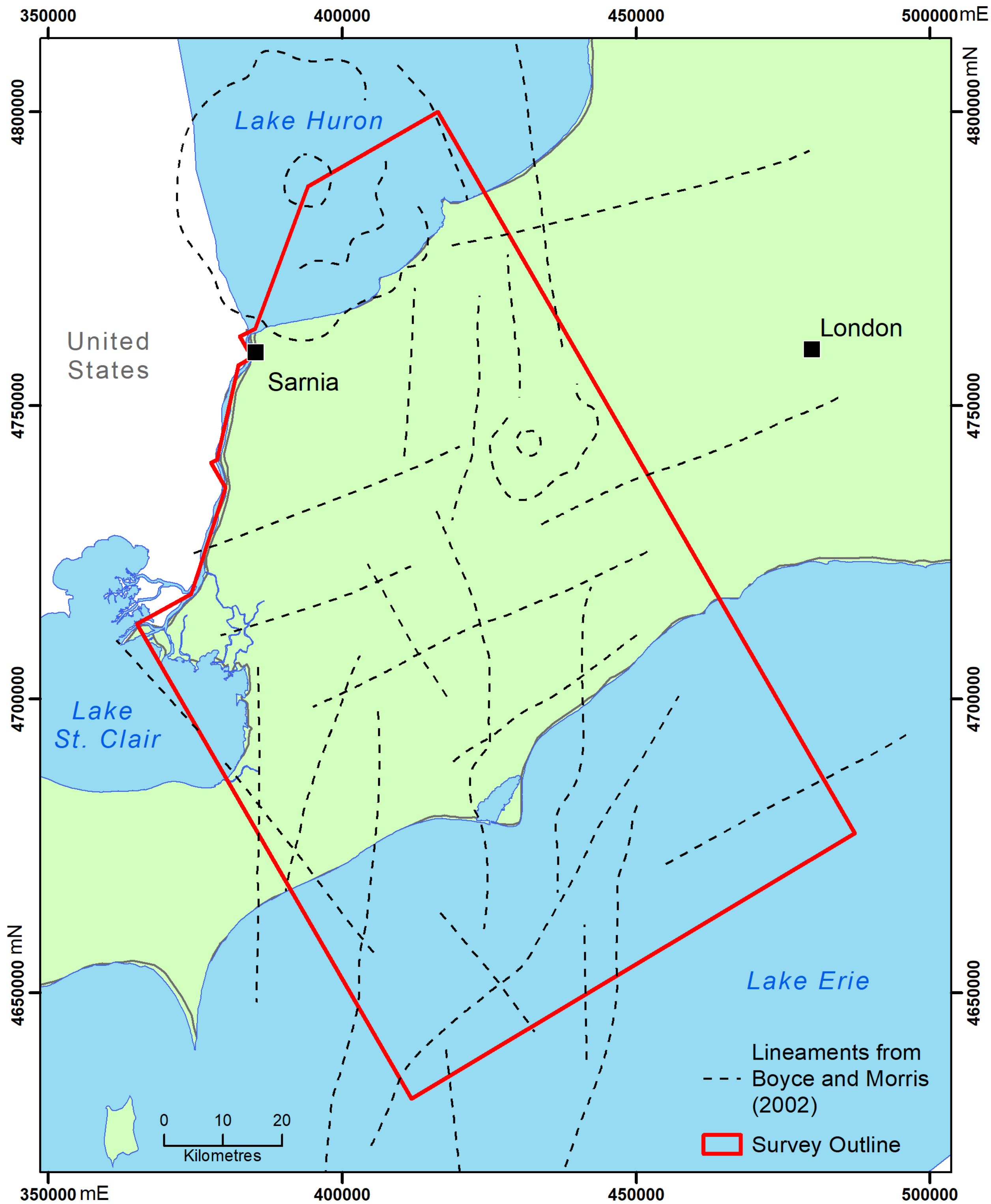

Figure 11. Lineaments interpreted from previous gravity (Boyce and Morris 2002) and aeromagnetic (Gupta 1991a, 1991b) surveys.

Davies and Smith (2006) proposed that deep-seated hot hydrothermal fluids flow either through the fractured Proterozoic crystalline basement rocks or the overlying basal sandstones and migrate upward along deep-seated faults until they reach an impermeable and unfractured cap rock, usually represented by a shale horizon. The fluids migrate horizontally along more porous limestone, dolomitizing the host rock and creating secondary porosity, hence enhancing reservoir properties. This large-scale dolomitization is also usually associated with a sag in the altered horizon, delimited by these deep faults. For the Ordovician Trenton Group–Black River Group Albion–Scipio reservoirs in Michigan, Davies and Smith (2006) proposed that the upward migration of the brines occurred soon after deposition, probably during the Taconic Orogeny (middle Late Ordovician to Early Silurian).

In southwestern Ontario, hydrothermal dolomites reservoirs can be found in the Ordovician Trenton Group–Black River Group carbonate strata and tend to be narrow (400–1200 m), but can be several kilometres long (Middleton et al. 1993; Carter, Trevail and Easton 1996; Trevail, Carter and McFarland 2004; Dorland et al. 2016). These reservoirs have only been identified in Essex and Kent counties and the Dover pool is the most well-known hydrothermal dolomitized reservoir in the study area (Carter, Trevail and Easton 1996; Colquhoun and Johnston 2004). In southern Ontario, some alteration has been identified in the Precambrian basement, in the few metres below the Paleozoic–Precambrian unconformity, supporting the hypothesis of fluid flow along this contact (Harper et al. 1995). Haeri-Ardakani, Al-Aasm and Coniglio (2013a, 2013b) suggested that hydrothermal dolomites observed in southwestern Ontario resulted from fluids originating from the Michigan Basin, as opposed to the Appalachian Basin, mainly because of the large presence of fracture-related dolomite in the periphery of the former. They also proposed that the Midcontinent Rift was probably a source of heat for hydrothermal fluid flow during the Late Devonian–Mississippian (Haeri-Ardakani, Al-Aasm and Coniglio 2013a).

Method

The main objective of this study was to evaluate the usefulness of lineament analysis of aeromagnetic survey for Paleozoic mapping in southern Ontario. To do so, the TerraNotes Ltd. lineament map was compared with data from the OPDS, as well as the Paleozoic fault and hydrocarbon pools map. The various steps taken in the project are described here.

AEROMAGNETIC SURVEY

In 2009, the OGS hired Goldak Airborne Surveys to fly a horizontal magnetic gradiometer airborne survey over the Chatham area. The survey was flown at a height of 200 m with a line spacing of 500 m. Most of the flight lines began and ended at the Canada–United States border and were oriented at 150°. All other specifications from the survey can be found in Geophysical Data Set 1065 (Ontario Geological Survey 2009). The study area corresponds to the survey area with an additional 10 km surrounding buffer (*see* Figure 6).

LINEAMENT ANALYSIS BY TERRANOTES LTD.

In 2013, TerraNotes Ltd. was contracted by the OGS to perform a lineament analysis of the 2009 Chatham aeromagnetic survey. The specific methods used to determine the lineaments are found in Miscellaneous Release—Data 317 (Ontario Geological Survey 2014). This analysis involved the delineation of structural lineaments in only the domains of the Grenville Province because the overlying Paleozoic sedimentary rocks are largely non-magnetic.

Table 1. Primary structural element properties identified from the Chatham aeromagnetic survey by TerraNotes Ltd. (Ontario Geological Survey 2014).

Feature Name	Type	Strike Direction	Relative Age	Confidence
K-H domains boundary	Domain contact	ENE	Older	Highest
HDF1	Fault	E-W	Older	Highest
HDF2	Fault	E-W	Indeterminate	Highest
HDF3	Fault	ENE	Indeterminate	High
HDF4	Fault	NW	Indeterminate	Low
HDF5	Fault	E-W	Intermediate	Intermediate
HDF6	Fault	WNW	Indeterminate	Low
HDF7	Fault	N-S	Younger	Lowest
HDF8	Fault	N-S	Indeterminate	Low
KDF1	Fault	NNE	Indeterminate	High
KDF2	Fault	NNE	Indeterminate	High
KDF3	Fault	ENE	Indeterminate	Intermediate
KDF4	Fault	NE	Indeterminate	Lowest
KDF5	Fault	N-S	Indeterminate	Lowest
KDF6	Fault	NNE	Indeterminate	Low
Can-Am circular feature*	Potential impact structure	n/a	Indeterminate	n/a
Block faulting	Normal faults or topographic lows	N-S	Indeterminate	n/a
HD circular feature	Unknown	n/a	Indeterminate	n/a
KD circular feature	Unknown	n/a	Indeterminate	n/a
Z folding	Folds	n/a	Indeterminate	n/a

**Initially referred to as "Can-Am Impact Structure" by TerraNotes Ltd.*
***Abbreviations**: HD, Huron Domain; HDF, Huron Domain fault; KD, Kent Domain; KDF, Kent Domain fault; K-H, Kent–Huron [domains]; n/a, not applicable.*

TerraNotes Ltd. identified 14 lineaments located in 2 domains: the Kent Domain in the south and the Huron Domain in the north (Ontario Geological Survey 2014; Easton and Carter 1995; Boyce and Morris 2002). The boundary between the 2 domains is associated with a change in magnetic intensity (*see* green line in Figure 6). Additional identified structures include 3 circular features, including the Can-Am "structure" in Lake Huron (Forsyth et al. 1990), some large Z-folding in the southeast and several subparallel magnetic lineaments in the northeast probably related to block faulting (*see* Figure 11; Table 1). Where possible, TerraNotes Ltd. provided relative ages for some of the lineaments (*see* Table 1).

ONTARIO PETROLEUM DATA SYSTEM (OPDS)

The Oil, Gas and Salt Resources Library (OGSRL, www.ogsrlibrary.com) houses and updates information on almost 27 000 Ontario wells, including geophysical logs, formations tops, well history and construction, oil–gas–water zones and analyses, initial completion results, and core analyses (Clark et al. 2019). Also, cores, drill cuttings and original paper submissions are stored at the OGSRL. Well records are maintained in the Ontario Petroleum Data System (OPDS).

In the last few years, significant improvements have been made on the quality assurance and quality control of the database, as well as updates on the stratigraphic chart used (Carter et al. 2017; Clark et al. 2019). For each formational contact reviewed by OGSRL staff or by Ontario MNRF staff, a quality assurance (QA) code was assigned (Clark et al. 2019). The value given by the geologist reflects their confidence in the formation pick. Negative QA codes reflect anomalous elevation values that could not be confirmed or corrected because of the lack of data (−2.0) or simply has yet to be reviewed (−1.0). All other QA codes refer to a combination of who reviewed the geological pick (professional geoscientist, geoscientist-in-training or graduate student, geology student), from which organization (MNRF or

OGSRL) and the availability and use of various data (drill cuttings, core, geophysical logs). Higher QA codes refer to a greater confidence level, reaching a maximum value of 2.0. Formational picks originating from the same well card can show different QA codes.

MAP PRODUCTION

For this project, only wells located within the aeromagnetic survey and the additional 10 km buffer zone around the survey limits were used. This represents 10 990 wells (Figure 12). Formational picks with negative QA codes were not considered. Additionally, for the outcropping stratigraphic units (Dundee Formation and younger) of the study area, only geological picks not interpreted as top of bedrock are presented on maps. This eliminates identification of offset explained by recent Quaternary erosion. The geological maps produced in this project show a point size proportional to the QA code of a formational pick. The legend is shown in Figure 13. As for the colour scheme used, greater elevation values are represented in red, whereas lower elevations are represented in blue.

Two sets of maps were produced as part of this project. The first set are regional elevation maps in Appendix 1 (Figures 16 to 68). These are coloured dot elevation maps of all OPDS formational picks and cover all of the study area. Elevation values are grouped at 50 m intervals. These maps help identify regional trends and broad structures seen within the Chatham Sag, as well as the most informative and useful stratigraphic units to follow up for local lineament description.

The second set of maps, in Appendix 2 (Figures 69 to 133), shows similar elevation data, but at smaller scale and specifically for wells around each lineament. Elevation values are grouped at 10 m intervals and, therefore, smaller offsets will not be recognized. Only the most informative maps are published in this report. These maps help to distinguish vertical offsets in the Paleozoic cover. An association of such an offset to a previously identified TerraNotes Ltd. lineament could indicate a relationship between Precambrian and Paleozoic structures.

Results

The maps produced as part of this project are divided into regional and local maps. Regional maps cover the entire study area, whereas local maps focus on a single or small group of features previously identified TerraNotes Ltd.

REGIONAL INTERPRETATIONS

The regional maps found in Appendix 1 (Figures 16 to 68) help distinguish stratigraphic units that will be used for the local maps. Also, regional maps can help identify regional trends, including location of arches, depocentre and local dip. Regional interpretations within the study area will be discussed briefly here.

Precambrian

To create the Precambrian basement structural map (Figure 16), 255 wells were used. Well distribution is uneven, with the highest number of wells located onshore, south of the Kent–Huron domains boundary. the lowest elevations are found in the north and south, toward the centre of the Michigan and Appalachian basins, whereas the highest elevations are observed in the middle of the study area, close to the eastern and western boundary of the study area, along the Algonquin Arch (*see* Figure 16). Also, in the middle of the study area, along the Algonquin Arch, a smaller scale depression can be identified, possibly corresponding to the Chatham Sag.

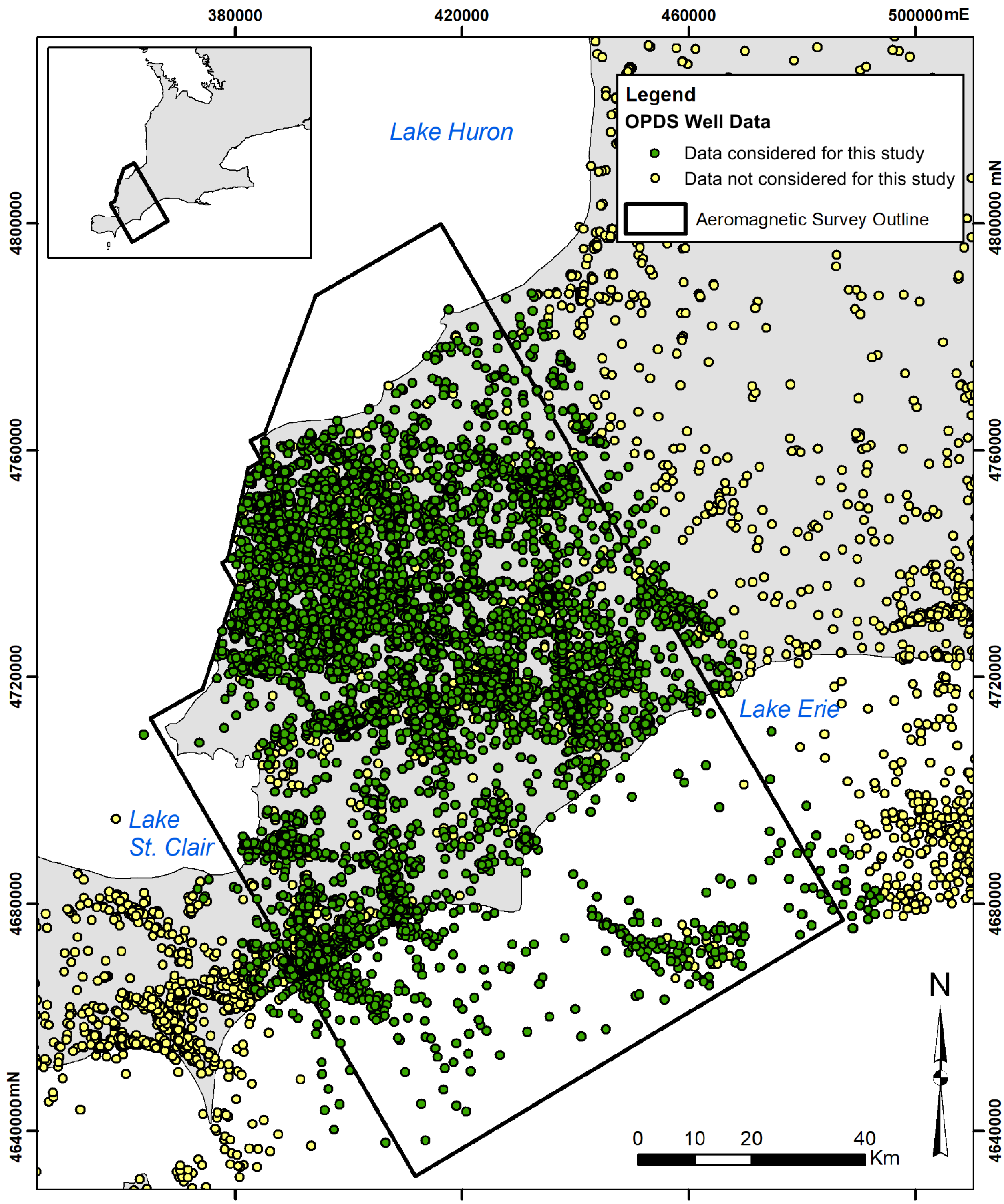

Figure 12. Well data (as of 2017) in the Ontario Petroleum Data System (OPDS) were examined: this figure shows the locations of those wells in and near the study area (black outline). Well data were evaluated for certain criteria (*see* text for explanations): data considered in this study are indicated as green dots; and data not considered are indicated as yellow dots.

Cambrian

As discussed previously, because of numerous absent formational picks within the Cambrian sediments, the only geological pick examined for structural maps was the top of the Cambrian rocks. The 325 wells used to create the Cambrian structural map (Figure 17) show similar trends identified for the Precambrian basement (highs along arches and lows toward basin depocentres). However, within the study area, elevation values are significantly lower on the Michigan Basin side than on the Appalachian Basin side of the arch.

Moreover, 38 wells, listed in the OPDS database, were drilled into the Proterozoic crystalline basement rocks and did not intersect Cambrian rocks (Figure 14). These wells are generally situated in the western half of the study area, close the Kent–Huron domains boundary. This would support the ideas of previous authors that the various uplifts of the Algonquin Arch caused the Cambrian rocks and the Shadow Lake Formation to be eroded, especially on its crest (Trevail 1990; Bailey 2005). However, some Cambrian rocks, recognized in some wells on or near the crest, correspond with Bailey's (2005) eroded Cambrian and Shadow Lake Formation sediments area. This implies a structural history coeval with and/or after Cambrian deposition more complex than previously suggested, especially on a local scale.

Ordovician

Based on well coverage and QA codes, some Ordovician formational picks were found to be the most meaningful and were used for the local maps. They include the Shadow Lake Formation (Figure 18), Coboconk Formation (Figure 20), Cobourg Formation (Figure 23), Georgian Bay–Blue Mountain formations (Figure 25) and Queenston Formation (Figure 26). Maps for the following formations are provided in Appendix 1, but will not be described here: Gull River Formation (Figure 19), Kirkfield Formation (Figure 21), Sherman Fall Formation (Figure 22) and Collingwood Member of the Cobourg Formation (Figure 24).

All Ordovician units deeper than the Queenston Formation show trends similar to those observed for the Cambrian and Precambrian structural maps. Highest elevations are located at the western and eastern extents of the study area along the Algonquin Arch. Also, lowest elevations are found toward the Michigan Basin and other lower values toward the Appalachian Basin. However, the Queenston Formation does not show lower elevations on the Appalachian Basin side, suggesting most of the Appalachian Basin subsidence occurred before and/or during deposition of the Queenston Formation.

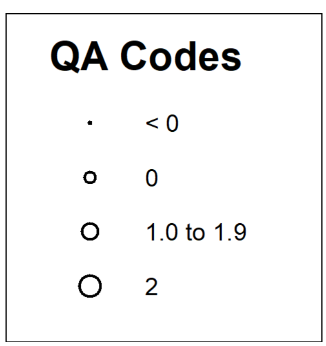

Figure 13. Size symbols used to represent quality assurance (QA) codes for maps found in Appendixes.

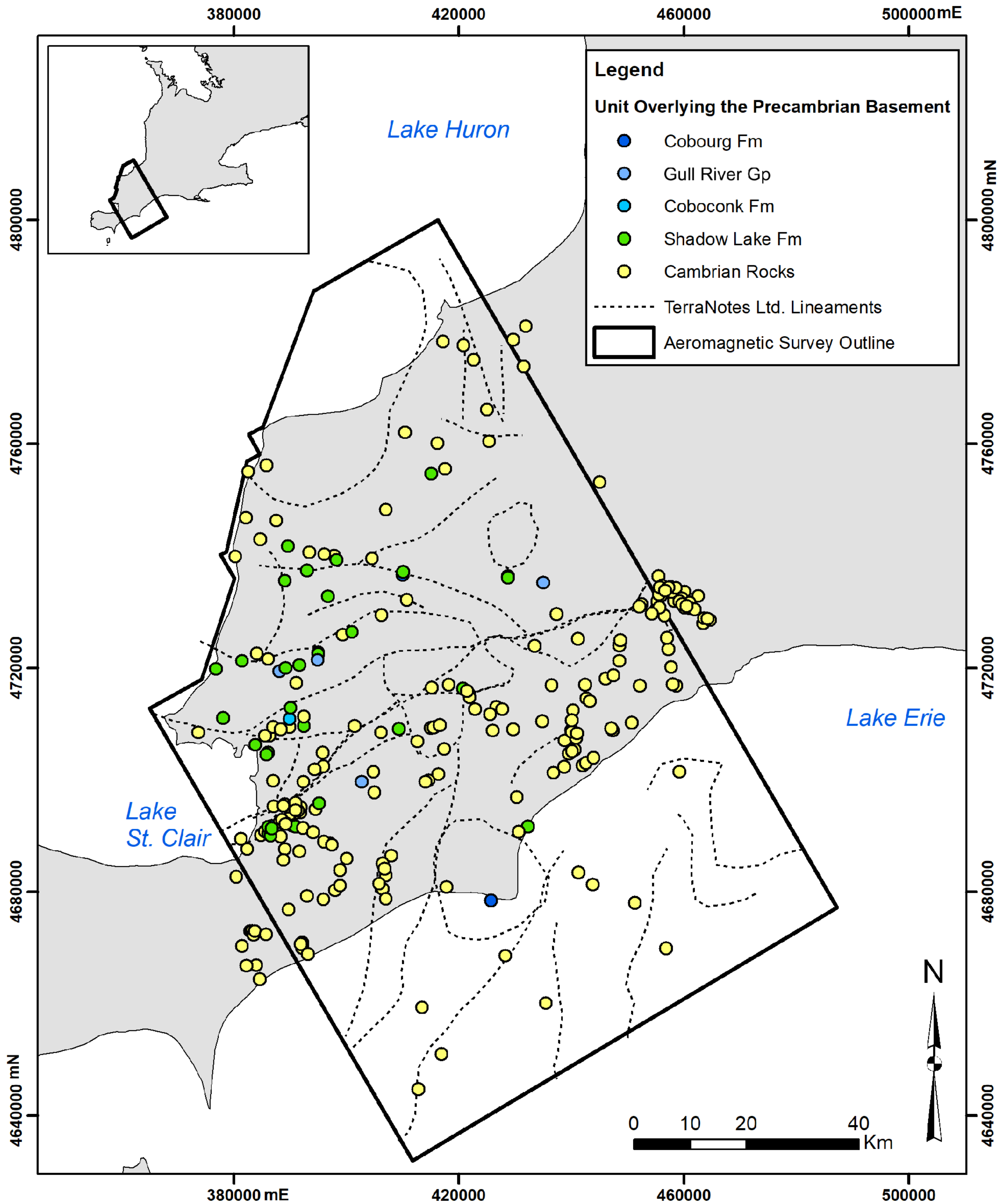

Figure 14. Paleozoic units, identified in the OPDS database, directly overlying the Precambrian basement. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; Gp, Group.

Silurian

For this project, Silurian strata are subdivided into 2 major categories: deposition before and deposition after the Lockport Group. As a structural approach, elevation offsets identified in the first category are most likely associated with a structural feature, whereas the second category may also be associated with karstification within the Lockport Group and/or Bass Islands Formation, as well as salt dissolution of the overlying Salina Group (*see* discussions in Carter 1991; Bailey Geological Services Ltd. and Cochrane 1985; Sun, Brunton and Jin 2014; Davis 2017).

The units selected to create the local maps and to evaluate structural offsets are the Manitoulin Formation (Figure 28), Cabot Head Formation (Figure 29), Reynales and Fossil Hill formations (Figure 33) and Rochester Formation (Figure 35). Rock units used to assess whether or not the lineaments acted as groundwater and/or deep fluid pathways, include the Gasport Formation (Figure 37), Goat Island Formation (Figure 38), Guelph Formation (Figure 39), Bass Islands Formation (Figure 57) and the salt units of the Salina Group. The Salina Group salt units comprise the A-1 Evaporite Unit (Figure 41), A-2 Salt Unit (Figure 44), B Salt Unit (Figure 48) and F Salt Unit (Figure 54). Lowest elevations are identified close to the head of the St. Clair River at the southern end of Lake Huron. As for deeper units, highest elevations are found at the eastern and western boundaries of the study area, just south of the Kent–Huron domains boundary, aligned with the Algonquin Arch. The Appalachian Basin side of the Algonquin Arch does not show a prominent depression as for Ordovician and Cambrian strata, suggesting minimal basin subsidence during the Silurian.

The other Silurian units were not used for local lineament maps because of poor well coverage or because of uncertain influence from structural movement, salt dissolution and/or karst collapse. These other units comprise the Whirlpool Formation (Figure 27), Grimsby Formation (Figure 30), Thorold Formation (Figure 31), Dyer Bay Formation (Figure 32), Irondequoit Formation (Figure 34) and DeCew Formation (Figure 36). Also the following units of the Salina Group were not found to be useful: A-0 Carbonate Unit (Figure 40), A-1 Carbonate Unit (Figure 42), A-2 Anhydrite Unit (Figure 43), A-2 Shale Unit (Figure 45), A-2 Carbonate Unit (Figure 46), B Anhydrite Unit (Figure 47), B Equivalent Unit (Figure 49), B Unit (Figure 50), C Unit (Figure 51), D Unit (Figure 52), E Unit (Figure 53), F Unit (Figure 55) and G Unit (Figure 56).

Devonian

Devonian units that show the greatest potential for geological interpretation are the Bois Blanc Formation (Figure 60), Amherstburg Formation (Figure 62), Lucas Formation (Figure 63), Dundee Formation (Figure 65), Hamilton Group (Figure 67) and Kettle Point Formation (Figure 68). The last 3 units do subcrop, but interpretations are made only for areas where they do not represent the top of bedrock.

The Devonian units show lowest elevations about halfway along the St. Clair River, south of where it was located for Cambrian, Ordovician and Silurian units. Highest elevations are located on the western and eastern limits of the study area, although the alignment with the Algonquin Arch, as recognized for older units, is not evident. Also, whereas the Cambrian, Ordovician and Silurian strata show elevation differences close to 500 m within the study area, Devonian units shallower than the Amherstburg Formation show a maximum variation of 250 m. This would suggest major structural movements before the Middle Devonian.

Additional significant units are the 3 Devonian sandstones: the Oriskany Formation (*see* Figure 58), the Springvale Member of the Bois Blanc Formation (Figure 59) and the Columbus Formation (Figure 64). Indeed, as suggested by previous authors, these units seem to infill depressions created either by salt dissolution of the Salina Group and karst collapse of the Bass Islands and Bois Blanc formations (Bailey Geological Services Ltd. and Cochrane 1985; Sun, Brunton and Jin 2014; Davis 2017). Since the lineaments may create pathways for fluids responsible for the salt dissolution, the analysis of the extent of those sandstones is valuable.

The only Devonian units that were found not to be useful for this project are the Sylvania Formation (Figure 61), Marcellus Formation (Figure 66) and the Port Lambton Group.

INTERPRETATIONS BY LINEAMENTS

The main goal of this study was to evaluate the usefulness of lineament analysis of aeromagnetic survey data to map structural features in the Paleozoic cover. To achieve this, the OPDS was used to consider elevation variations of the most significant stratigraphic units described above for each lineament. Also, TerraNotes Ltd. lineaments locations were compared to the positions of hydrocarbon pools, salt dissolution features, pinnacles and previously mapped faults. Note: In this report, lettered lineaments representing segments of lineaments (e.g., “HDF5a” and “HDF5bi”) will be referred to as “sublineaments”.

Kent–Huron Domains Boundary

The Kent–Huron domains boundary is a generally west-southwest-trending feature near the middle of the study area. It is somewhat linear, but its width varies from a few hundred metres to just over 10 km wide. Only 2 lineaments (HDF5a and HDF7) seem to crosscut the boundary, whereas other lineaments (HDF1, HDF2, HDF4 and KDF2) terminate on the feature (Figure 69). When compared to previously mapped faults from Armstrong and Carter (2010) and Brigham (1971), only 1 north-trending fault of the Kent Domain seems to end on the boundary feature, whereas other faults, including the Electric and Dawn faults, cross the feature (*see* Figure 69). Numerous hydrocarbon pools have been found along the Kent–Huron domains boundary. Some are found near previously mapped faults and some are aligned, but no clear relationship with the domains boundary can be identified.

Most elevation maps show the same features. Only the maps for the Shadow Lake Formation (Figure 70), Cobourg Formation (Figure 71), Rochester Formation (Figure 72), Guelph Formation (Figure 73) and Dundee Formation (Figure 74) are included in the report. Elevations tend to be the highest at the eastern extremity of the feature, whereas the lowest values are found in the middle, corresponding to the centre of the Chatham Sag. Finally, no pinnacles (*see* Figure 73) or salt dissolution features (*see* Figure 74) seem linked to the Kent–Huron domains boundary.

The Kent–Huron domains boundary is possibly an important Precambrian feature. However, its structural control on the overlying Paleozoic rocks is unclear. Identification of vertical offsets related to the domains boundary is difficult because this is an area with multiple confirmed faults, some of them showing major displacements (e.g., Electric and Dawn faults). The relationship between these faults and the Kent–Huron domains boundary should probably be studied further. Finally, some alignments observed with the hydrocarbon pools (*see* Figure 69) possibly suggest additional faults need to be mapped in the area.

HDF1 Lineament

The HDF1 lineament has a general easterly trend and crosses the entire aeromagnetic survey area. Because of its significant length, this lineament was divided into 3 portions (Figure 75). The western portion is defined as the part west of the intersection with HDF5bi sublineament where it corresponds approximately to the previously mapped Electric Fault. The eastern portion, limited to the west by the HDF4 lineament, is equivalent to the Kent–Huron domains boundary, as mapped by TerraNotes Ltd. The middle portion is the part between the eastern and western portions. The HDF4 and HDF7 lineaments and the HDF2i and HDF5bi sublineaments all terminate on the HDF1 lineament. Numerous hydrocarbon pools are present in this area, but almost none are found aligned with the HDF1 lineament.

The western portion of the HDF1 lineament corresponds approximately to the western extent of the Electric Fault (*see* Figure 75) and trends west. In Cambrian and Ordovician strata, limited well coverage suggests a vertical offset of approximately 40 m, with the southern block being downthrown (Figures 76 and 77). In the Silurian strata below the Salina Group (Figures 78 and 79), similar movement is suggested by very limited data. As for Silurian and Devonian strata above or the Salina Group (Figure 81), a minimal offset of 4 m is identified with lower elevations found on the north side of the lineament. This can probably be explained by some level of salt dissolution north of the fault (Figure 80) after Dundee Formation deposition. Some evaporite units (e.g., B Salt Unit) south of the lineament were probably preserved because they were too deep to be reached and dissolved by shallow groundwaters. This implies some structural movement occurring between the Salina Group deposition and dissolution of its salts.

The middle portion of the HDF1 lineament is the portion between the HDF5bi sublineament and the HDF4 lineament, closely related to the section between the Dawn and Electric faults (*see* Figure 75). It is oriented approximately west-northwest. Wells reaching the Cambrian and Ordovician rocks are all situated on the south side of the middle portion and, therefore, no interpretation can be made for these strata (*see* Figures 76 and 77). No offset related to the middle portion of the HDF1 lineament has been identified in Silurian and Devonian rocks (*see* Figures 78 to 81). Vertical offsets are present, but are more closely related to the presence of the Electric and Dawn faults.

The eastern portion of the HDF1 lineament corresponds to the northern extent of the Kent–Huron domains boundary, east of the HDF4 lineament (*see* Figure 75). For all strata, wells are found on both sides of the lineament. However, as described for the Kent–Huron domains boundary, no elevation variation seems related to the lineament.

The HDF1 lineament crosses the entire study area, but only its western portion can be categorized as a major structure. Indeed, this corresponds to the trajectory of the Electric Fault and limited data suggest a minimal 40 m offset for strata below the Salina Group, with the southern block being downthrown. Structural interpretations for younger units are problematic because of apparent differential salt dissolution on both sides of the lineament.

HDF2 Lineament

The HDF2 lineament is composed of 2 approximately west-trending sublineaments. The HDF2i sublineament is the longest and is mostly equivalent to the Dawn Fault (Figure 82). Its western extremity is defined as the western boundary of the study area, correlative to the St. Clair River and its eastern extremity terminates on the HDF1 lineament and/or the Kent–Huron domains boundary. The HDF2i sublineament also seems to bound the HDF8 lineament to the south. The smaller northern HDF2ii sublineament is subparallel to the HDF2i sublineament and does not cross any other known structures or TerraNotes Ltd. lineament (*see* Figure 82). The HDF2i sublineament is positioned along numerous hydrocarbon pools situated in the Salina Group and the Guelph Formation. Numerous hydrocarbon pools located in the area are aligned along the HDF2i sublineament, whereas no clear relationship can be established with the HDF2ii sublineament.

Distribution of wells reaching Cambrian and Ordovician strata is very uneven on both sides of the HDF2i sublineament, although these limited data do not show any offset associated with the lineament (Figure 83). Silurian units (Figure 84) show better coverage, but identified vertical offsets seem to be more closely related to the presence of the Dawn Fault than to the HDF2i sublineament. The Guelph Formation shows more pinnacles on the north side of the lineament than on the south, although the exact demarcation between those 2 strata is difficult to determine (Figure 85). Also, an A-2 Salt Unit (Salina Group) dissolution front is subparallel to the HDF2i sublineament, but seems to better match the Dawn Fault located to the south (Figure 86). Indeed, it appears that only the salts located to the south of the fault were dissolved by shallow groundwaters, whereas the salts downthrown to the north were preserved.

No interpretations can be made for the Cambrian and Ordovician rocks around the HDF2ii lineament because too few wells reach those strata in this area (*see* Figure 83). Also, no link between elevation variation, presence of pinnacles, salt dissolution and the location of the HDF2ii lineament could be identified (Figures 84 to 87).

The HDF2i sublineament corresponds approximately to the portion of the Dawn Fault north of the Kent–Huron domains boundary. Various geological features (elevation variation, presence of pinnacles, salt dissolution) seem to be related to the HDF2i sublineament, but may better correspond to the track of the Dawn Fault. Because the Dawn Fault and the HDF2i sublineament are subparallel and are closely spaced, it is proposed that the aeromagnetic lineament possibly represents the Precambrian root of the Dawn Fault. There is no indication that the HDF2ii sublineament has influence on the Paleozoic strata.

HDF3 Lineament

The HDF3 lineament was mapped as the boundary between 2 magnetic intensities (Ontario Geological Survey 2014). Its western extent almost reaches the St. Clair River, with an orientation approximately directly east, and it intersects the HDF8 lineament (Figure 88). Its intersection with the HDF4 lineament corresponds to where it crosses the eastern extension of the Kimball–Colinville fault. This is also where the orientation of the HDF3 lineament changes to northeast. Its eastern extent is just north of the Huron Domain circular feature. Some small hydrocarbon pools are found along the HDF3 lineament, but no clear alignment is identified. Almost no reservoirs are identified between the HDF3 and HDF4 lineaments.

Poor well coverage for stratigraphic units deeper than the Rochester Formation prevents any deep structural interpretations (Figure 89). For the Rochester Formation, apparent elevation offsets are observed, but can most likely be explained by the regional northwest-dipping strata (Figure 90). A 40 to 50 m offset is identified along the Kimball–Colinville fault, with the southern block being downthrown. There is no apparent alignment of Guelph Formation pinnacles along the HDF3 lineament (Figure 91). The eastern extent of HDF3 lineament (east of its intersection with the HDF4 lineament) and the Kimball–Colinville fault correspond to the southern extent of the current distribution of the F Salt Unit (Figure 93). This suggests fluid flow along the HDF3 lineament, limiting salt dissolution to the south of the lineament where Paleozoic strata are found at higher elevations (*see* Figures 90 and 91). Fluids responsible for dissolution of the F Salt Unit therefore had a shallow origin. Also, the G Unit of the Salina Group does not show any offset associated with this dissolution front, suggesting the process took place shortly after deposition of the F Salt Unit (Figure 94). The HDF3 lineament represents the approximate northern extent of the Oriskany Formation (Figure 95), the Springvale Member of the Bois Blanc

Formation and possibly the Columbus Formation. This conforms with previous ideas that stated that these sandy units were deposited in depressed areas caused by salt dissolution (Bailey Geological Services Ltd. and Cochrane 1985; Sun, Brunton and Jin 2014; Davis 2017). Finally, the Dundee Formation shows an approximate 20 m offset along the Kimball–Colinville fault, with deeper strata located on the south of the structure (Figure 96). This confirms the likelihood of late structural movement, possibly after the Devonian for the Kimball–Colinville fault. Indeed, movement soon after salt deposition would probably have preserved F Salt Unit strata located south of the fault.

For strata with adequate well coverage, most geological features suggest the HDF3 lineament has no key control on overlying Paleozoic strata. Indeed, all major vertical offsets around the TerraNotes Ltd. lineament are associated with the Kimball–Colinville fault. However, because the F Salt Unit dissolution front corresponds to the eastern part of the HDF3 lineament, the lineament may have created a shallow brittle pathway for dissolving fluids.

HDF4 Lineament

The HDF4 lineament is subparallel to the HDF2 lineament and the Dawn Fault (*see* Figure 88). It extends from the HDF3 lineament to the Kent–Huron domains boundary (equivalent to the HDF1 lineament). The HDF4 lineament trends approximately northwest, correlating with the eastern extension of the Kimball–Colinville fault (*see* Figure 88). Some hydrocarbon pools are found along the HDF4 lineament, although no clear correlation can be identified.

Along most of the lineament, there are too few wells reaching Cambrian and Ordovician strata to interpret movement, except where the HDF4 lineament intersects the Kimball–Colinville fault eastern extension (*see* Figure 89). The elevation values possibly suggest a 20 m offset, with the north side being downthrown. Looking at the same area for the Rochester Formation, highly varied elevation values are observed, and no clear trend is identified relative to the HDF4 lineament. Also, the lineament goes through multiple pinnacles of the Guelph Formation, but additional structures are found in the area with no apparent relationship to TerraNotes Ltd. lineaments or previously mapped faults (*see* Figure 91). There is a clear alignment of lower elevations of the G Unit of the Salina Group along the HDF4 lineament, which also extends northwest (*see* Figure 94). This corresponds to the location of the eastern extension of the Kimball–Colinville fault. These lower elevations are also observed for most Devonian units and probably associated with dissolution within the B Salt Unit (Figures 92, 94 and 96).

No evident vertical offset is identified along the HDF4 lineament for all strata below the Salina Group. However, elevations of the Salina Group and overlying units show an alignment of lower values along the lineament, probably associated with dissolution in the B Salt Unit (*see* Figure 92). The scale of the offset generally decreases with upward stratigraphy. For example, 60 m offsets are prevalent in the G Unit (Salina Group), whereas only a few (shorter) 40 m offsets are seen for the Dundee Formation, suggesting some dissolution before and after deposition of the Dundee Formation. These offsets are only found in the western half of the HDF4 lineament where it correlates with the eastern extension of the Kimball–Colinville fault.

HDF5 Lineament

The HDF5 lineament is represented by 4 lineaments (Figure 97). TerraNotes Ltd. suggested that the HDF5 lineament represents a second-order fault of the Electric Fault and that it was possibly offset by the HDF7 lineament (Ontario Geological Survey 2014). Indeed, the HDF5a and HDF5bi sublineaments correspond generally to the path of the Electric Fault.

The east-trending HDF5a sublineament has extremities defined by the HDF7 lineament and the southern border of the Kent–Huron domains boundary. The curved HDF5bi sublineament is located between the HDF1 and HDF7 lineaments, subparallel to the Electric Fault. West of its intersection with the HDF5bii sublineament, the HDF5bi sublineament matches the northern edge of the Kent–Huron domains boundary. The HDF5bii sublineament corresponds to the northern border of the Kent–Huron domains boundary zone, from the St. Clair River to its intersection with the HDF5bi sublineament. The HDF5biii sublineament is located west of the HDF5bii sublineament, and is limited to the north by the HDF5bi sublineament and to the south by the Kent–Huron domains boundary, equivalent to the HDF5bii sublineament. Few hydrocarbon pools are found only along the HDF5a sublineament.

Limited data do not show any offset related to the HDF5a sublineament (Figures 98 to 104). However, major elevation variations are observed along the Electric Fault, located just north of the HDF5a sublineament, and indicate that the south block was downthrown.

For the HDF5bi sublineament, the Shadow Lake Formation shows a 24 m offset, with the north side found at lower elevations (*see* Figure 98). This is also observed for all other strata situated below the Salina Group (*see* Figures 99 to 102). For units above the Salina Group, variations in elevation do not show a constant direction of offset, probably explained by salt dissolution (*see* Figure 103). For the shallowest units, elevation variations are almost indistinguishable (*see* Figure 104).

Well coverage around the HDF5bii sublineament is too limited for offset interpretation. Indeed, no wells are located on the east side of the lineament, except some wells surrounding previously mapped faults. For the HDF5biii sublineament, too few wells reach Cambrian and Ordovician strata. Also, the few wells located in the area do not show any variations in elevation.

In conclusion, the Electric Fault relates to the HDF5 lineament, especially to the HDF5a and the HDF5bi sublineaments, both of which are offset by the HDF7 lineament, although this offset is not recognized for the Electric Fault.

HDF6 Lineament

The HDF6 lineament is a relatively short lineament with a west-northwest strike. It is located just south of the block faulting feature identified by TerraNotes Ltd. in the northeast corner of the study area (Figure 105). No faults nor hydrocarbon pools have been previously identified around those features.

No offset interpretations can be made for strata below the Rochester Formation because of poor deep well coverage (Figure 106). Shallower units do not show any offset associated the HDF6 lineament (Figures 107 to 110). Furthermore, the eastern end of the lineament corresponds to the eastern end of the F Salt Unit subcrop area, suggesting the lineament did not allow groundwater flow (*see* Figure 109). Finally, there is no indication that the HDF6 lineament has any influence on the Paleozoic strata.

HDF7 Lineament

The north-northwest-trending HDF7 lineament is bound on the north by the HDF1 lineament and on the south by the southern extent of the Kent–Huron domains boundary (*see* Figure 97). TerraNotes Ltd. suggested that it crosscuts and offsets the HDF5 lineament equivalent to the Electric Fault in this area (Ontario Geological Survey 2014). There is no obvious alignment of hydrocarbon zones along the lineament.

Very limited data for Cambrian and Ordovician rocks suggest a possible slight offset of 11 m, with the eastern block being downthrown (*see* Figures 98 and 99). However, the top of the Queenston Formation and other overlying units do not show any clear offset associated with the HDF7 lineament (*see* Figures 100 to 103). For the Dundee Formation (*see* Figure 104), the western block seems to be downthrown by at least 10 m, reaching 30 m in some places in the southern half of the lineament.

The HDF7 lineament is surrounded by multiple major structural features, such as the HDF1 and HDF5 lineaments, and crosses the entire Kent–Huron domains boundary. Also, hydrocarbon pools located in the Salina Group–Guelph Formation interval have been identified, but no clear alignment parallel to the HDF7 lineament is observed. Therefore, the HDF7 lineament probably offsets Paleozoic strata; however, it is difficult to characterize vertical movements related solely to the HDF7 lineament because numerous other structures are found in its vicinity.

HDF8 Lineament

The HDF8 lineament is a generally north-trending, semi-circular feature, subparallel to the St. Clair River. It is limited to the south by the HDF2i sublineament (Dawn Fault equivalent) and its northern extent is located between the Kimball–Colinville fault and the HDF3 lineament (Figure 111). Many hydrocarbon pools are found throughout the area, although a clear alignment with the HDF8 lineament is undistinguishable. However, numerous reservoirs are present near the intersection of the HDF8 lineament and the Dawn Fault (equivalent to the HDF2i sublineament).

No offset interpretations can be made for strata deeper than the Rochester Formation because of poor well coverage (Figure 112). For the Rochester Formation, local dip seems to explain all elevation variations (Figure 113). For all overlying units, offsets are observed, but seem explained either by local dip or by the presence of pinnacles, which do not seem aligned with the HDF8 lineament (Figures 114 to 116). The HDF8 lineament does not seem to have any major influence on the Paleozoic cover.

Huron Domain Circular Feature

The circular feature identified by TerraNotes Ltd. in the Huron Domain is located between the HDF3 and HDF4 lineaments in the eastern extent of the study area (*see* Figure 88). The diameter varies between 10 and 12 km. No hydrocarbon pools are found within the feature, although numerous small-scale reservoirs have been identified just to the north.

Because only 2 wells around the Huron Domain circular feature reach strata deeper than the Rochester Formation, no interpretation can be made for Cambrian and Ordovician units (*see* Figure 89). For the Rochester Formation, elevation variations are related to local northwest-oriented dip (*see* Figure 90). For younger units, including the Guelph Formation (*see* Figure 91), the G Unit of the Salina Group (*see* Figure 94) and the Dundee Formation (*see* Figure 96), some elevation offsets are observed, but none seem associated with the circular feature. Therefore, the Huron Domain circular feature is not thought to have impacted Paleozoic sedimentation and/or structures.

Can-Am Circular Feature

The Can-Am circular feature is in the northernmost region of the study area and has a maximum diameter of about 45 km (*see* Figure 105). It was initially recognized on magnetic and gravity maps by Forsyth et al. (1990). Although never proven, the authors suggested an impact origin for this structure. TerraNotes Ltd.

subsequently used the term “Can-Am Impact structure” (Ontario Geological Survey 2014); however, this term will not be used in this report. The aeromagnetic survey does not fully extend to the estimated outer limit of the feature. Also, most of the structure is in Lake Huron, where no geological data from oil and gas drilling are available and the middle of the feature intersects with the border between Canada and the United States. Therefore, interpretations for this structure are challenging.

The feature does not intersect any other previously mapped Precambrian nor Paleozoic structures. Hydrocarbon pools are present in the area, but no clear link to the Can-Am circular feature can be identified. The deepest elevations of the vast majority of stratigraphic units below the Salina Group are found within the Can-Am circular feature (*see* Figures 16 to 54). For shallower units, this depocentre is found along the St. Clair River, south of the Can-Am circular feature.

Poor well coverage, including strata below the Rochester Formation, makes it impossible to identify offset around the Can-Am circular feature (*see* Figure 106). Data from available wells do show that strata dip toward the Michigan Basin depocentre located to the northwest. Elevation values from the Rochester Formation to the Salina Group (*see* Figures 107 to 109) show similar dip orientation and do not suggest offsets associated with vertical movements. For the Guelph Formation, up to 100 m scale pinnacles are aligned in the southeast of the structure (*see* Figure 108). Elevation maps from units overlying the Salina Group do not indicate any influence from the Can-Am circular feature (*see* Figure 110).

Finally, because the Can-Am circular feature is under Lake Huron where no geological information is available from oil and gas drilling and that half the structure is situated on the American side, interpretations about its influence on Paleozoic sedimentation is difficult. Also, the various interpretations made from oil and gas wells located in Ontario do not suggest any influence on Paleozoic strata.

Block Faulting Feature

TerraNotes Ltd. identified a group of 3 subparallel lineaments in the northeast corner of the study area, which were thought to be related to block faulting (*see* Figure 105; Ontario Geological Survey 2014). The lineaments are oriented approximately north and north-northwest and are limited by the HDF6 lineament in the south. No other structure nor hydrocarbon pool has been previously identified in this area.

The few wells reaching Ordovician strata suggest northwestern dipping strata (*see* Figure 106). Additional wells intersecting Silurian and Devonian strata show similar dip orientation, with no offset suggesting faulting (*see* Figures 107 to 110). There are some Guelph Formation pinnacles identified, but with no apparent relationship to the block faulting feature (*see* Figure 108).

Elevation values of most strata do not support Paleozoic vertical movements for the block faulting feature identified in the Huron Domain by TerraNotes Ltd.

KDF1 Lineament

The KDF1 lineament is the westernmost lineament of the Kent Domain identified by TerraNotes Ltd. (Figure 117; Ontario Geological Survey 2014). It trends approximately north-northeast and is subparallel to and terminates on the KDF2 lineament. Its southern extent is the study area boundary and about half of its length is located offshore. Also, it represents the easterly extent of 2 previously mapped faults, including the Dover fault. No clear alignment of hydrocarbon reservoirs is observed along the KDF1 lineament, but the feature intersects the Silurian Tilbury gas pool.

All Paleozoic rocks deeper than the Salina Group show elevation variations probably related to northeast- (centre of the Chatham Sag) and southwest- (Appalachian Basin) dipping strata and have no clear offset associated with the KDF1 lineament (Figures 118 to 121). The Salina Group and overlying units still show a general deepening of units toward the northeast and southwest, with some anomalously low elevations in a few wells (Figure 122). This is probably attributed to some salt dissolution of the Salina Group.

The KDF1 lineament does not seem to have direct influence on the Paleozoic strata. However, after examining its relationship with previously mapped fault, it may influence the extent of Paleozoic structures.

KDF2 Lineament

The KDF2 lineament trends generally north-northeast and terminates at the Kent–Huron domains boundary (*see* Figure 117). It corresponds to the western extent of the Kent Domain circular feature. Half of its length is located offshore and probably extends beyond the aeromagnetic survey outline. A previously mapped easterly fault located to the west terminates on the KDF2 lineament. Also, some Silurian gas pools are found along the lineament.

Elevation values obtained from the few wells reaching Ordovician and Cambrian strata suggest variations resulting from the regional dip toward the southeast, but have no fault offset (*see* Figures 118 and 119). Similar interpretations are drawn from the Rochester Formation, whereas the Guelph Formation seems to be dipping toward the east (*see* Figures 120 and 121). Around the KDF2 lineament, the Dundee Formation seems to be dipping slightly toward the southeast and northeast, although the elevation variations are probably related to salt dissolution (*see* Figure 122).

The KDF2 lineament does not have a clear influence on Paleozoic strata. However, it corresponds to the western extent of a previously mapped fault on land.

KDF3 Lineament

The KDF3 lineament was mapped as a distinct contrast between low and high magnetism by TerraNotes Ltd. (Ontario Geological Survey 2014). It was also suggested that it may represent the edge of some block faulting. The northeast-trending lineament is located onshore and terminates in the Devonian Rodney oil pool (Figure 123). It also closely corresponds to the northern extent of 2 previously mapped faults, including the Clearville fault.

Well coverage around the KDF3 lineament is poor for all Paleozoic strata. Some vertical offsets are observed, but are more closely related to the previously mapped faults in the area than to the TerraNotes Ltd. lineament (Figures 124 to 127).

KDF4 Lineament

The northeast-trending KDF4 lineament measures over 60 km long and intersects the southwest corner of the study area (*see* Figure 117). It is located entirely offshore and does not intersect any known hydrocarbon pool. The KDF3 lineament corresponds to the eastern extent of the Kent Domain circular feature, and to the western extent of a previously mapped fault.

The few wells drilled in the vicinity of the KDF3 lineament do not show any important vertical offset and, therefore, suggest that the feature did not have any major influence on Paleozoic rocks.

KDF5 Lineament

The approximately north-trending KDF5 lineament is located entirely offshore under Lake Erie between the KDF4 and KDF6 lineaments and extends south of the study area (Figure 128). The lineament does not cross any other structural feature nor hydrocarbon pool.

Very few wells were drilled around the KDF5 lineament and none indicate the presence of vertical movements during or after Paleozoic deposition (Figures 129 to 133).

KDF6 Lineament

The KDF6 lineament is located entirely offshore under Lake Erie, in the south of the study area between the KDF5 lineament and the Z-folding feature (*see* Figure 128). It trends approximately north-northeast and probably extends farther south under Lake Erie. It crosses the Silurian Morpeth gas pool and the subparallel fault associated with this reservoir. This fault shows the southern block being downthrown.

Poor well coverage limits interpretations for deeper strata, but, for shallower Paleozoic units, no vertical offset associated with the KDF6 lineament has been identified (*see* Figures 129 to 133).

Kent Domain Circular Feature

The 20 km diameter circular feature in the Kent Domain is located along the Lake Erie shoreline between the KDF2 and KDF4 lineaments (*see* Figure 117). Also, a previously mapped northwestern fault terminates where the KDF4 lineament and the Kent Domain circular feature intersect.

No elevation values from wells in the area surrounding the Kent Domain circular feature suggest that Paleozoic strata were influenced by the feature identified by TerraNotes Ltd. (*see* Figures 118 to 122). They do not show major vertical offsets, nor higher nor lower elevation values, within the Precambrian structure.

Z-Folding Feature

TerraNotes Ltd. identified some Z folding in the Precambrian basement in the southeast corner of the study area, offshore, under Lake Erie (*see* Figure 128; Ontario Geological Survey 2014). No hydrocarbon pools seem to be associated with the feature. However, 2 previously mapped easterly faults, located on each side of the Z-folding feature, terminate on the TerraNotes Ltd. lineament.

Based on elevation, the Z-folding feature does not seem to be associated with vertical offsets (*see* Figures 129 to 133). However, interpretation is based solely on shallow units because only 1 well intersects strata deeper than Silurian strata.

Discussion

The main goal of this project is to evaluate the utility of the aeromagnetic survey lineament study to map Paleozoic structures (tectophases). To accomplish this, the possible association between Precambrian lineaments (structures, domain boundaries) identified by TerraNotes Ltd. on the Chatham Sag aeromagnetic survey and the overlying Paleozoic strata was examined, as discussed in the previous section. TerraNotes Ltd. features can be categorized into 3 groups: Precambrian lineaments that correspond to Paleozoic faults, lineaments associated with Paleozoic features (other than faults) and those with no apparent association with the Paleozoic cover (Figure 15).

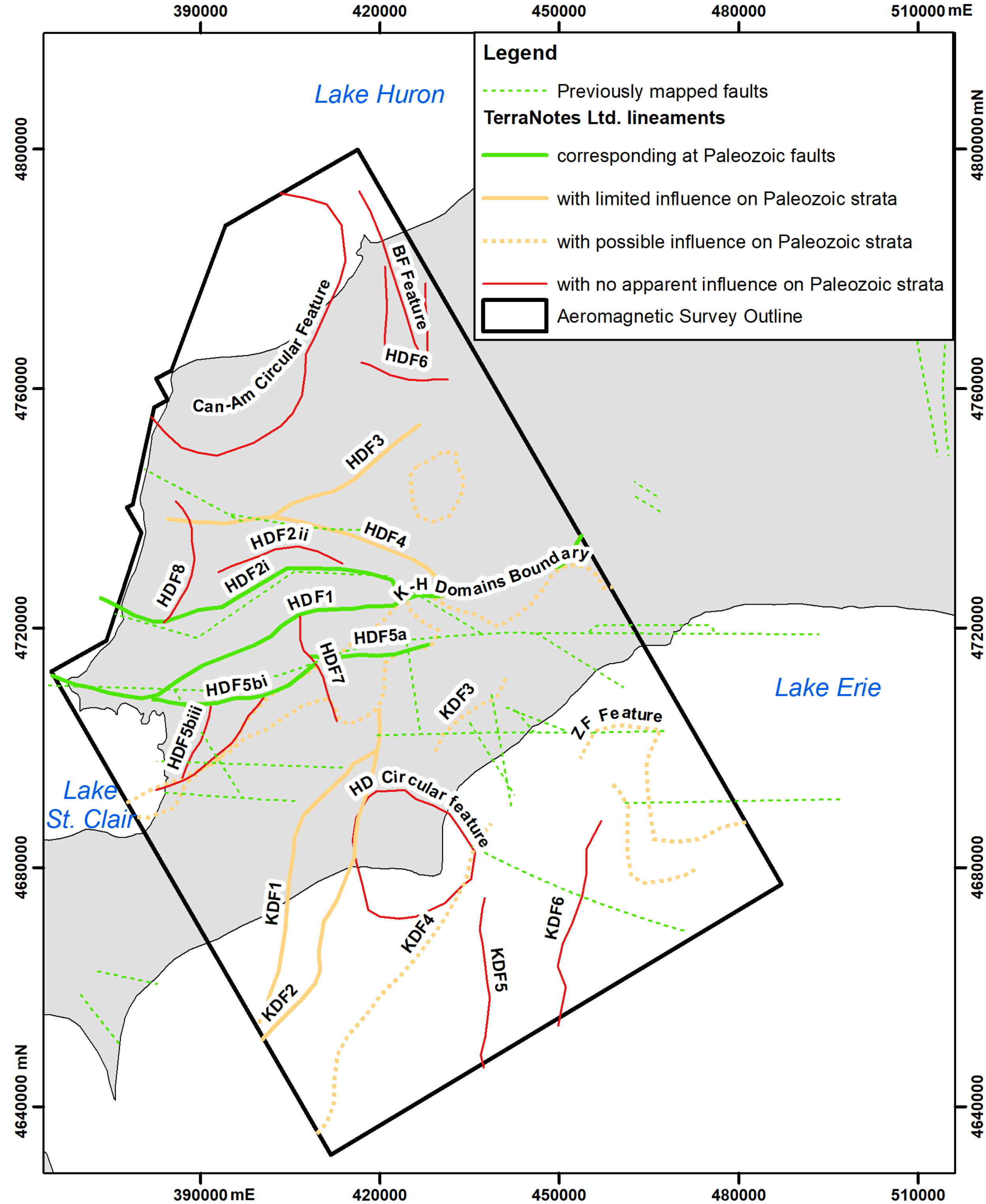

Figure 15. Previously mapped faults and TerraNotes Ltd. lineaments categorized by their apparent influence on Paleozoic strata (Armstrong and Dodge 2007; Armstrong and Carter 2010; Brigham 1971; Ontario Geological Survey 2009, 2014). Abbreviations: BF, block faulting feature; ZF, Z-folding feature; HD, Huron Domain; KD, Kent Domain; K-H, Kent–Huron.

The TerraNotes Ltd. features classified as probable faults include the western portion of the HDF1 lineament and the HDF2i, HDF5a and HDF5bi sublineaments. All these structures correspond to some sections of the Electric or Dawn faults and no new Paleozoic faults from the TerraNotes Ltd. lineament study have therefore been recognized.

For some lineaments identified from the TerraNotes Ltd. lineament study, no clear associated vertical offset is obvious, although they appear related to some Paleozoic features. These lineaments include the HDF3, HDF4, KDF1, KDF2 lineaments and possibly the Kent–Huron domains boundary, the KDF3 and KDF4 lineaments, the Kent Domain circular feature and the Z-folding feature. All those features, except the Kent–Huron domains boundary, do not correspond to previously mapped Paleozoic structures. Some are related to the salt dissolution front location and/or the karst formation and collapse alignment. These lineaments may possibly represent a strike–slip movement that does not show vertical displacement, or they could simply create a fracture network allowing groundwater flow. Furthermore, some lineaments in this category seem to constrain the extent of Paleozoic faults. Indeed, some Kent Domain lineaments are found at the extremities of previously mapped Paleozoic faults.

For most of the TerraNotes Ltd. lineaments, there is no apparent relationship with the overlying Paleozoic strata. For the majority of lineaments, surrounding well coverage, especially for deeper strata, is poor, preventing reliable interpretations. Also, by looking at elevation variations from oil and gas geological picks, only vertical displacements are identified, whereas strike–slip movements are not distinguished. Therefore, even for TerraNotes Ltd. lineaments with no apparent influence on Paleozoic strata, some undetected movement may have occurred.

UTILITY OF LINEAMENT ANALYSIS

The benefits of the TerraNotes Ltd. lineament analysis are evaluated for the Chatham Sag area (*see* "Chatham Sag Lineament Analysis"). Then, the value of similar work done on recently gathered or future aeromagnetic surveys in southern Ontario is discussed (*see* "Potential New Lineament Analyses").

Chatham Sag Lineament Analysis

As described in previous sections of this report, the Chatham area TerraNotes Ltd. lineament analysis did identify a few structures influencing the Paleozoic cover above, although most of those were previously mapped structures or subparallel to those structures. Although no new structures with clear vertical offsets were found, there are still newly identified possible secondary structures influencing Paleozoic fault extent, salt dissolution, karst formation and collapse.

The current lineament analysis, although performed on a recent high-resolution aeromagnetic survey, did not modify greatly previous interpretations for the Precambrian basement in the Chatham Sag area. Boyce and Morris (2002) already performed a lineament analysis of southern Ontario based on a previous data set, which included both aeromagnetic and gravity survey data (Gupta 1991a, 1991b). General lineament orientations identified by TerraNotes (Ontario Geological Survey 2014) agree with interpretations by Boyce and Morris (2002), although exact positioning may be slightly offset (*see* Figure 11).

The easterly trending group of faults that comprises the Dover fault is an important conduit for deep hydrothermal fluids (Colquhoun and Johnston 2004). These fluids originate from the basal Cambrian sandstones and/or the Proterozoic crystalline basement rocks and migrate upward through faults to dolomitize Ordovician carbonates producing secondary porosity and, consequently, create potential hydrocarbon reservoirs (Davies and Smith 2006). It has been proposed that the faults associated with such reservoirs have a strike–slip movement, but, unfortunately, they would not be identified on an aeromagnetic survey (Davies and Smith 2006; Colquhoun and Johnston 2004).

One main enhancement from the Chatham area aeromagnetic survey and its associated lineament study is a better definition of the Kent–Huron domains boundary position. This important structure delineates 2 domains with different lithologies, magnetic signatures and structural features (Easton and Carter 1995; Ontario Geological Survey 2014). Indeed, the Huron and Kent domains have distinct Precambrian lineament orientations, but also relationships with previously mapped Paleozoic faults (*see* Figure 9). In the Huron Domain, Paleozoic faults are generally subparallel to the Precambrian lineaments, whereas in the Kent Domain, they seem controlled by the Precambrian features. Indeed, at least 1 extremity of all the Paleozoic faults over the Kent Domain ends at the intersection with a TerraNotes Ltd. lineament. Moreover, fewer Paleozoic faults reach the Precambrian basement in the Kent Domain than in the Huron Domain (*see* Figure 9). This possibly suggests that these Paleozoic faults, located in the southern portion of the study area, may have been influenced by a different stress regime, possibly the Appalachian Orogen and the opening of the Iapetus Ocean.

Potential New Lineament Analyses

The TerraNotes Ltd. lineament study did not provide new or different interpretations for the Chatham Sag area. However, this does not necessarily support the idea that lineament analyses are of little or no use. Indeed, the Chatham Sag area has had a long history of hydrocarbon exploration and, hence, a large geological data set is available. For other Paleozoic-covered areas with much poorer well coverage, an aeromagnetic survey and an associated lineament analysis may be valuable.

For example, in the Huron Domain, the locations and orientations of major structures, such as the Electric and Dawn faults, correspond generally with lineaments identified by TerraNotes Ltd. It is expected that in other areas in southern Ontario, especially those with thinner Paleozoic cover, a link exists between deep Precambrian structures and shallower faults. However, since not all lineaments align with Paleozoic faults, the main task would be to identify which ones do align by examining and comparing other geological information available for the area surrounding each lineament. For example, this could include any geological maps, geology intersected in any nearby wells and seismic data. If only limited or no geological information is available for an area, additional work should be carried out. Such additional work could involve, for example, running local seismic lines and/or drilling wells on each side of a lineament.

It is important to mention that strike–slip faults, which are associated with important hydrocarbon hydrothermal dolomite reservoirs in southwestern Ontario, cannot be recognized by an aeromagnetic lineament analysis. These structures are best identified with seismic surveys because usually they terminate vertically into a flower structure (Davies and Smith 2006; Colquhoun and Johnston 2004).

Conclusions

The Chatham Sag area is a region with a long history of hydrocarbon exploration and a resultant extensive oil and/or gas well coverage. This area represents the thickest Paleozoic succession of sedimentary strata preserved in southern Ontario. It is underlain by Proterozoic Grenvillian crystalline basement rocks.

An aeromagnetic survey was flown over this region in 2009 and a lineament analysis was subsequently contracted to TerraNotes Ltd. in 2014 (Ontario Geological Survey 2009, 2014). Because Paleozoic sedimentary rocks are non-magnetic, they appear transparent on magnetic surveys. Therefore, the aeromagnetic survey only portrays the magnetic fabric of the Precambrian terrains of the Grenville Province.

The main objective of this study was to evaluate the utility of lineament analysis of the aeromagnetic survey data to identify and map structures in the overlying Paleozoic strata. The relevance of lineament analysis to map Precambrian basement was not evaluated as part of this project. To achieve this, elevation variations from geological picks from the Ontario Petroleum Data System (OPDS) were examined. Also examined were regional maps covering the entire study area and local maps focussing on single or small groups of lineaments.

It was found that some stratigraphic units were more useful than others to map Paleozoic structures. Criteria used to select stratigraphic units included their extent in the study area, the depth of the units (how close they are to the Precambrian basement), the number of wells reaching those depths and the quality and consistency of its formational picks. In theory, vertical offsets related to Precambrian structures are more likely to be observed in deeper units of the Paleozoic succession than for the youngest and shallowest units. Cambrian and Ordovician strata were, therefore, the initial focus of this study. However, in some areas, only a few wells reach those deeper strata, making it near impossible to identify any vertical offsets. Then again, shallow units sitting stratigraphically above the Silurian Lockport Group can show variations in elevations because of karst formation and collapse, as well as salt dissolution. Therefore, for this project, interpretations were based on offsets observed for the entire Paleozoic succession.

For the Huron Domain, most of the previously mapped faults are closely related to the lineaments identified by TerraNotes Ltd., although no new faults were identified (Armstrong and Carter 2010; Brigham 1971; Ontario Geological Survey 2014). Faults and lineaments tend to be subparallel with a general eastern trend. However, some TerraNotes Ltd. lineaments not associated with previously mapped faults are closely associated with salt dissolution and/or karst development and collapse, suggesting the lineaments possibly create a brittle weaker zone in the Paleozoic succession, allowing shallow fluid flow.

In the Kent Domain, orientation of Paleozoic faults does not correspond with the lineaments identified by TerraNotes Ltd., but the extent of Paleozoic structures appears to be controlled by the tectonic fabric of the underlying Proterozoic Grenvillian crystalline basement rocks. In fact, at least 1 extremity of all mapped Paleozoic faults is located at an intersection with a Precambrian lineament. Salt dissolution and karst location seem better related to the position and orientation of Paleozoic faults than to those of Precambrian lineaments. Also, in areas where little or no geological information is available, a lineament analysis represents a low-cost exploration option, especially if a high-resolution aeromagnetic survey is already available. To determine which lineaments affect Paleozoic strata, additional geological work would be required.

Recommendations

During the course of this study, a multitude of stratigraphic and structural issues arose and could not be resolved because of time constraints and data gaps. Below is a list of recommendations for future studies. Some of these studies are already planned as part of a multi-phase approach associated with the development of the first 3-D Paleozoic bedrock model (Brunton et al. 2017; Carter et al. 2019).

- Create a new fault map for the Paleozoic rocks of southern Ontario based on the updated OPDS and bedrock map layers. This study should include any publicly available 2-D and 3-D seismic lines.
- Evaluate the utility of a lineament analysis to map the Precambrian basement.
- Interpret the relative ages of various Paleozoic events (faulting, salt dissolution and/or karst formation and collapse, etc.) for southern Ontario based on the updated OPDS. A few previous studies cover some aspects, but a compilation of different events and their chronology should be considered now that the OPDS has been updated.

- Determine the relationship between Precambrian lineaments and Paleozoic faults of different orientations within the various Precambrian domains.
- Establish if there is a relationship between deep features (e.g., the Kent–Huron domains boundary, the Midcontinent Rift) and the actual position of Paleozoic regional structures (e.g., Chatham Sag, Algonquin Arch, Findlay Arch).

Acknowledgments

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Appendix 1.

Regional Elevation Maps

This appendix contains elevation dot maps for the entire study area.

Size of symbols (dots) reflects the QA code (*see* Figure 13).

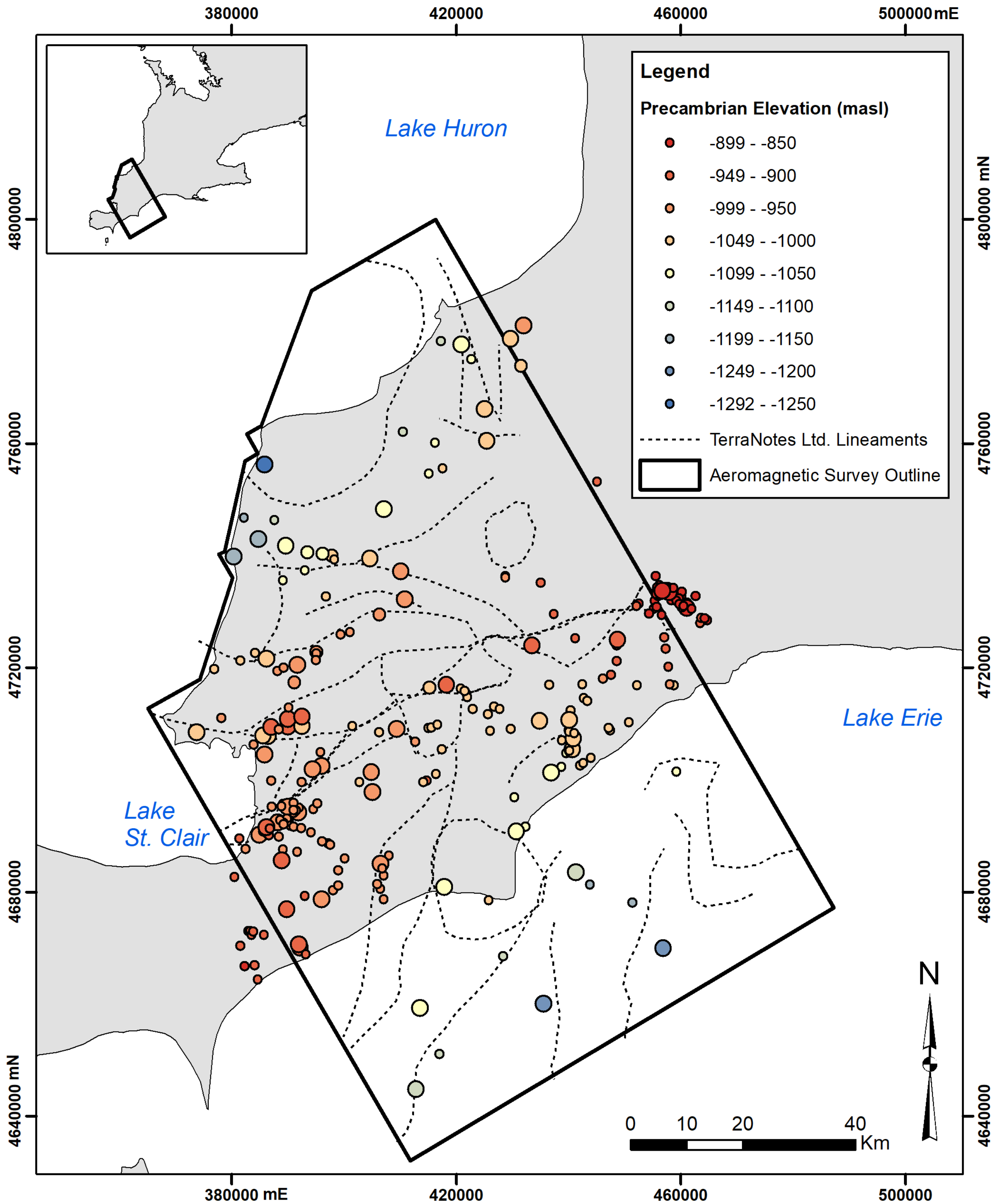

Figure 16. Precambrian basement elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

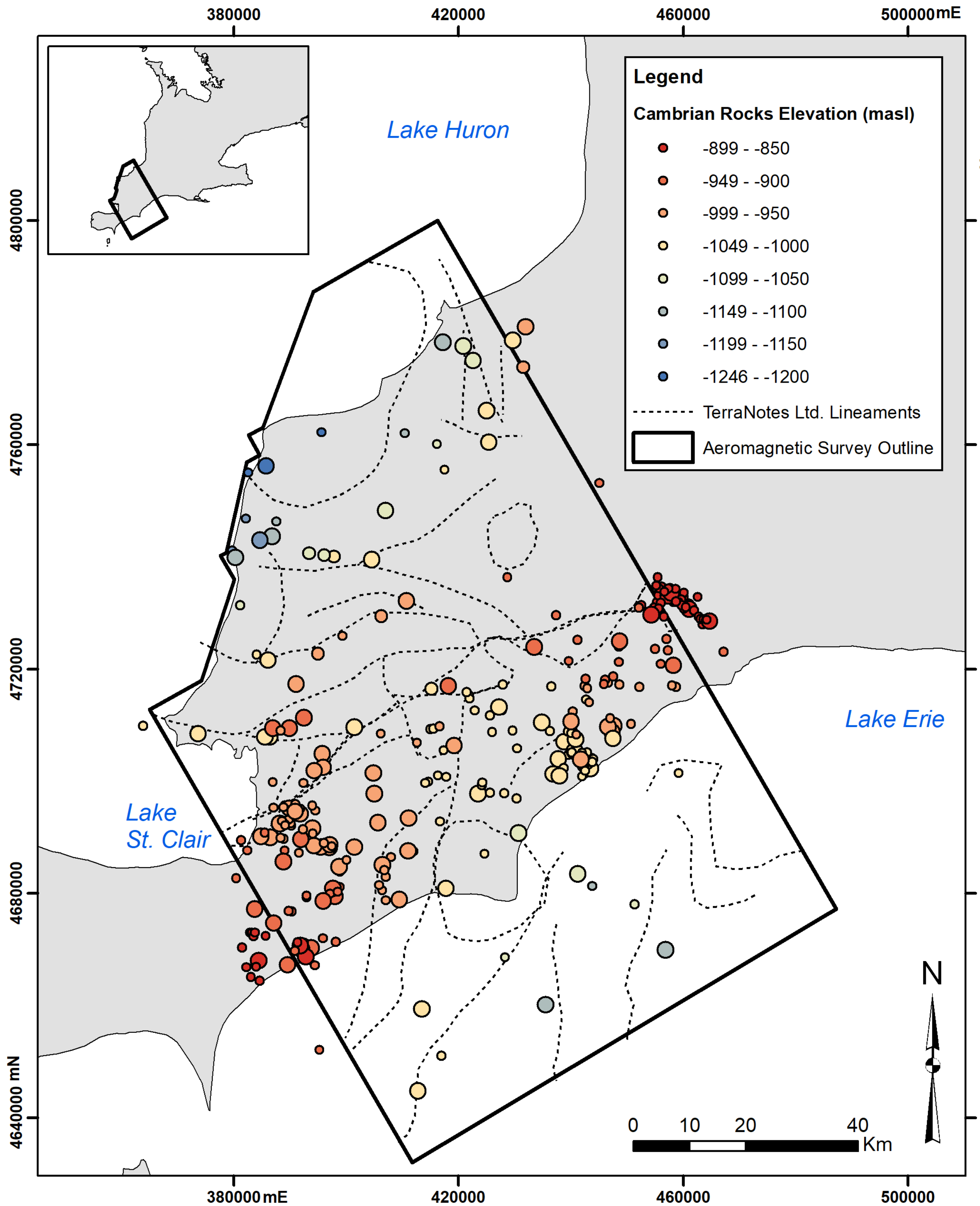

Figure 17. Cambrian rocks elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

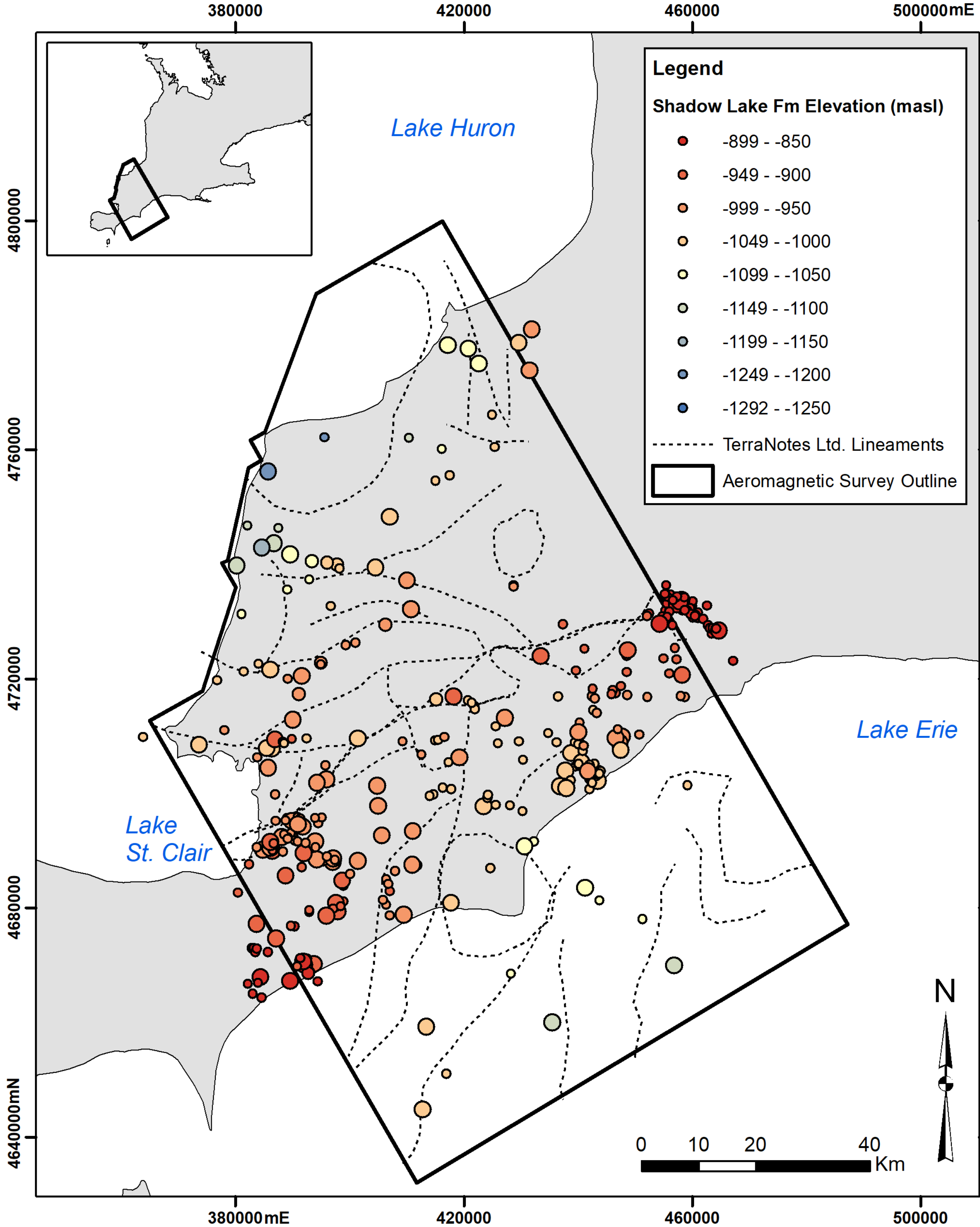

Figure 18. Shadow Lake Formation (Black River Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

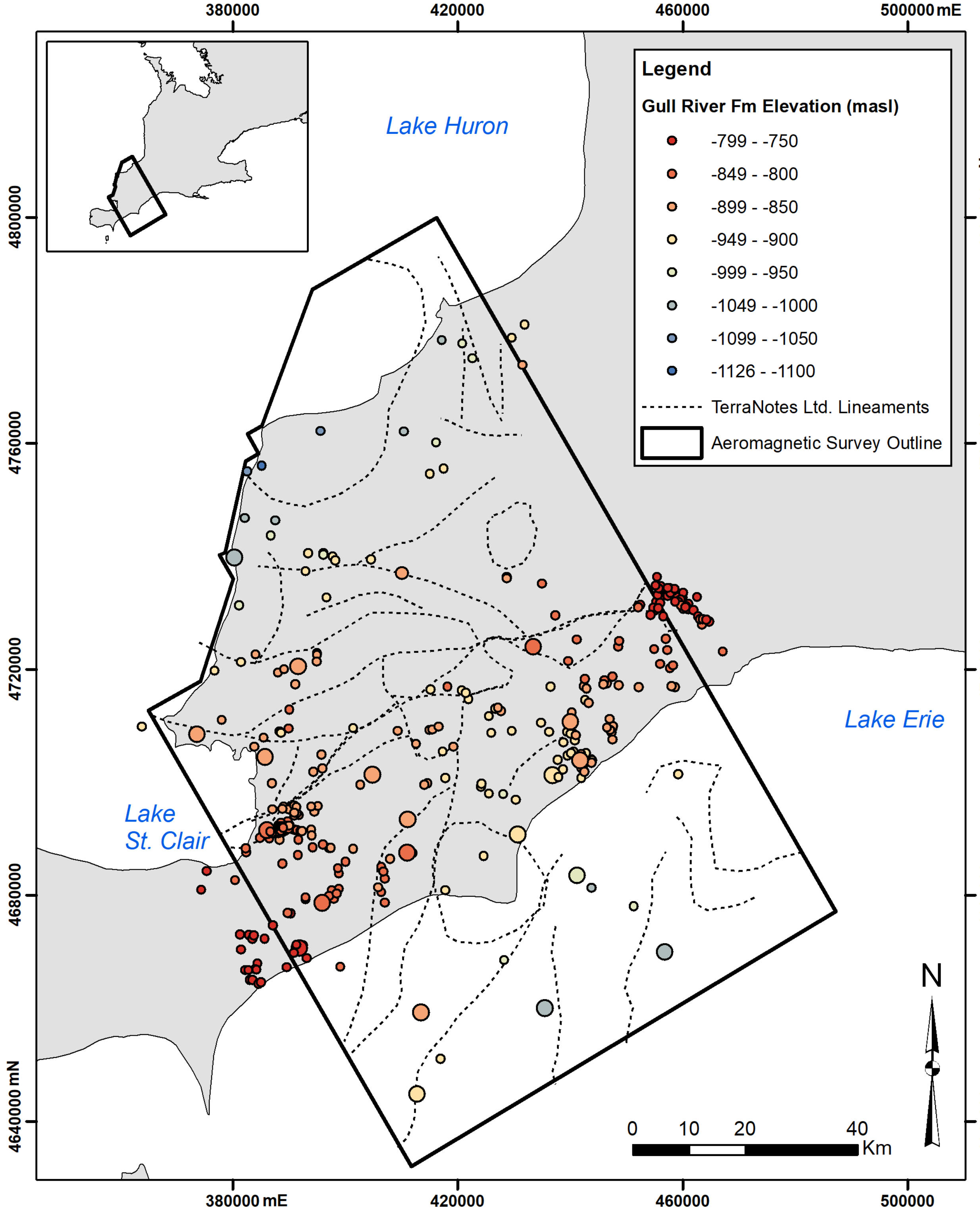

Figure 19. Gull River Formation (Black River Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

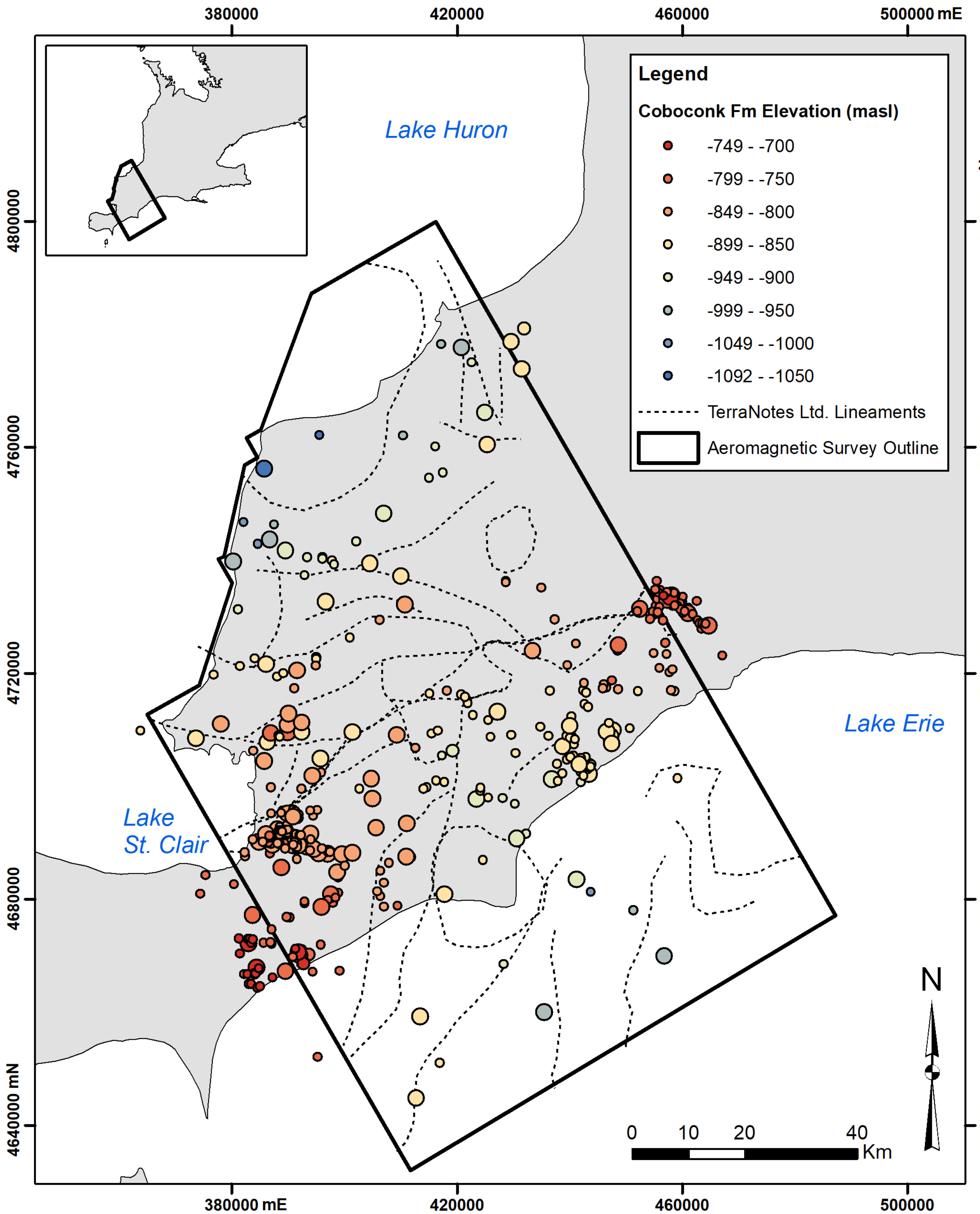

Figure 20. Coboconk Formation (Black River Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

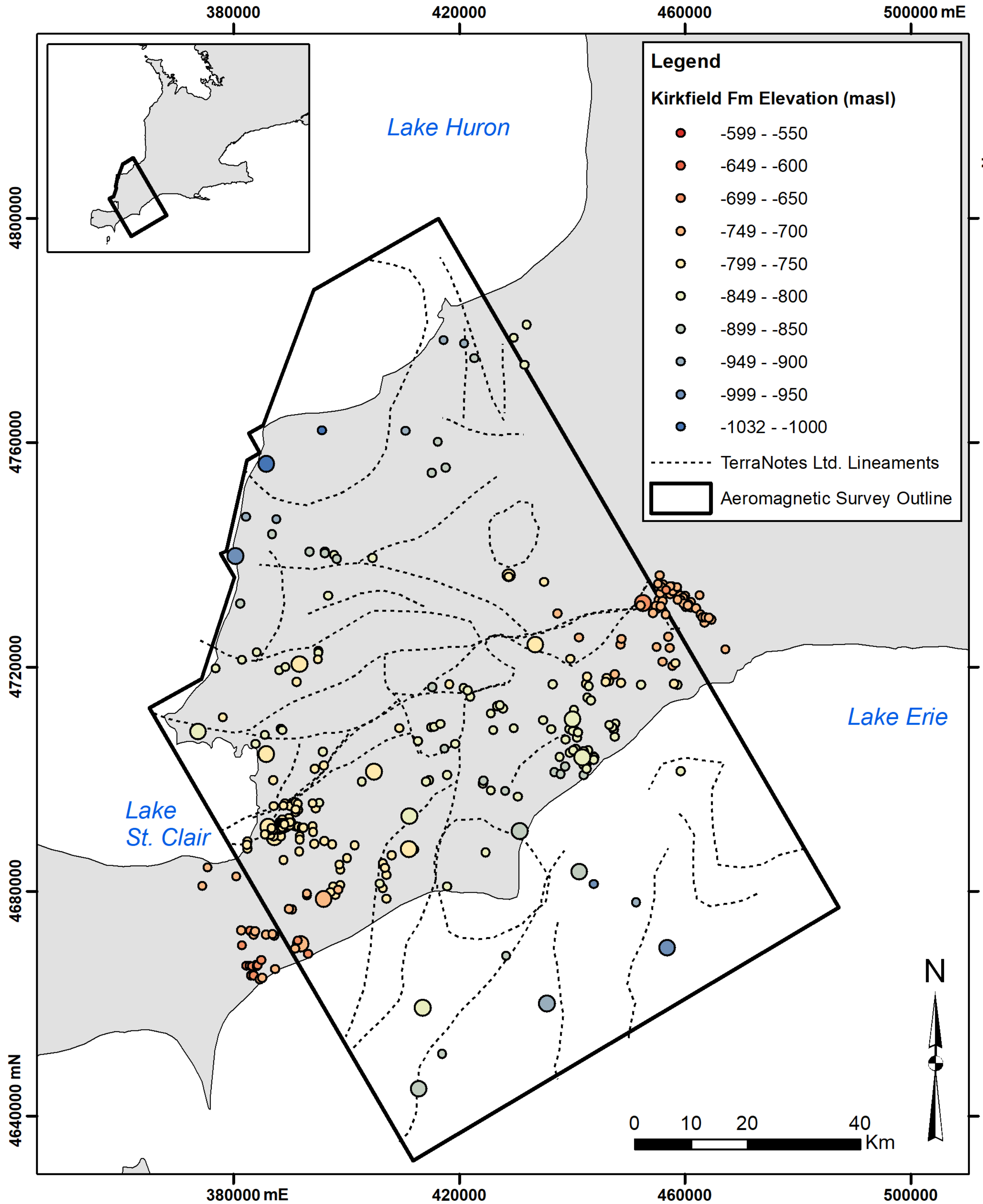

Figure 21. Kirkfield Formation (Trenton Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

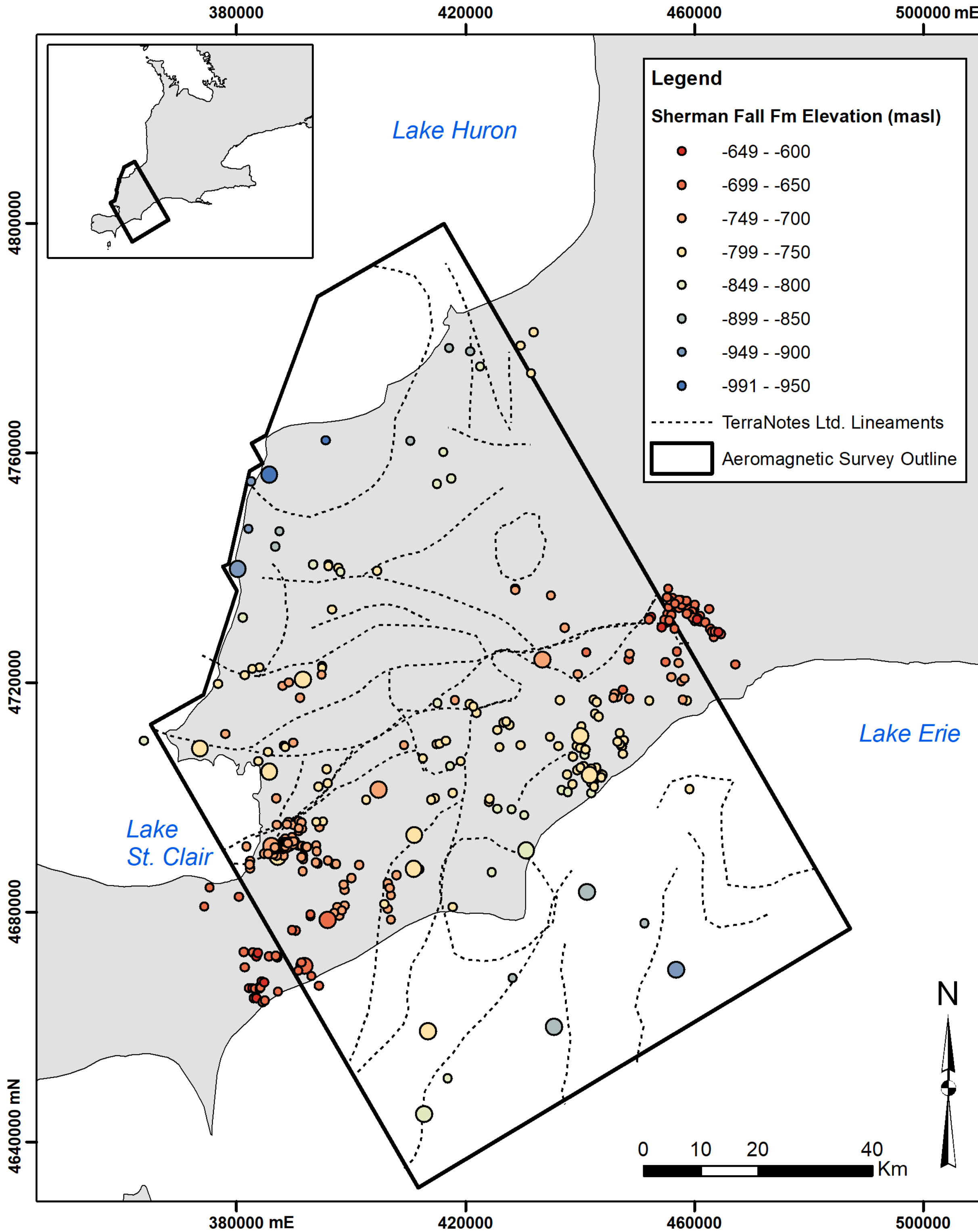

Figure 22. Sherman Fall Formation (Trenton Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

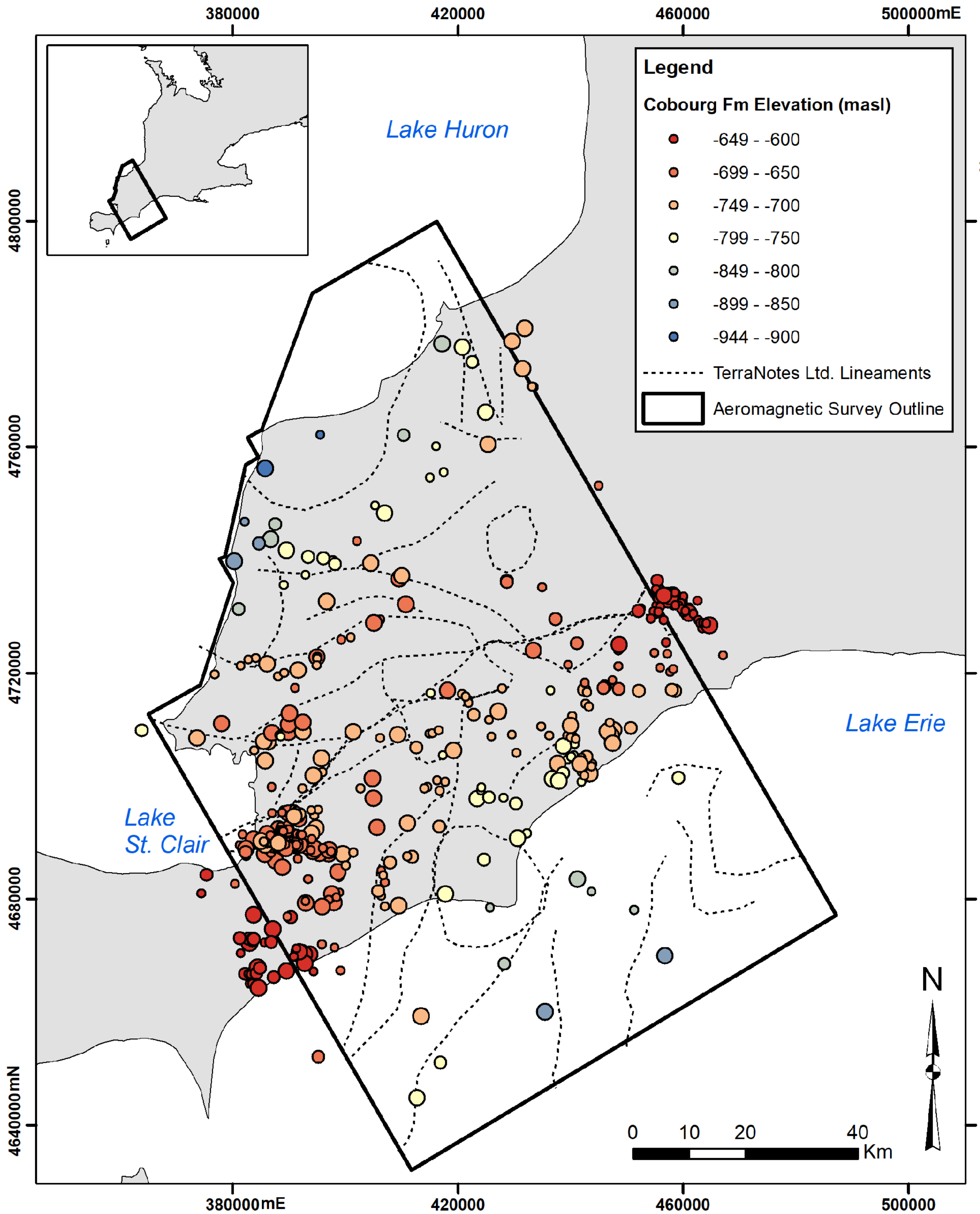

Figure 23. Cobourg Formation (Trenton Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

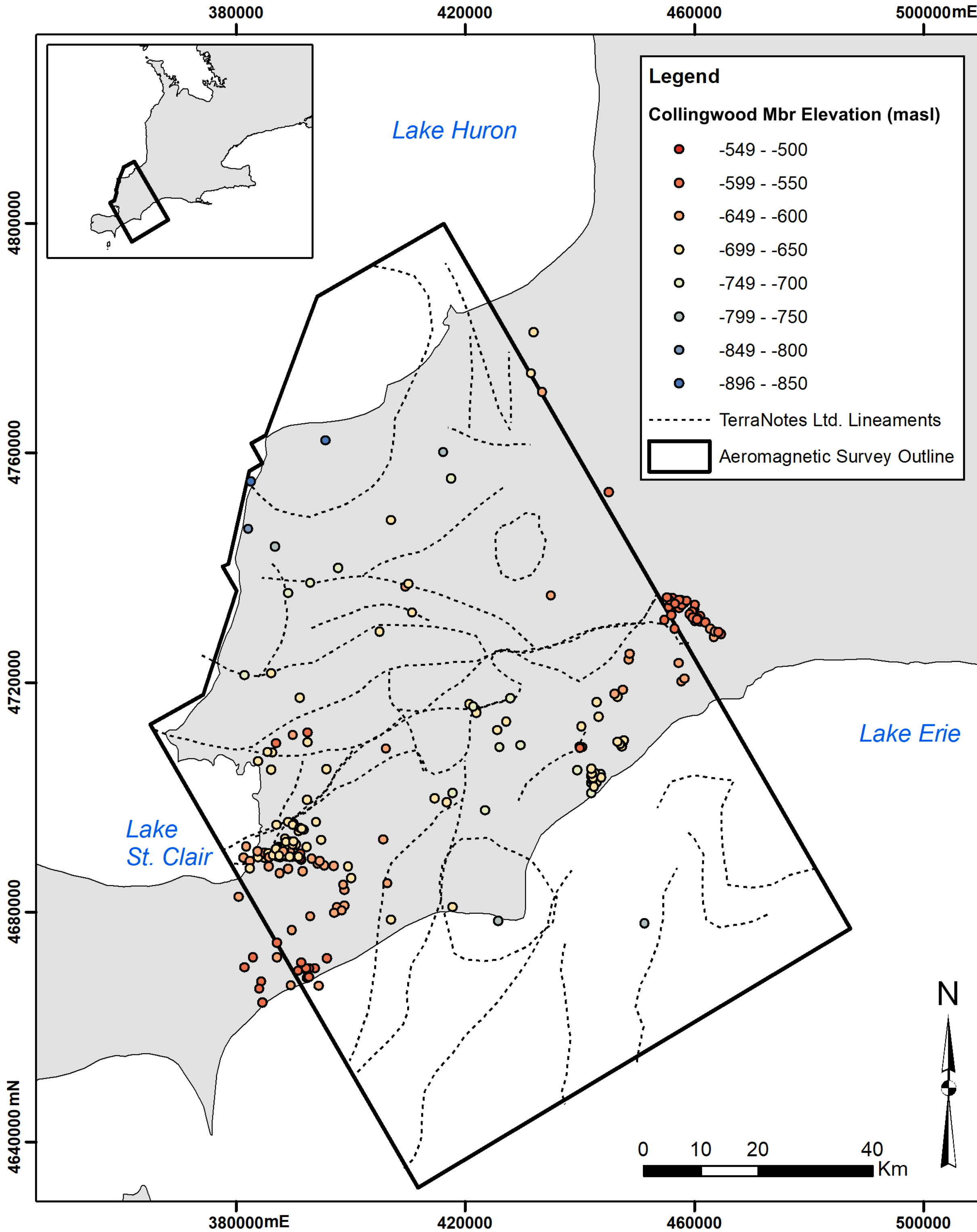

Figure 24. Collingwood Member of the Cobourg Formation (Trenton Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Mbr, Member; masl, metres above sea level.

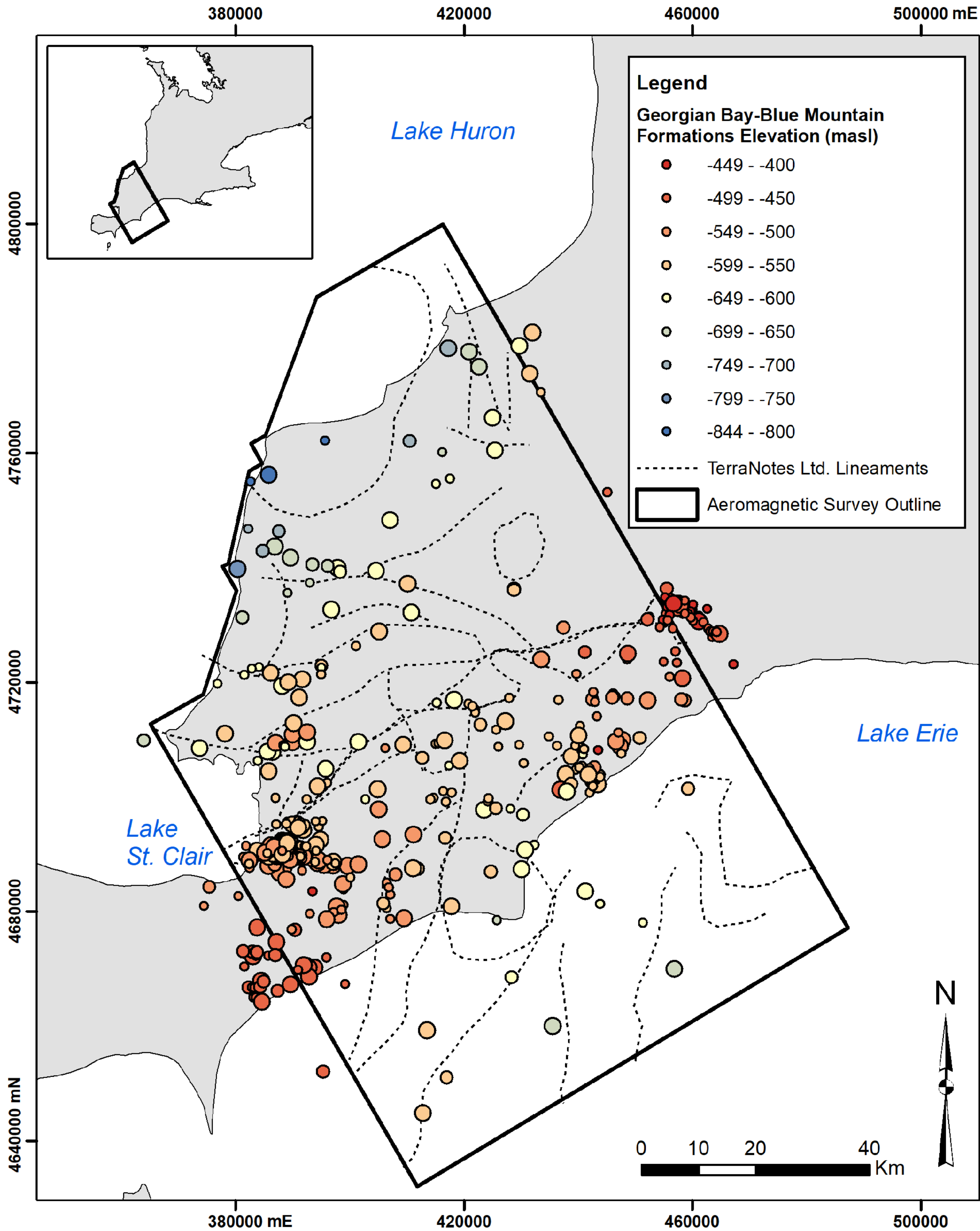

Figure 25. Georgian Bay–Blue Mountain formations elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

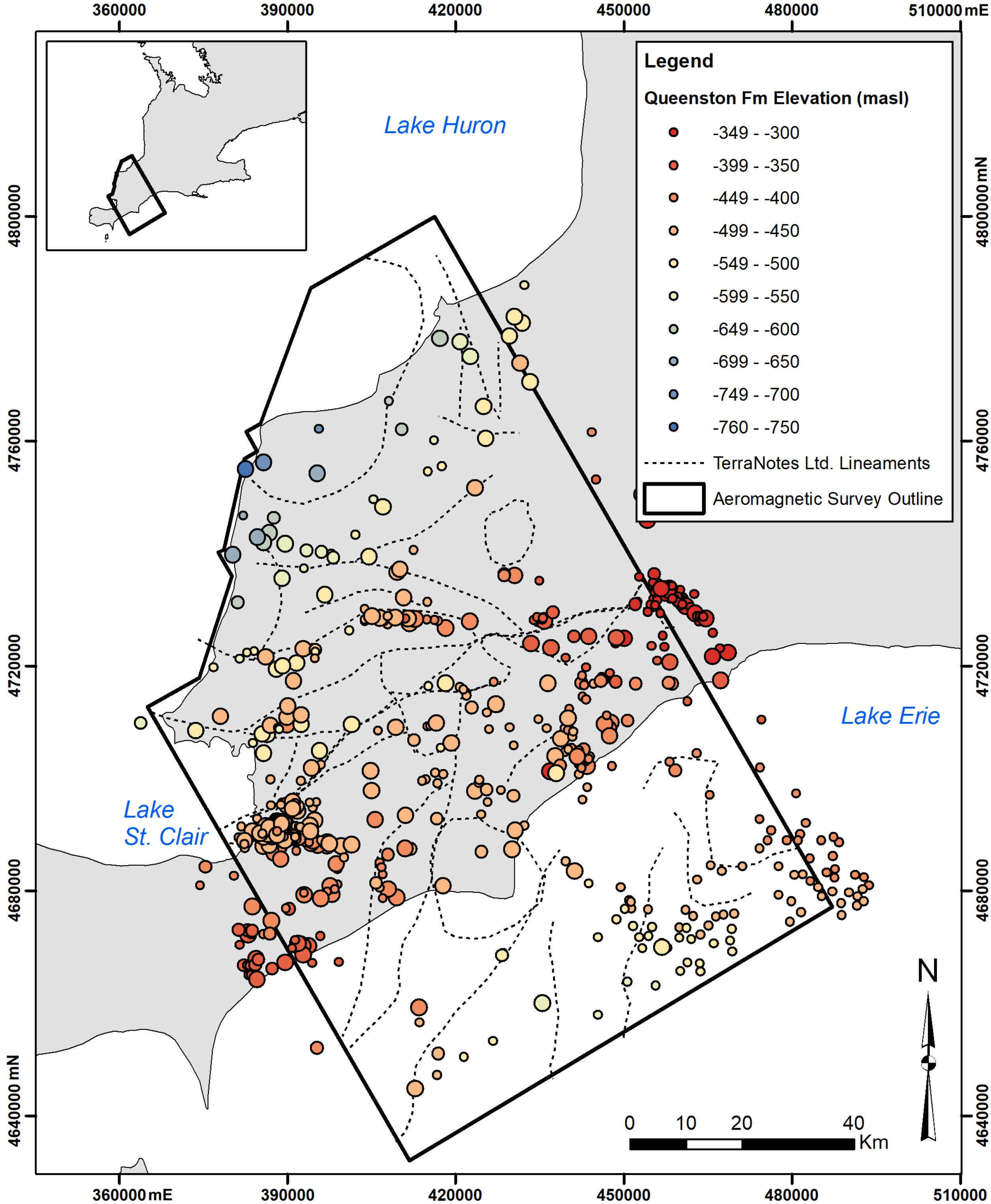

Figure 26. Queenston Formation elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

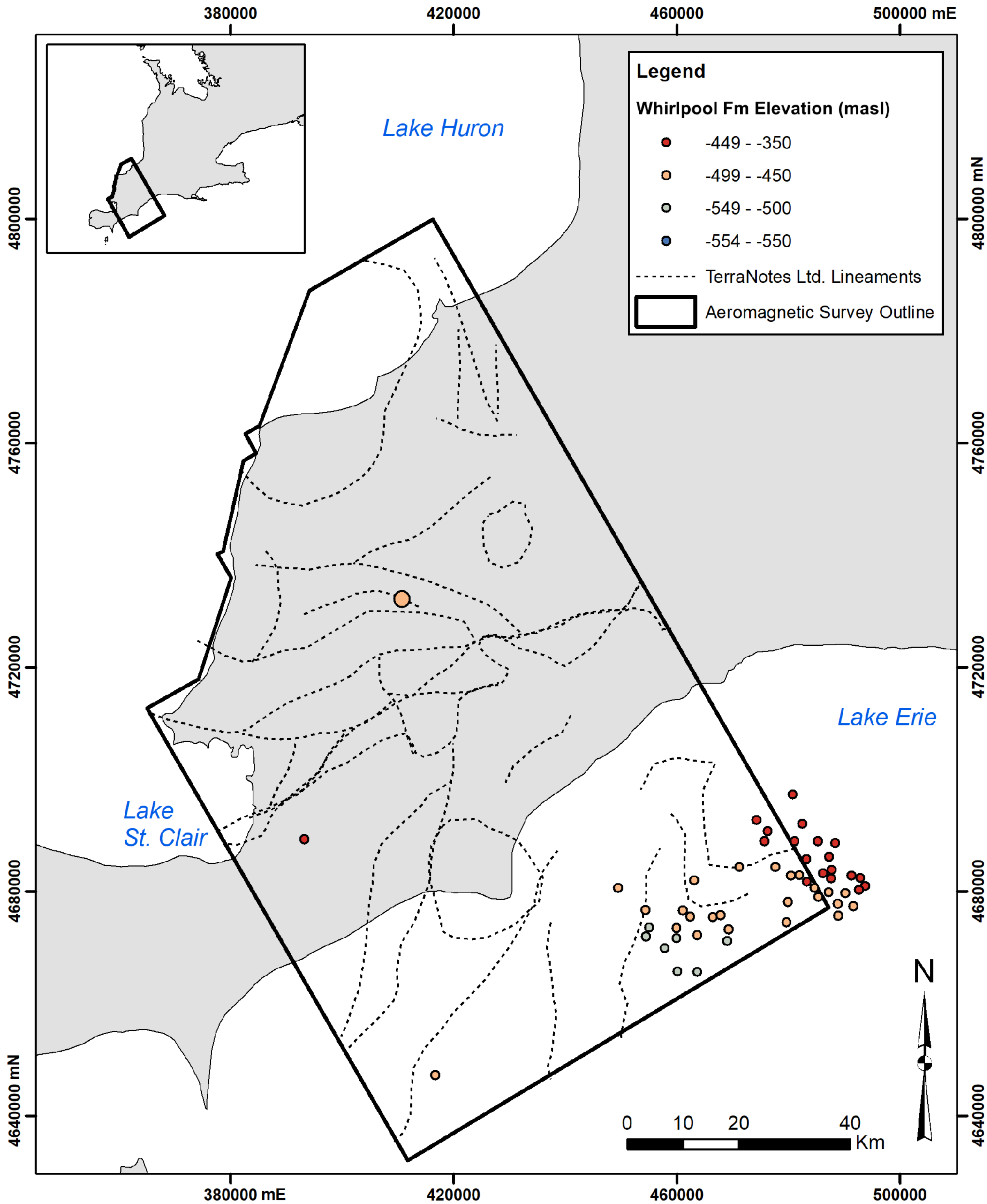

Figure 27. Whirlpool Formation (Medina (Cataract) Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

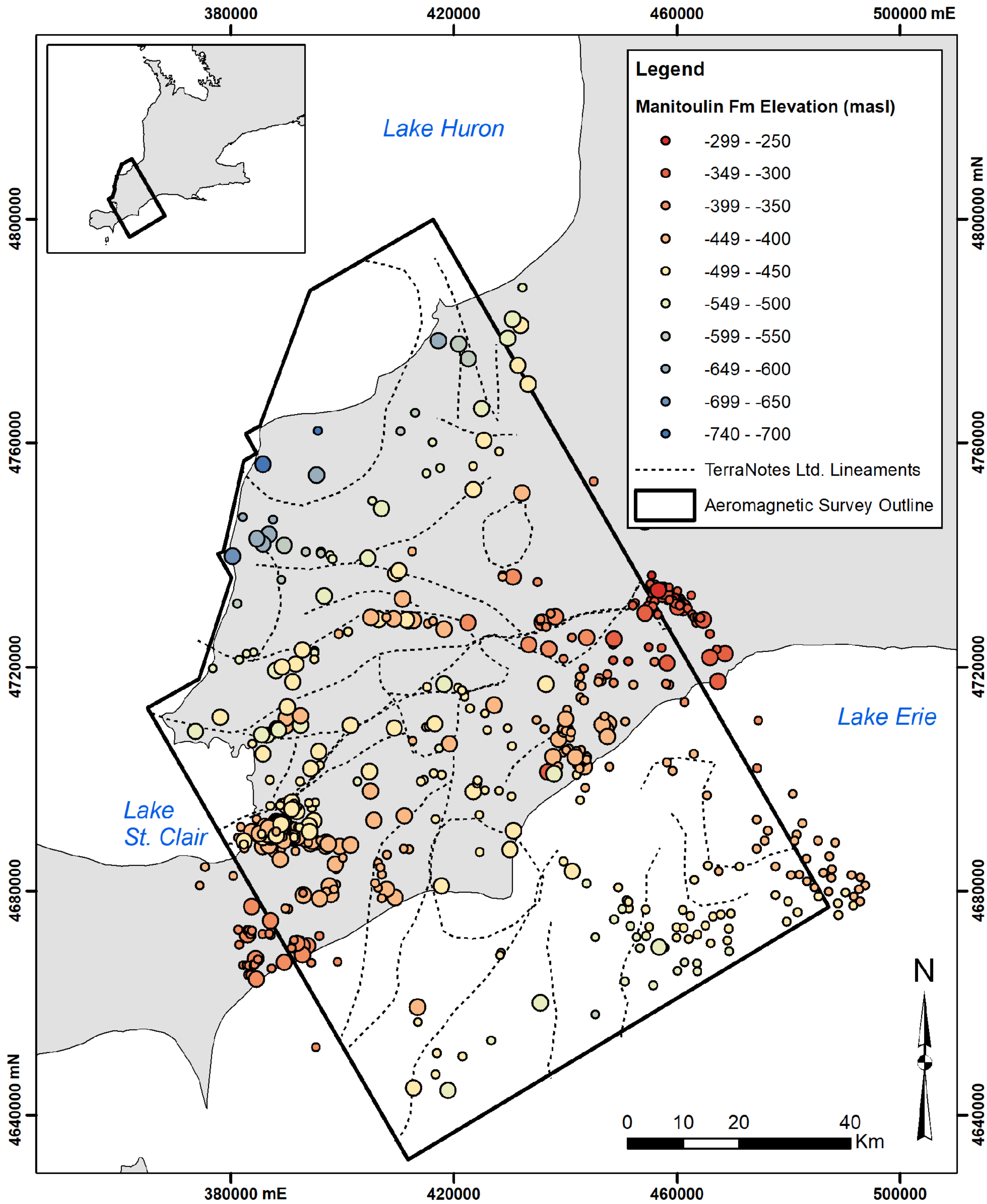

Figure 28. Manitoulin Formation (Medina (Cataract) Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

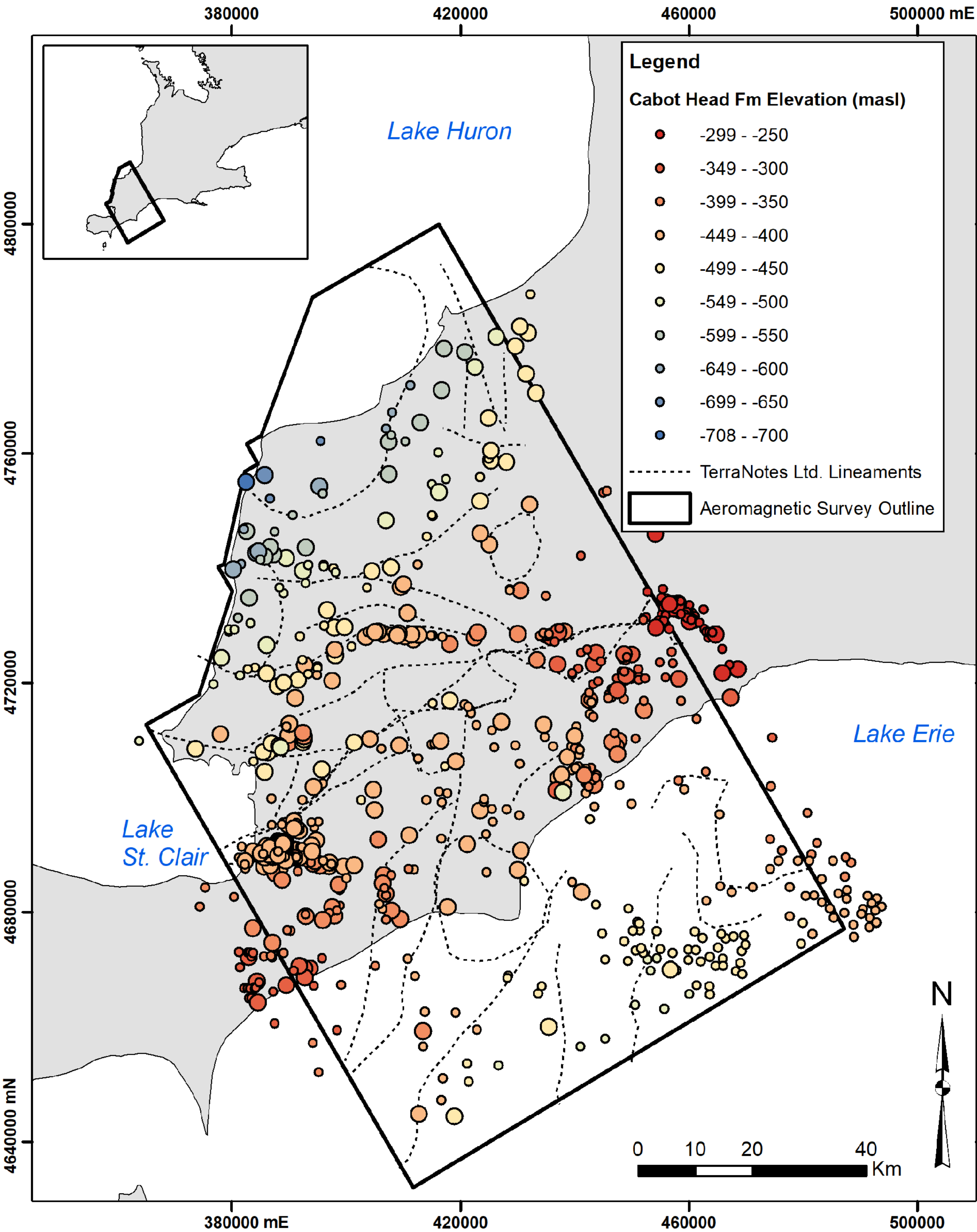

Figure 29. Cabot Head Formation (Medina (Cataract) Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

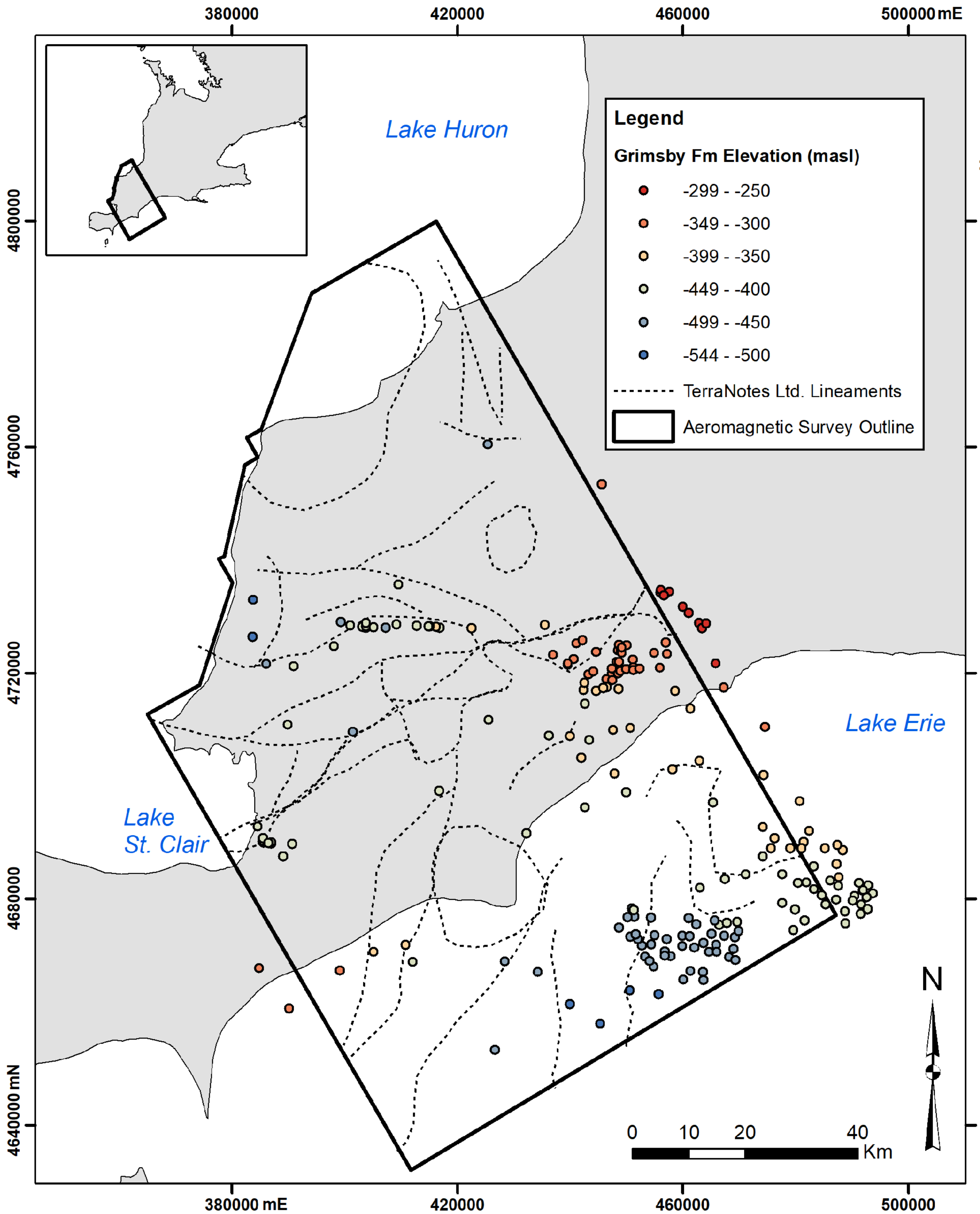

Figure 30. Grimsby Formation (Medina (Cataract) Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

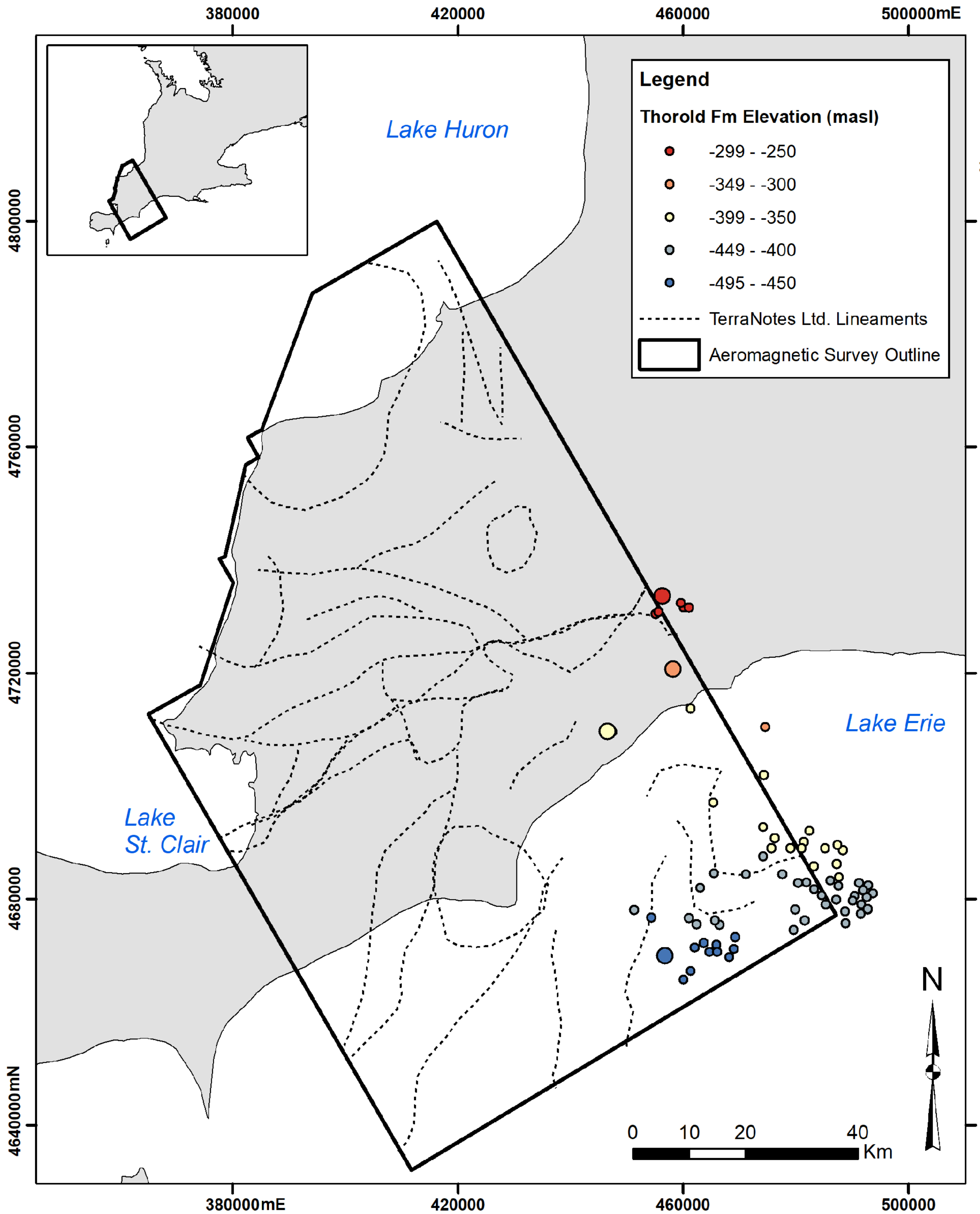

Figure 31. Thorold Formation (Medina (Cataract) Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

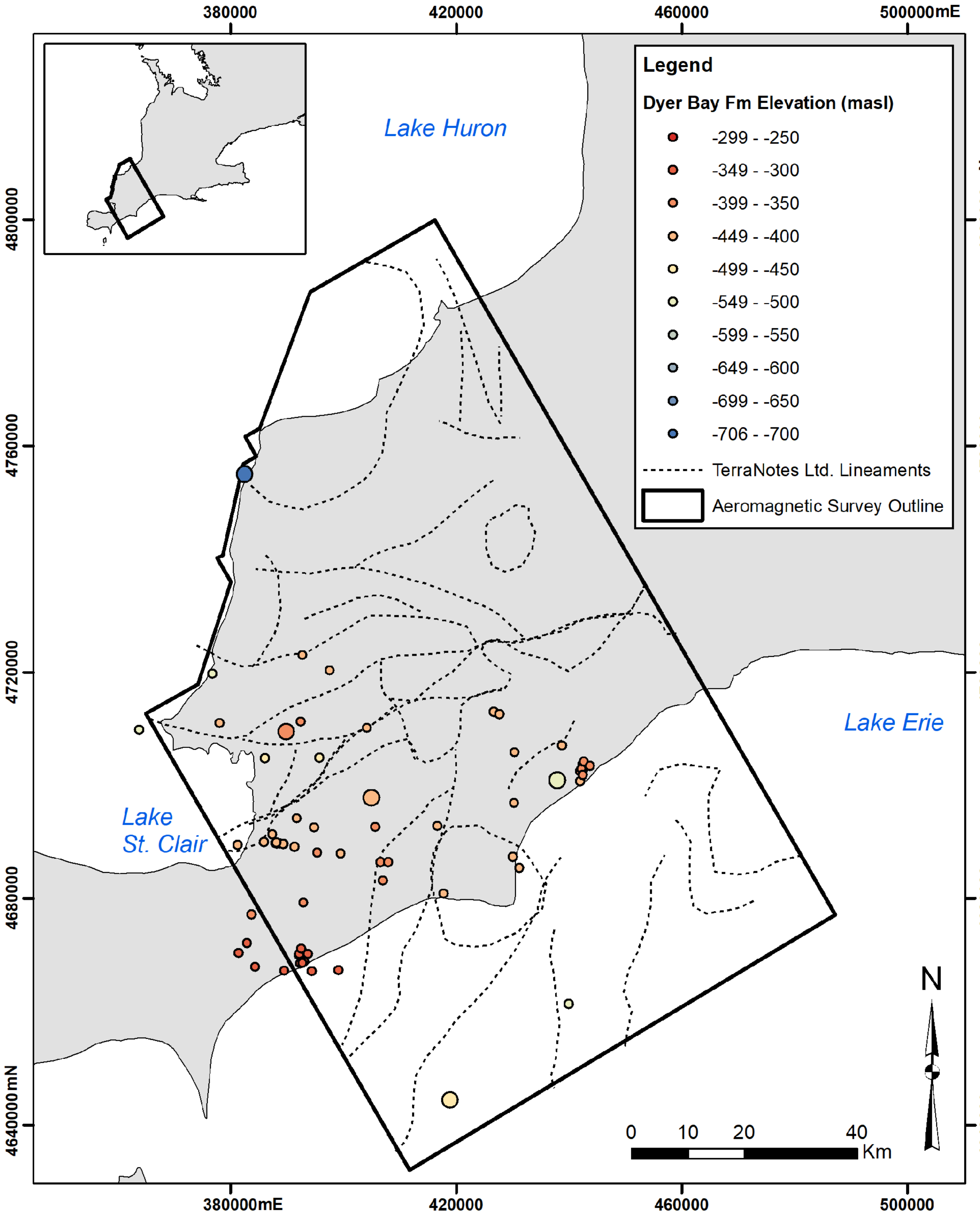

Figure 32. Dyer Bay Formation (Clinton Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

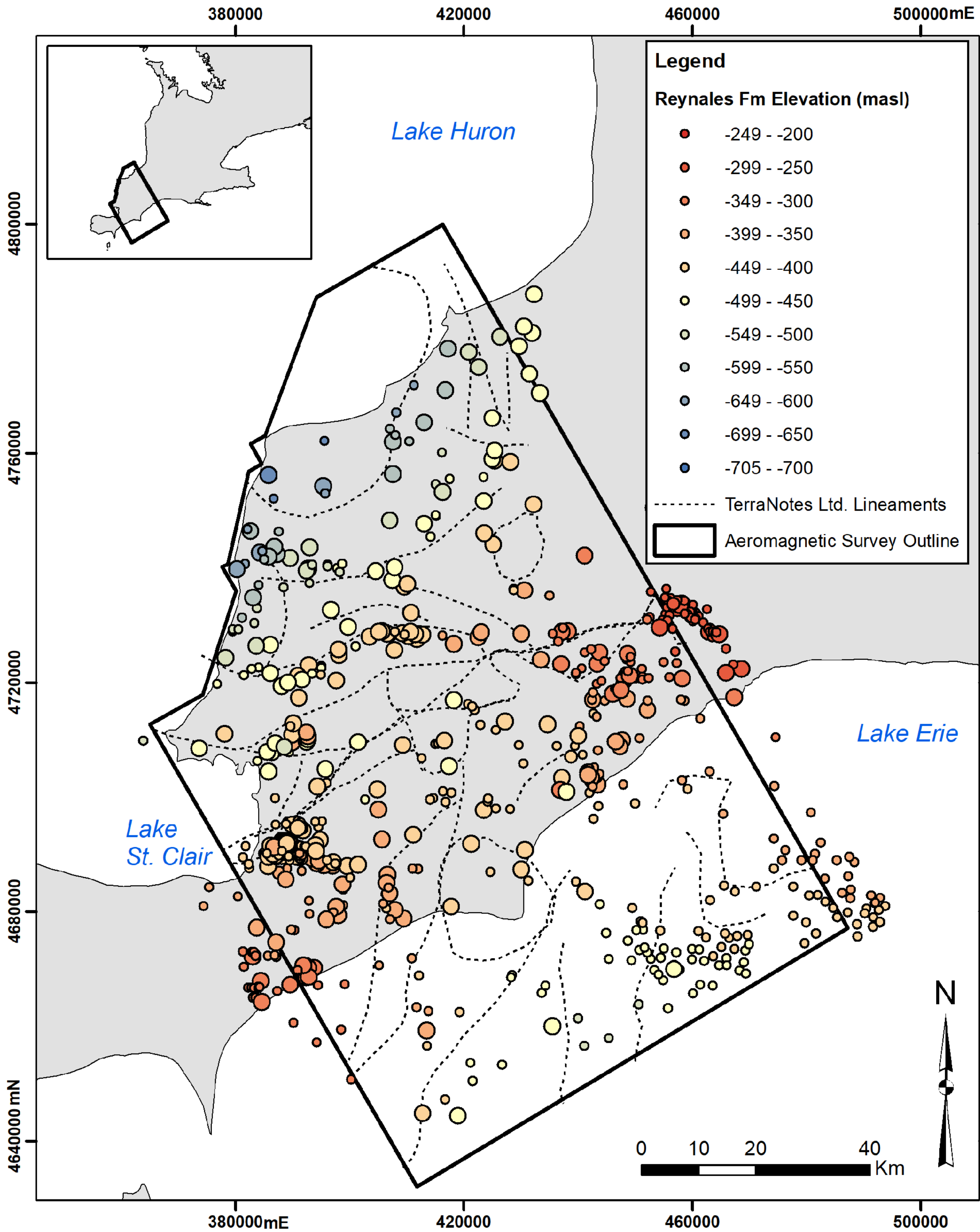

Figure 33. Reynales Formation (Clinton Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

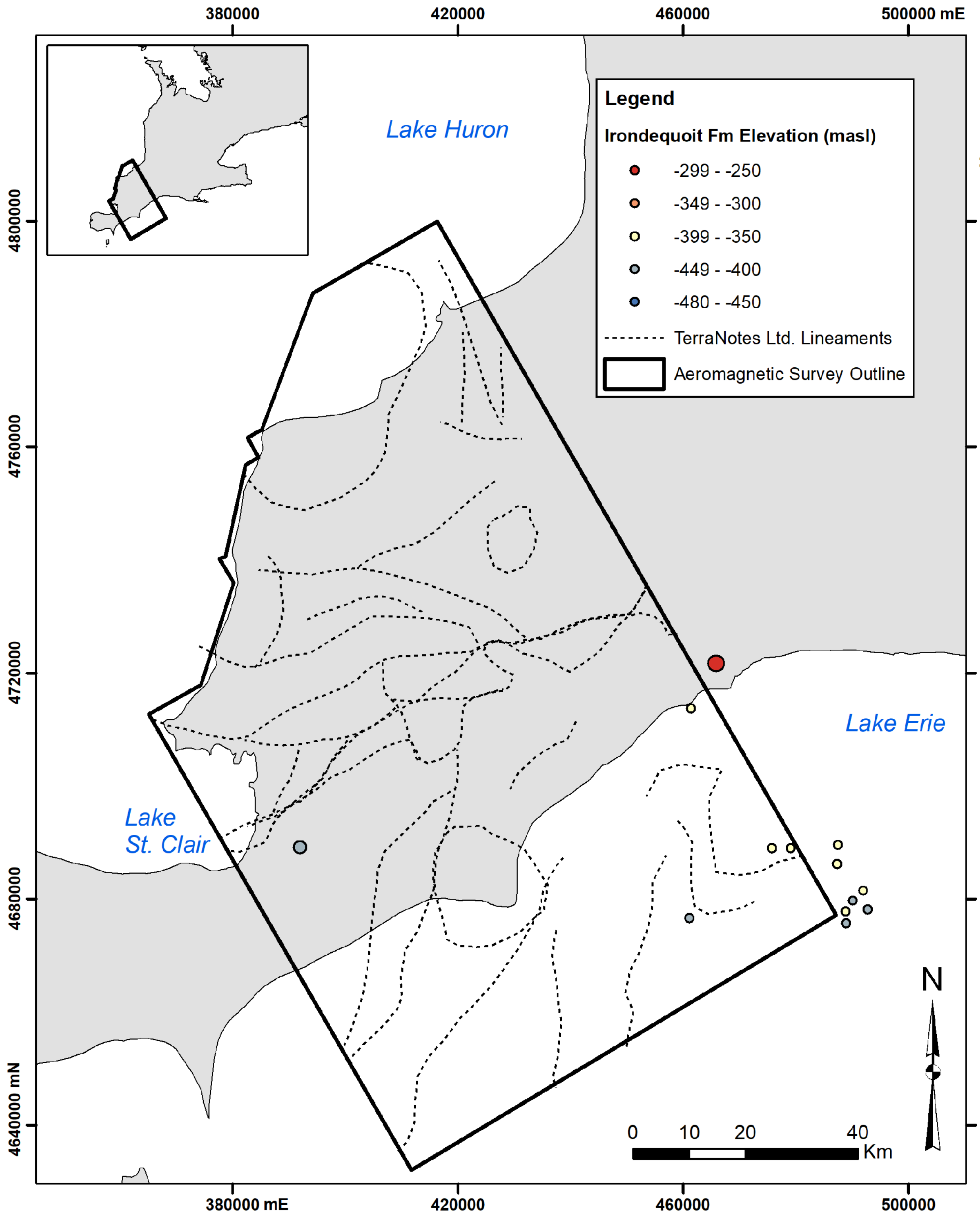

Figure 34. Irondequoit Formation (Clinton Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

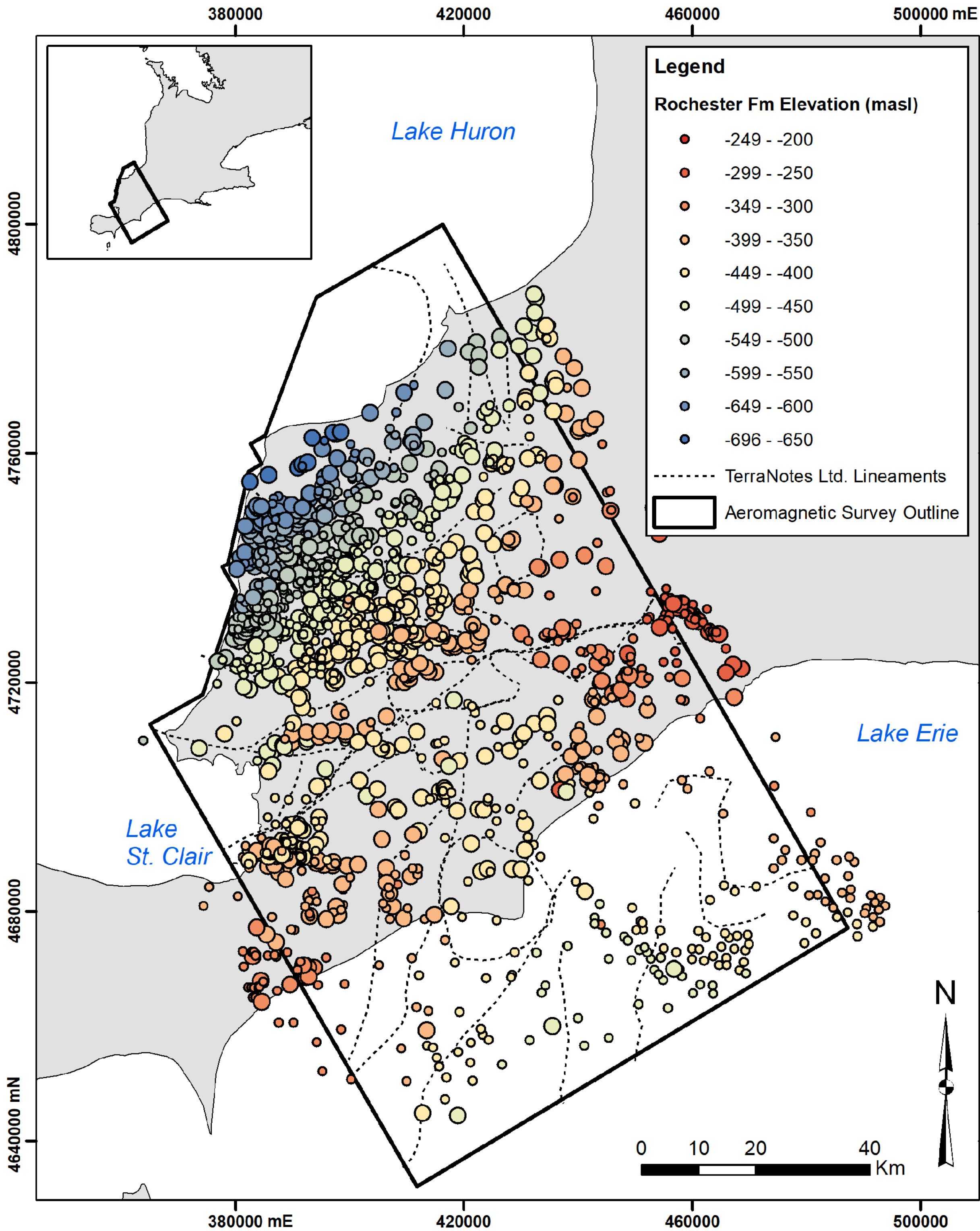

Figure 35. Rochester Formation (Clinton Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

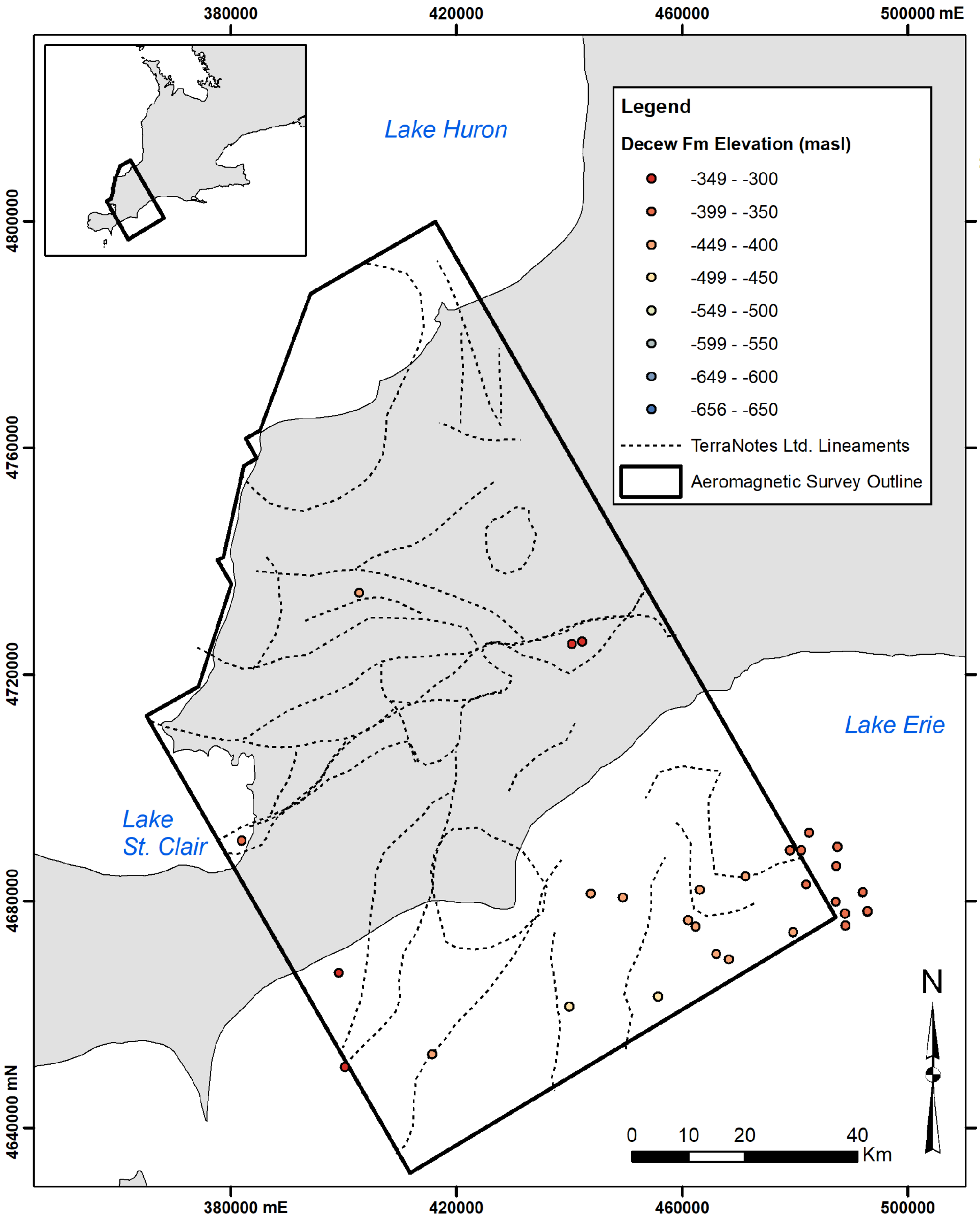

Figure 36. DeCew Formation (Clinton Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

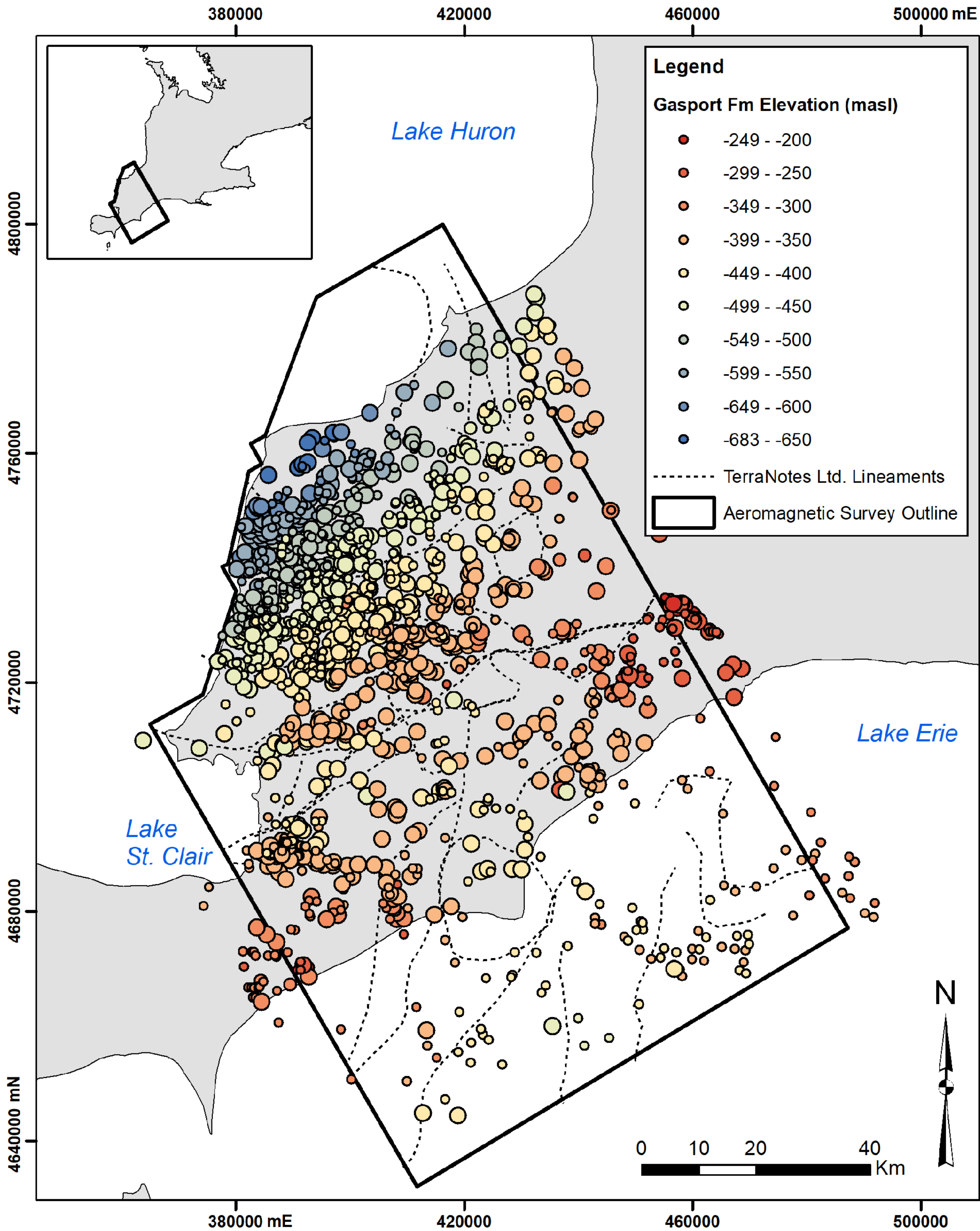

Figure 37. Gasport Formation (Lockport Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

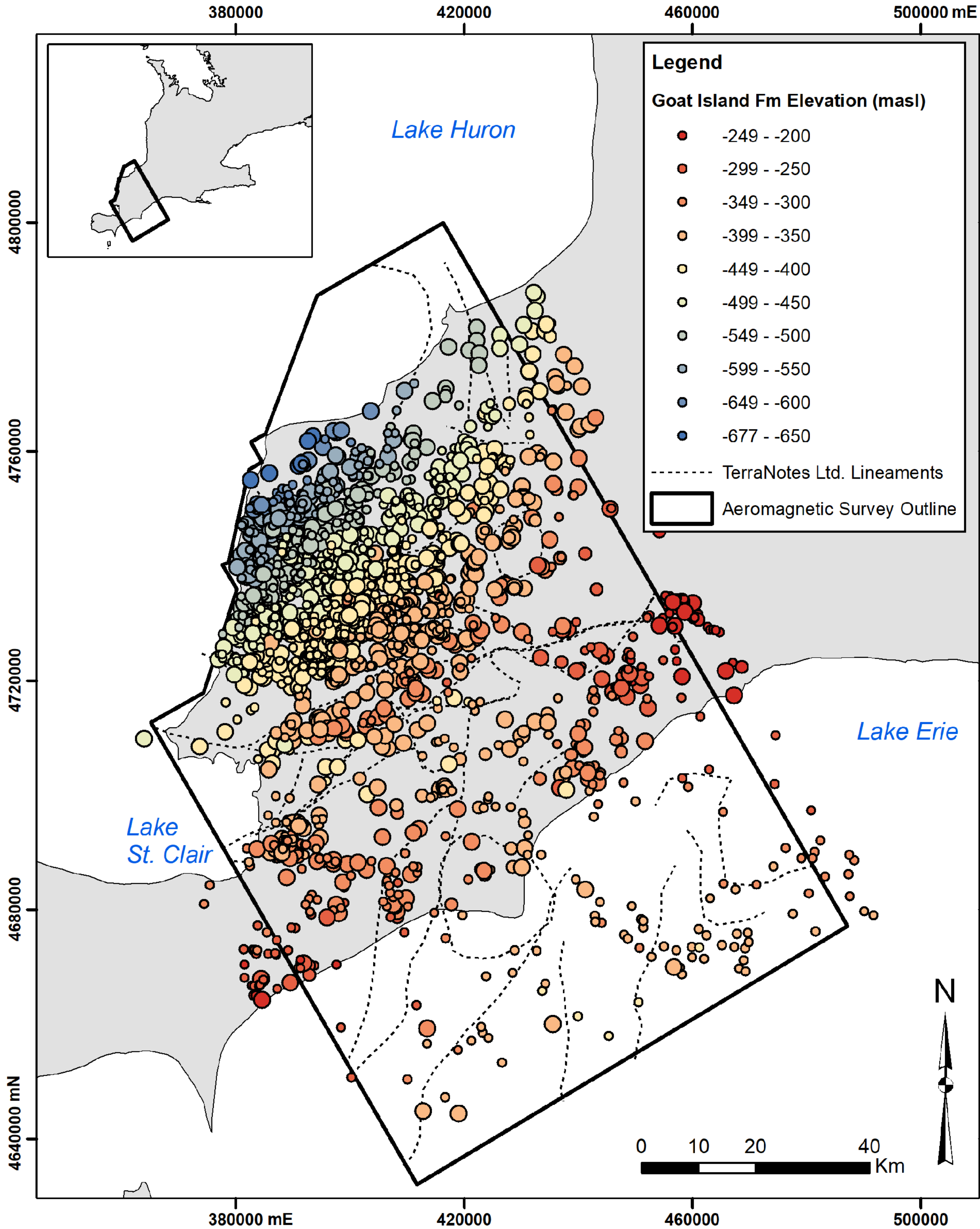

Figure 38. Goat Island Formation (Lockport Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

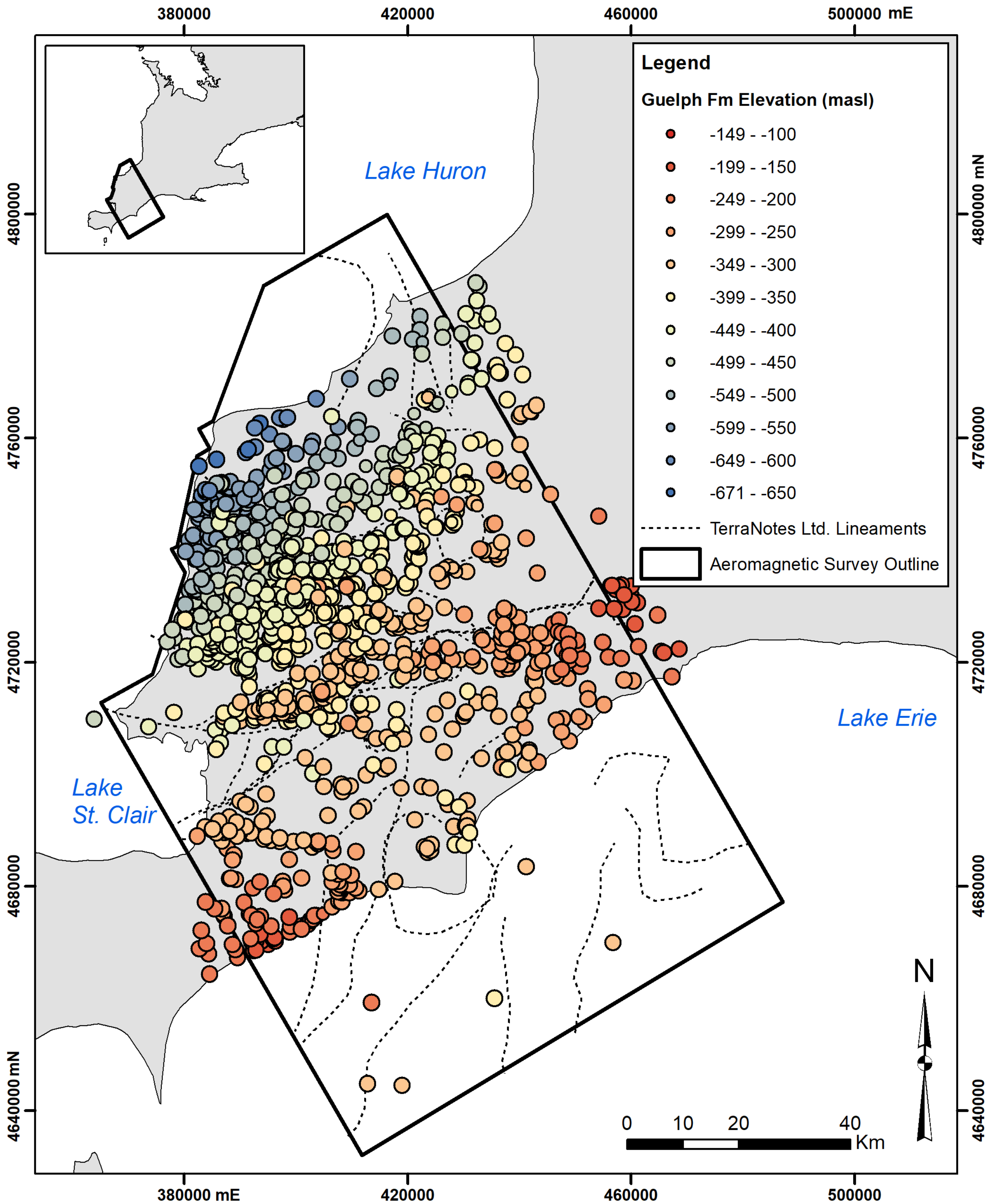

Figure 39. Guelph Formation (Lockport Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

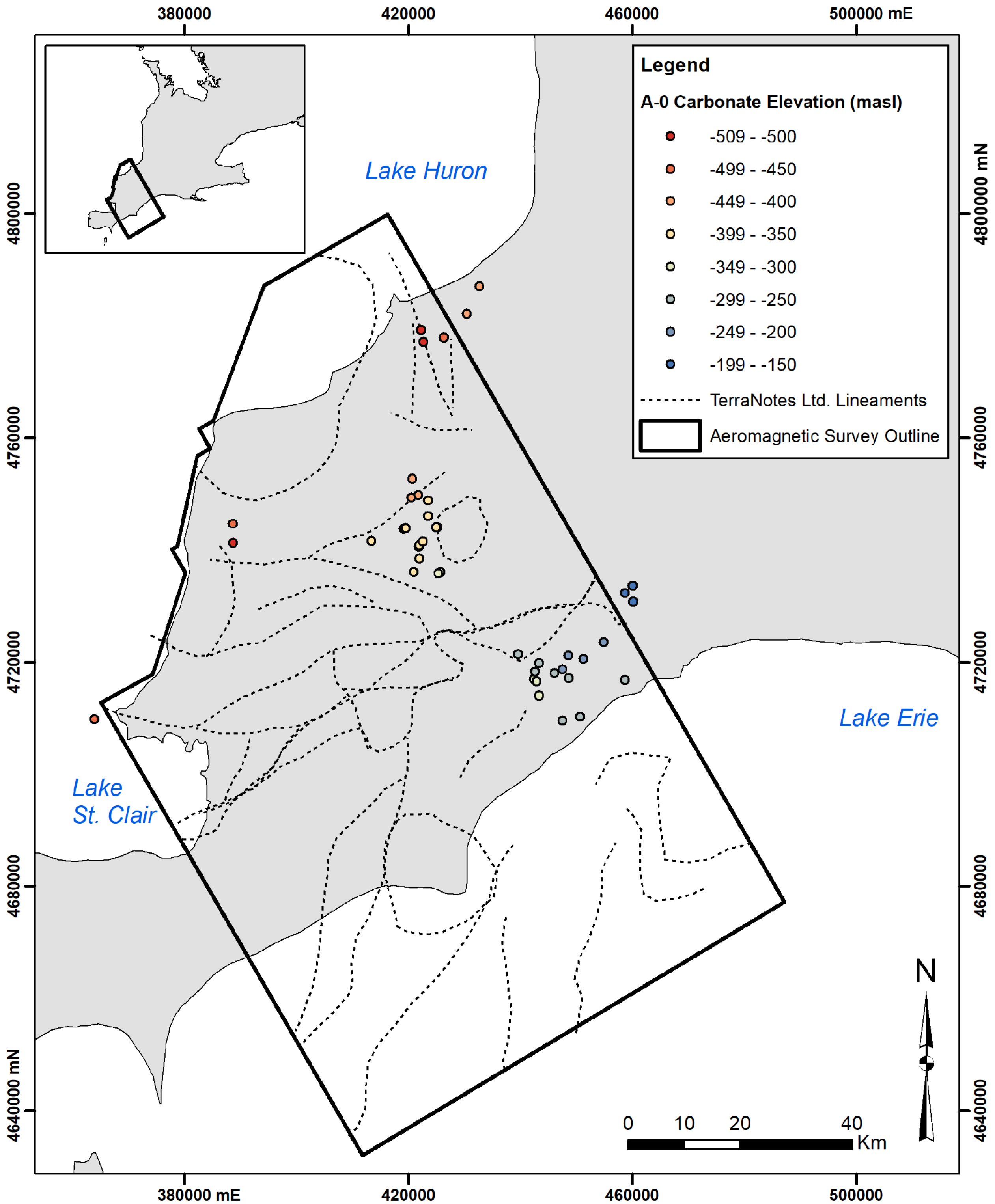

Figure 40. A-0 Carbonate Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

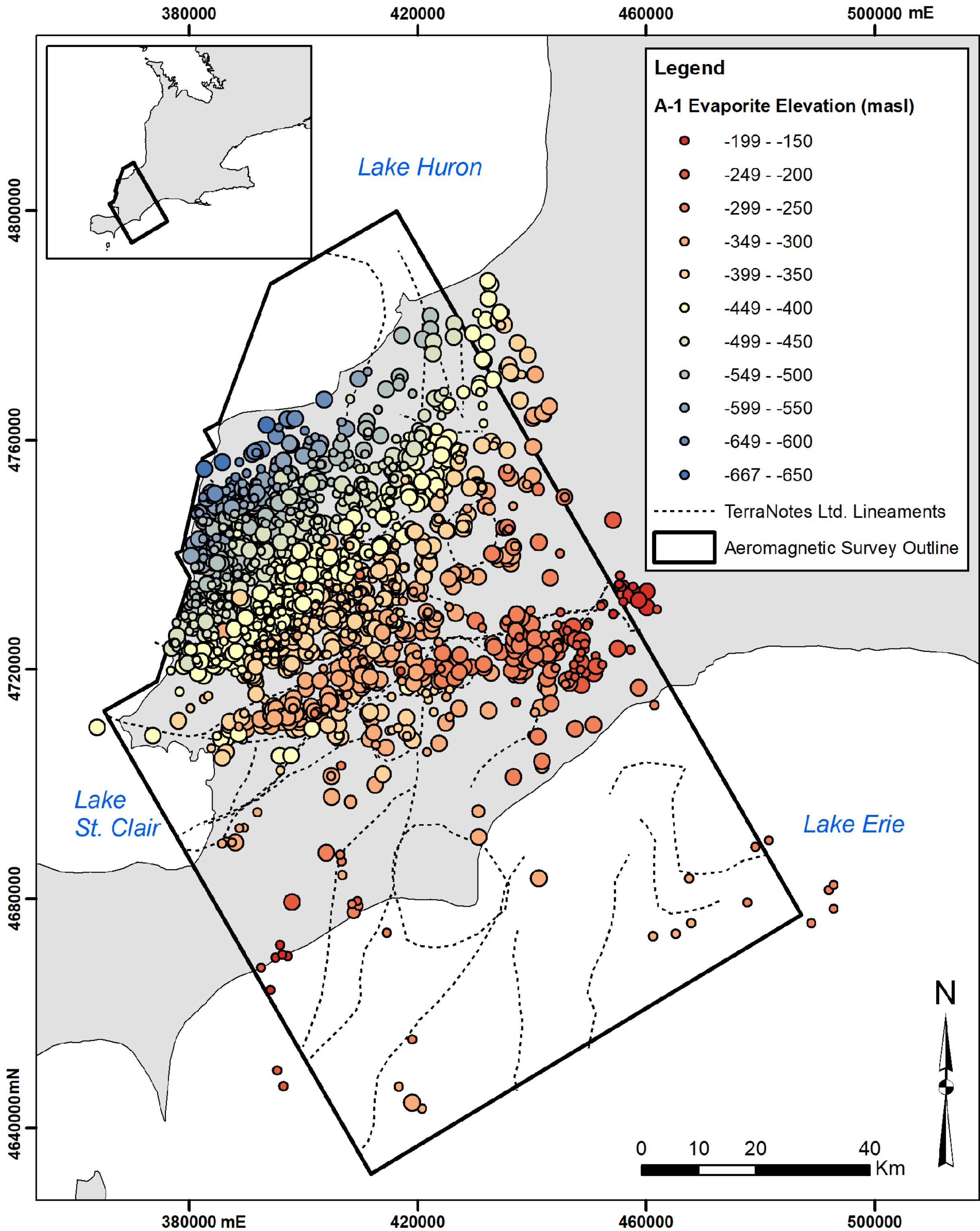

Figure 41. A-1 Evaporite Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

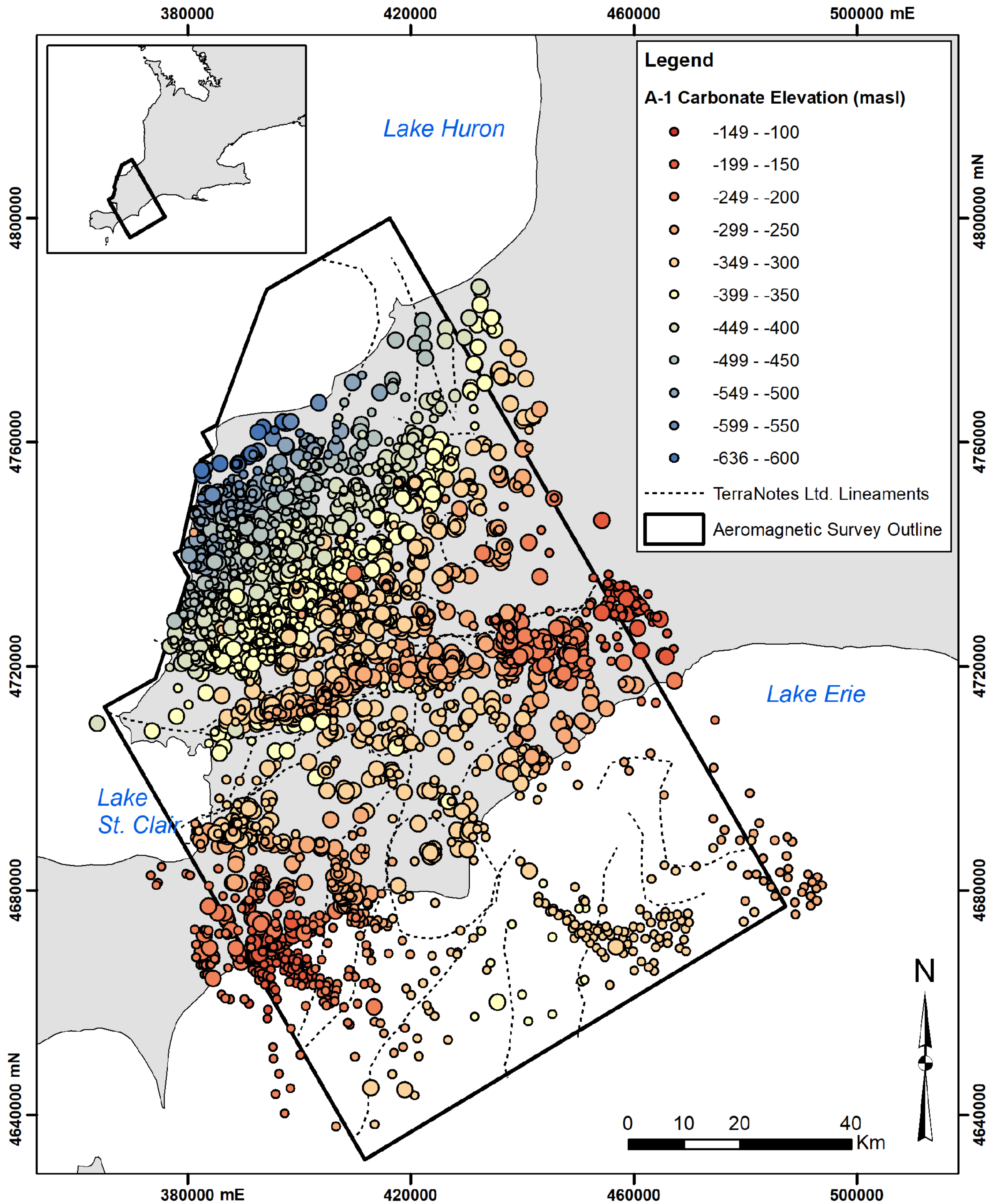

Figure 42. A-1 Carbonate Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

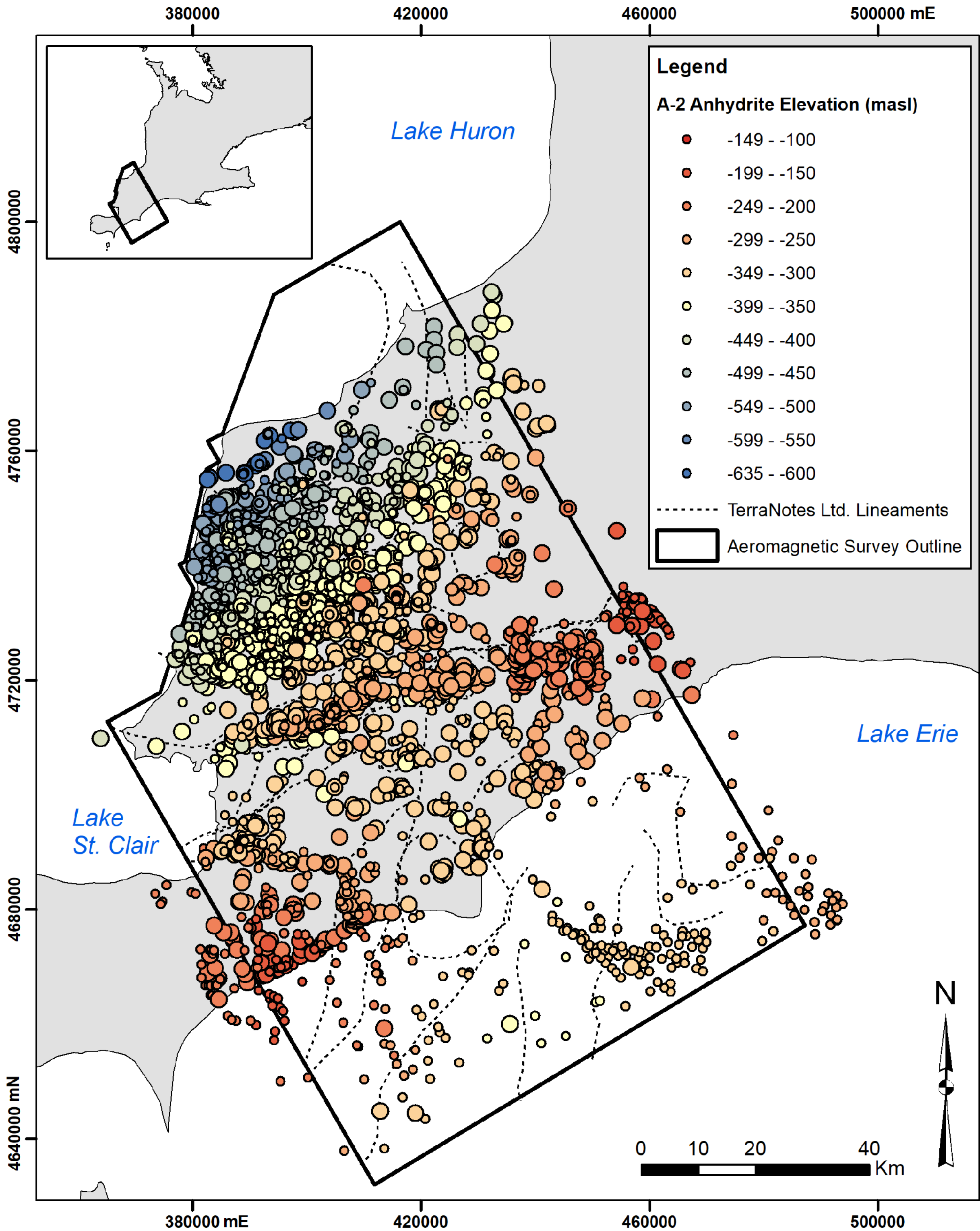

Figure 43. A-2 Anhydrite Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

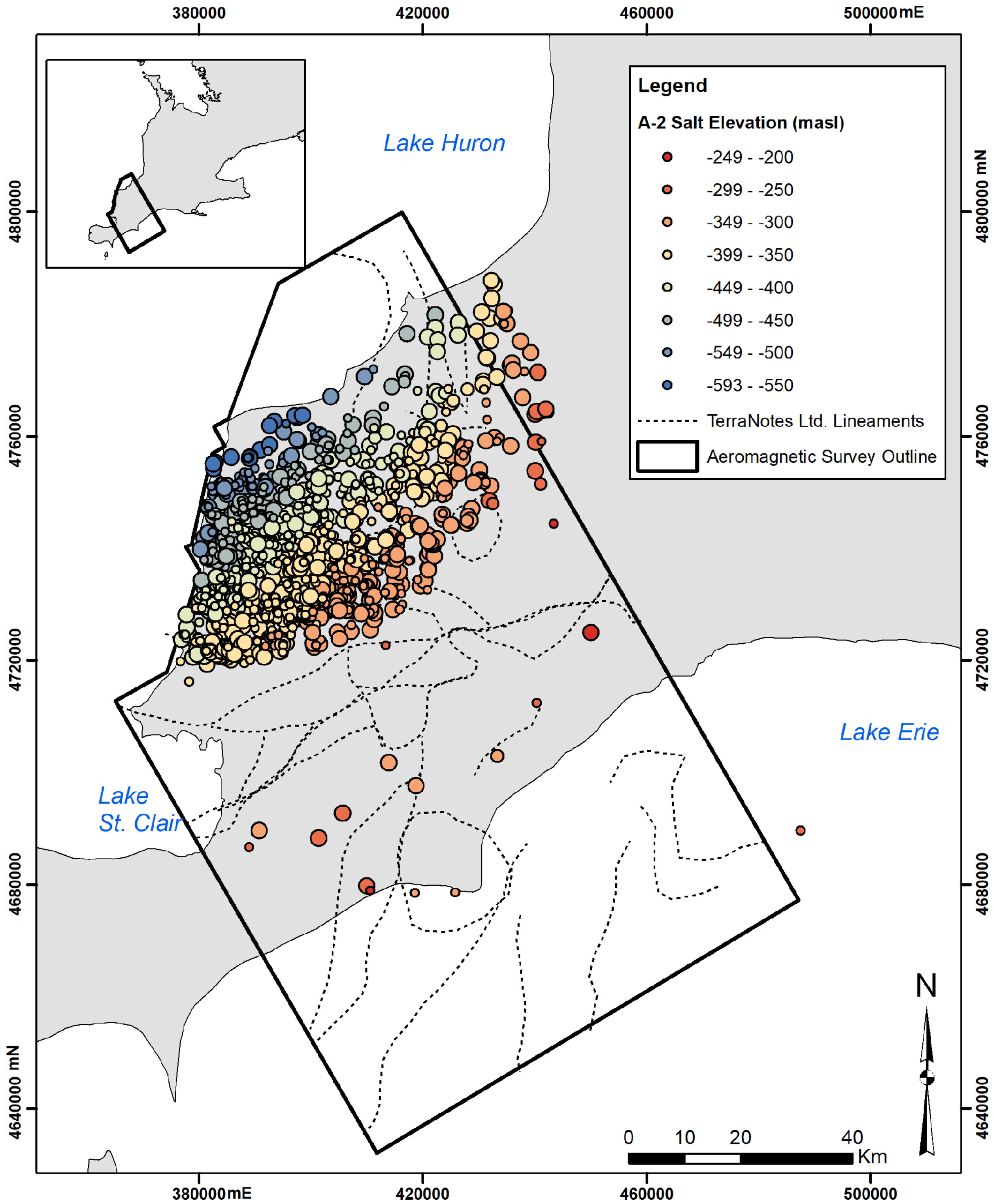

Figure 44. A-2 Salt Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

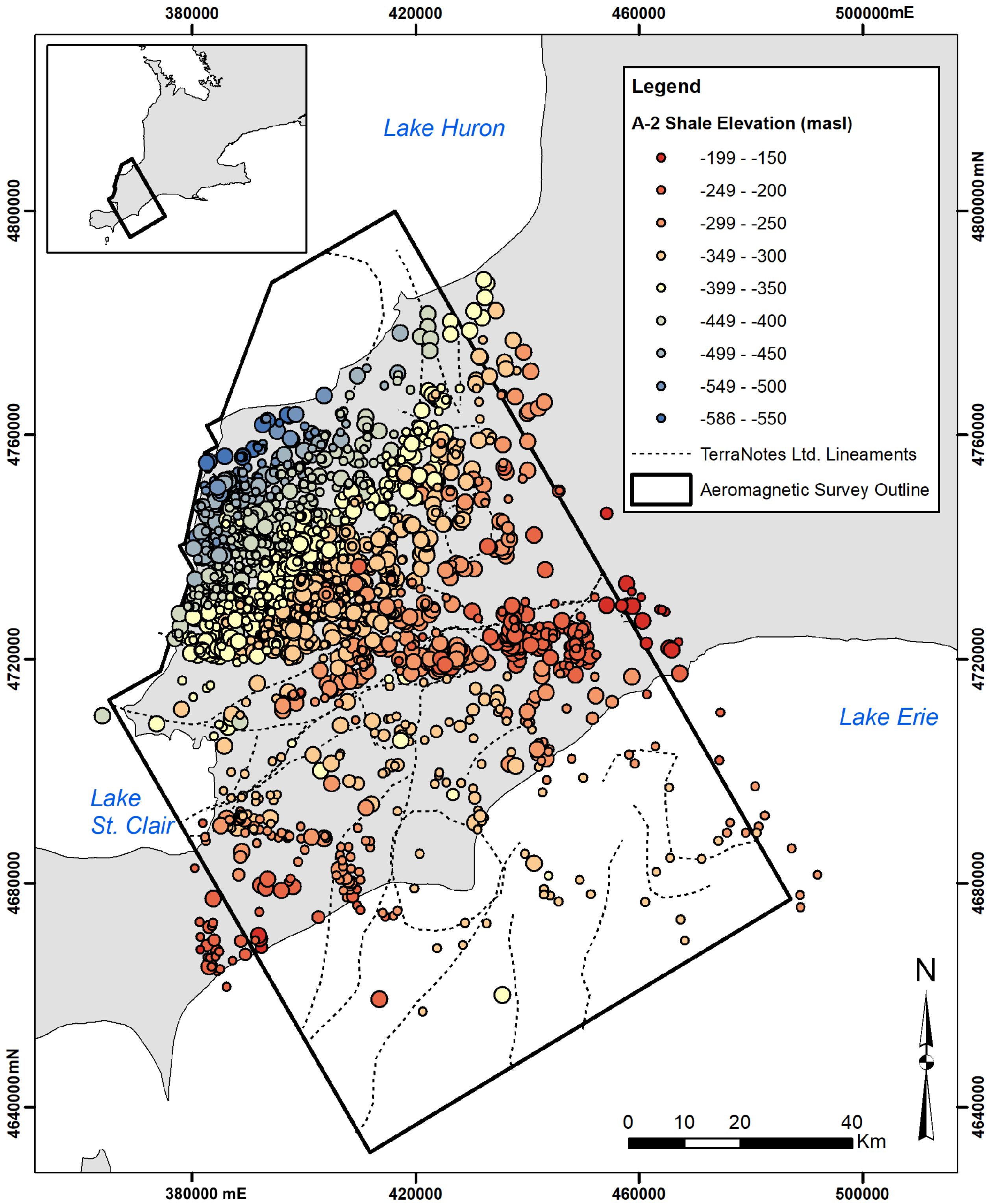

Figure 45. A-2 Shale Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

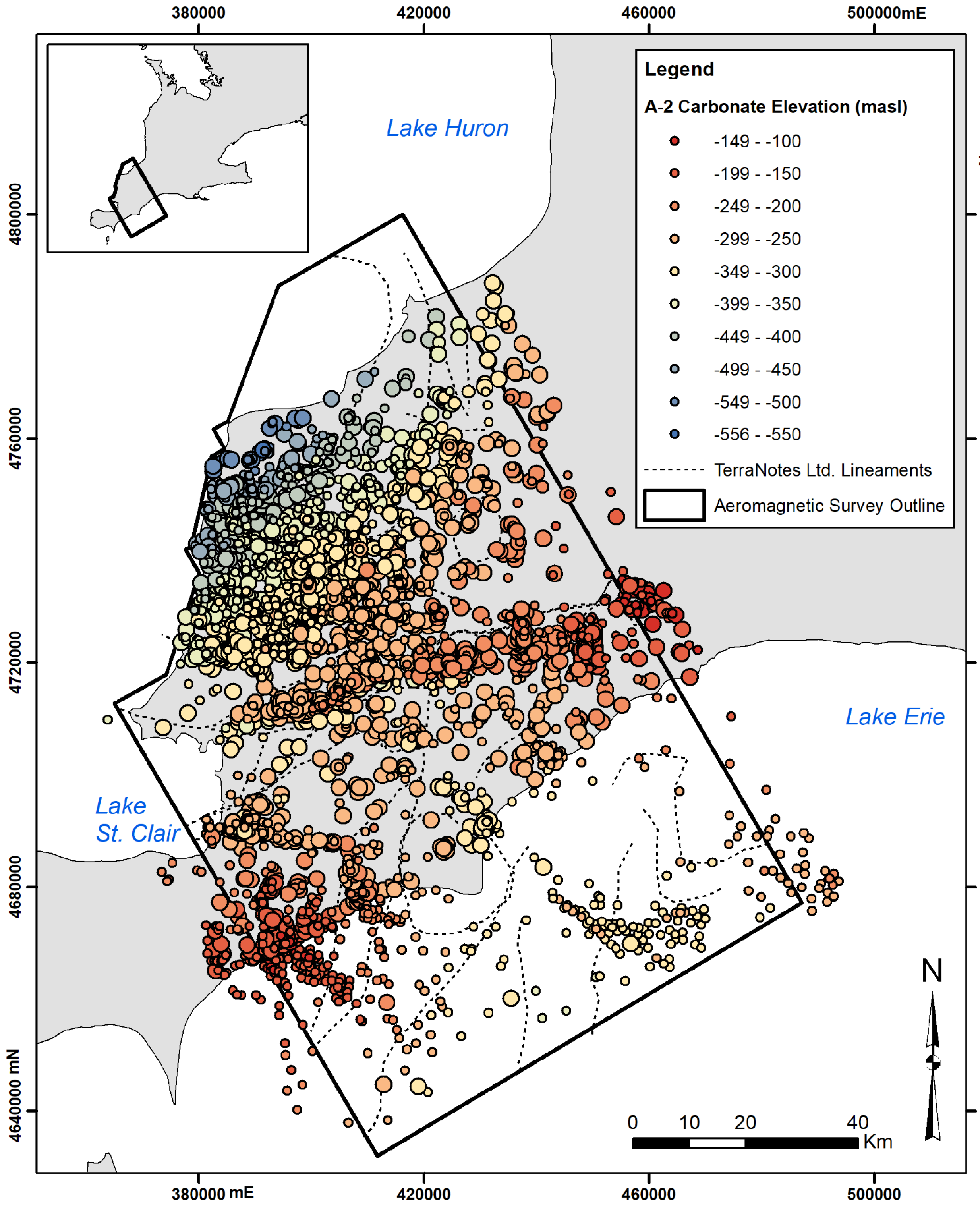

Figure 46. A-2 Carbonate Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

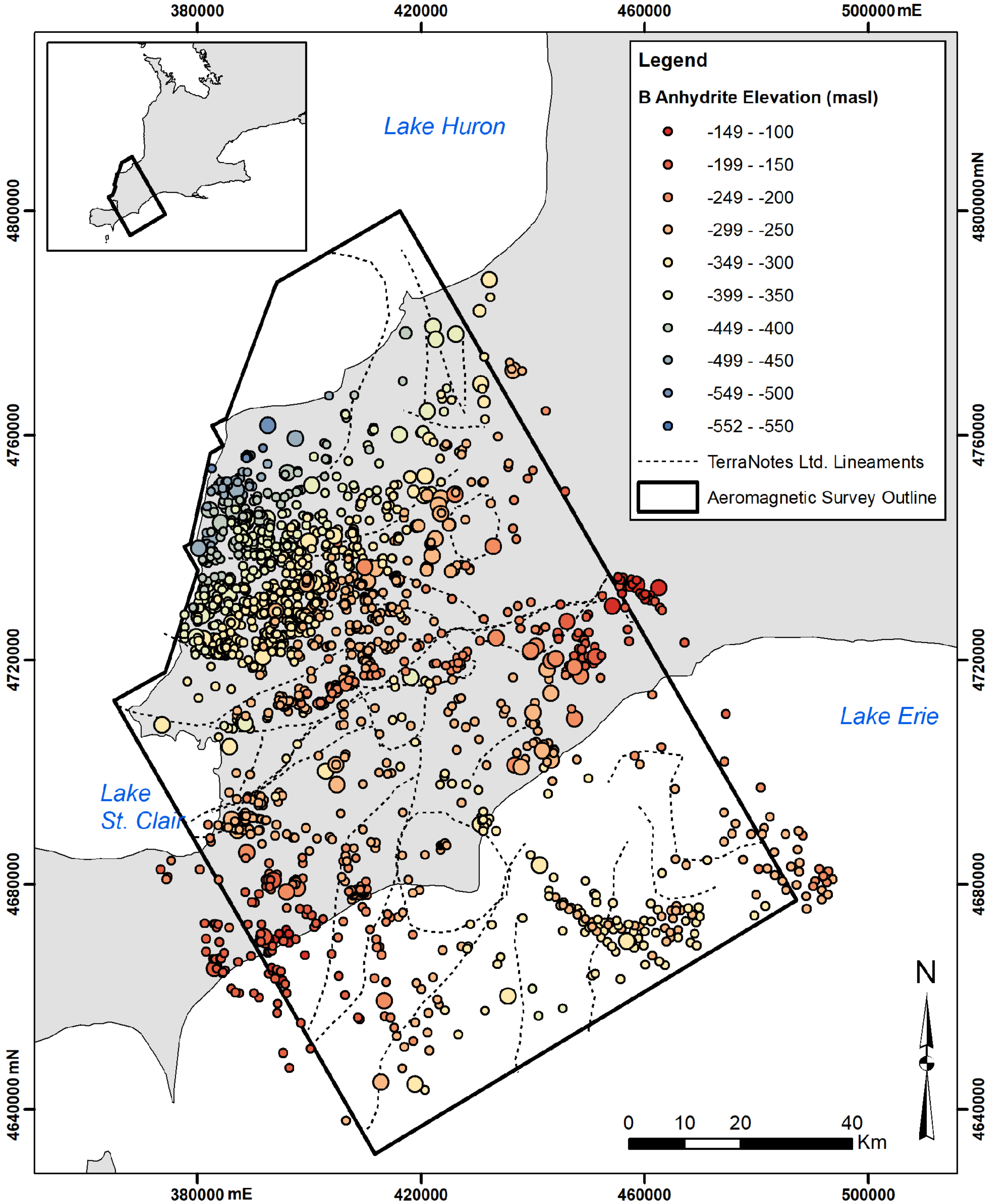

Figure 47. B Anhydrite Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

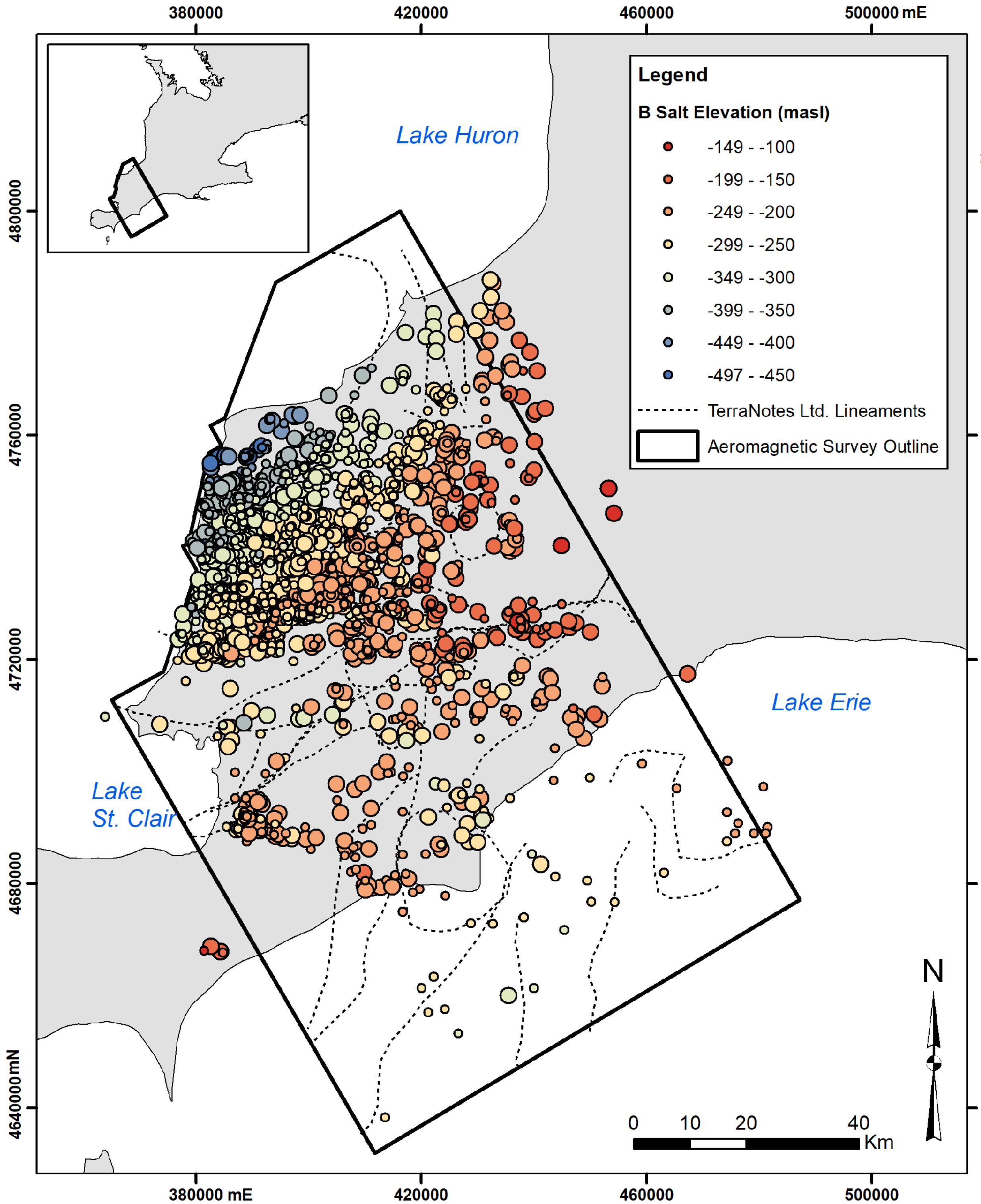

Figure 48. B Salt Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

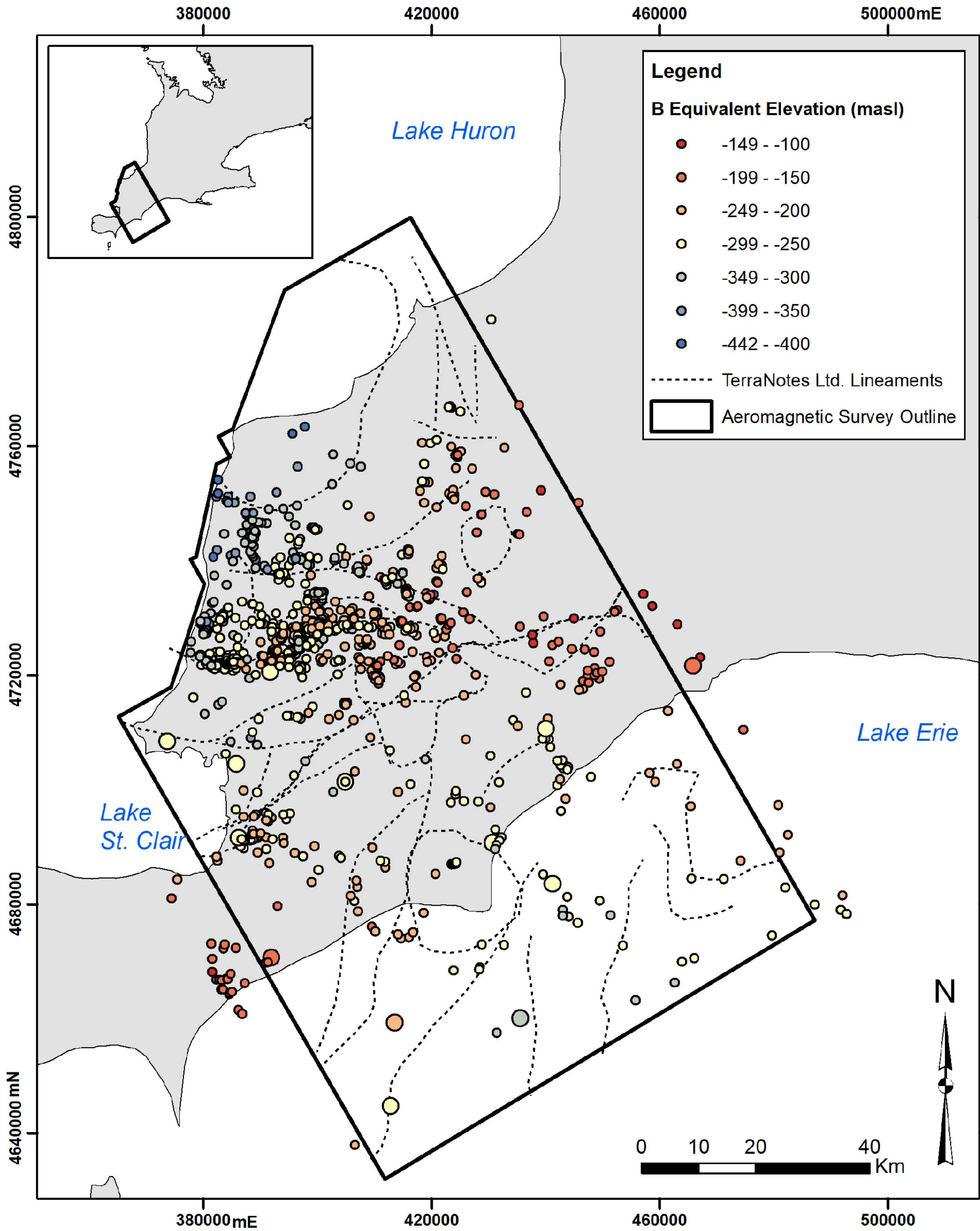

Figure 49. B Equivalent Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

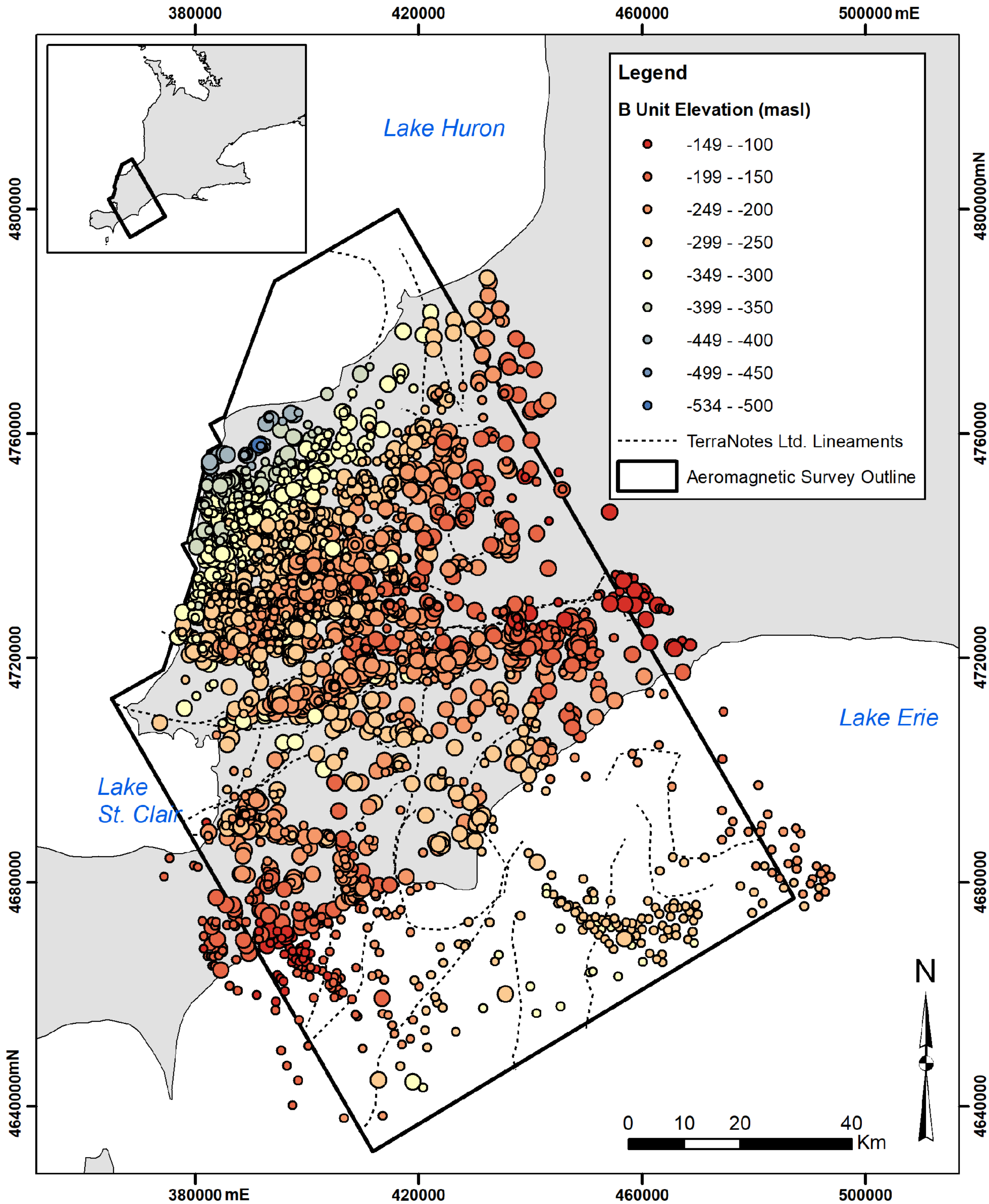

Figure 50. B Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

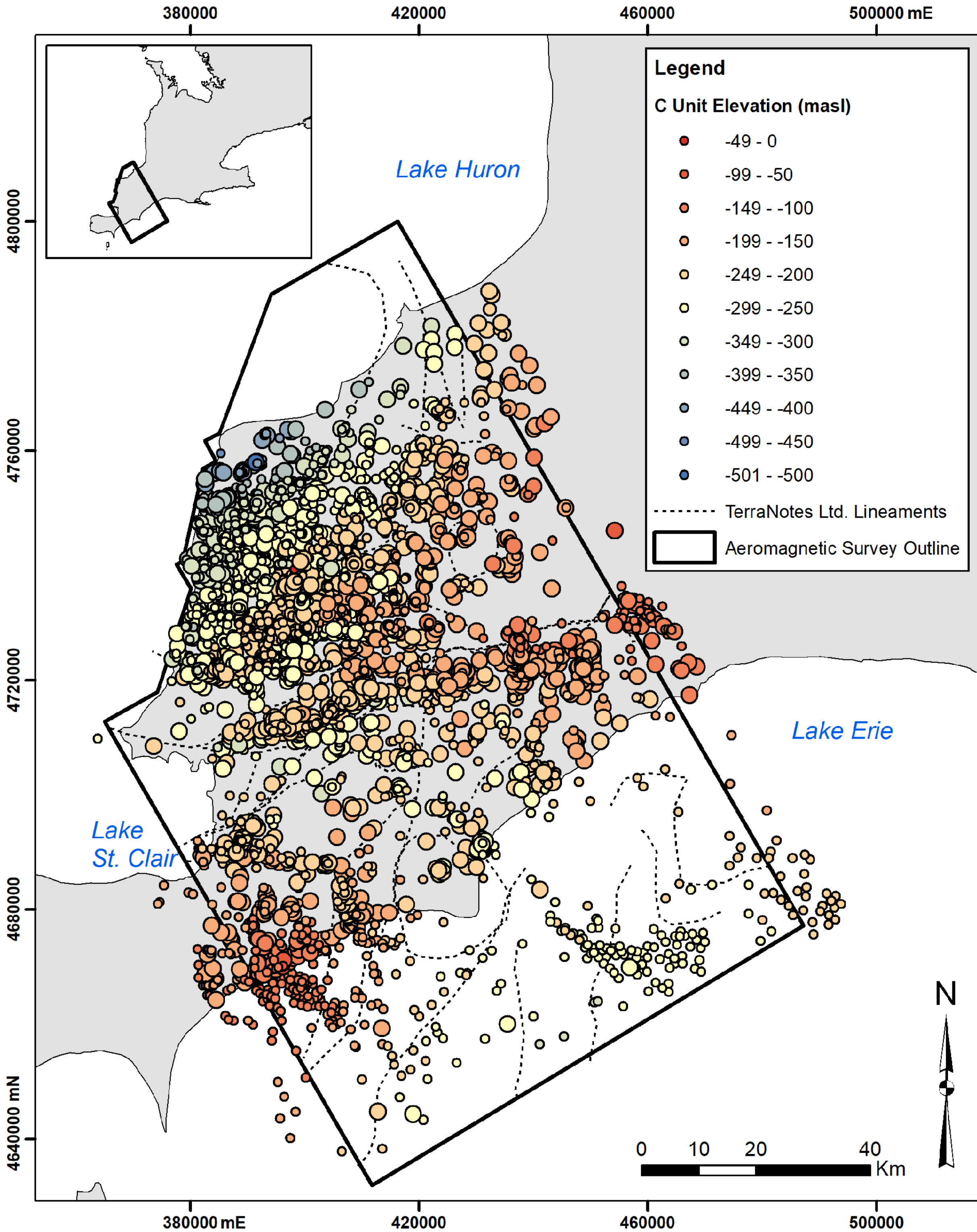

Figure 51. C Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

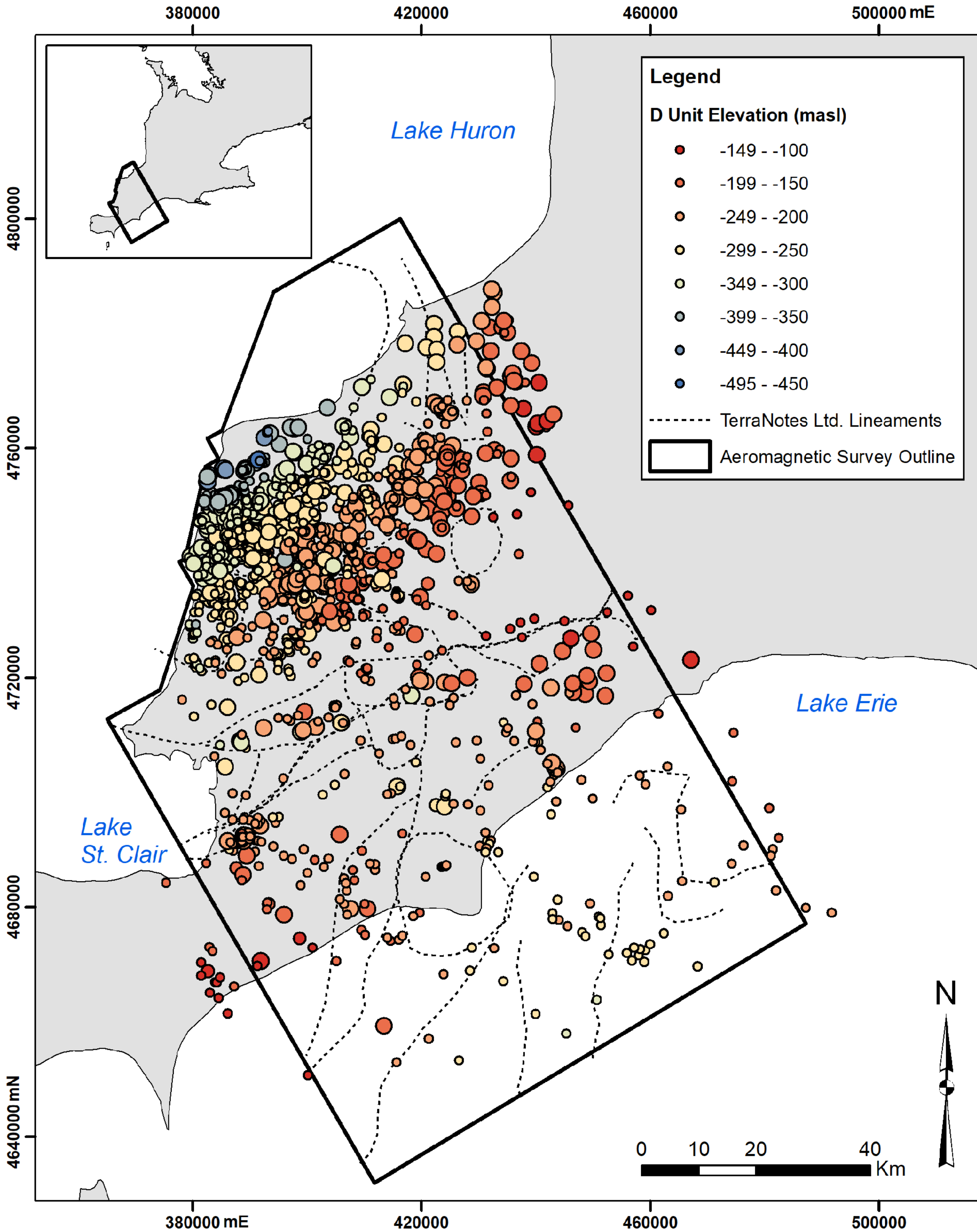

Figure 52. D Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

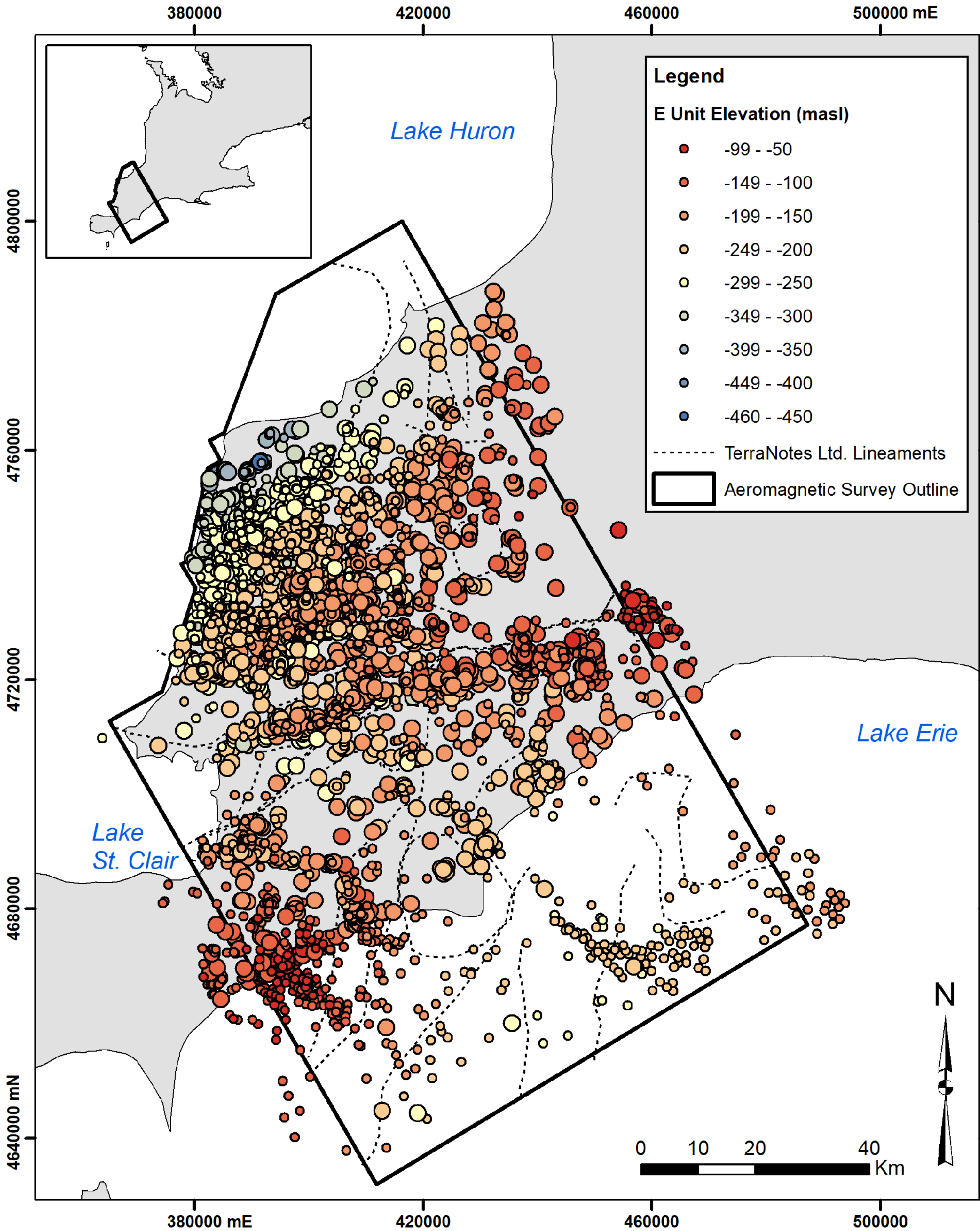

Figure 53. E Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

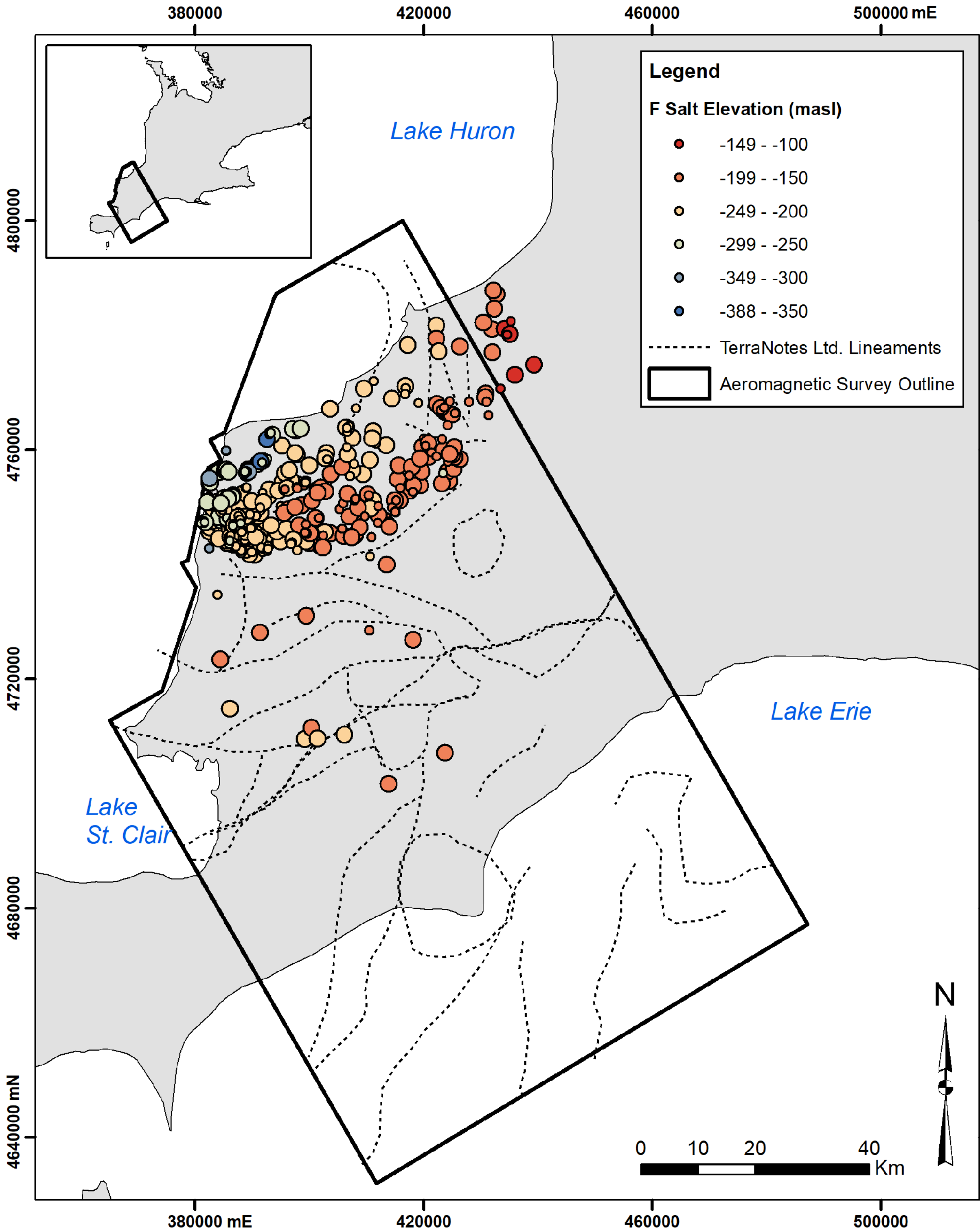

Figure 54. F Salt Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

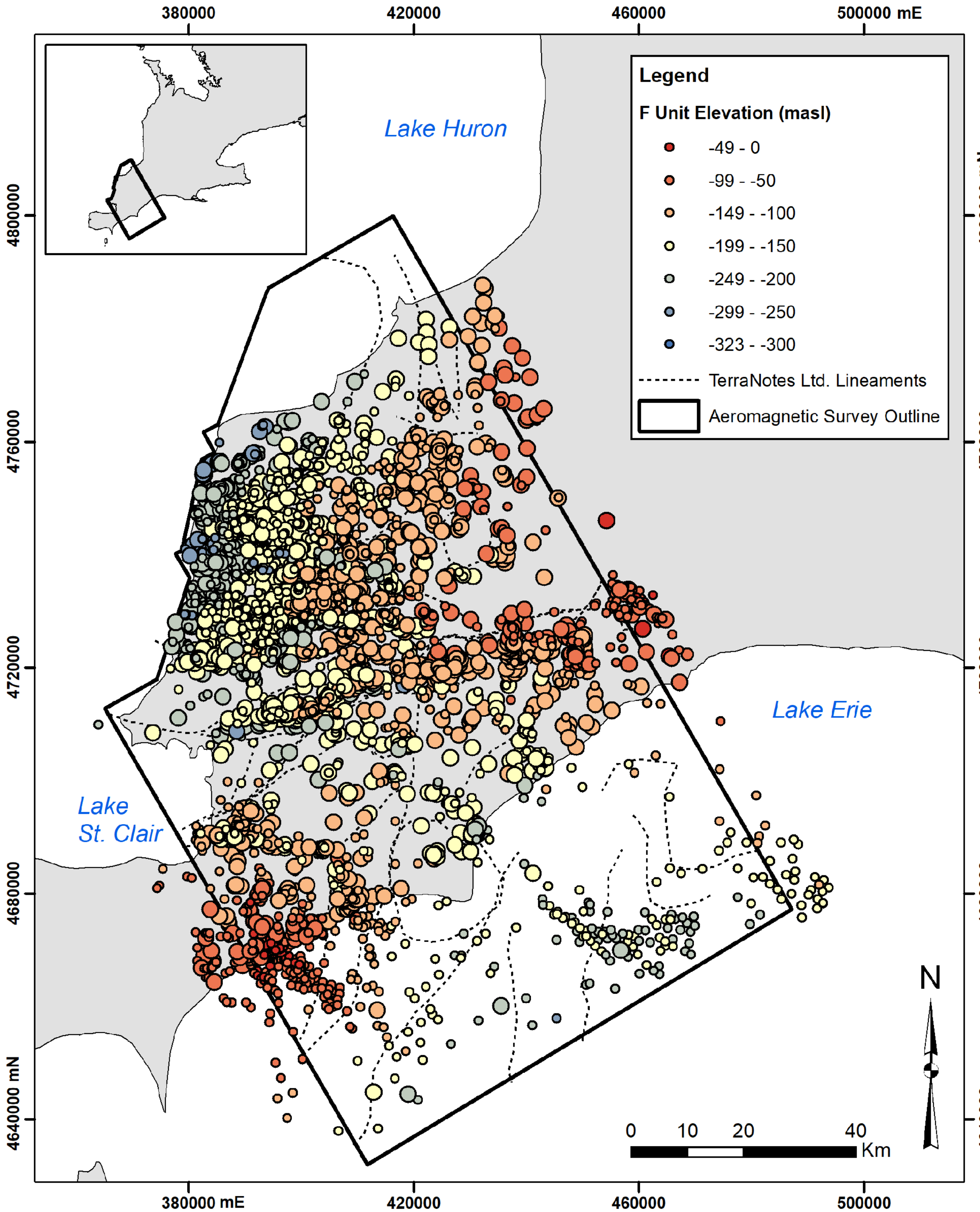

Figure 55. F Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

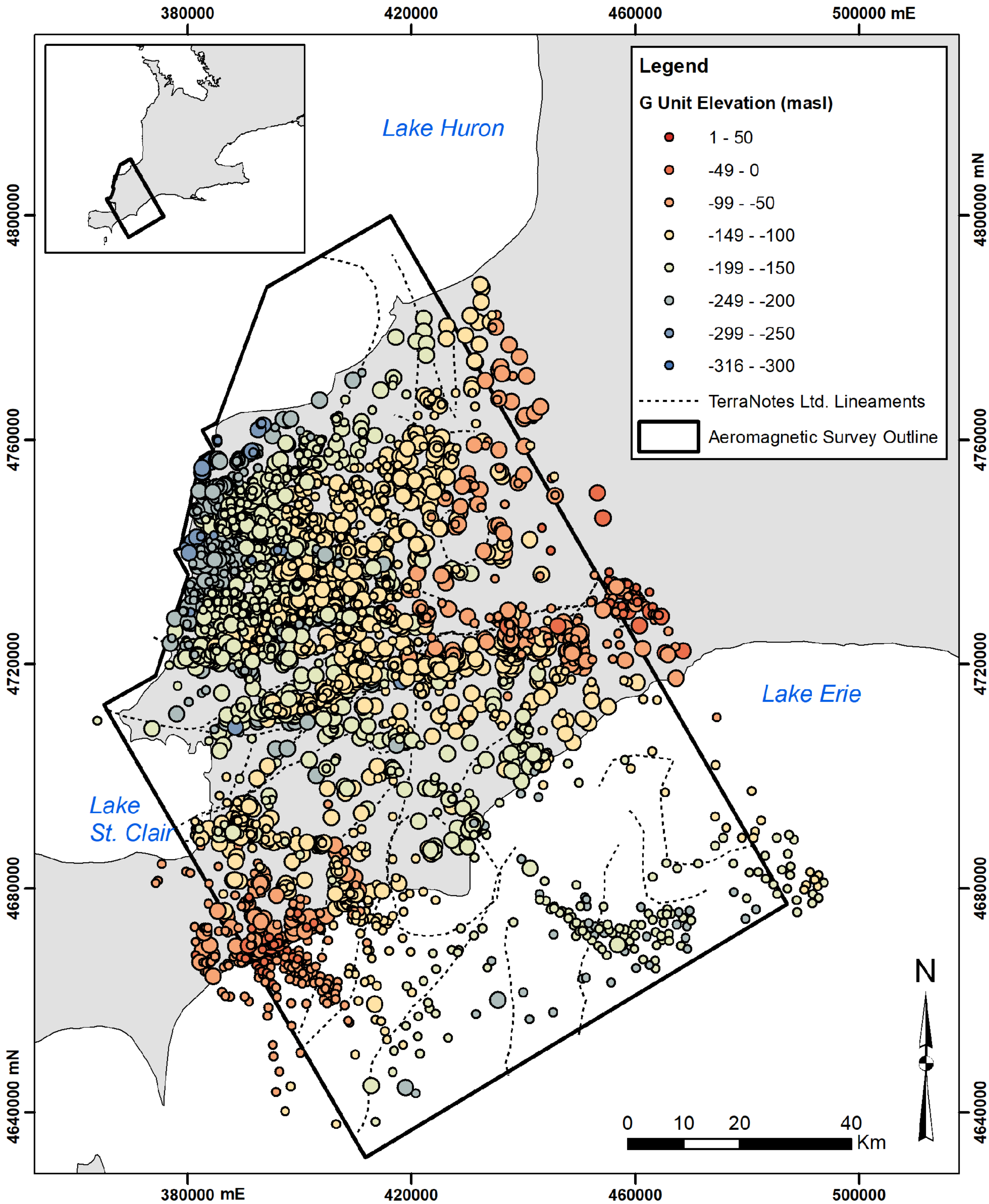

Figure 56. G Unit (Salina Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

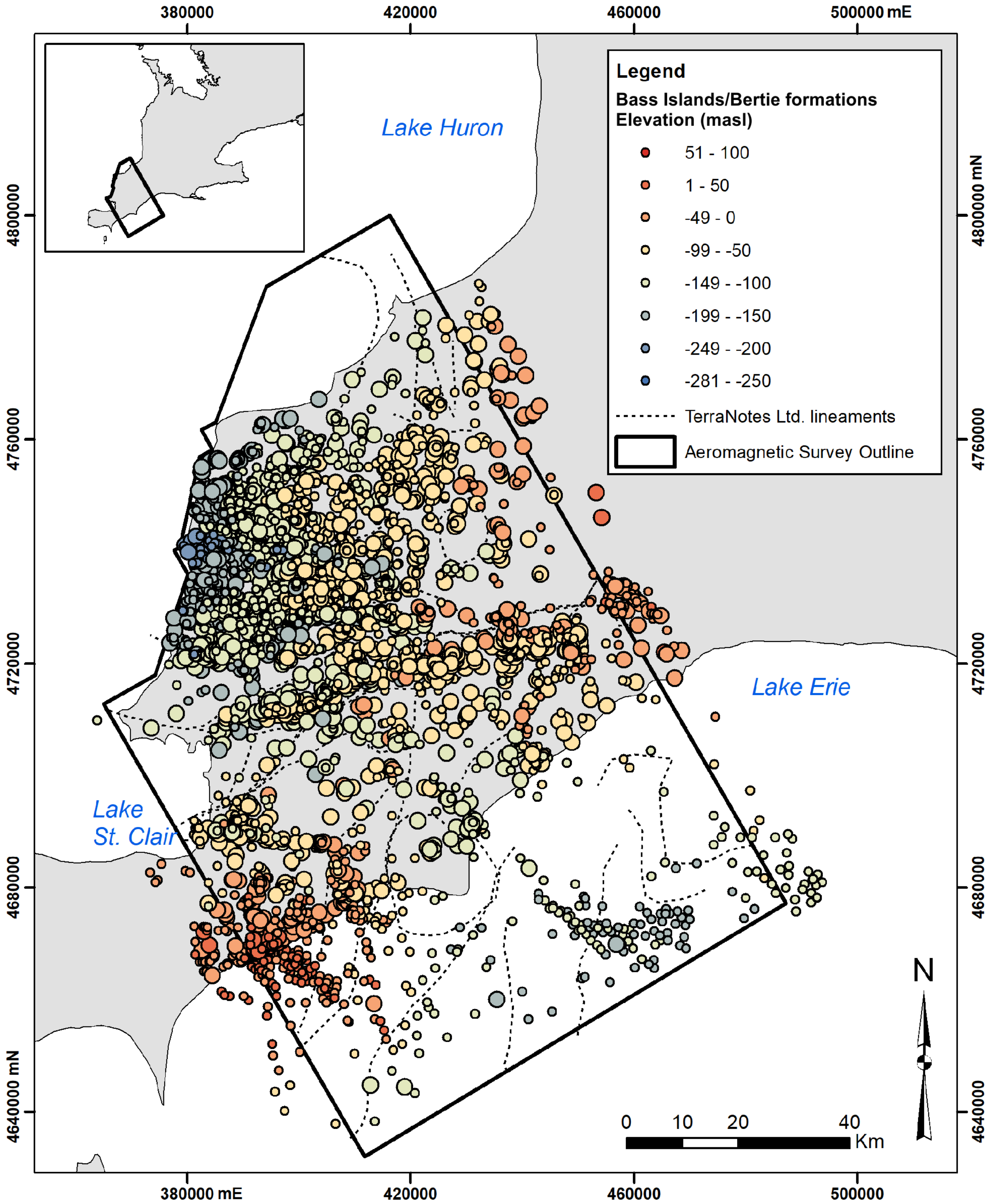

Figure 57. Bass Islands and Bertie formations elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviation: masl, metres above sea level.

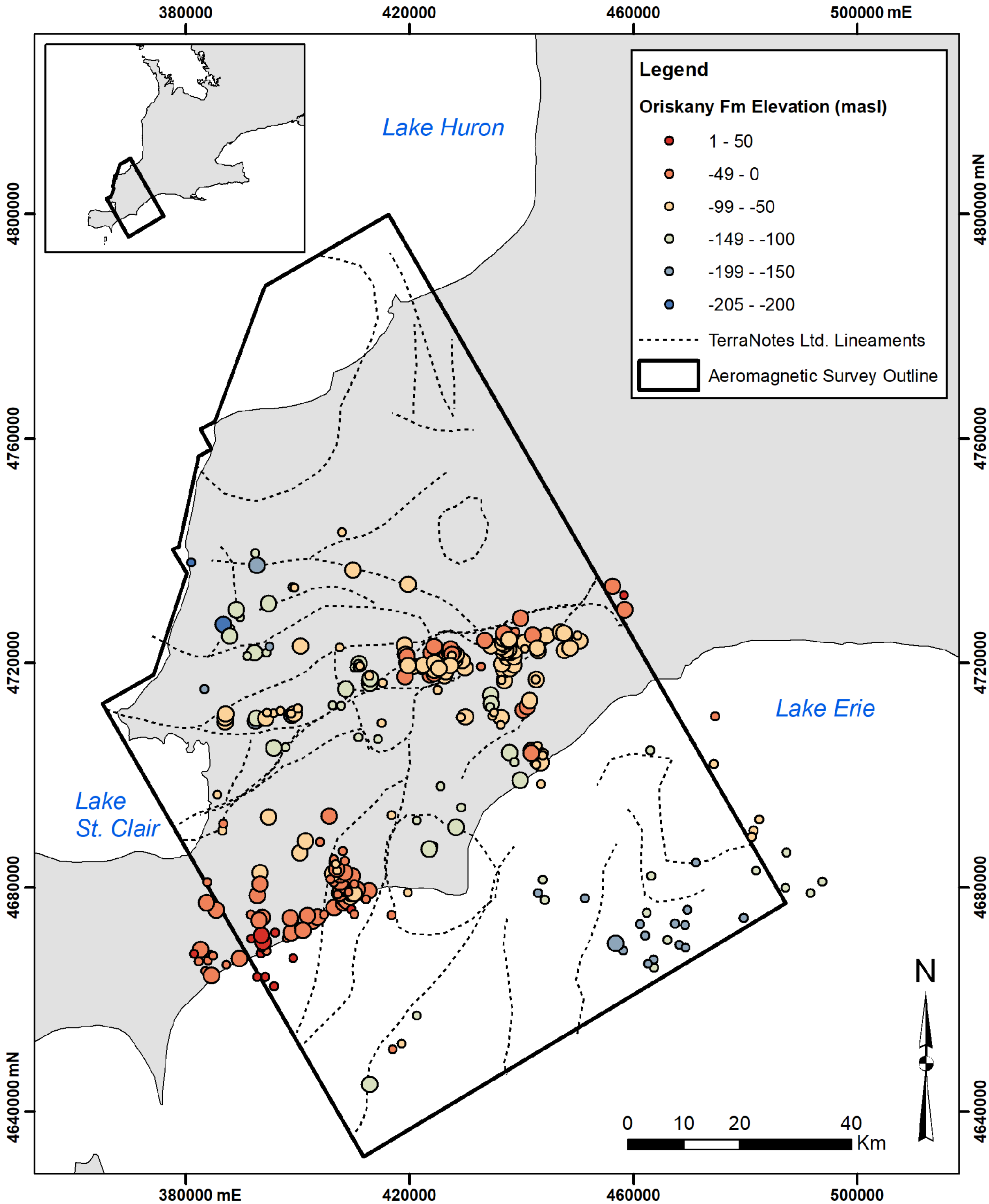

Figure 58. Oriskany Formation elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

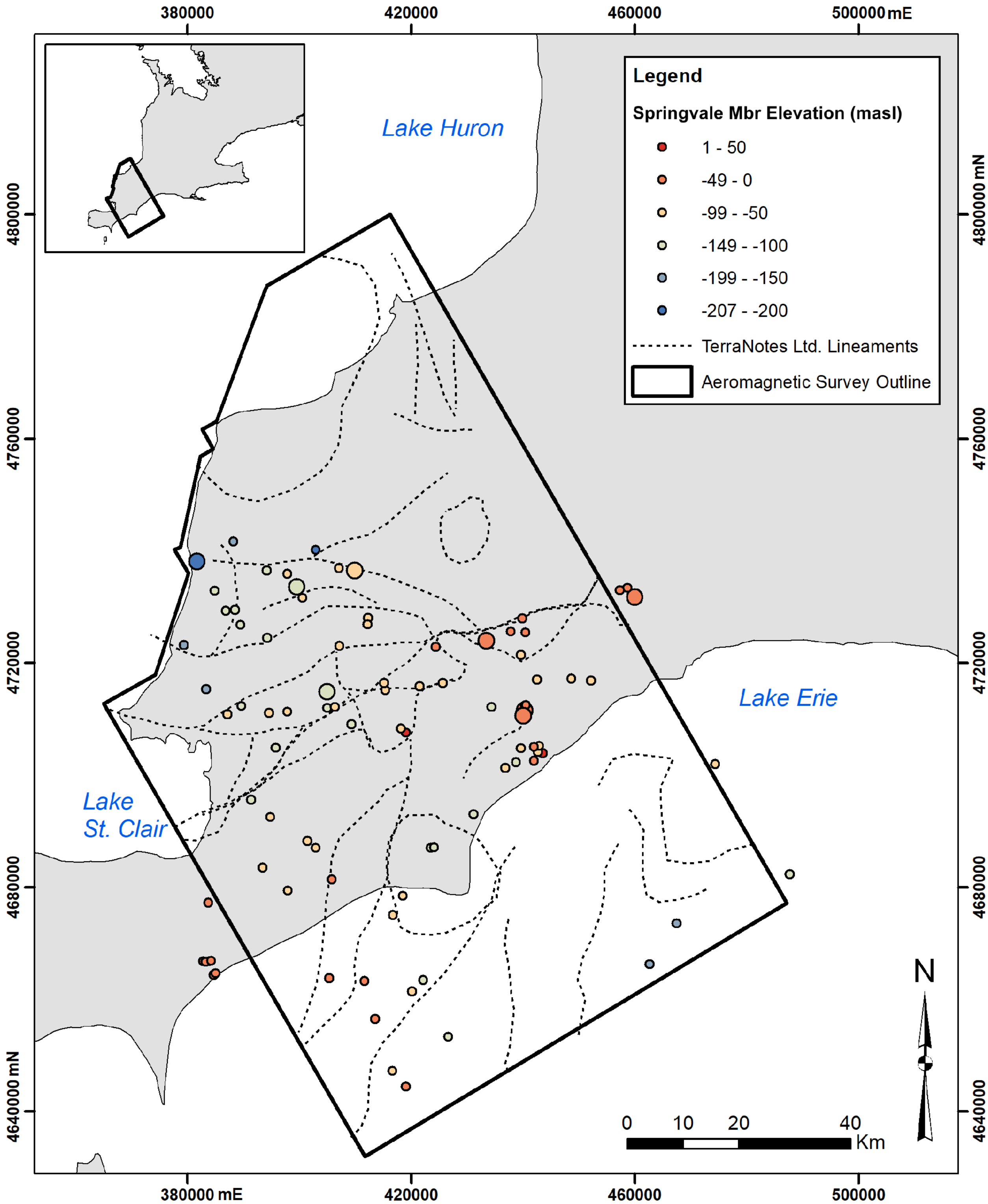

Figure 59. Springvale Member of the Bois Blanc Formation elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Mbr, Member; masl, metres above sea level.

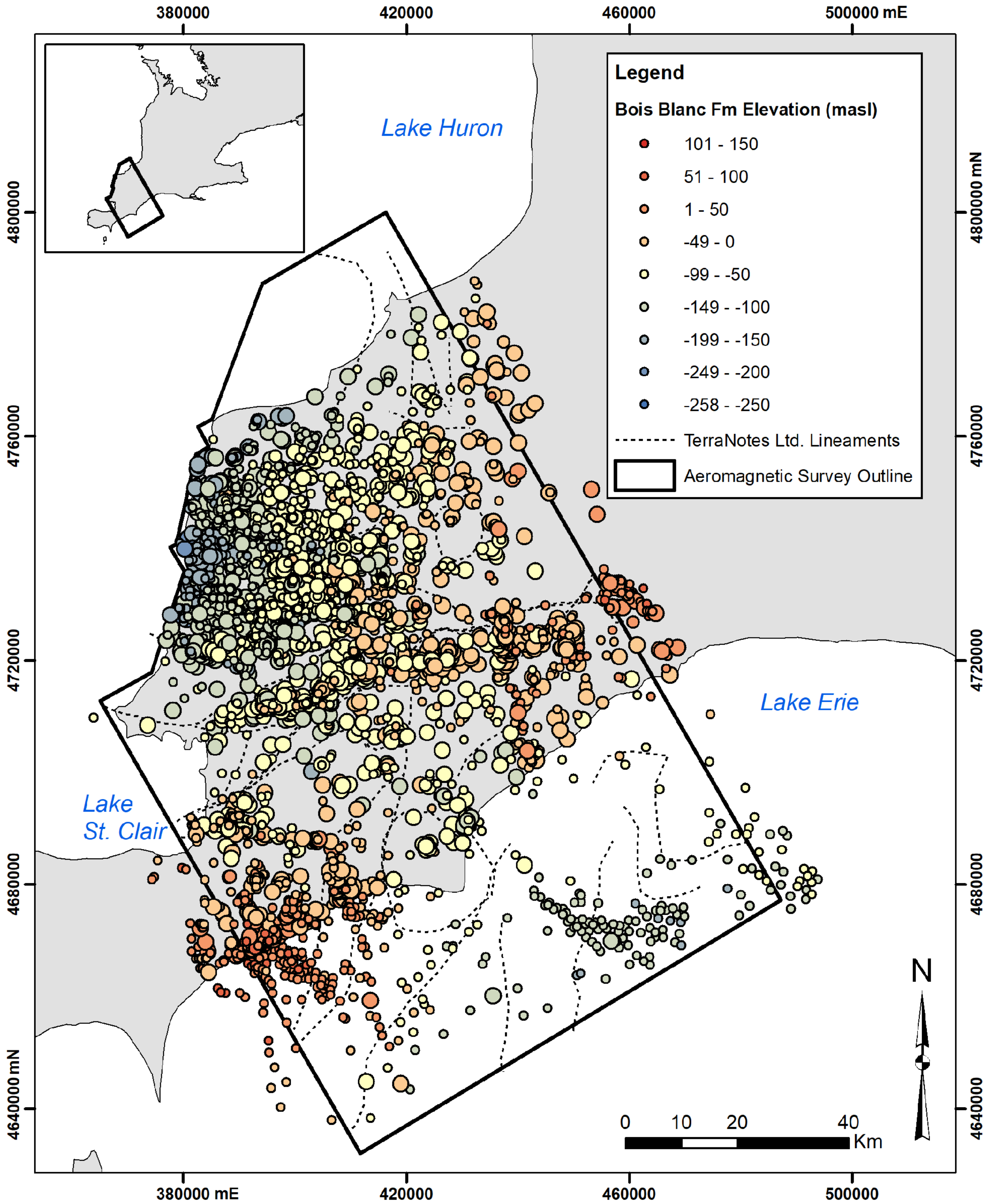

Figure 60. Bois Blanc Formation elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

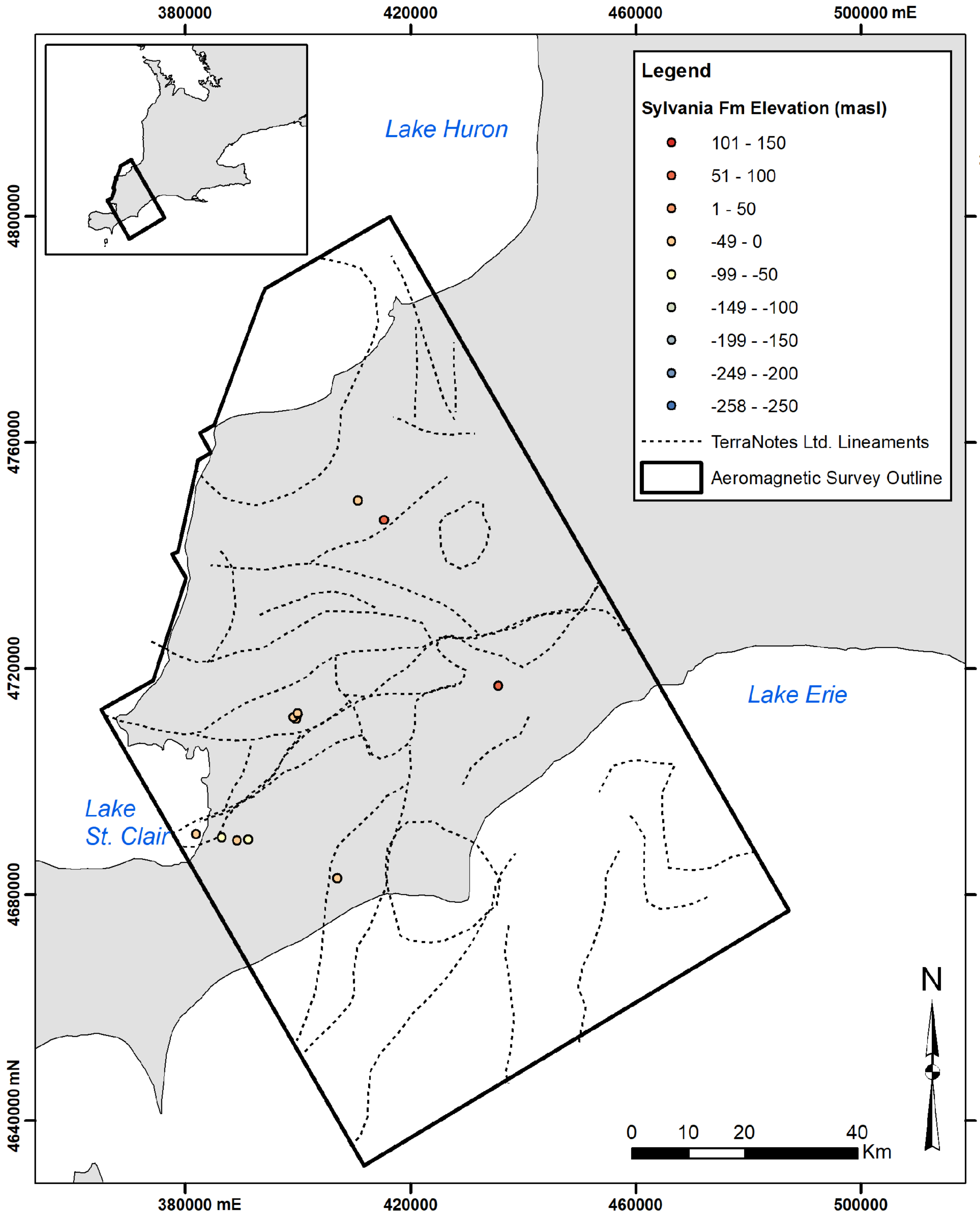

Figure 61. Sylvania Formation (Detroit River Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

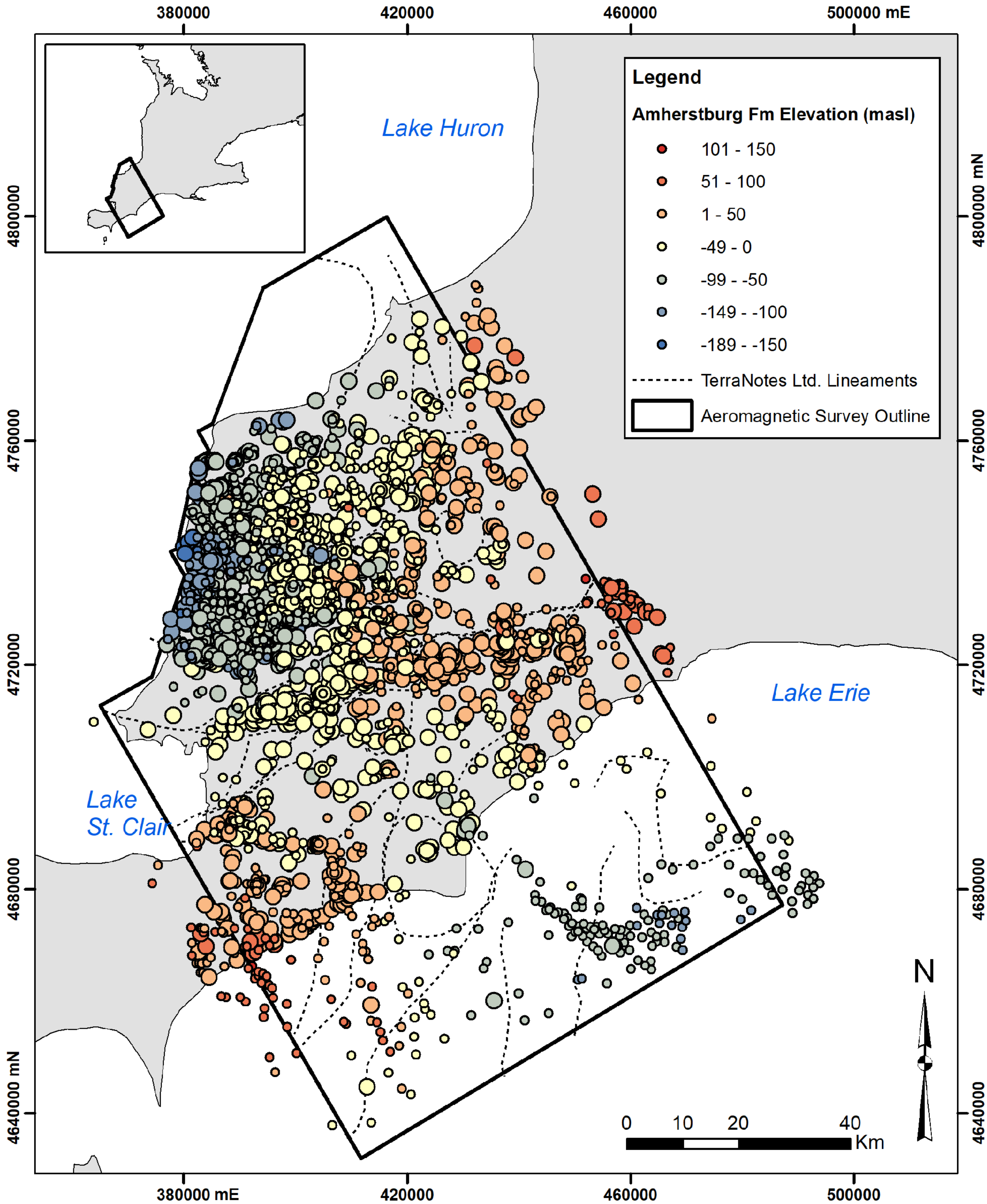

Figure 62. Amherstburg Formation (Detroit River Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

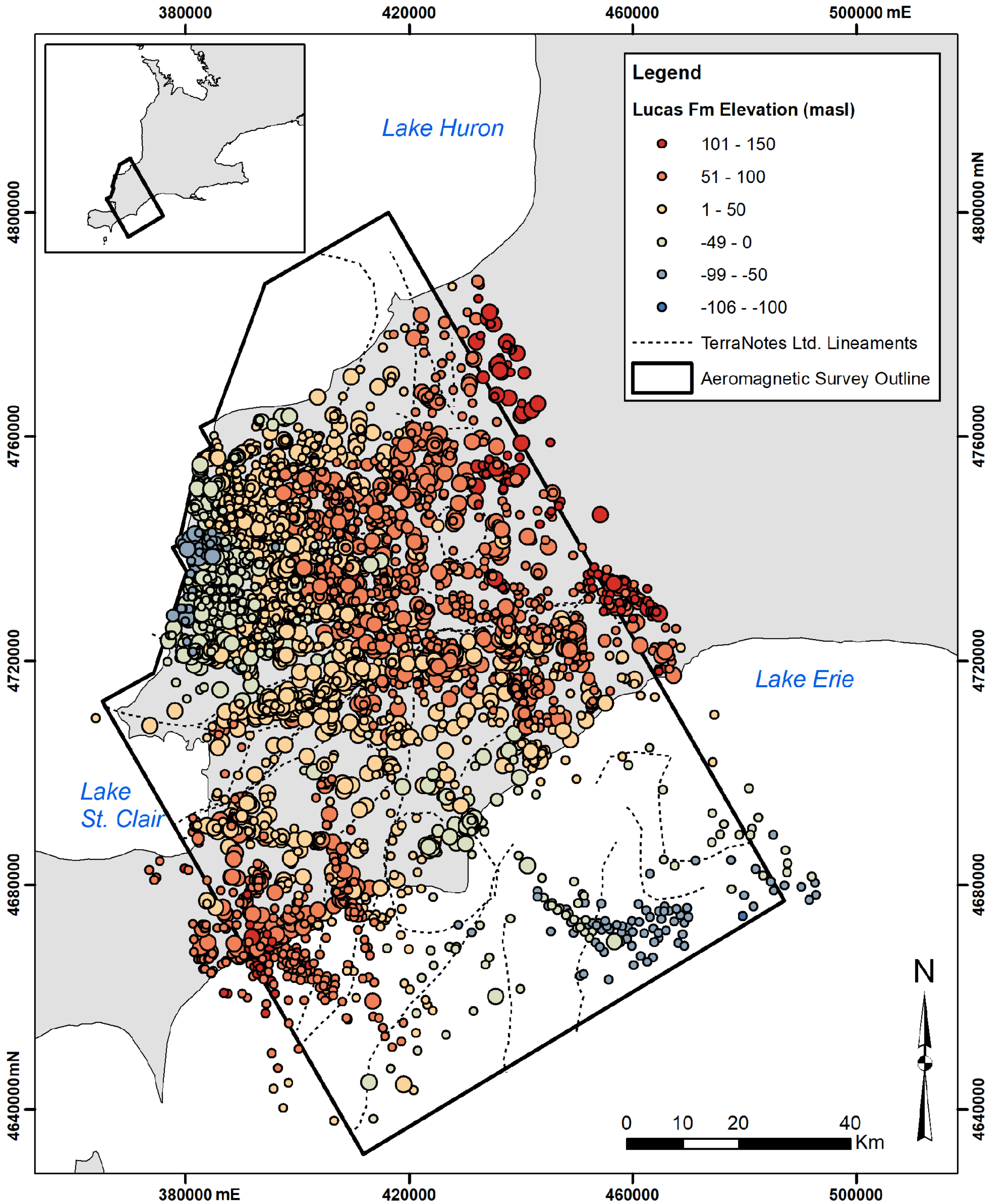

Figure 63. Lucas Formation (Detroit River Group) elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

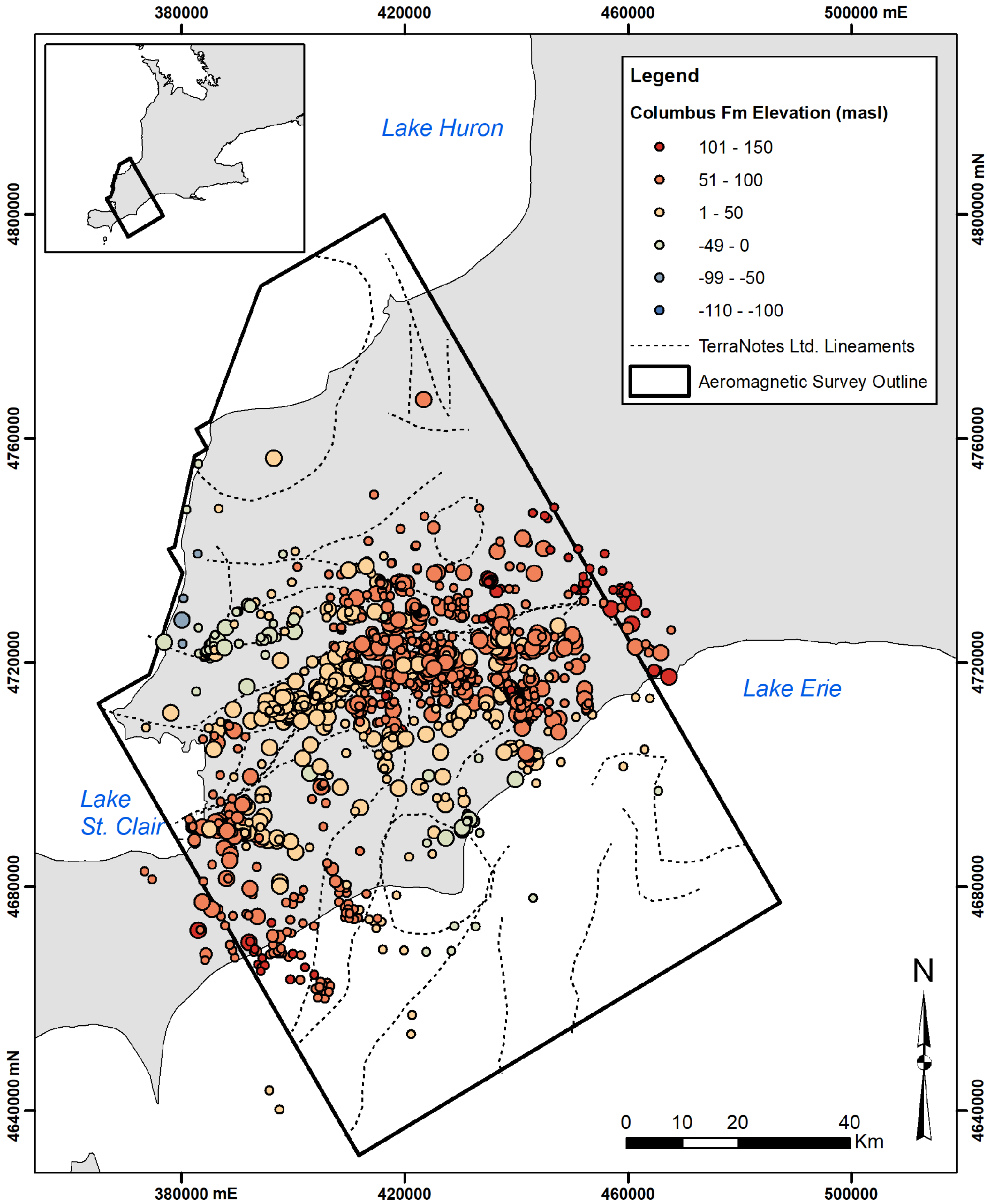

Figure 64. Columbus Formation elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

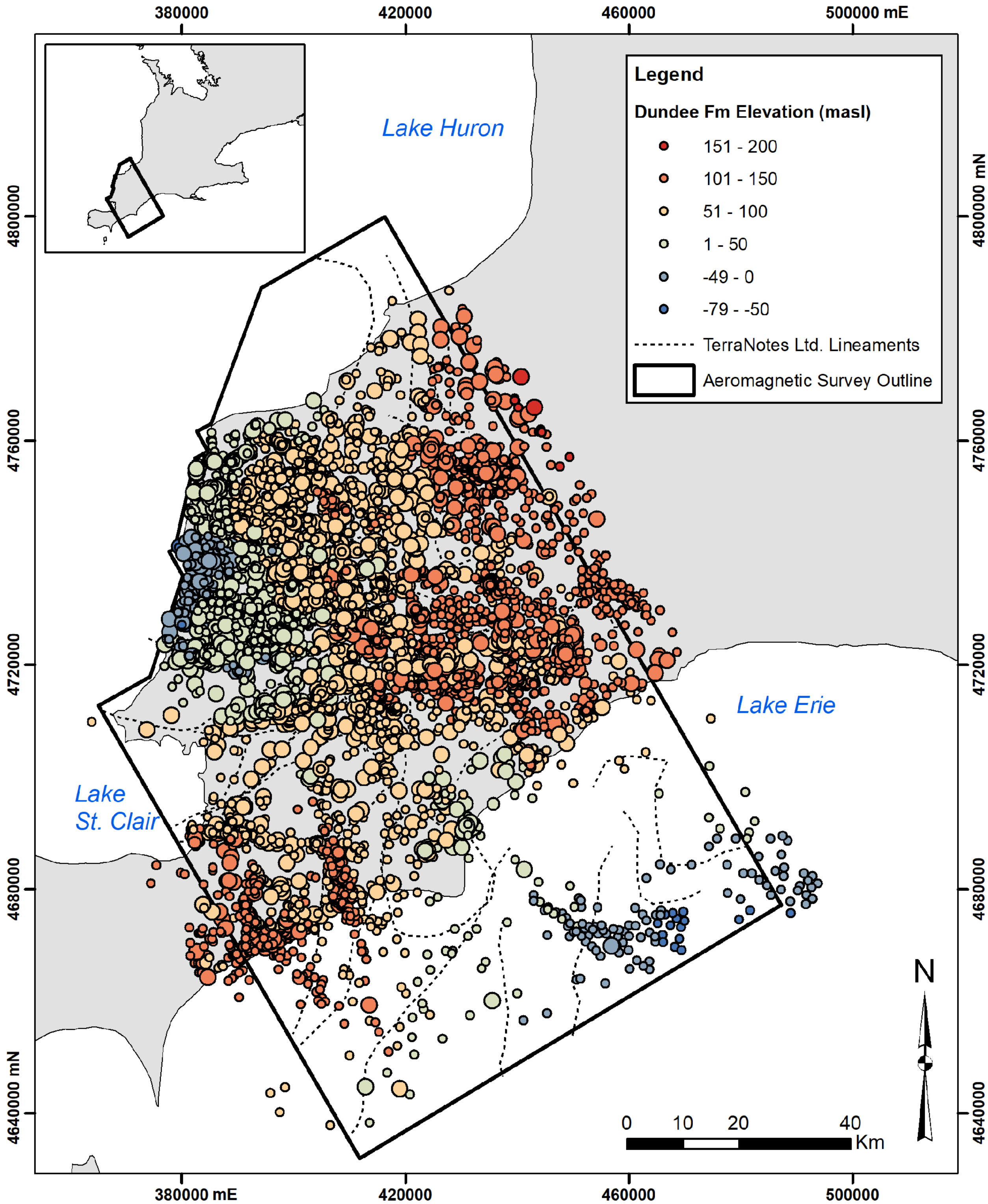

Figure 65. Dundee Formation elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

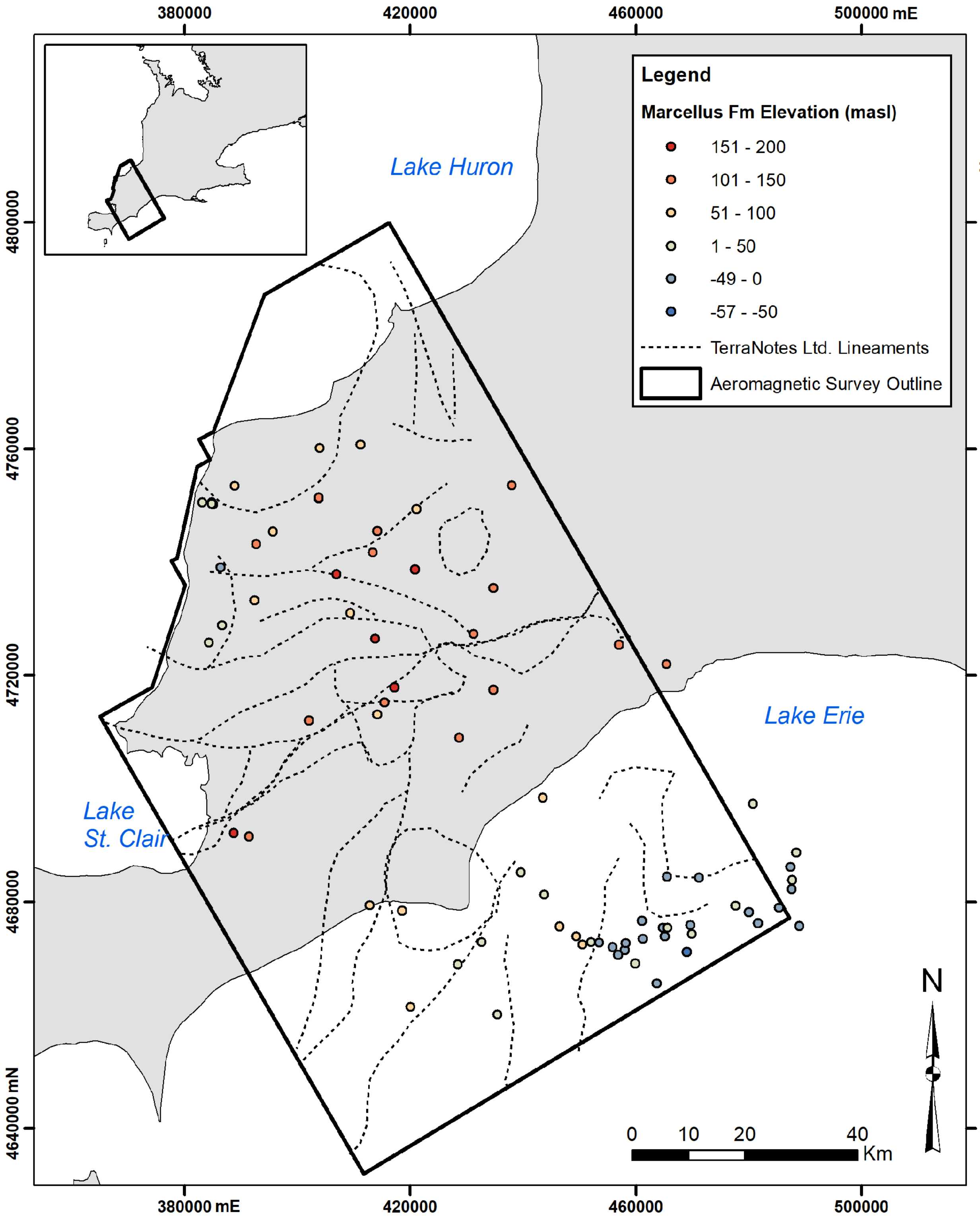

Figure 66. Marcellus Formation elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

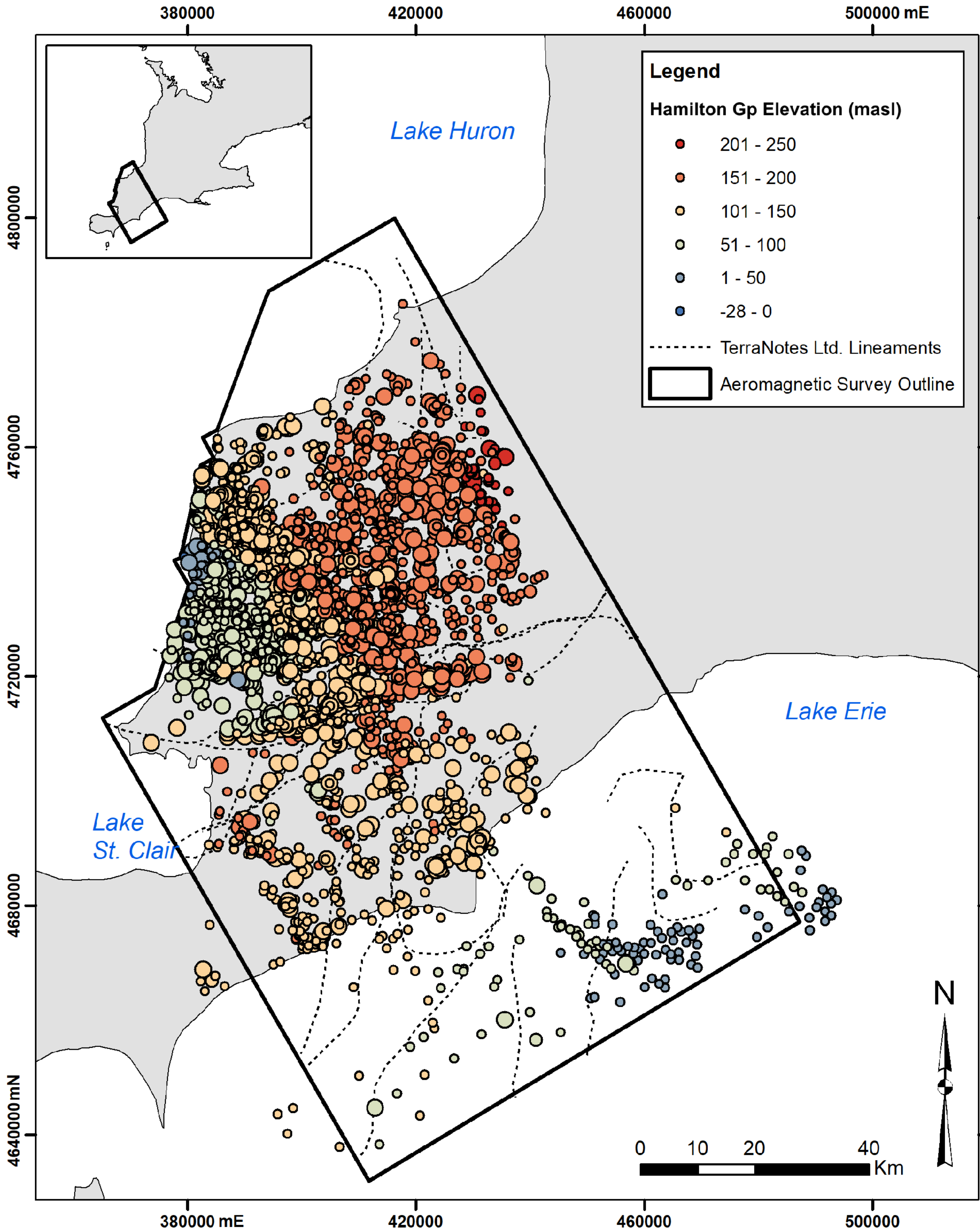

Figure 67. Hamilton Group elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Gp, Group; masl, metres above sea level.

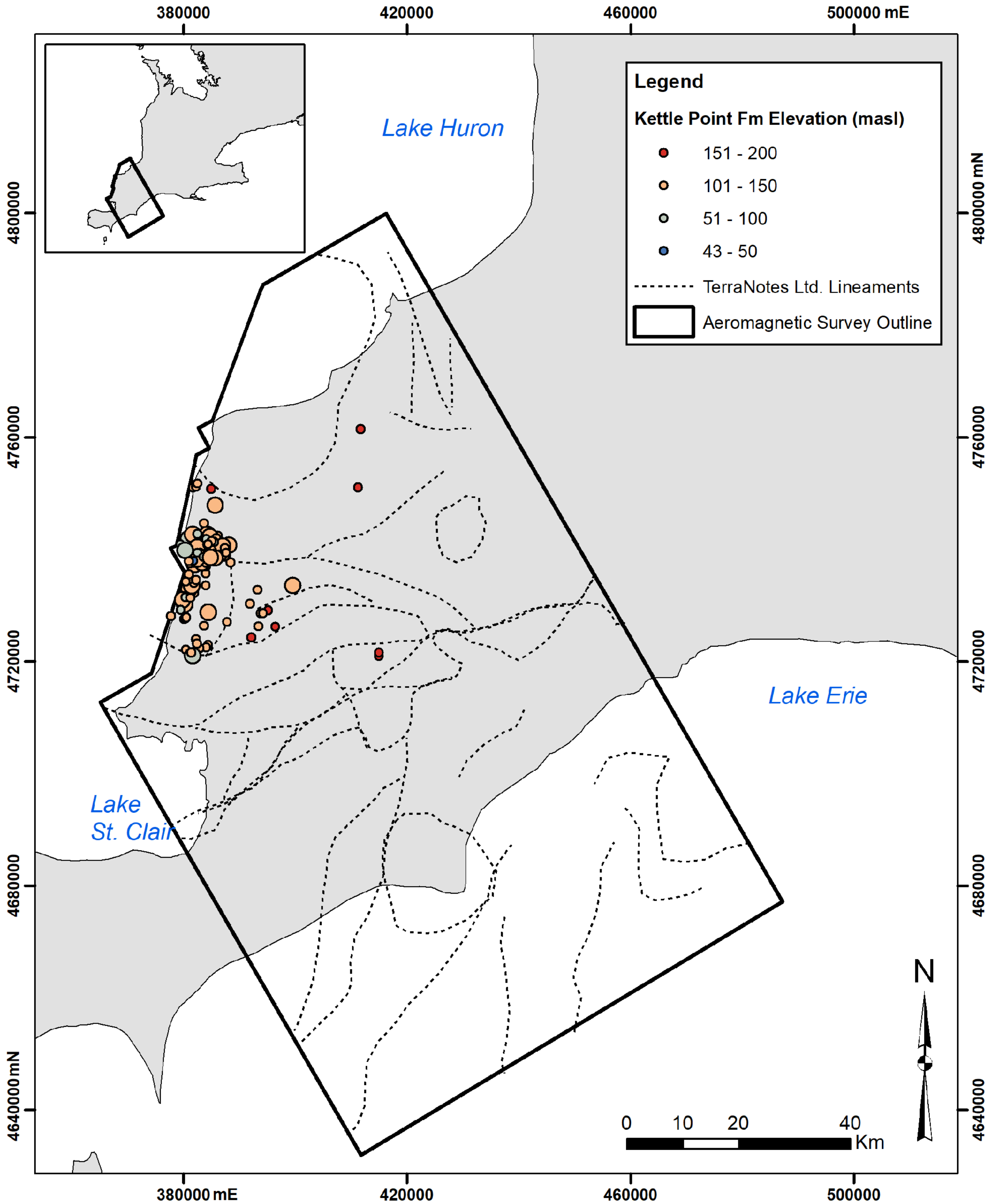

Figure 68. Kettle Point Formation elevation for wells within the study area. Lineaments *from* Ontario Geological Survey (2014). Abbreviations: Fm, Formation; masl, metres above sea level.

Appendix 2.

Local Elevation Maps

This appendix contains elevation dot maps, focussing on single or small group of TerraNotes Ltd. lineaments.

Size of symbols (dots) reflects the QA code (*see* Figure 13).

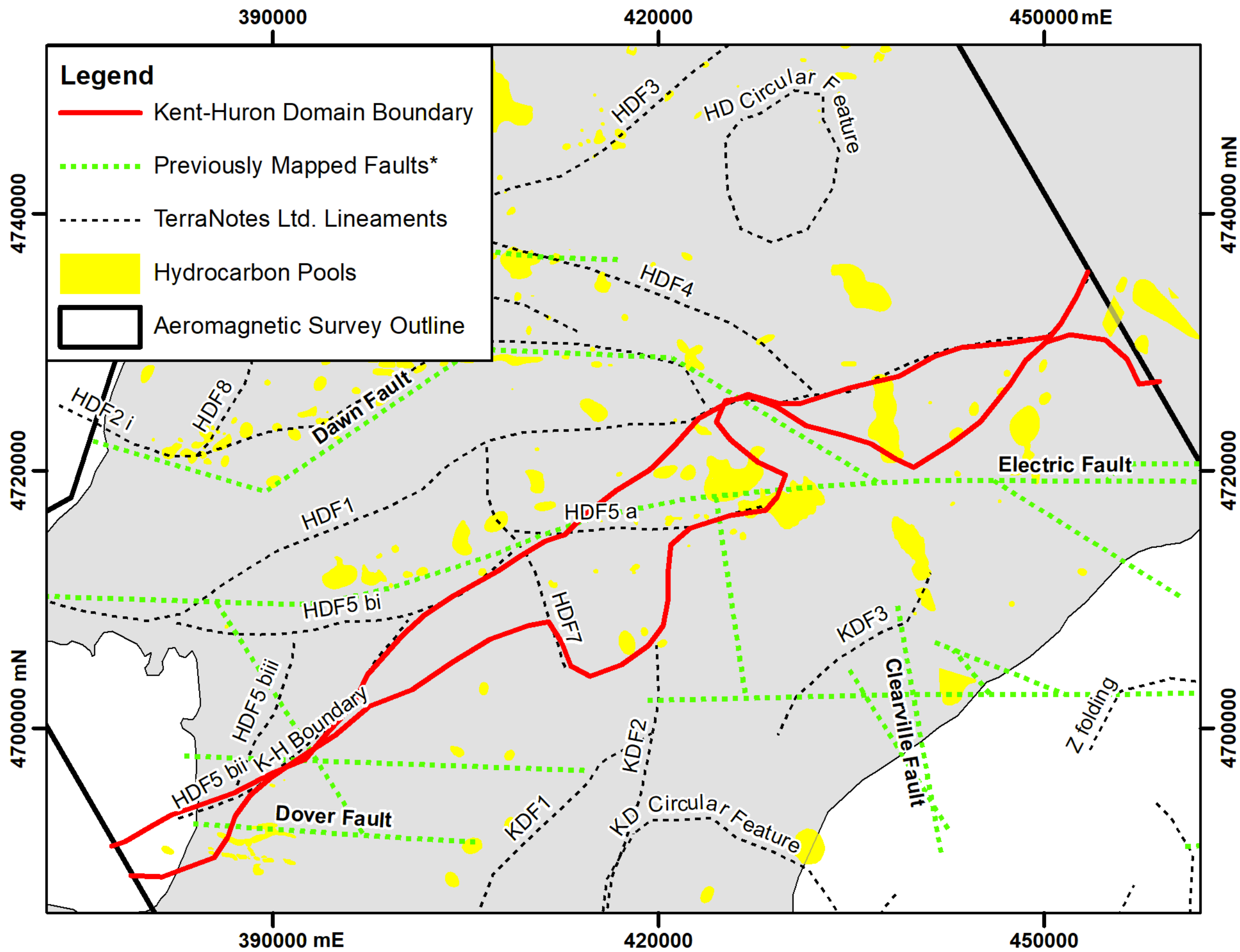

Figure 69. Location of Kent–Huron domains boundary compared to previously mapped faults, other TerraNotes Ltd. lineaments and known hydrocarbon pools. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

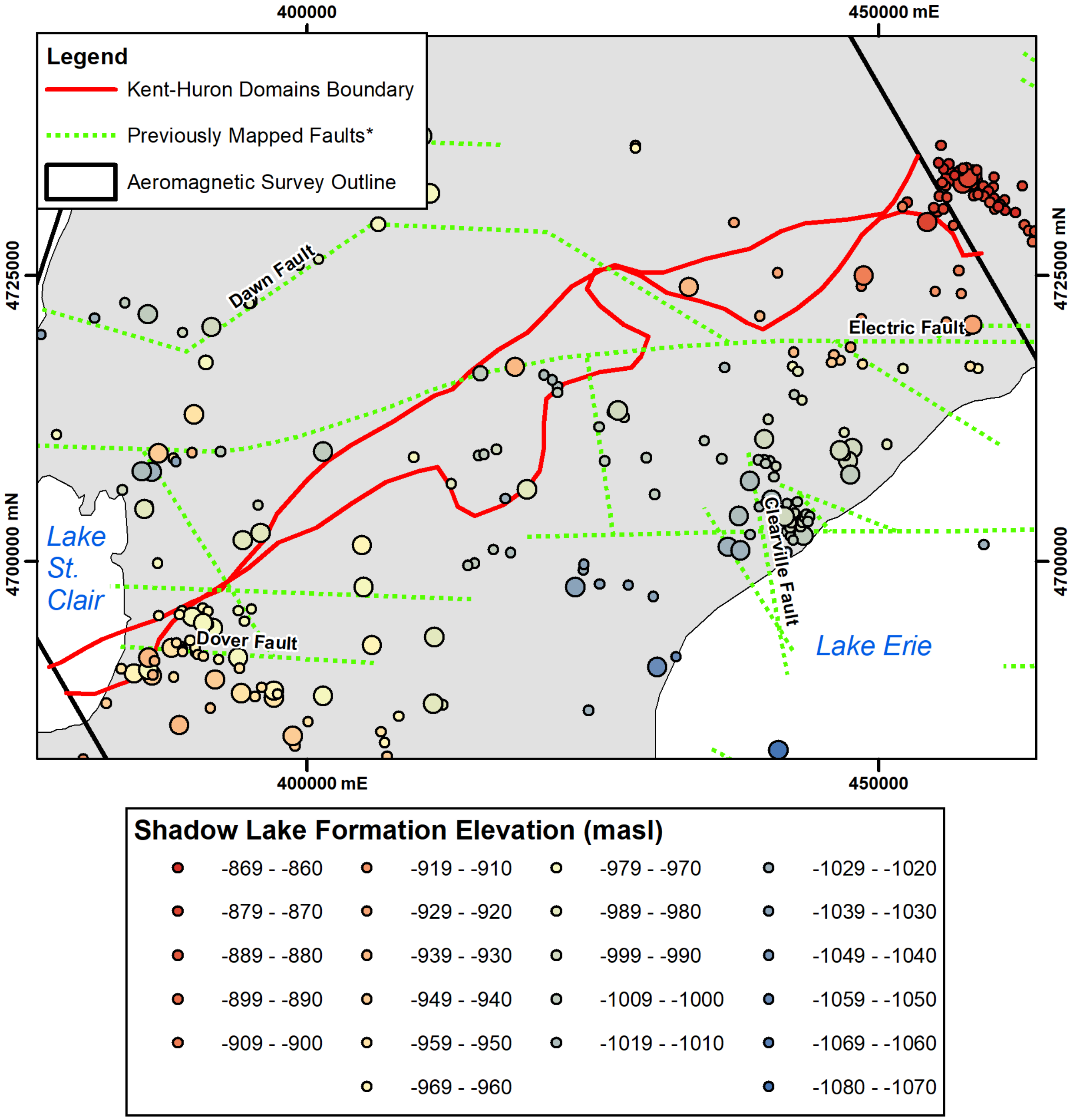

Figure 70. Shadow Lake Formation (Black River Group) elevation around the Kent–Huron domains boundary. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

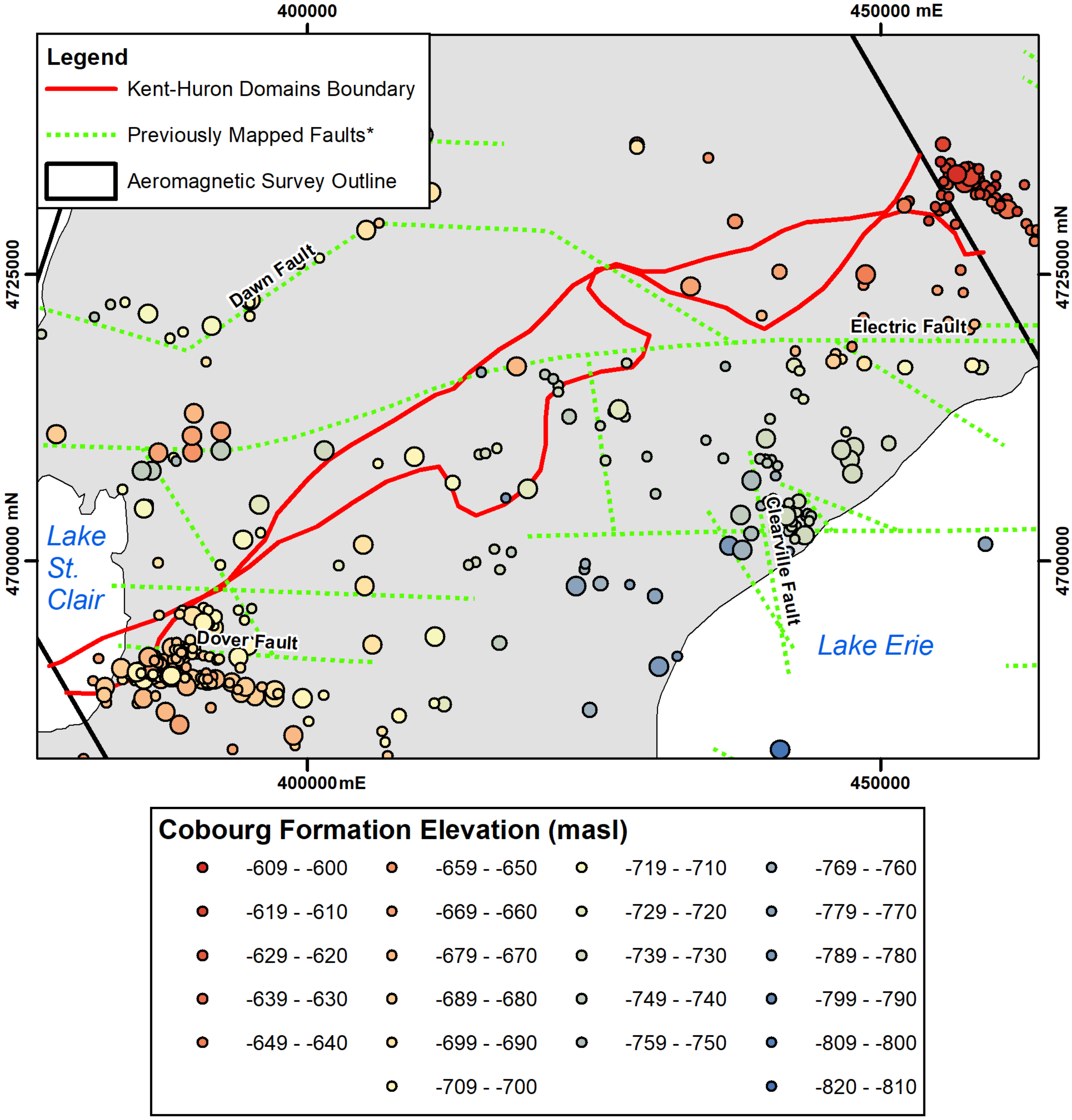

Figure 71. Cobourg Formation (Trenton Group) elevation around the Kent–Huron domains boundary. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

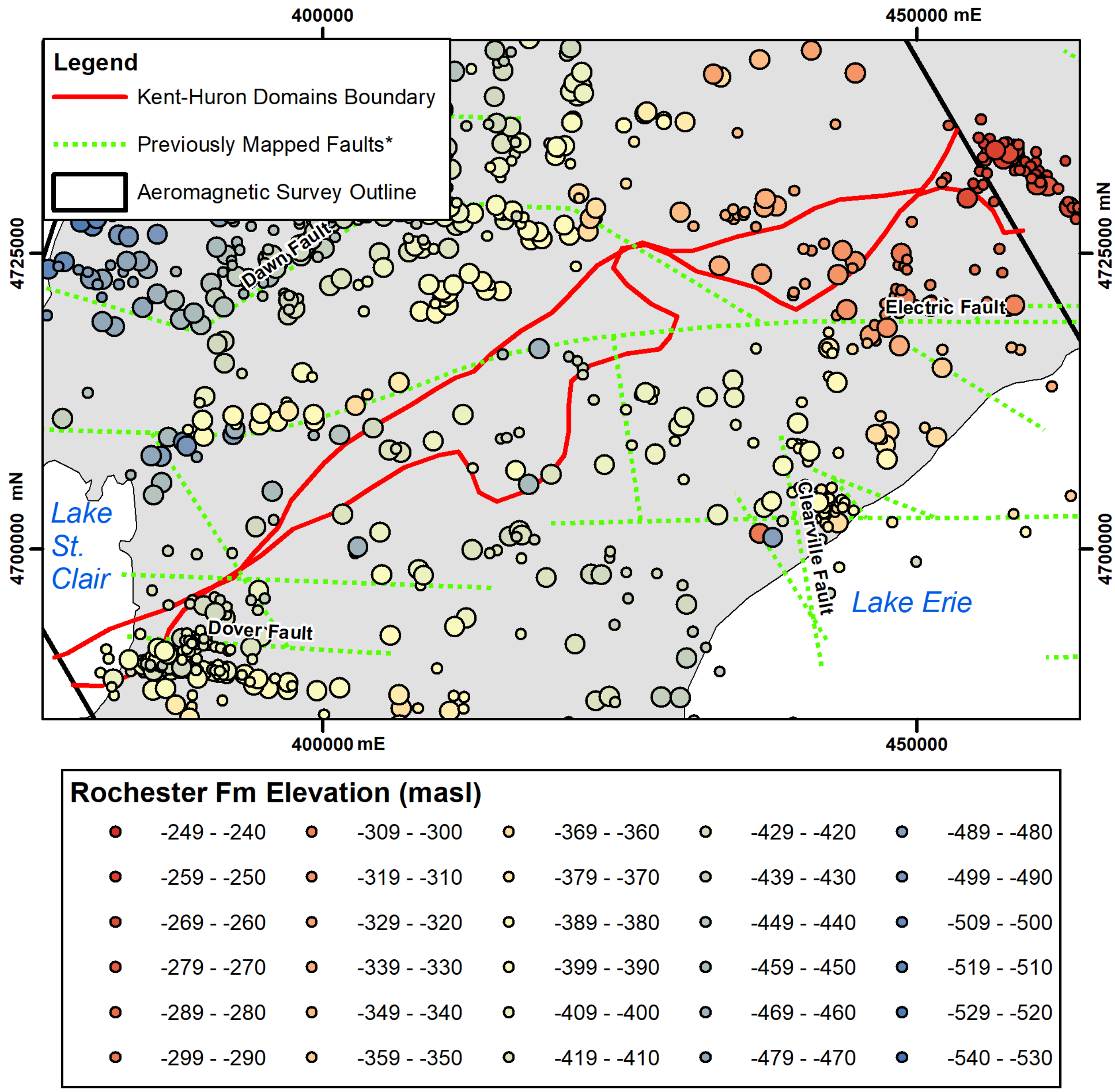

Figure 72. Rochester Formation (Clinton Group) elevation around the Kent–Huron domains boundary. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

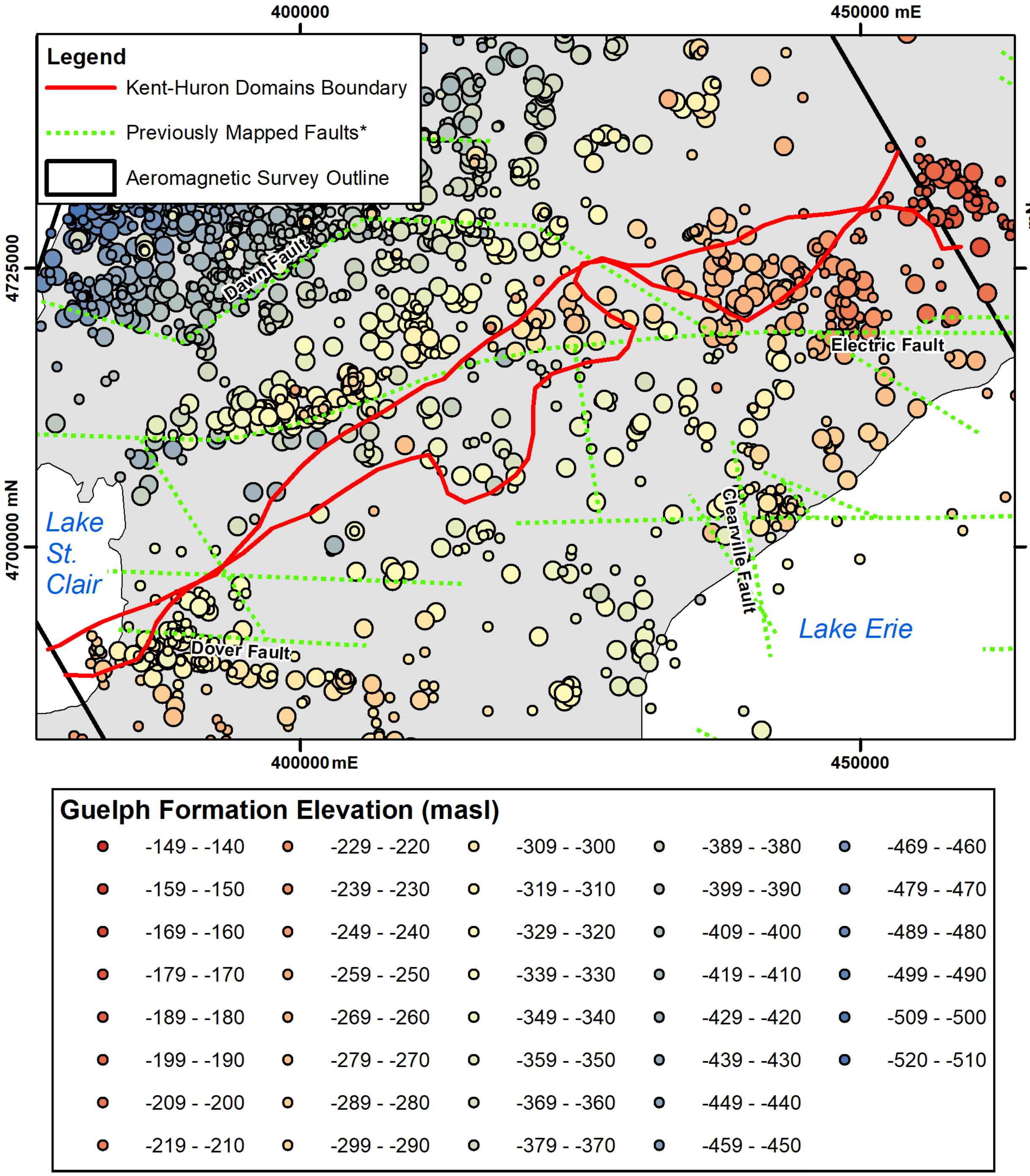

Figure 73. Guelph Formation (Lockport Group) elevation around the Kent–Huron domains boundary. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

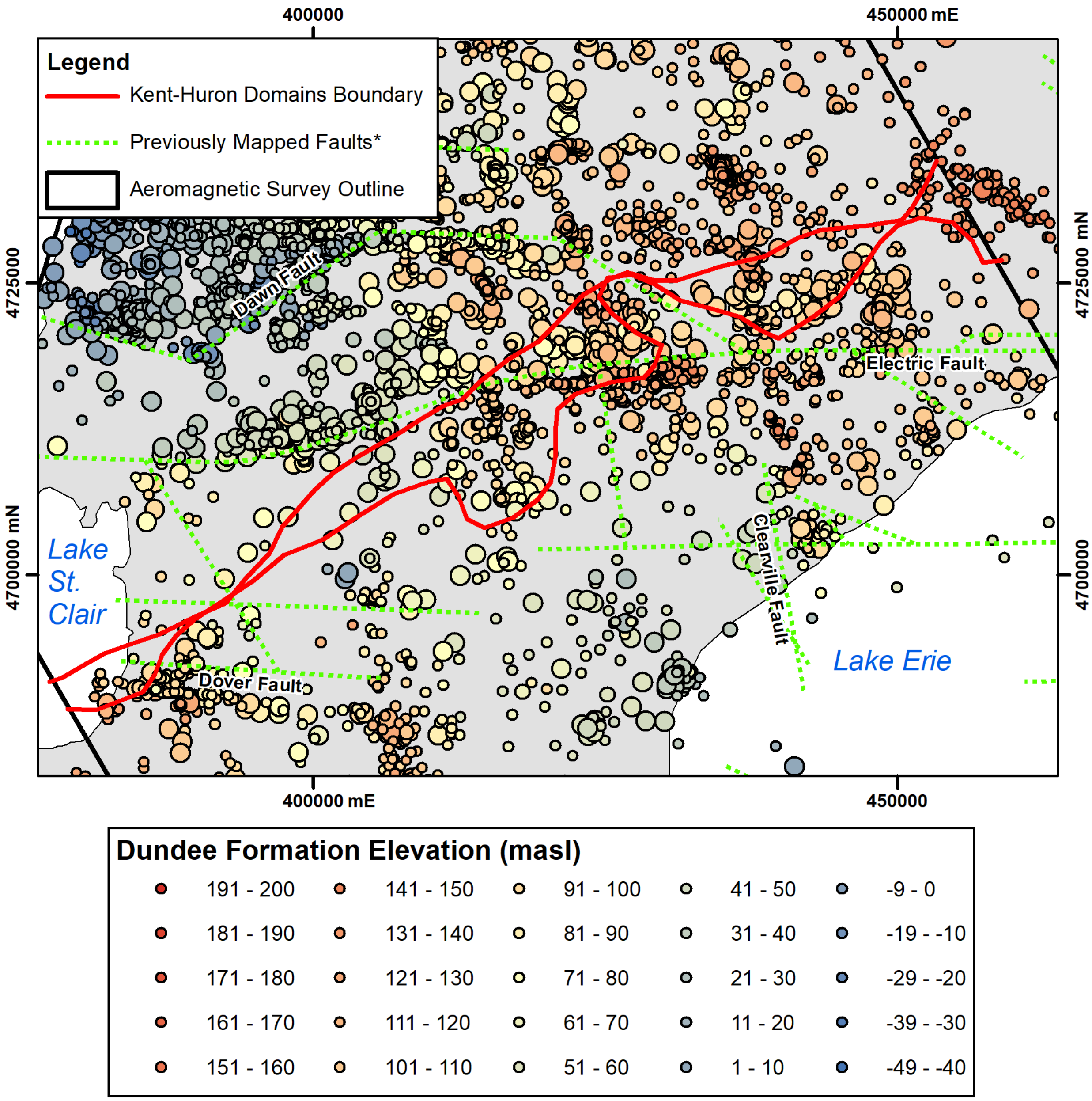

Figure 74. Dundee Formation elevation around the Kent–Huron domains boundary. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

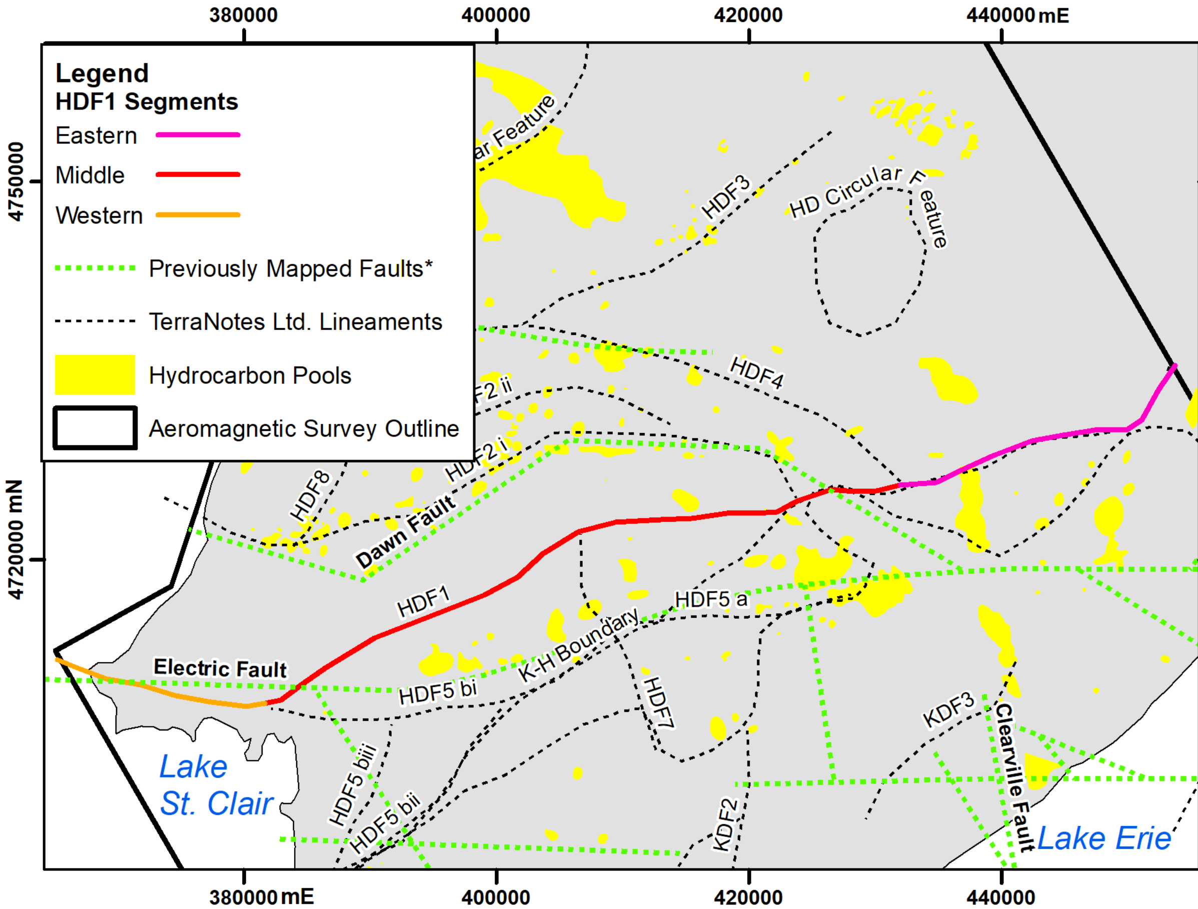

Figure 75. Locations of western, middle and eastern portions of the HDF1 lineament compared to previously mapped faults, other TerraNotes Ltd. lineaments and known hydrocarbon pools. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

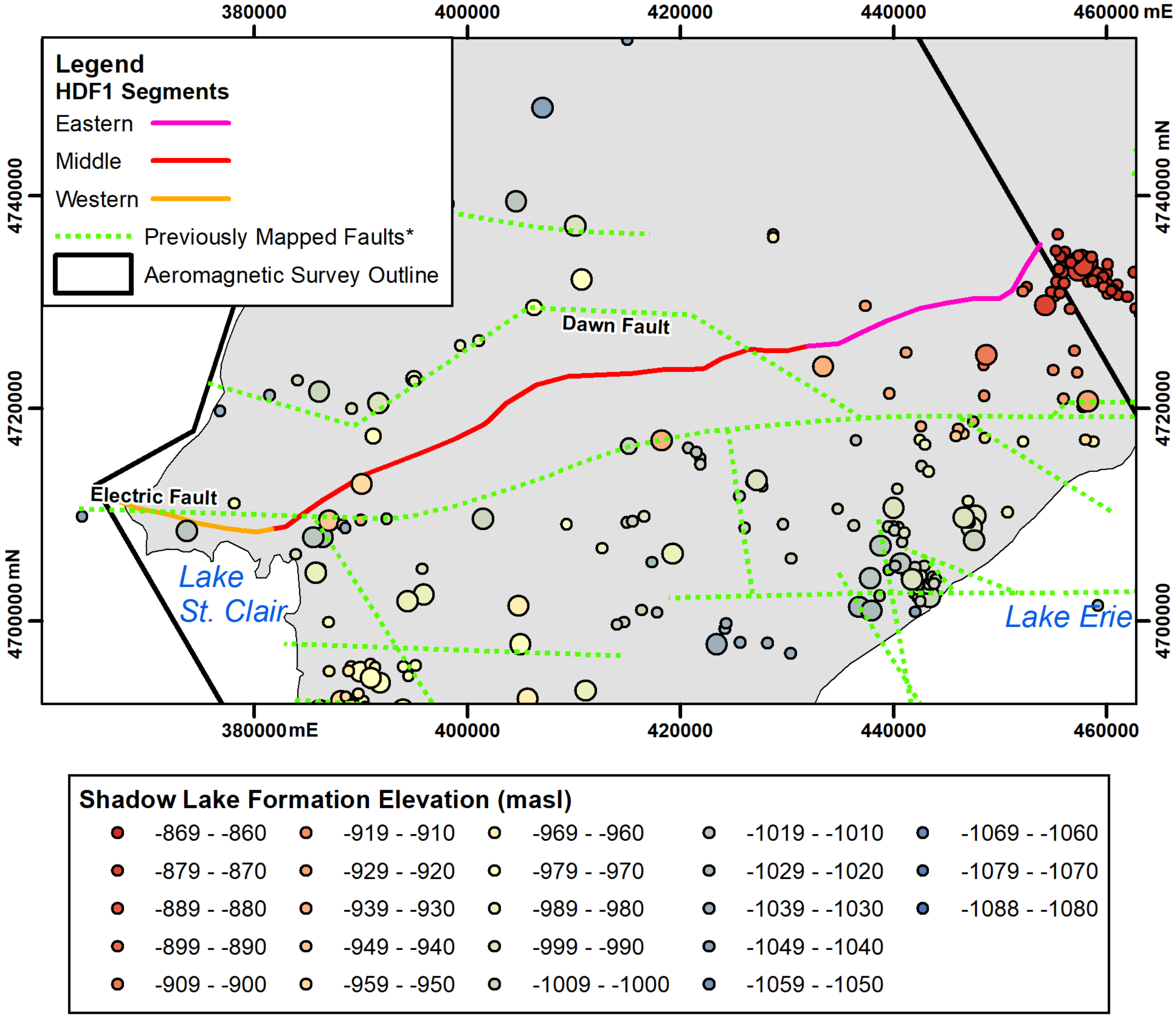

Figure 76. Shadow Lake Formation (Black River Group) elevation around the HDF1 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

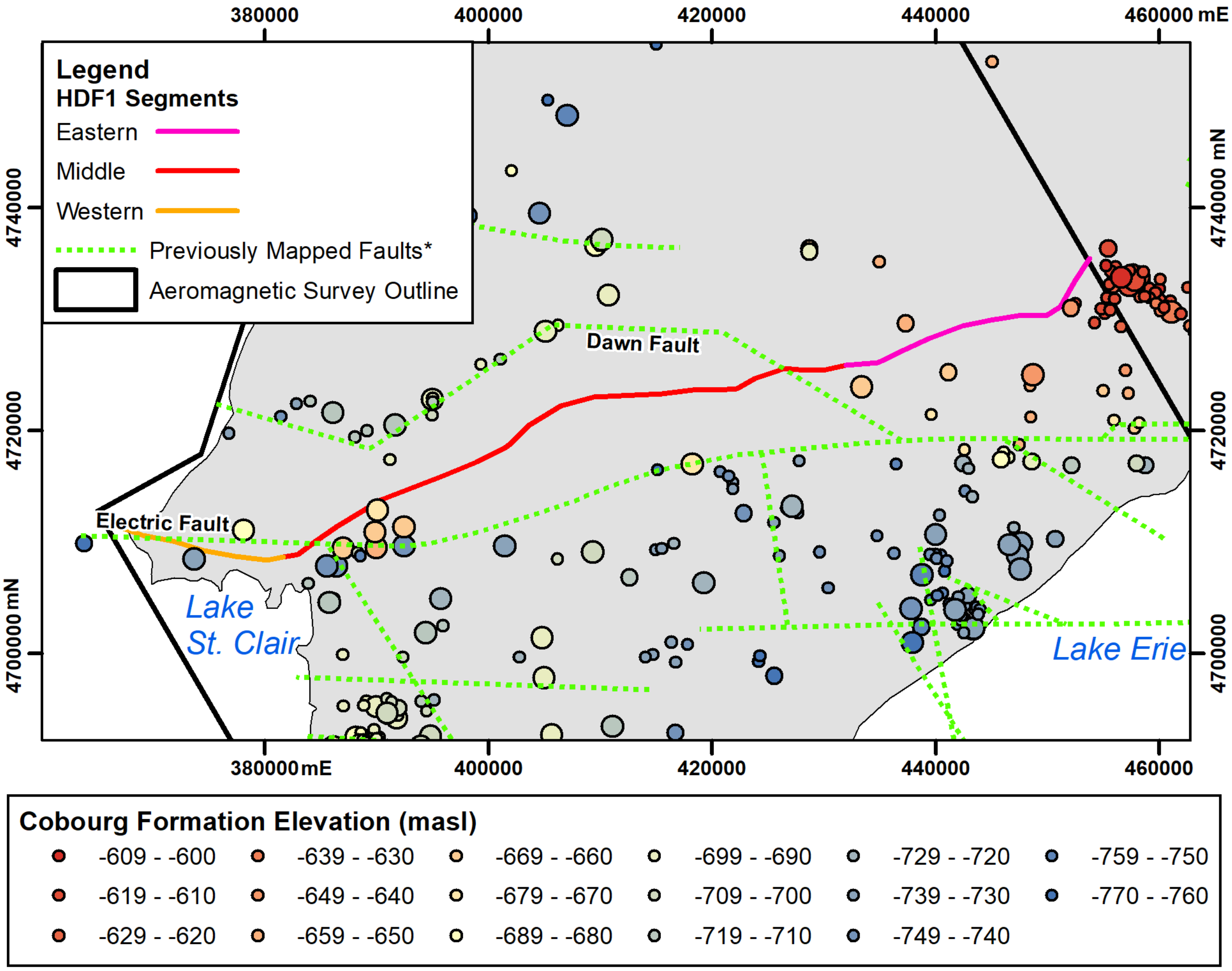

Figure 77. Cobourg Formation (Trenton Group) elevation around the HDF1 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

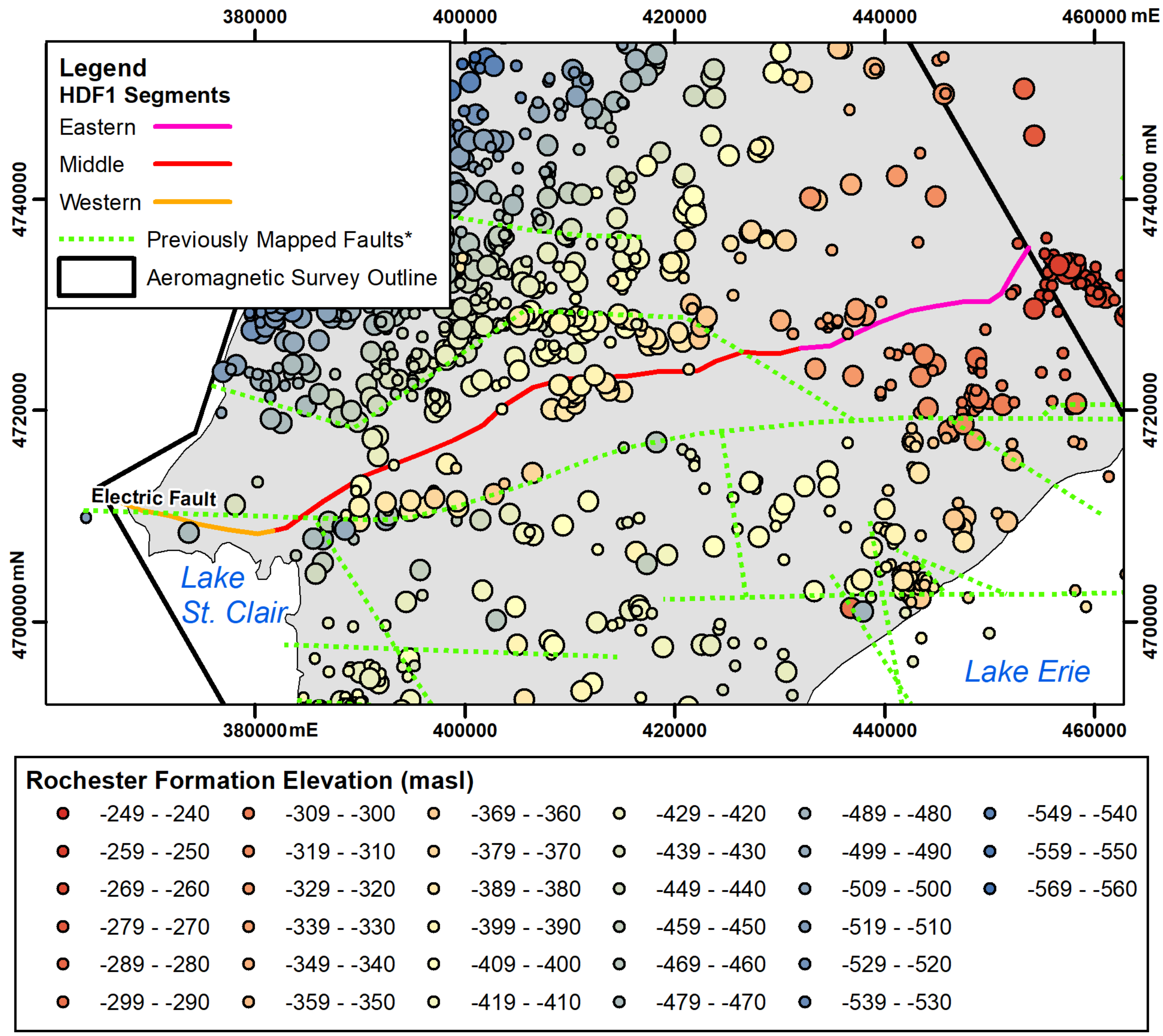

Figure 78. Rochester Formation (Clinton Group) elevation around the HDF1 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

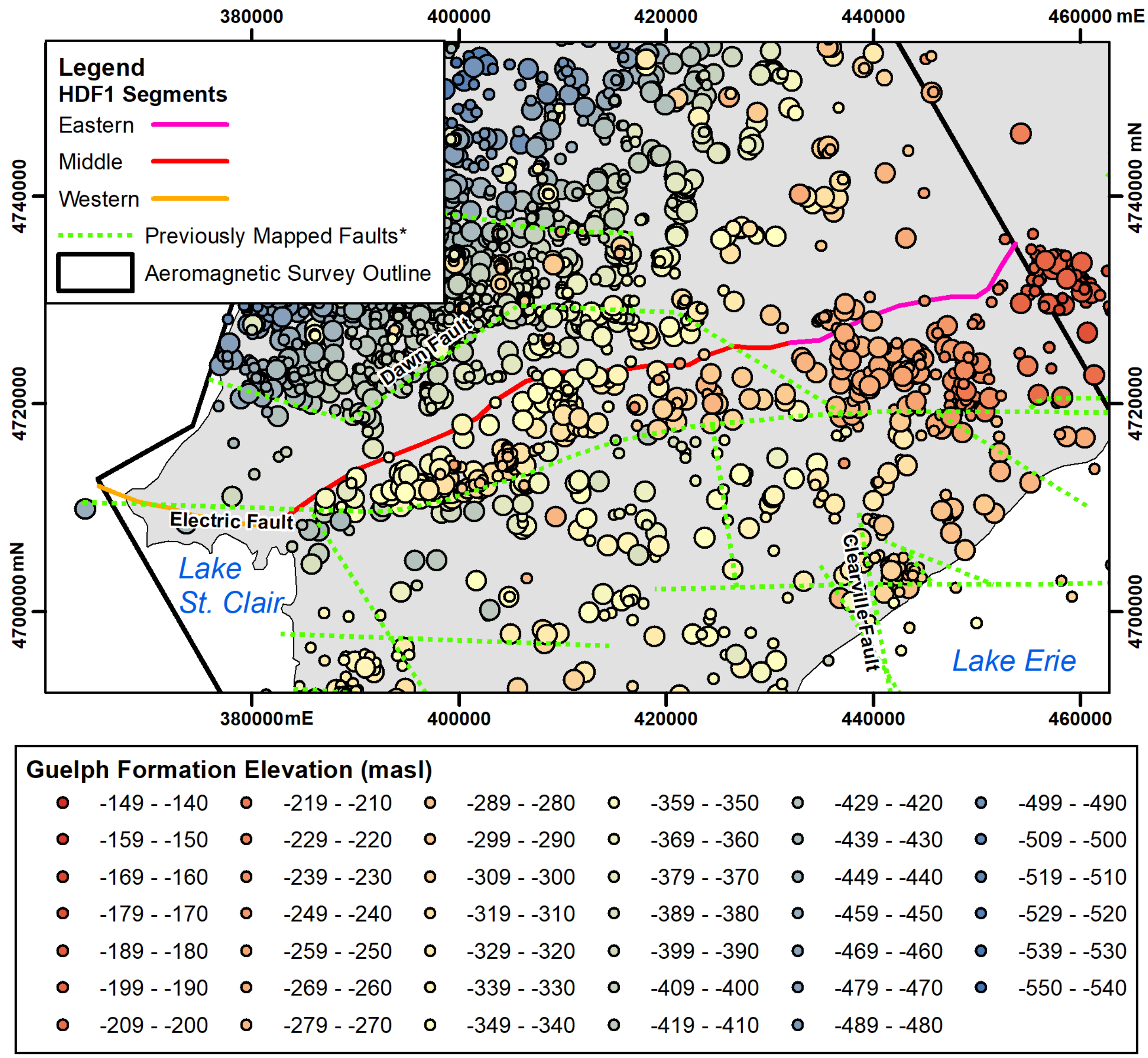

Figure 79. Guelph Formation (Lockport Group) elevation around the HDF1 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

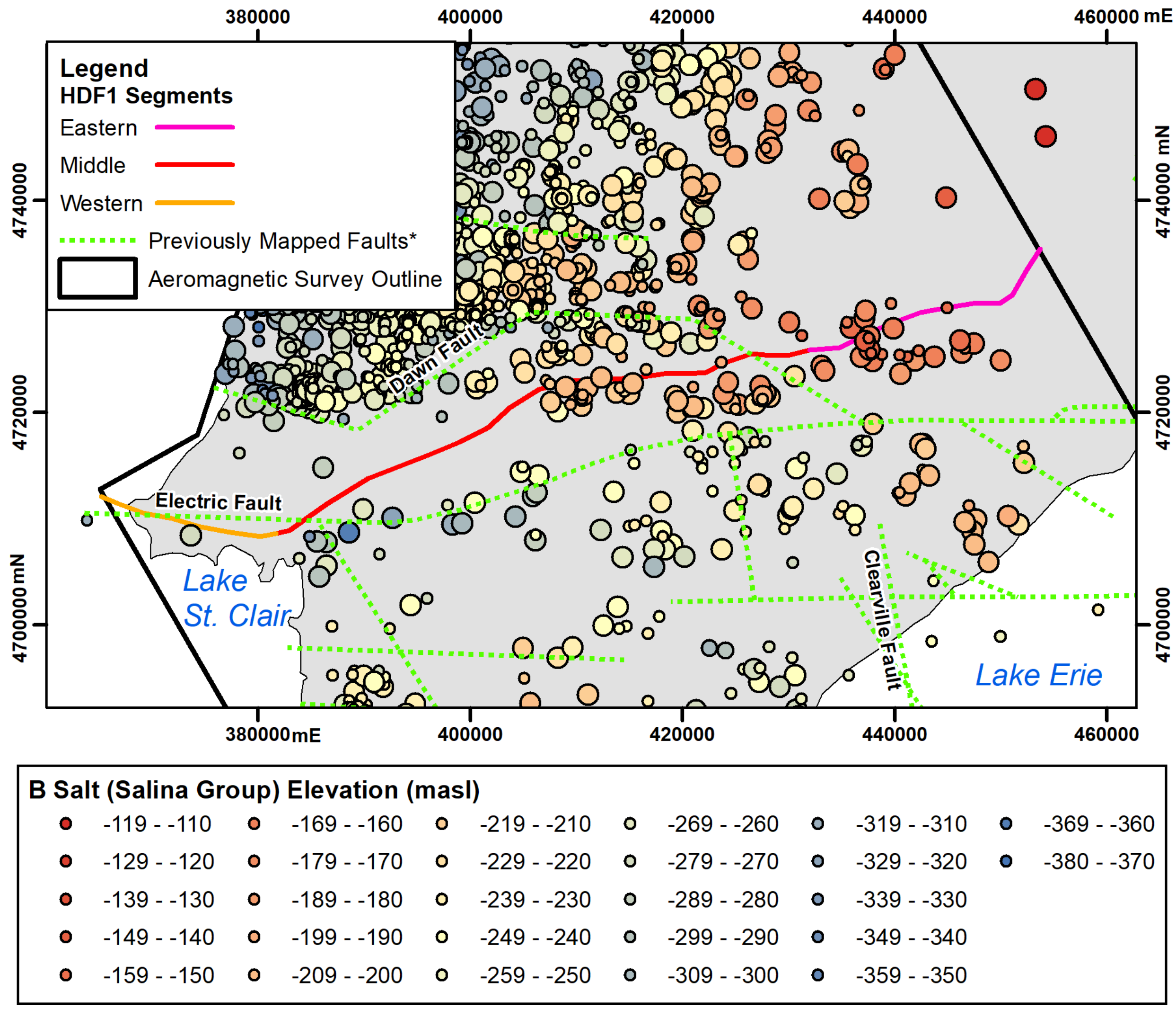

Figure 80. B Salt Unit (Salina Group) elevation around the HDF1 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

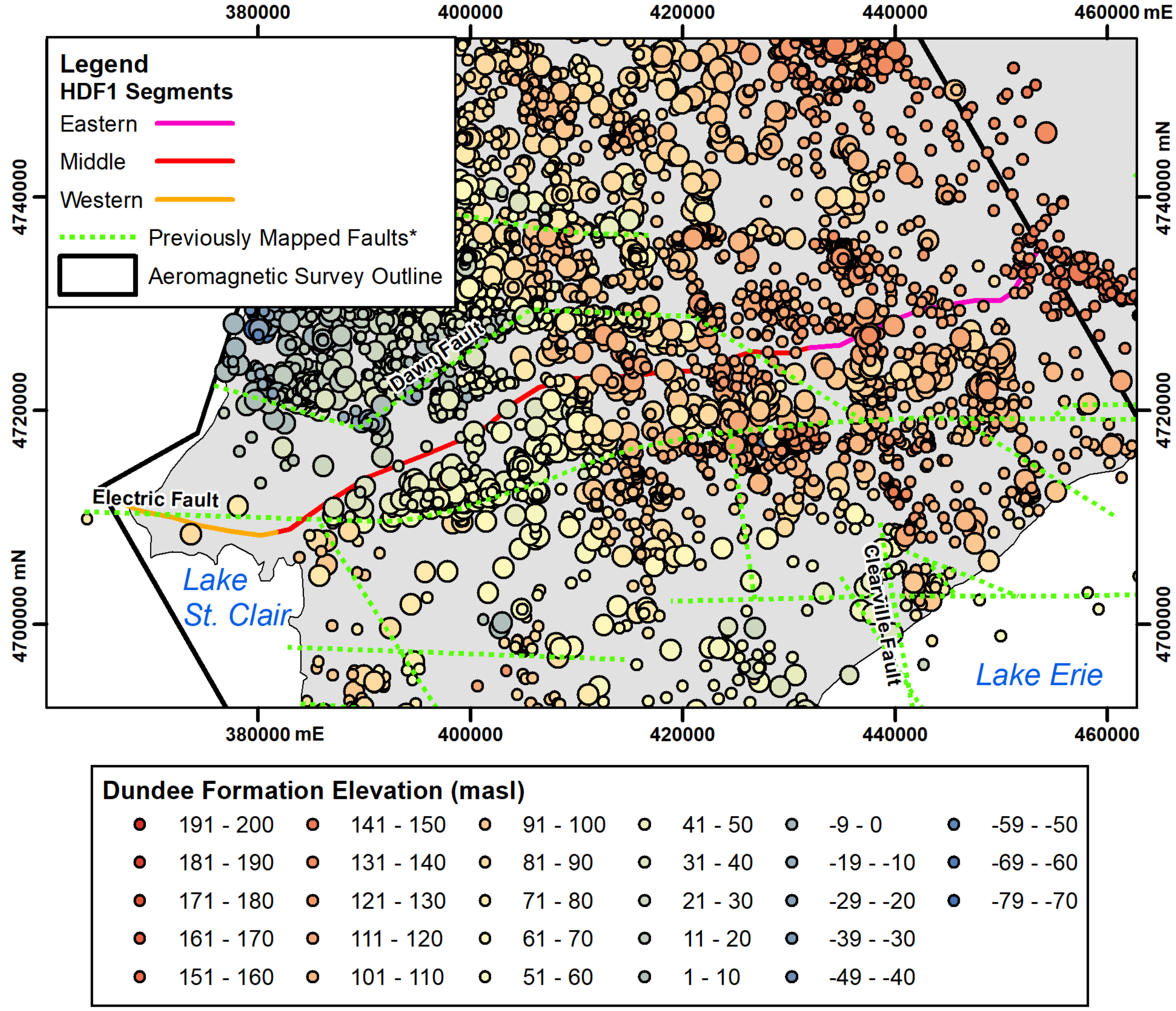

Figure 81. Dundee Formation elevation around the HDF1 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

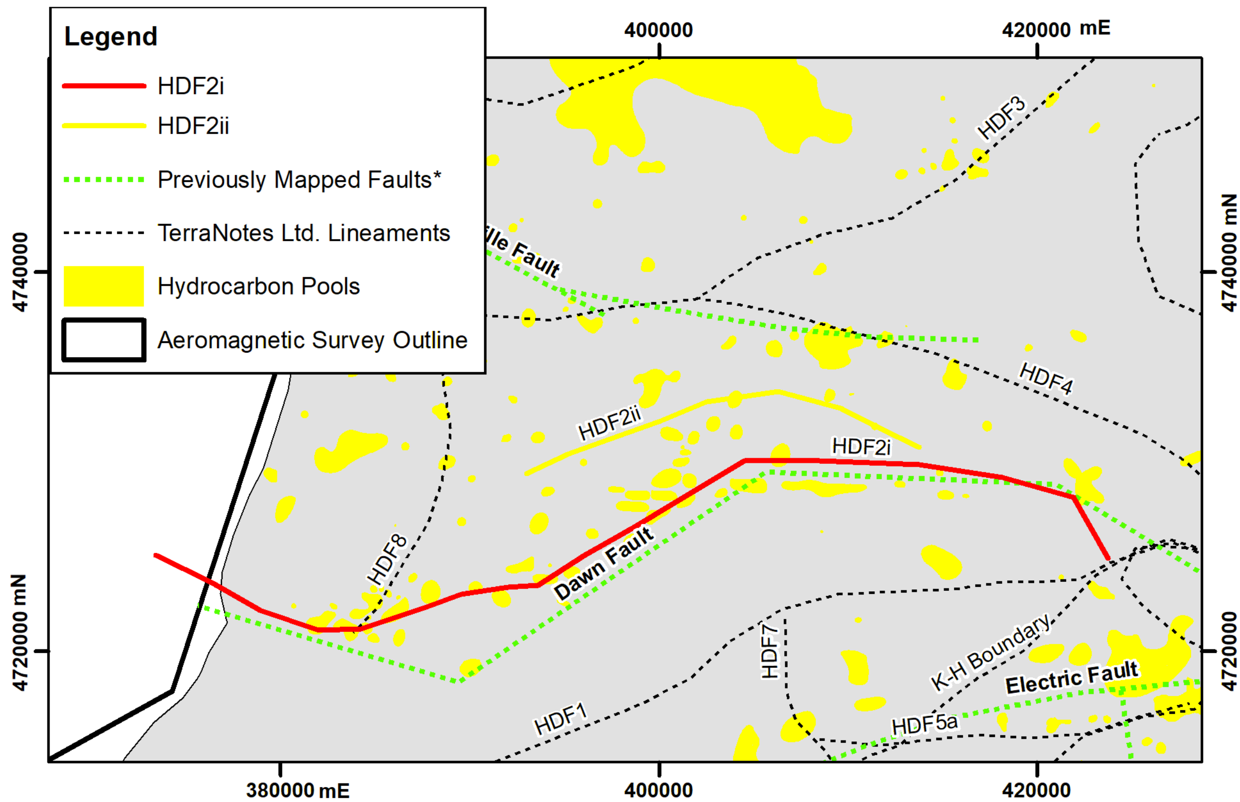

Figure 82. Locations of the HDF2i and HDF2ii sublineaments compared to previously mapped faults, other TerraNotes Ltd. lineaments and known hydrocarbon pools. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

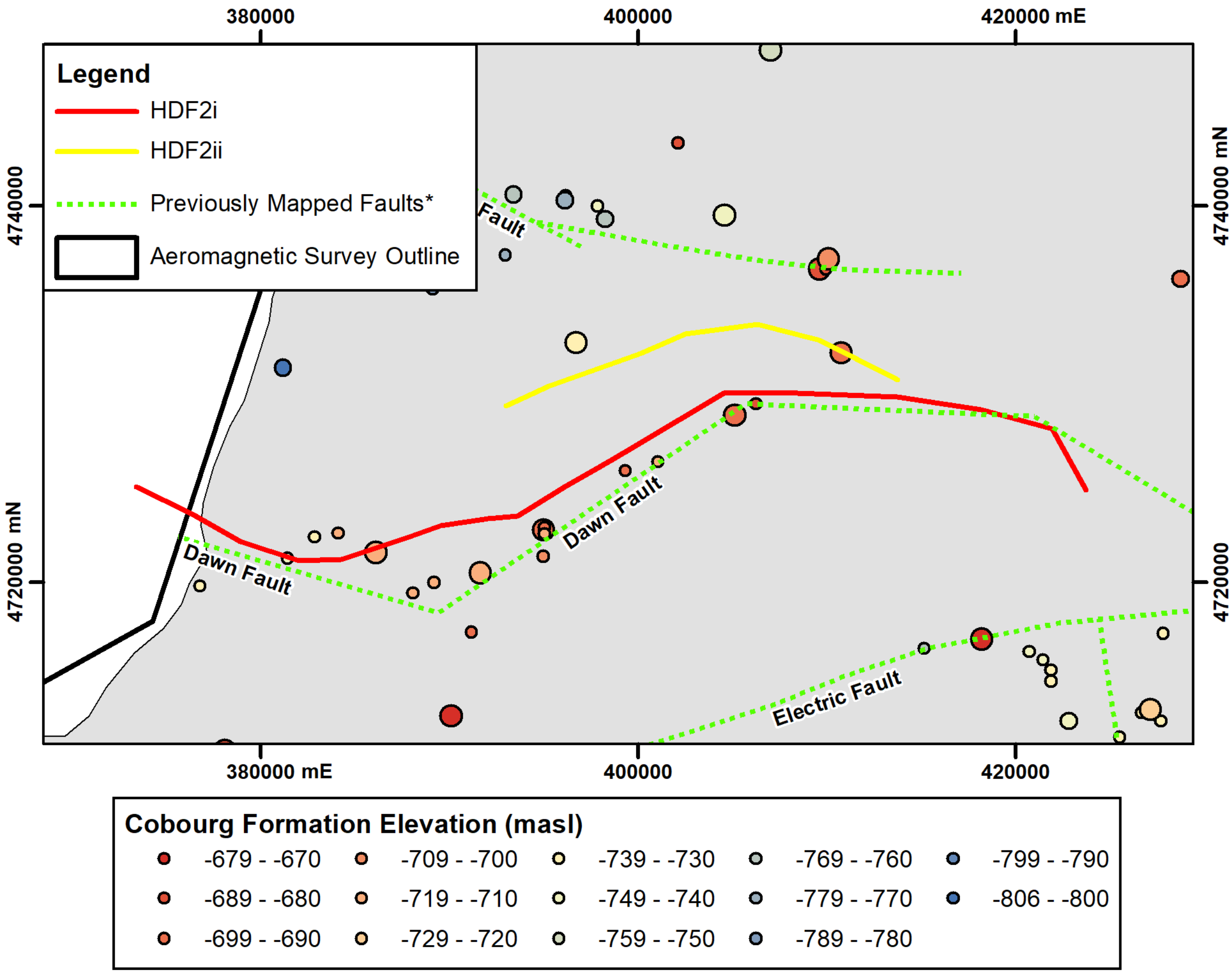

Figure 83. Cobourg Formation (Trenton Group) elevation around the HDF2 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

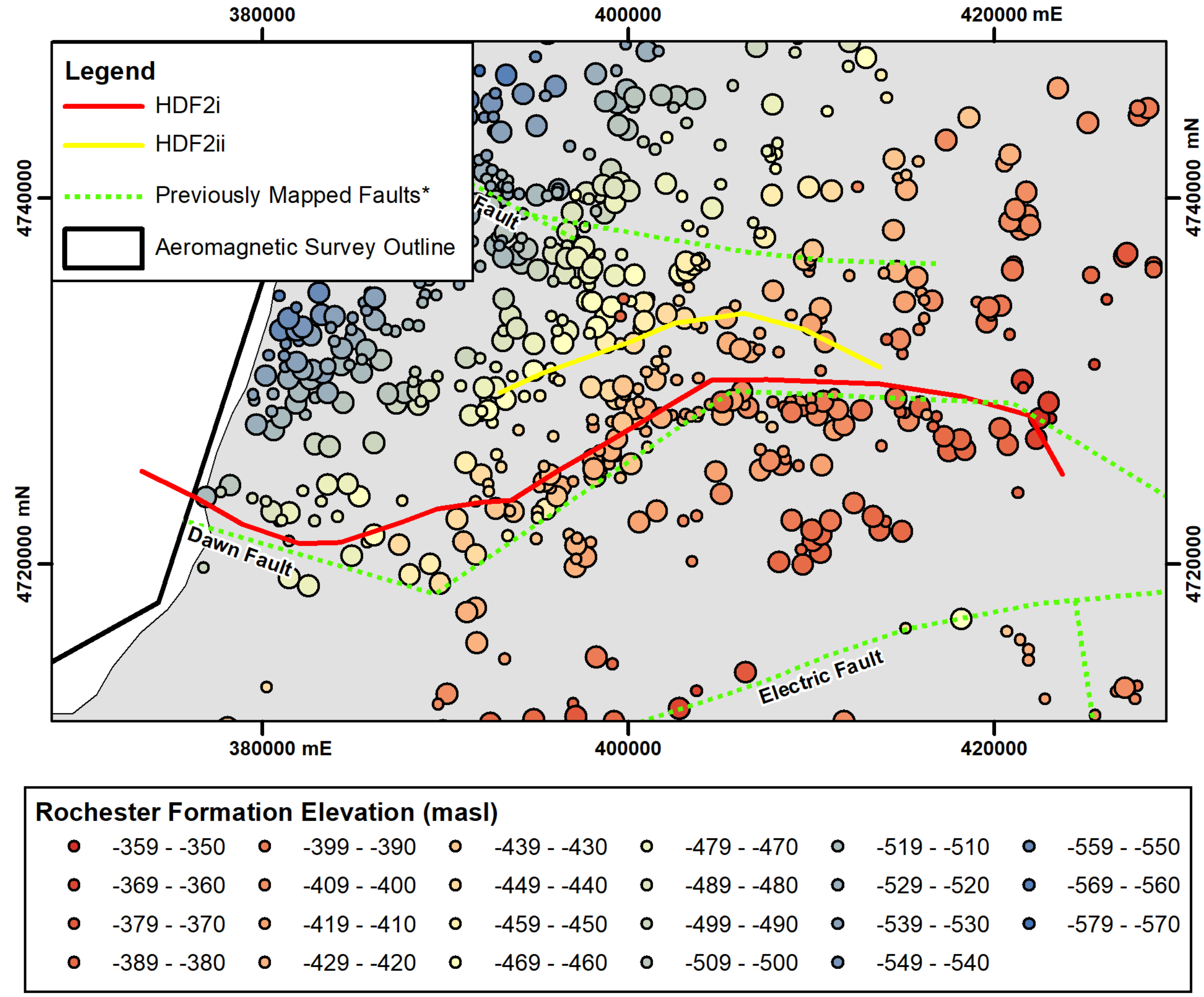

Figure 84. Rochester Formation (Clinton Group) elevation around the HDF2 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

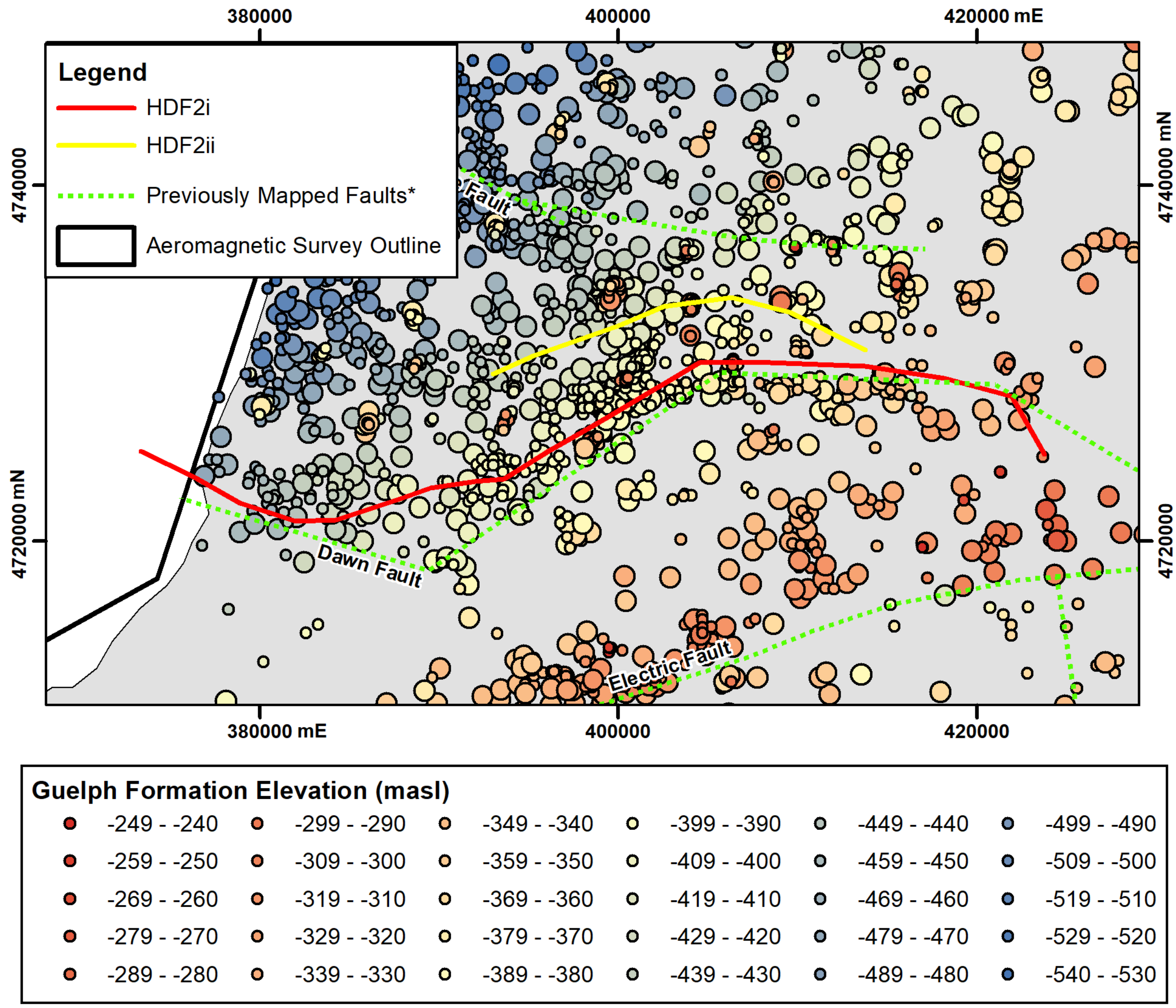

Figure 85. Guelph Formation (Lockport Group) elevation around the HDF2 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

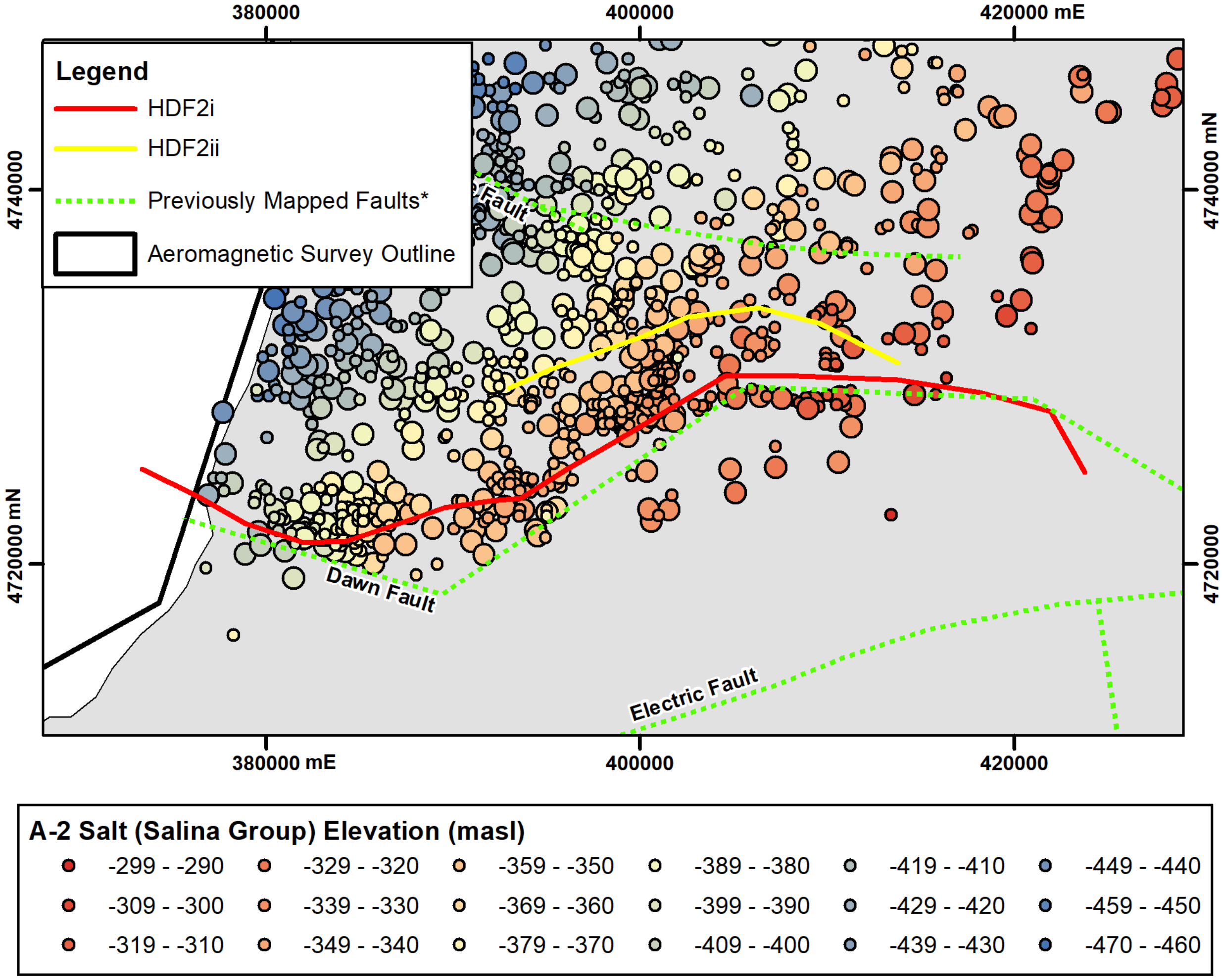

Figure 86. A-2 Salt Unit (Salina Group) elevation around the HDF2 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

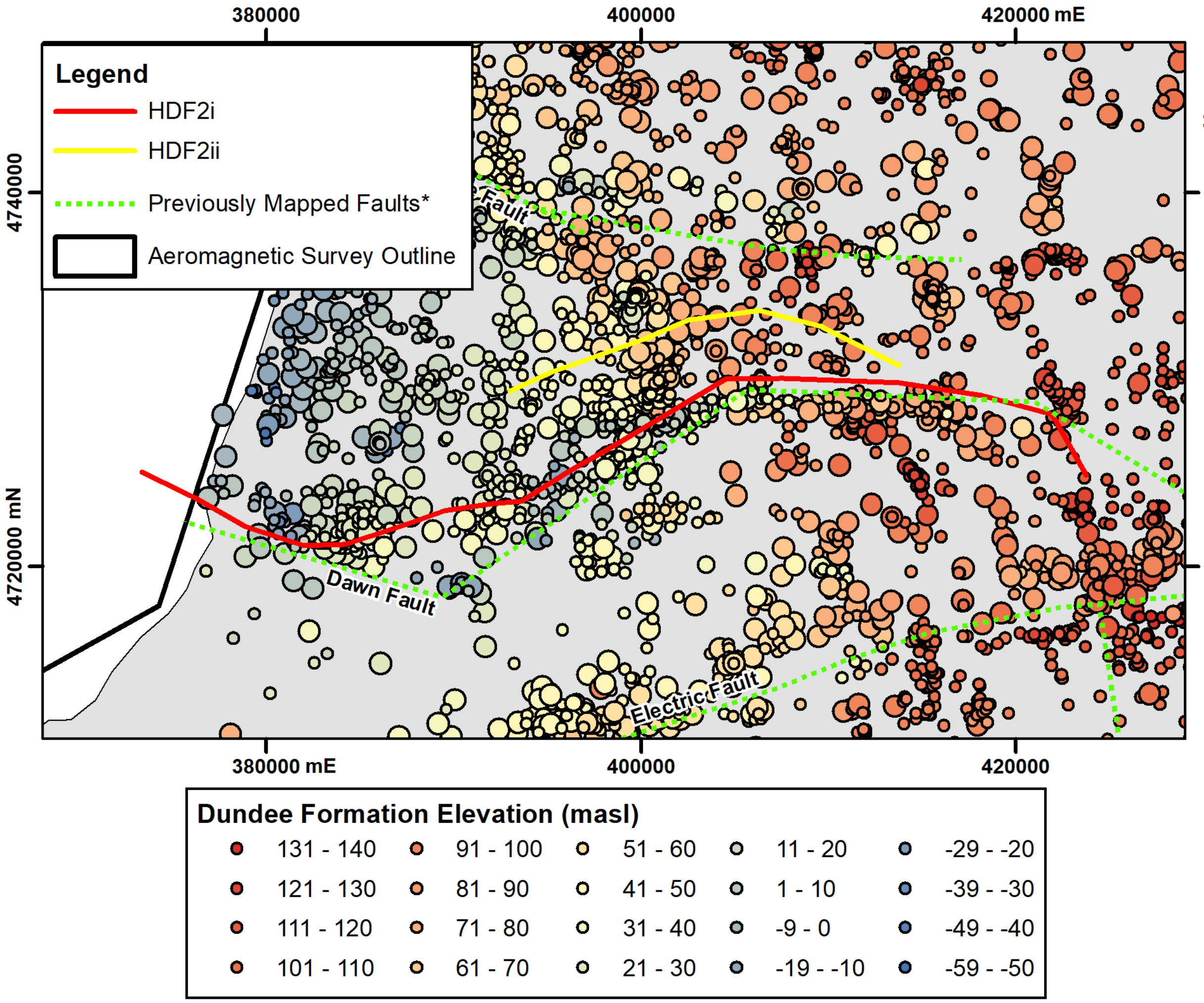

Figure 87. Dundee Formation elevation around the HDF2 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

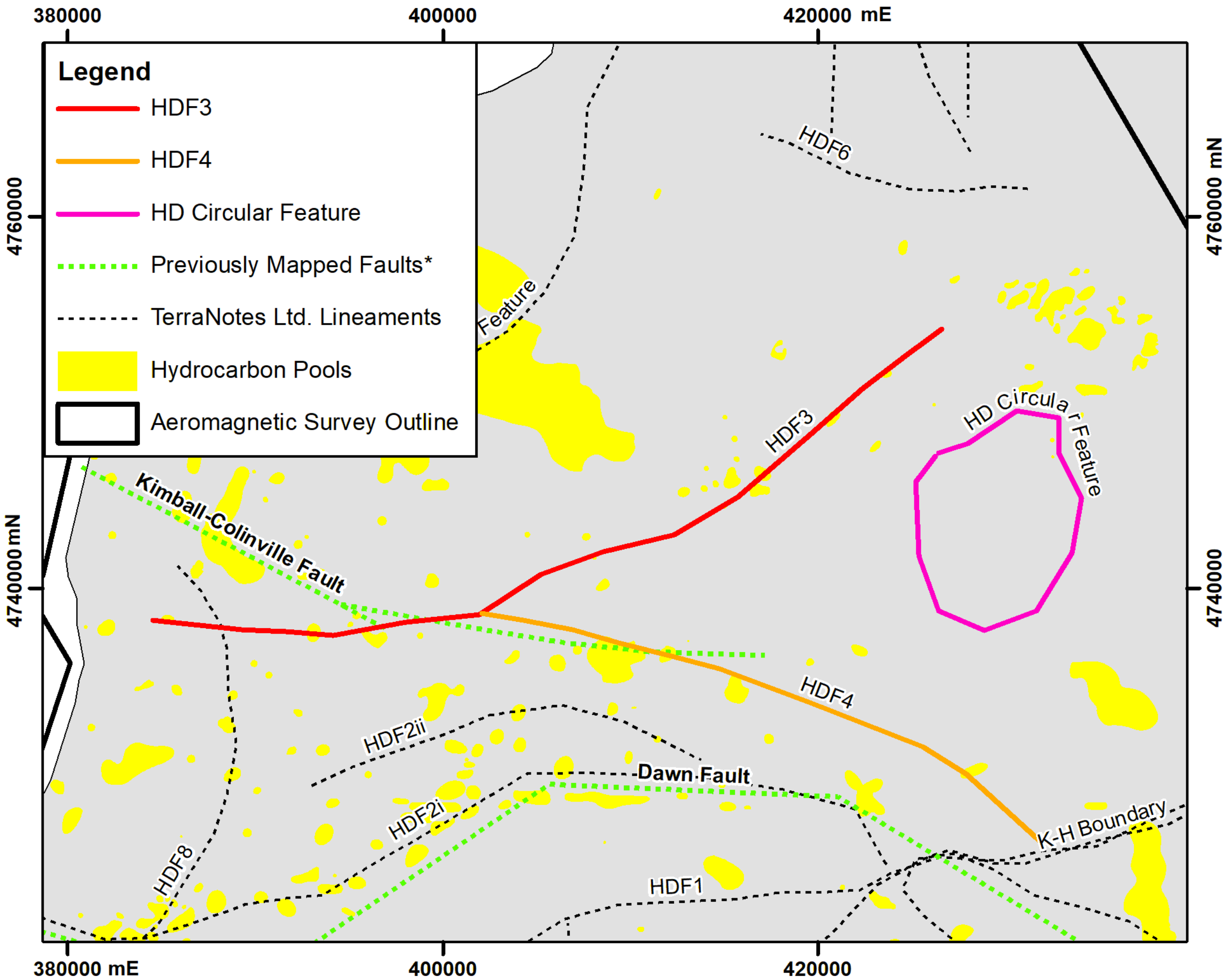

Figure 88. Locations of the HDF3 and HDF4 lineaments and the Huron Domain circular feature compared to previously mapped faults, other TerraNotes Ltd. lineaments and known hydrocarbon pools. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

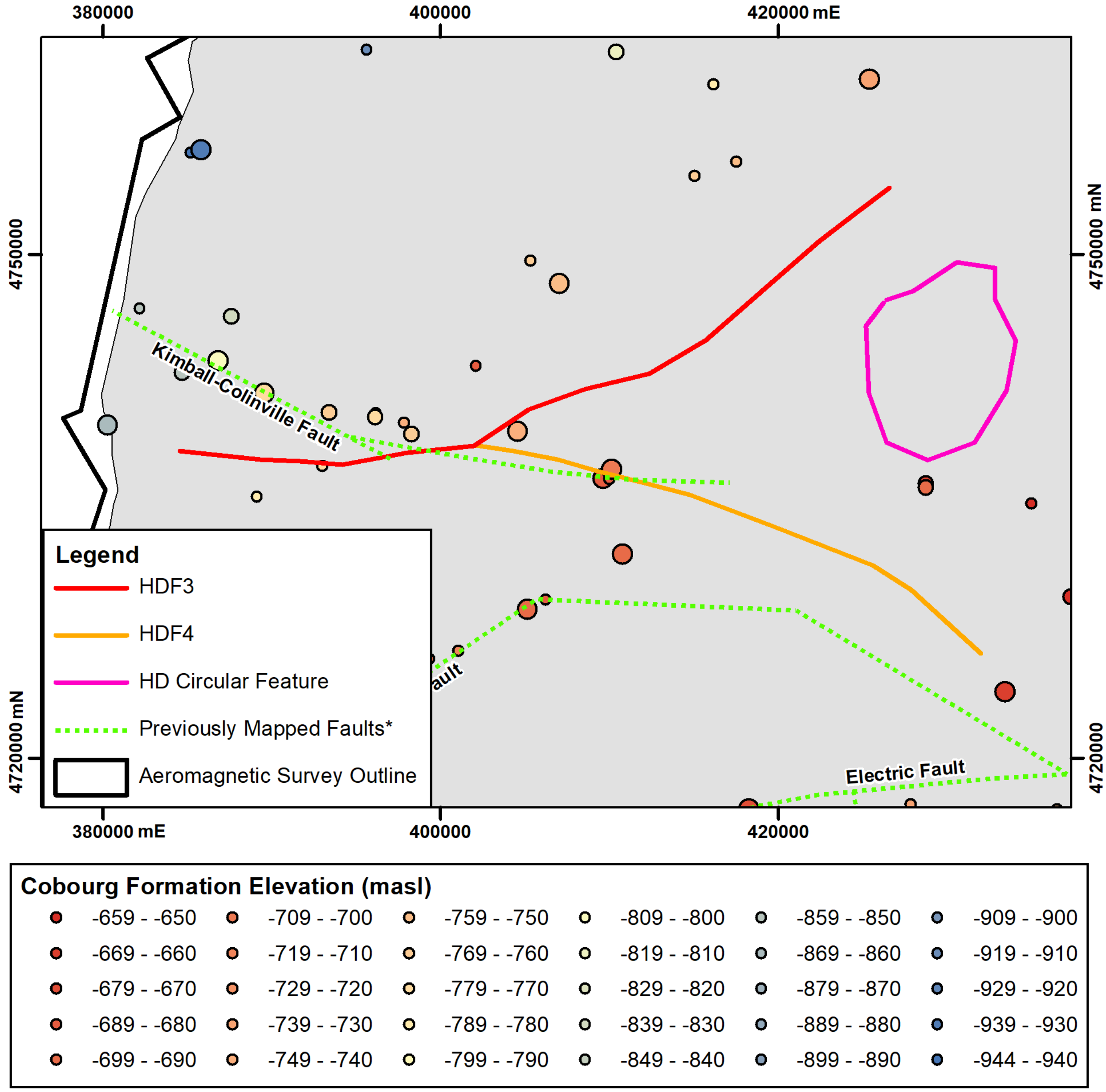

Figure 89. Cobourg Formation (Trenton Group) elevation around the HDF3, HDF4 lineaments and the Huron Domain circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

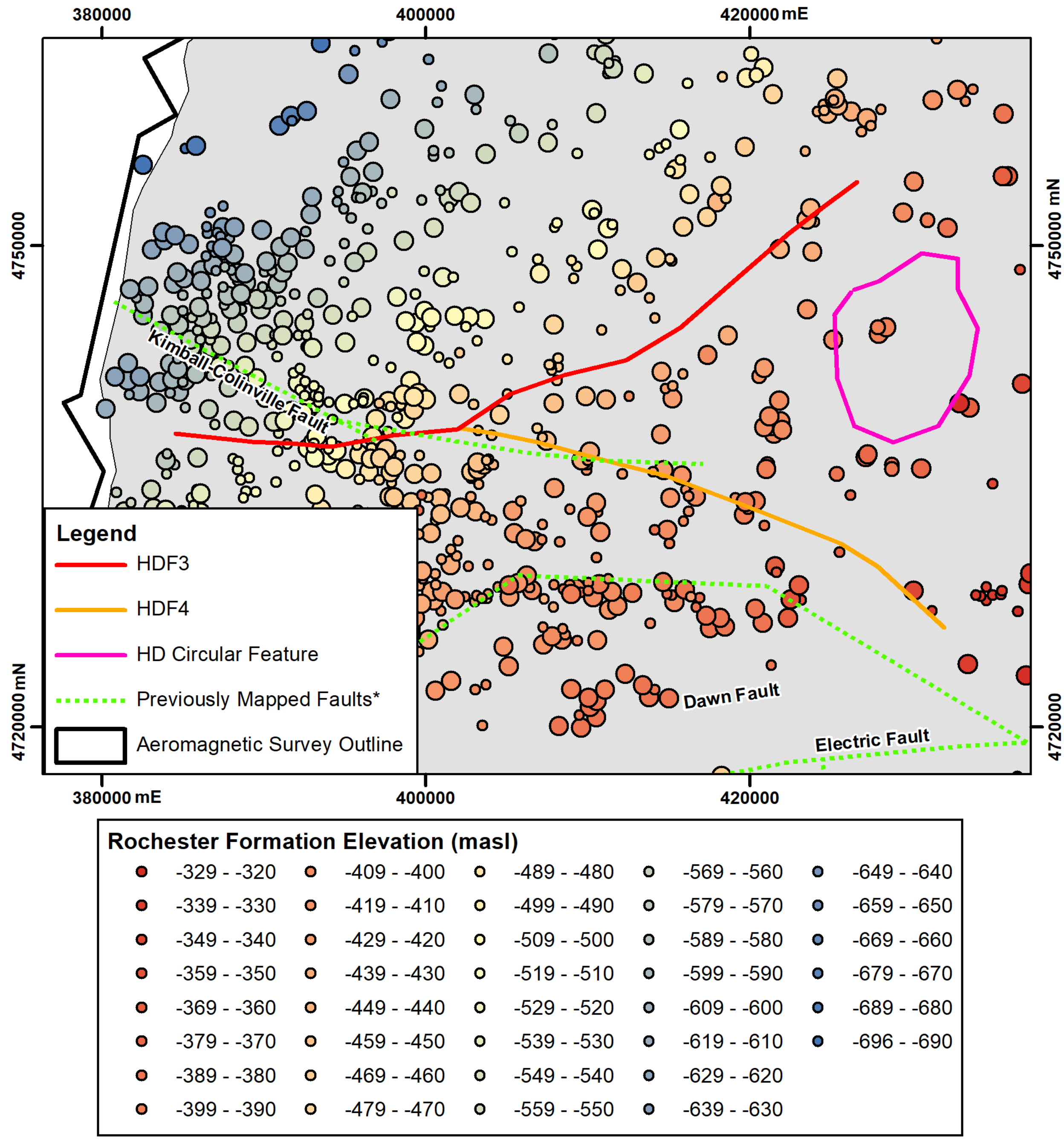

Figure 90. Rochester Formation (Clinton Group) elevation around the HDF3, HDF4 lineaments and the Huron Domain circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

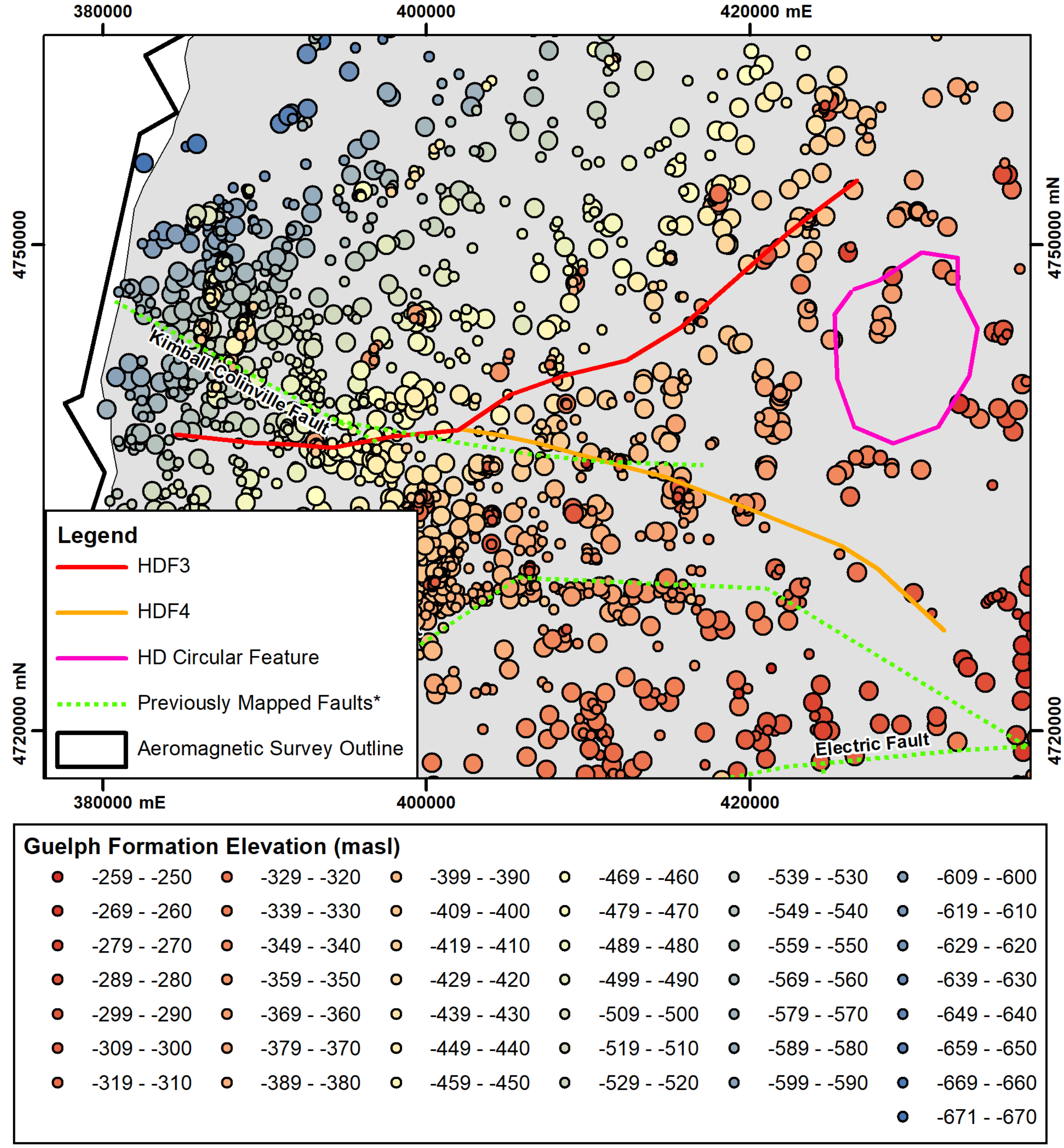

Figure 91. Guelph Formation (Lockport Group) elevation around the HDF3, HDF4 lineaments and the Huron Domain circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

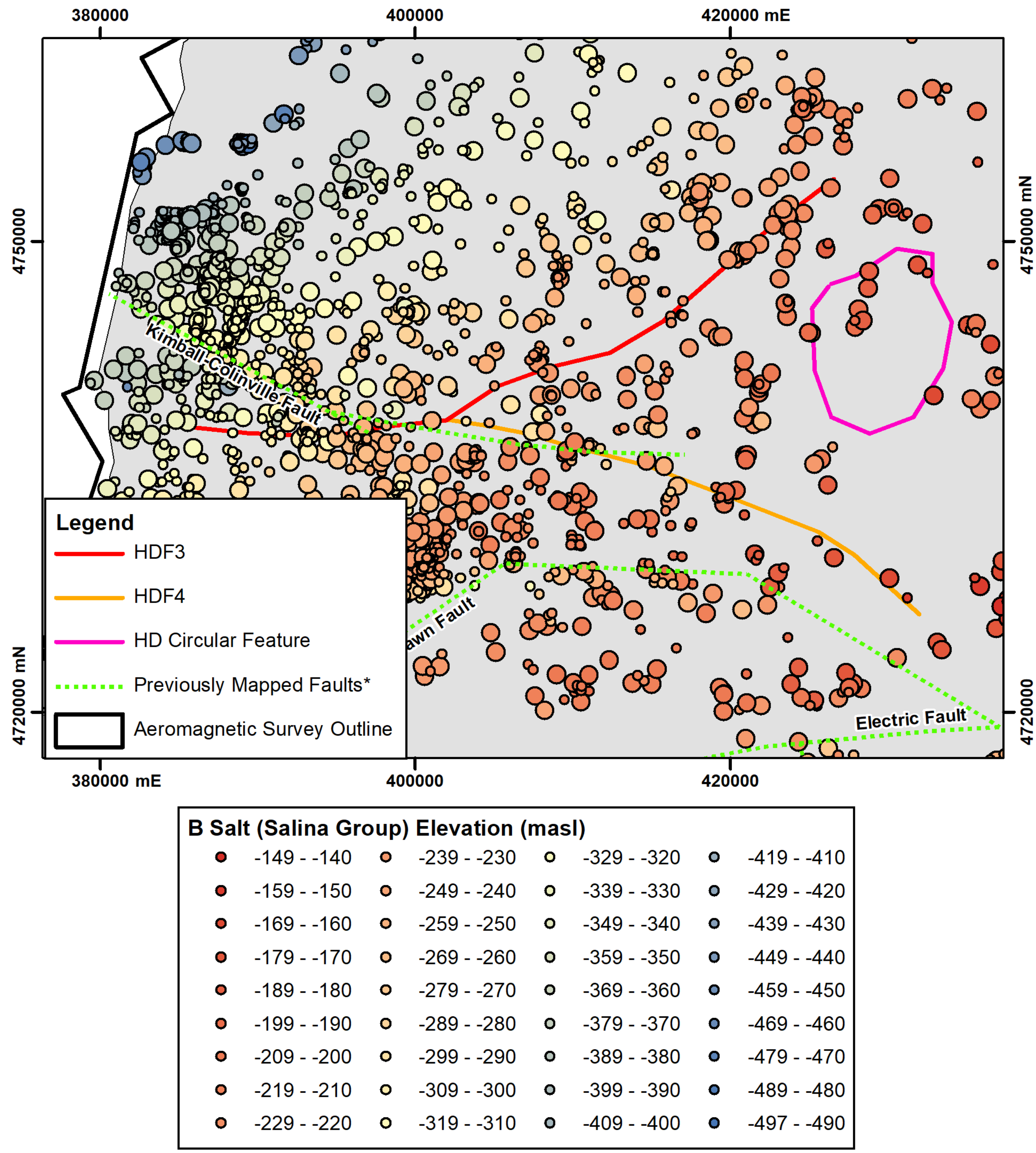

Figure 92. B Salt Unit (Salina Group) elevation around the HDF3, HDF4 lineaments and the Huron Domain circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

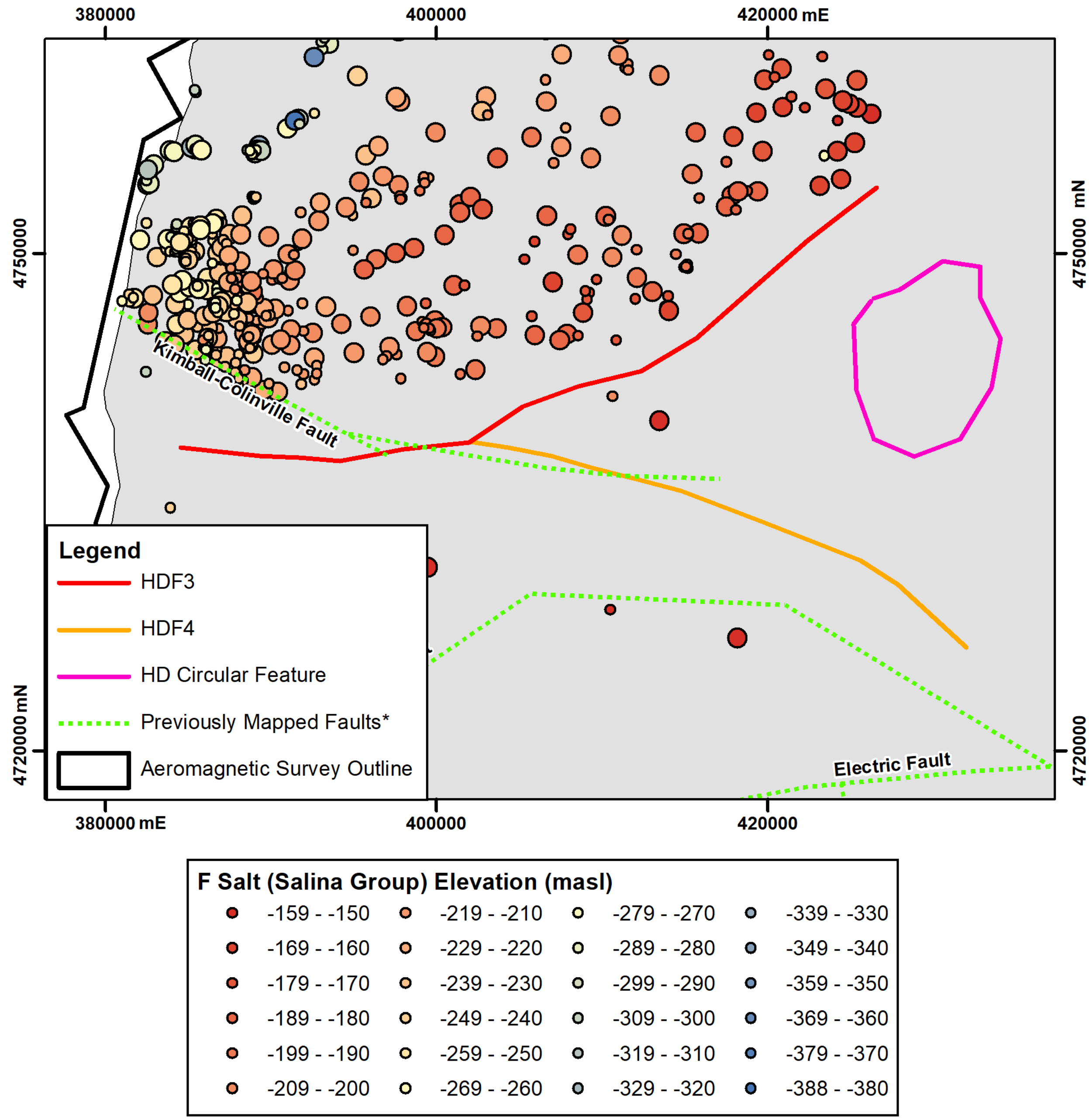

Figure 93. F Salt Unit (Salina Group) elevation around the HDF3, HDF4 lineaments and the Huron Domain circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

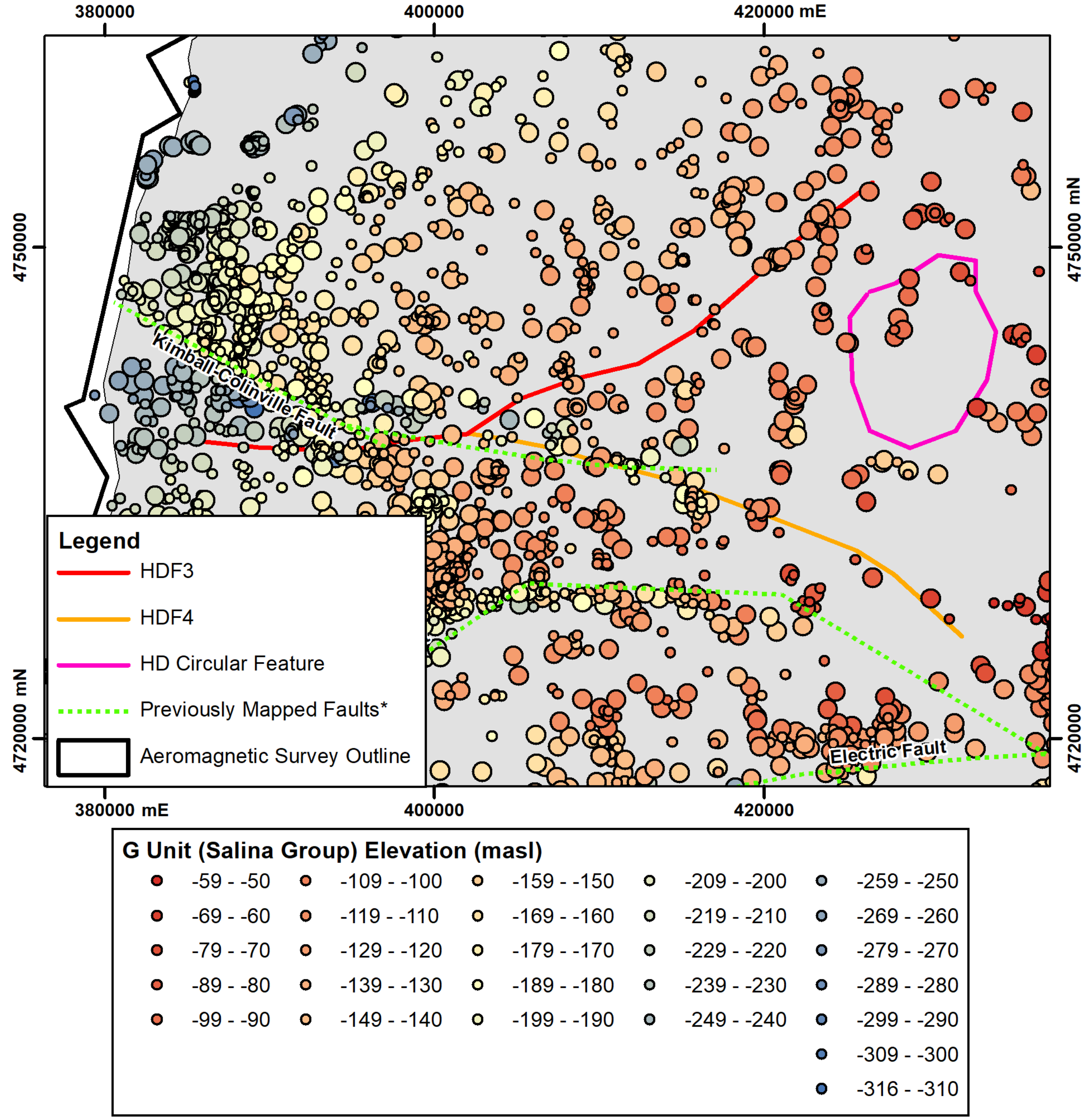

Figure 94. G Unit (Salina Group) elevation around the HDF3, HDF4 lineaments and the Huron Domain circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

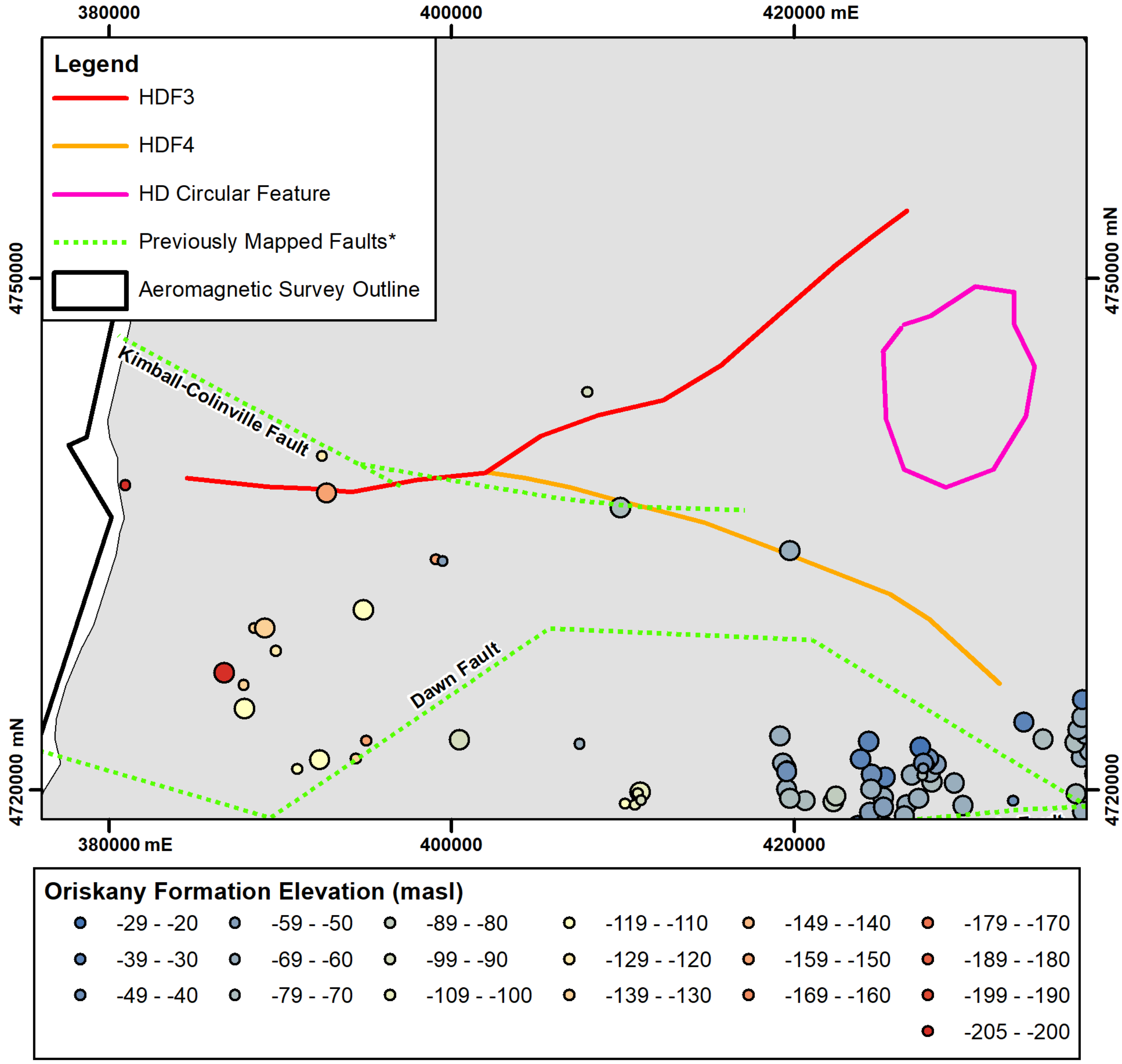

Figure 95. Oriskany Formation elevation around the HDF3, HDF4 lineaments and the Huron Domain circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

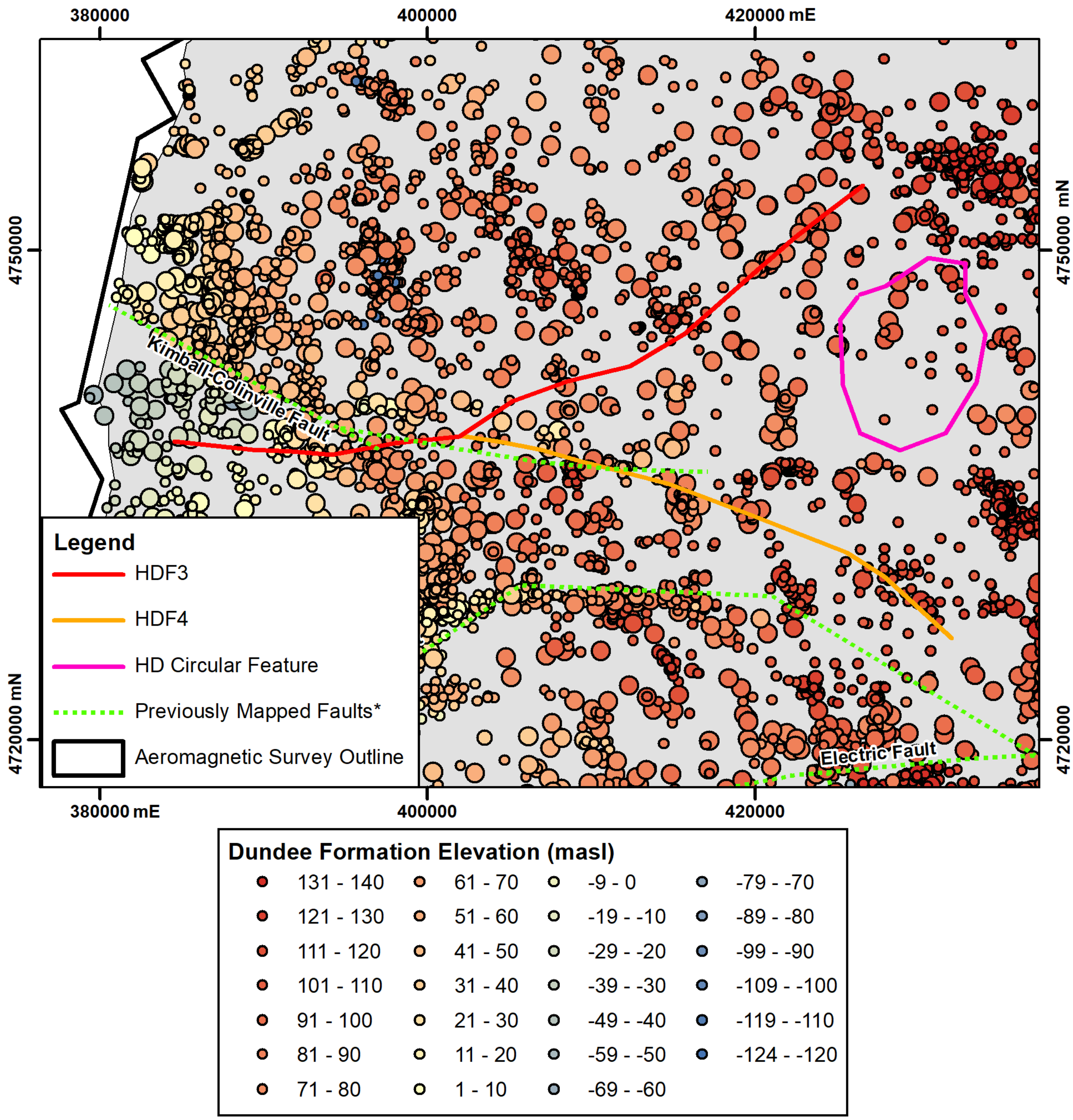

Figure 96. Dundee Formation elevation around the HDF3, HDF4 lineaments and the Huron Domain circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

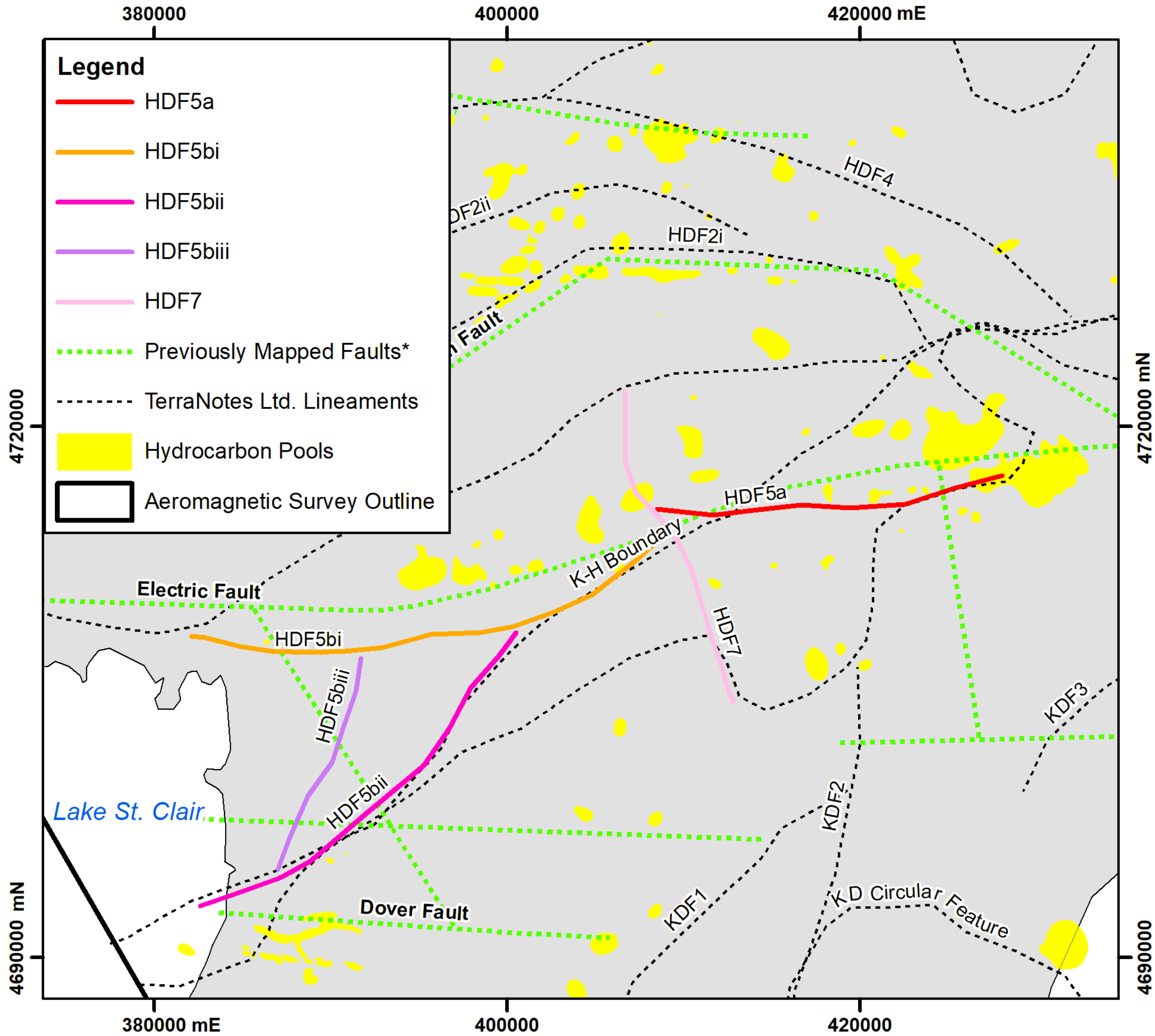

Figure 97. Locations of the HDF5a, HDF5bi, HDF5bii and HDF5biii sublineaments and the HDF7 lineament compared to previously mapped faults, other TerraNotes Ltd. lineaments and known hydrocarbon pools. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

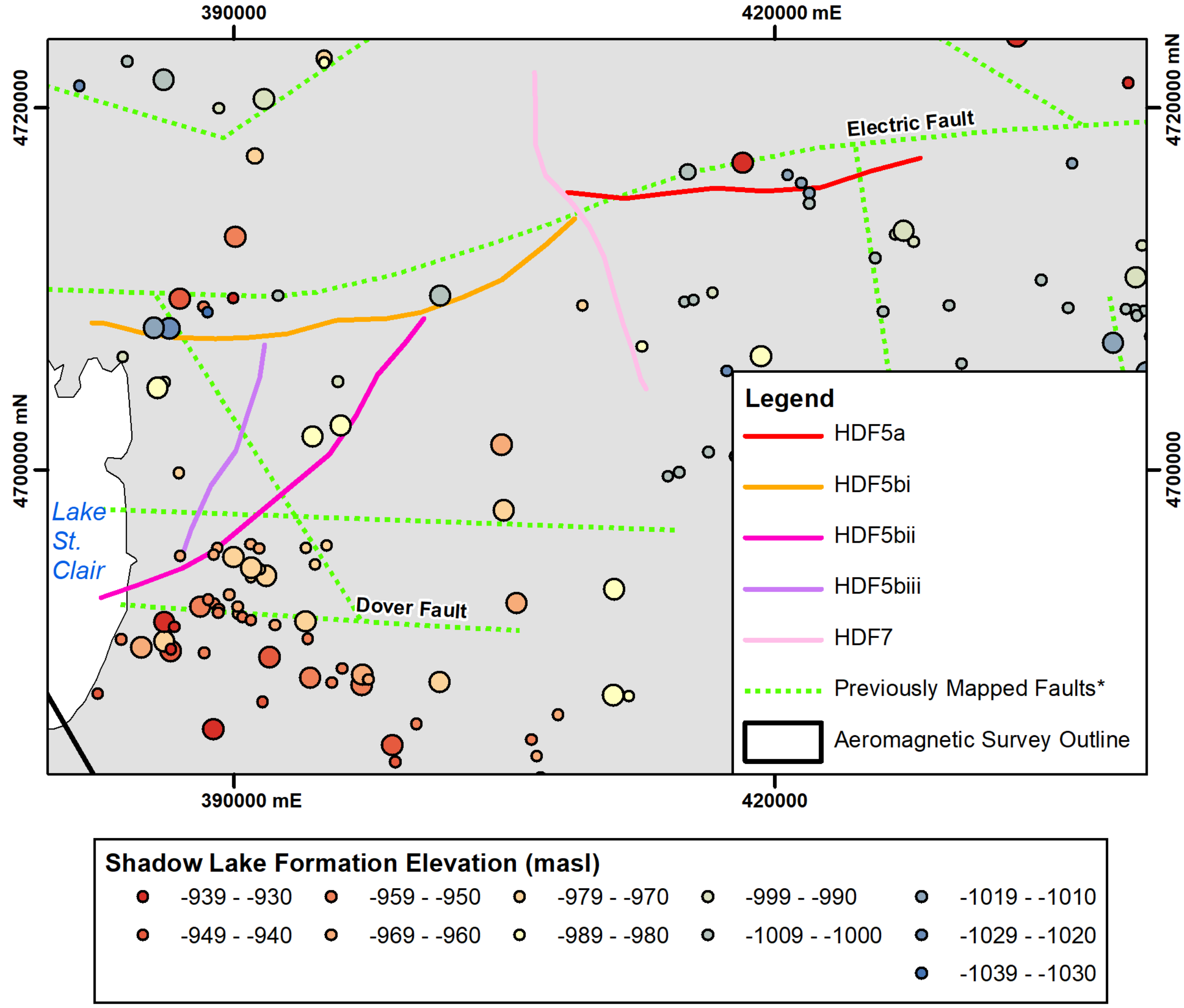

Figure 98. Shadow Lake Formation (Black River Group) elevation around the HDF5 and HDF7 lineaments. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

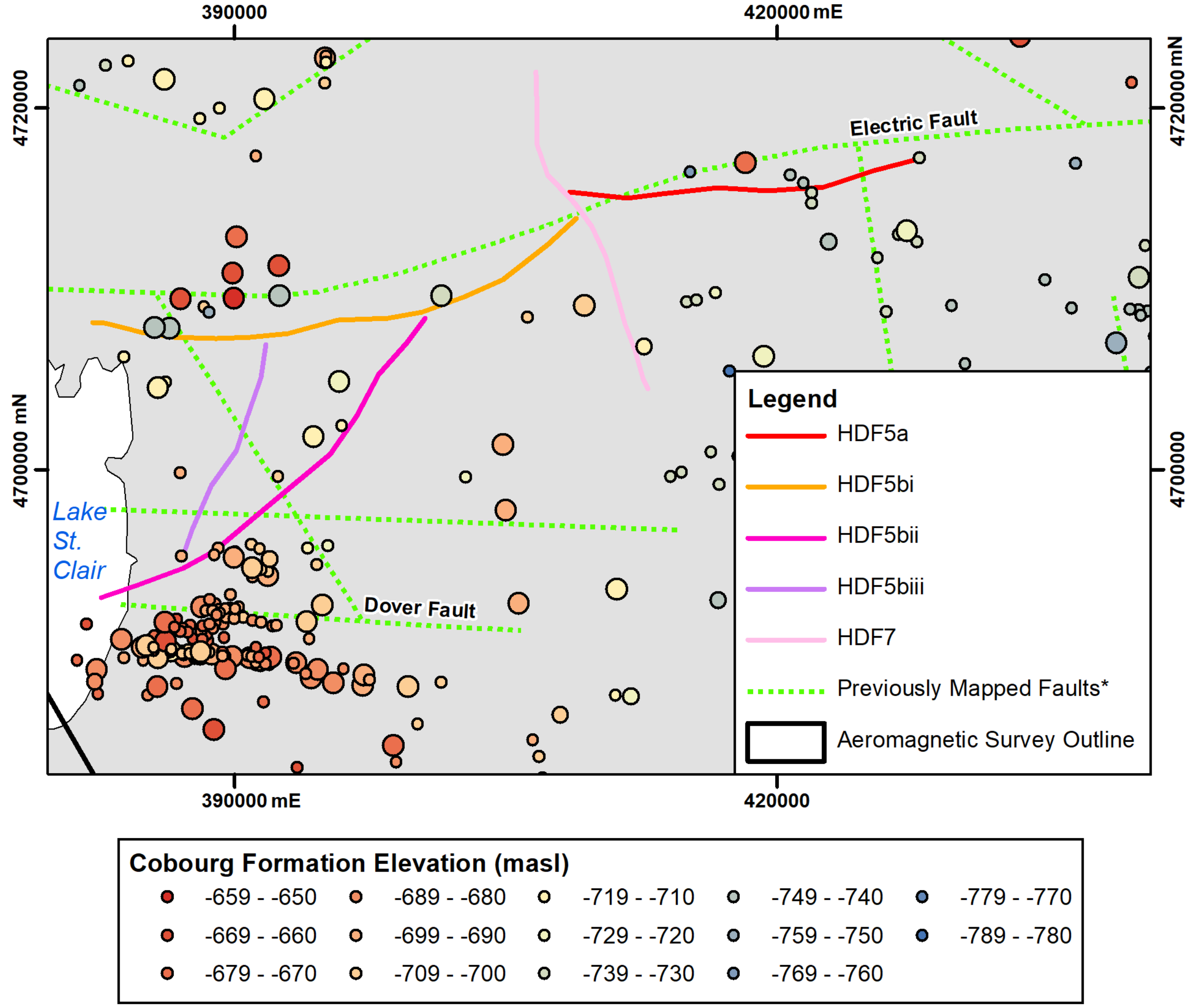

Figure 99. Cobourg Formation (Trenton Group) elevation around the HDF5 and HDF7 lineaments. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

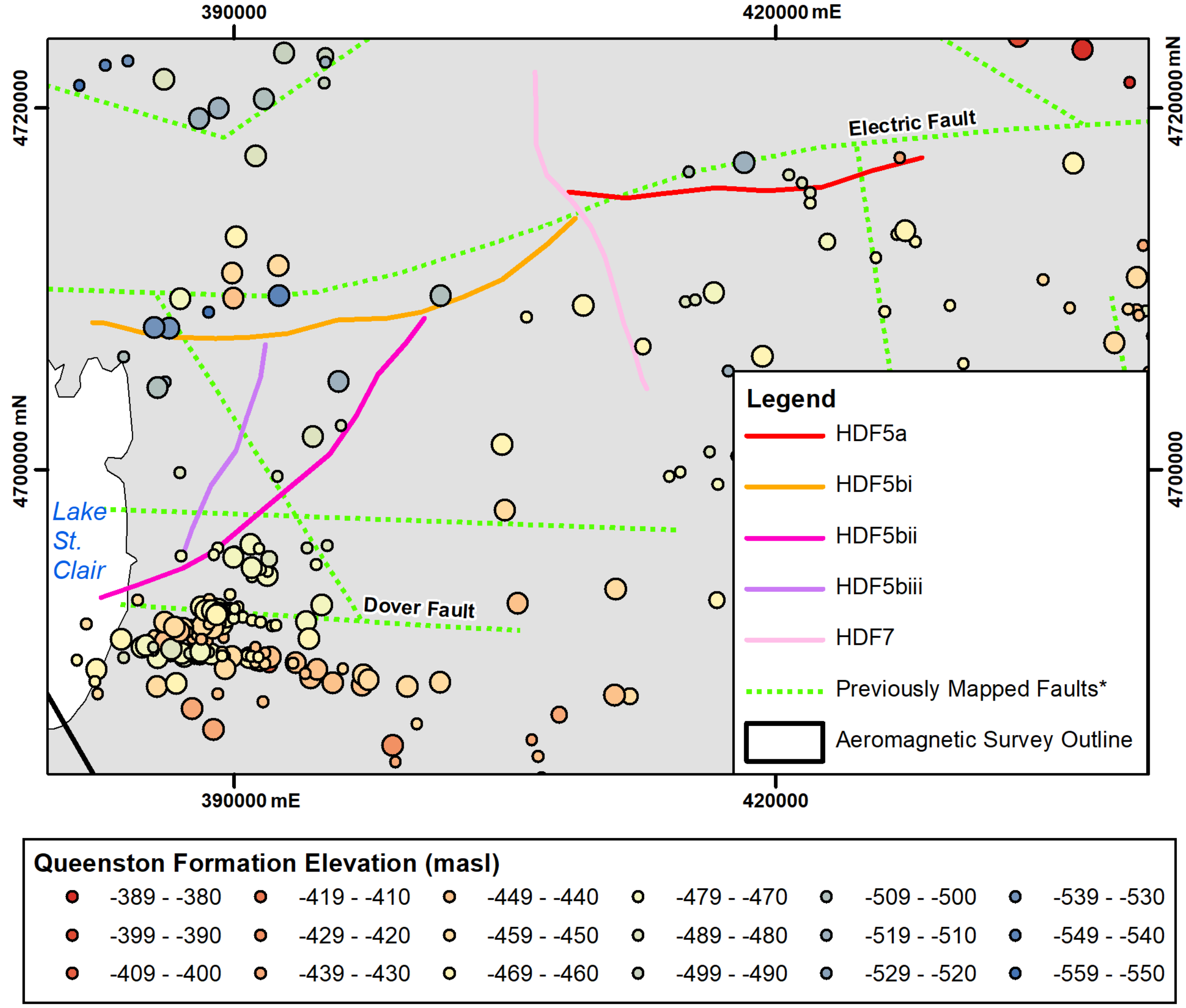

Figure 100. Queenston Formation elevation around the HDF5 and HDF7 lineaments. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

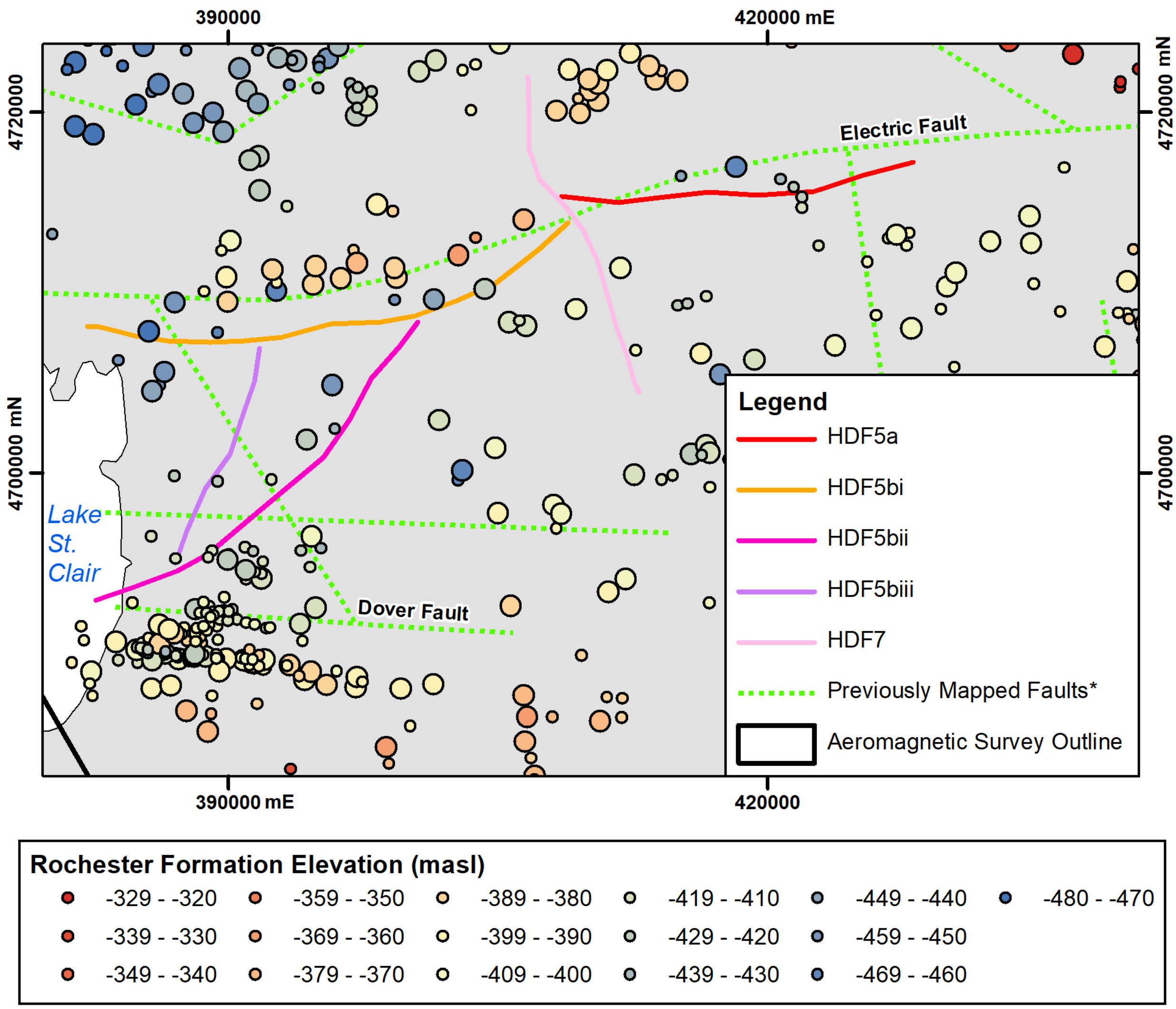

Figure 101. Rochester Formation (Clinton Group) elevation around the HDF5 and HDF7 lineaments. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

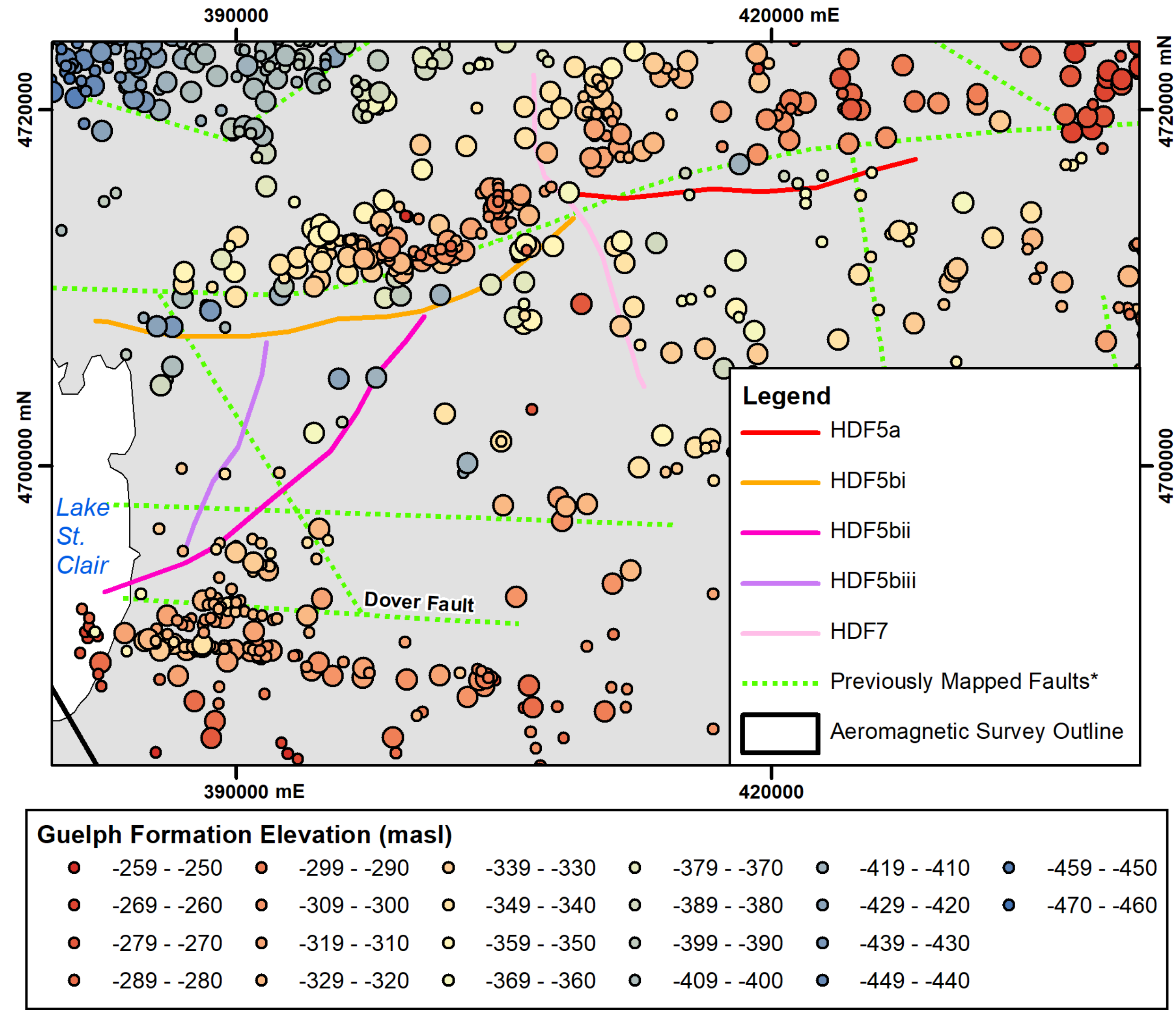

Figure 102. Guelph Formation (Lockport Group) elevation around the HDF5 and HDF7 lineaments. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

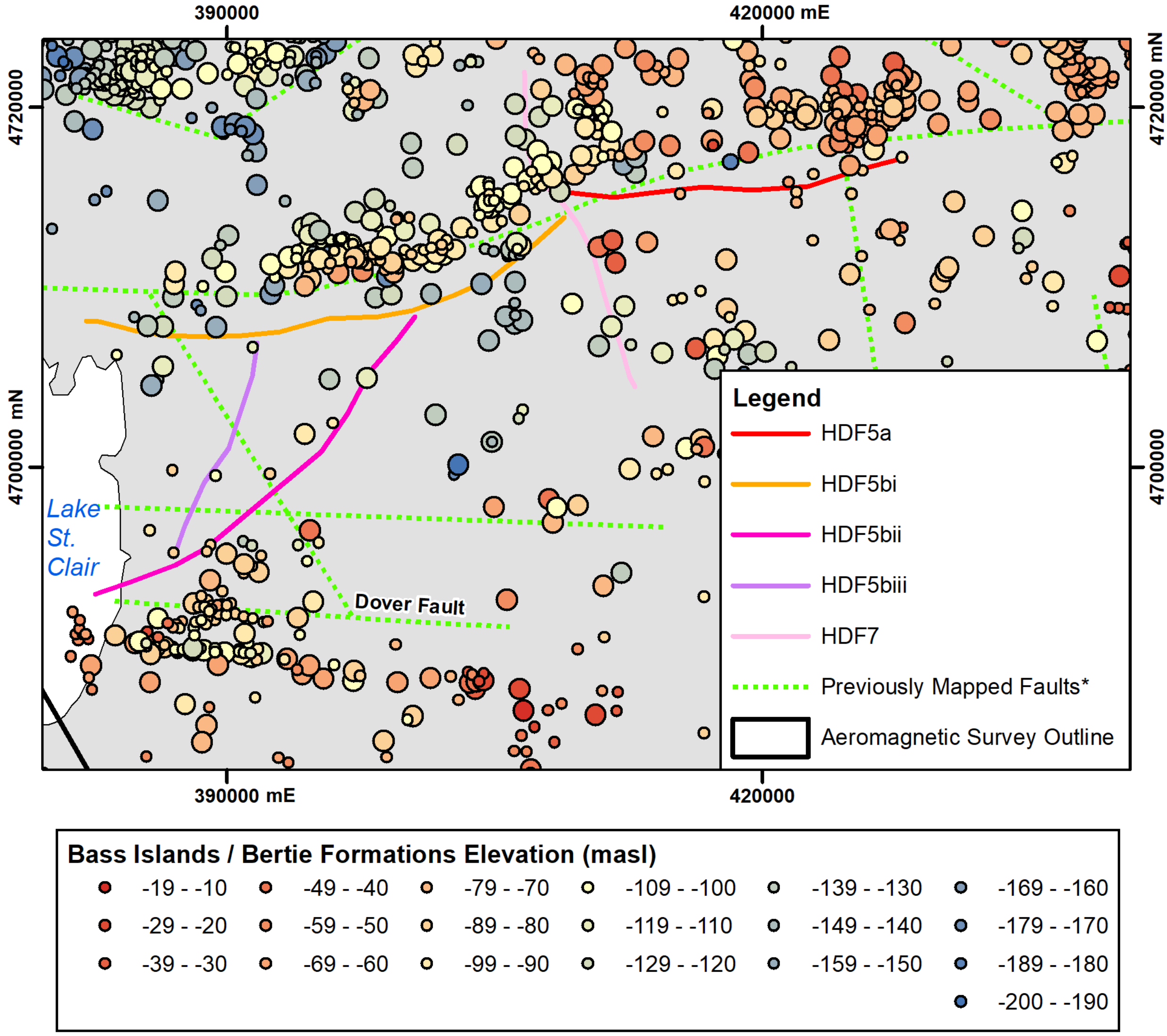

Figure 103. Bass Islands and Bertie formations elevation around the HDF5 and HDF7 lineaments. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

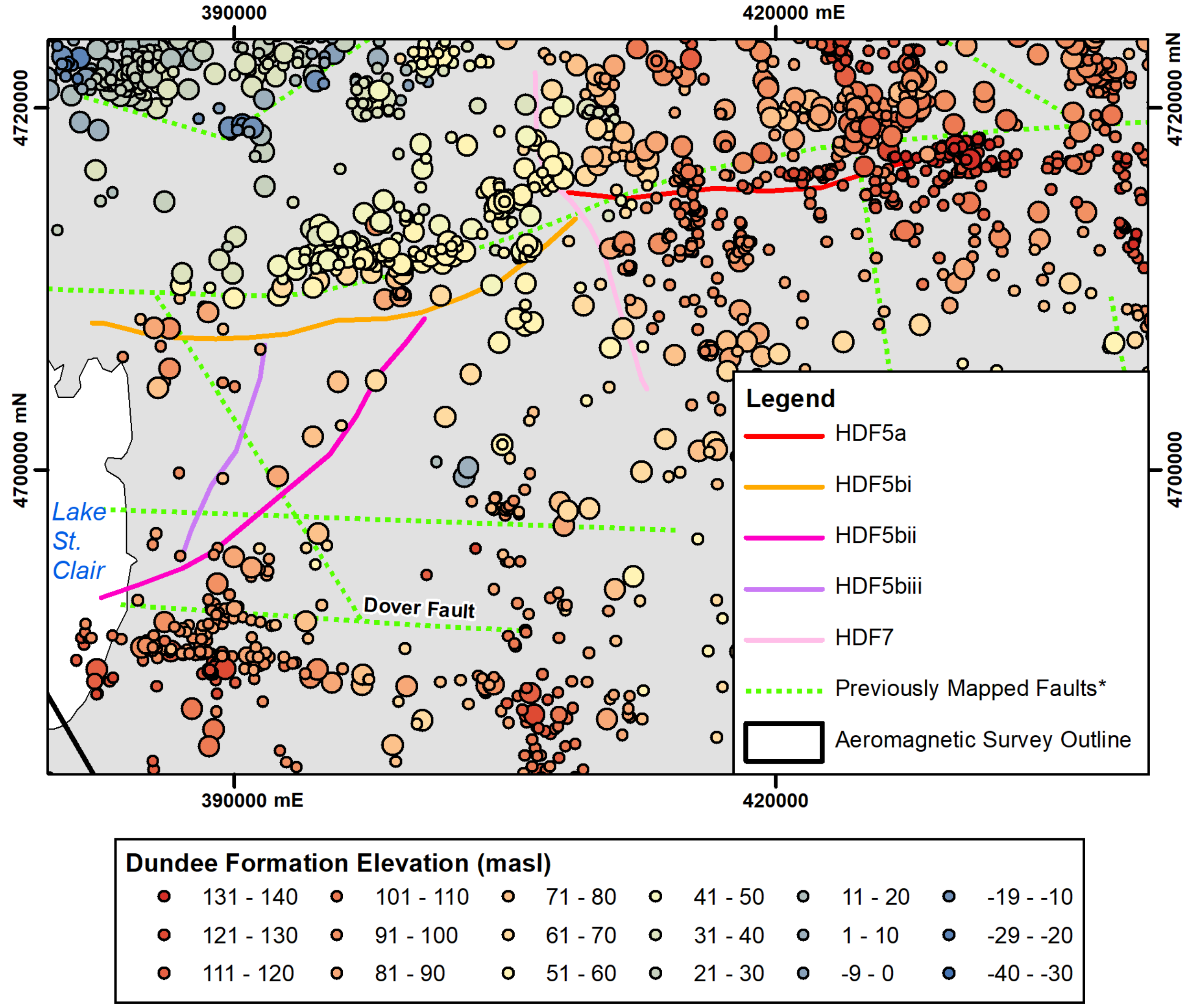

Figure 104. Dundee Formation elevation around the HDF5 and HDF7 lineaments. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

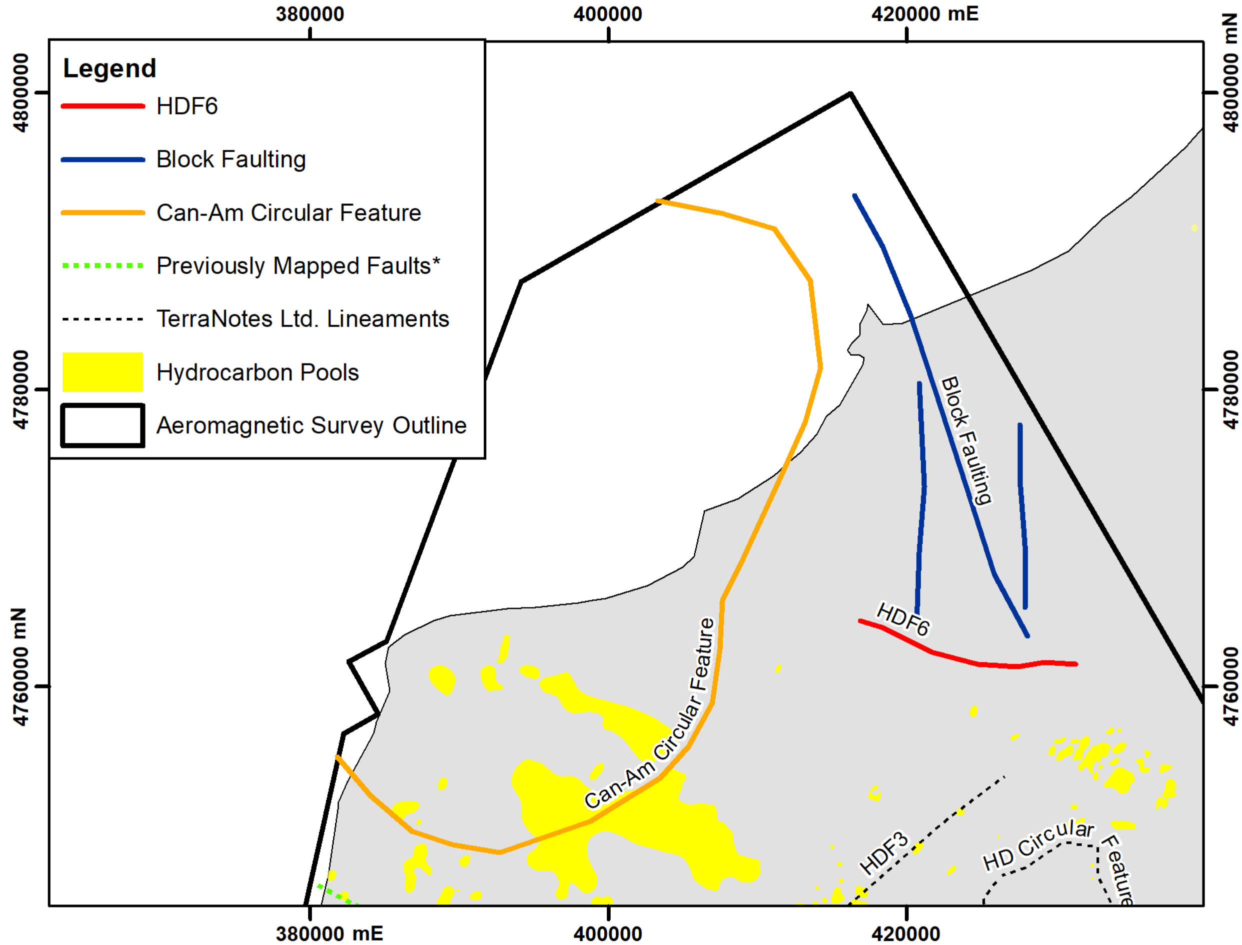

Figure 105. Locations of the HDF6 lineament, the Huron Domain block faulting feature and the Can-Am circular feature compared to previously mapped faults, other TerraNotes Ltd. lineaments and known hydrocarbon pools. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

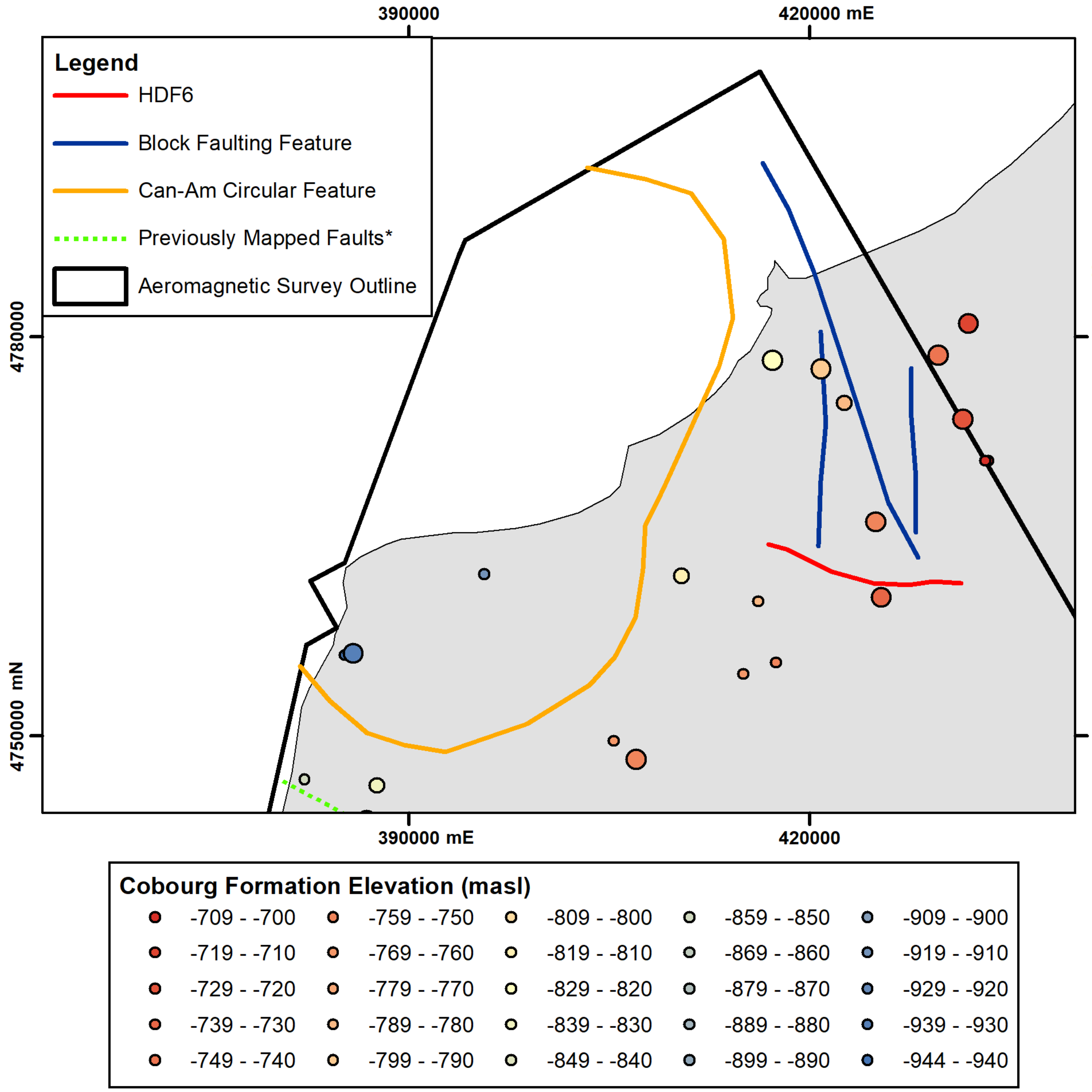

Figure 106. Cobourg Formation (Trenton Group) elevation the HDF6 lineament, the Huron Domain block faulting feature and the Can-Am circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

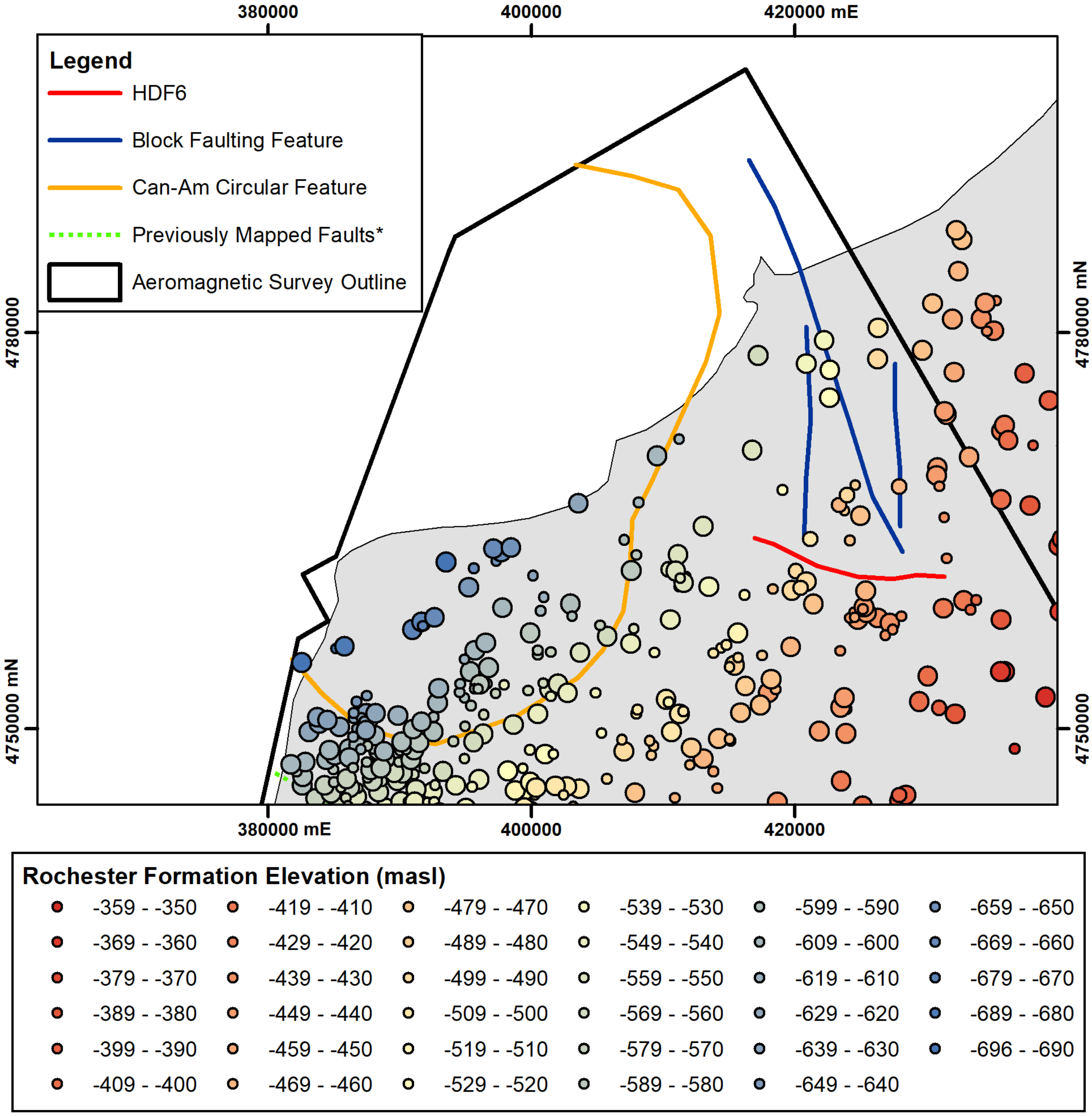

Figure 107. Rochester Formation (Clinton Group) elevation around the HDF6 lineament, the Huron Domain block faulting feature and the Can-Am circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

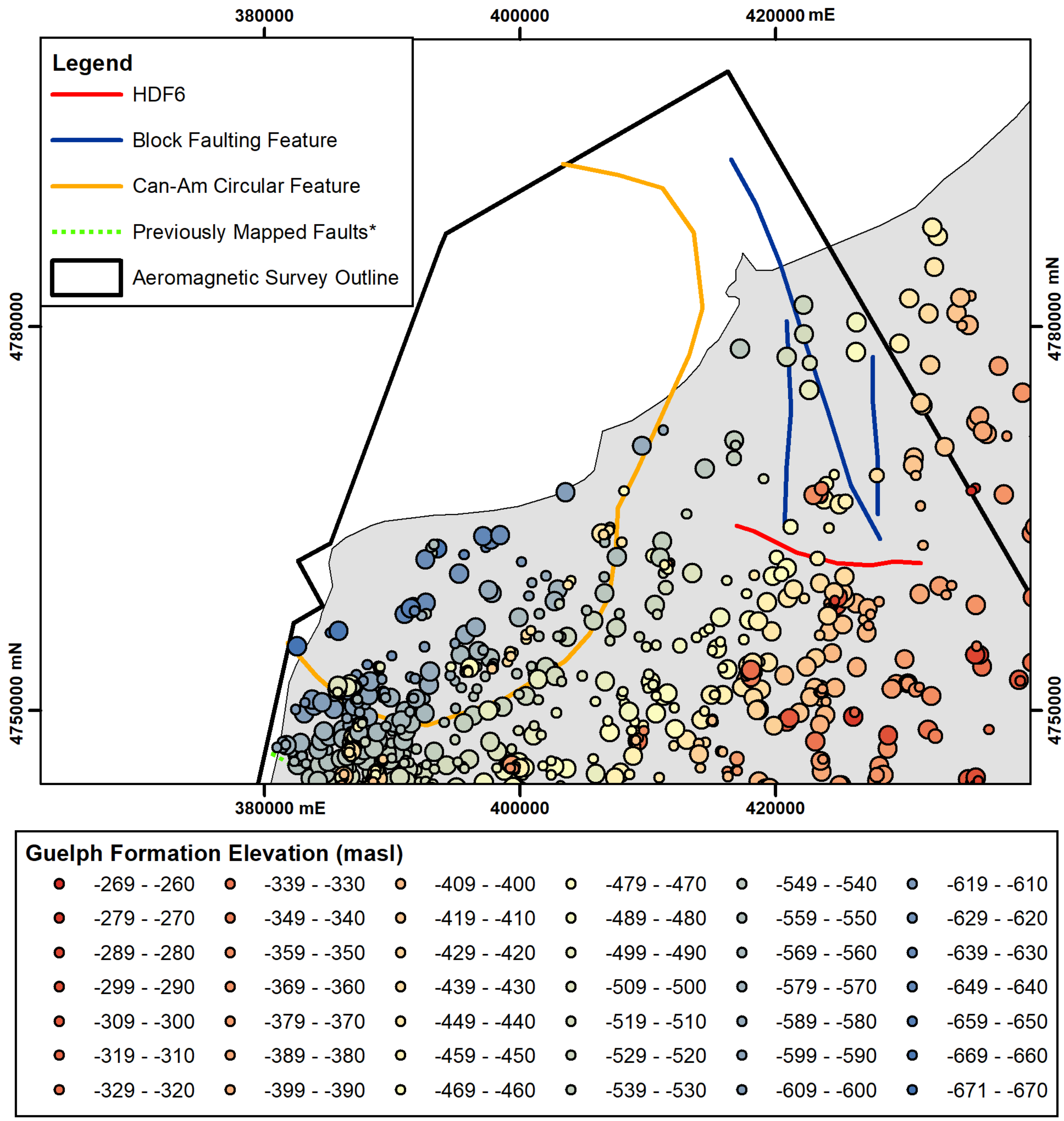

Figure 108. Guelph Formation (Lockport Group) elevation around the HDF6 lineament, the Huron Domain block faulting feature and the Can-Am circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

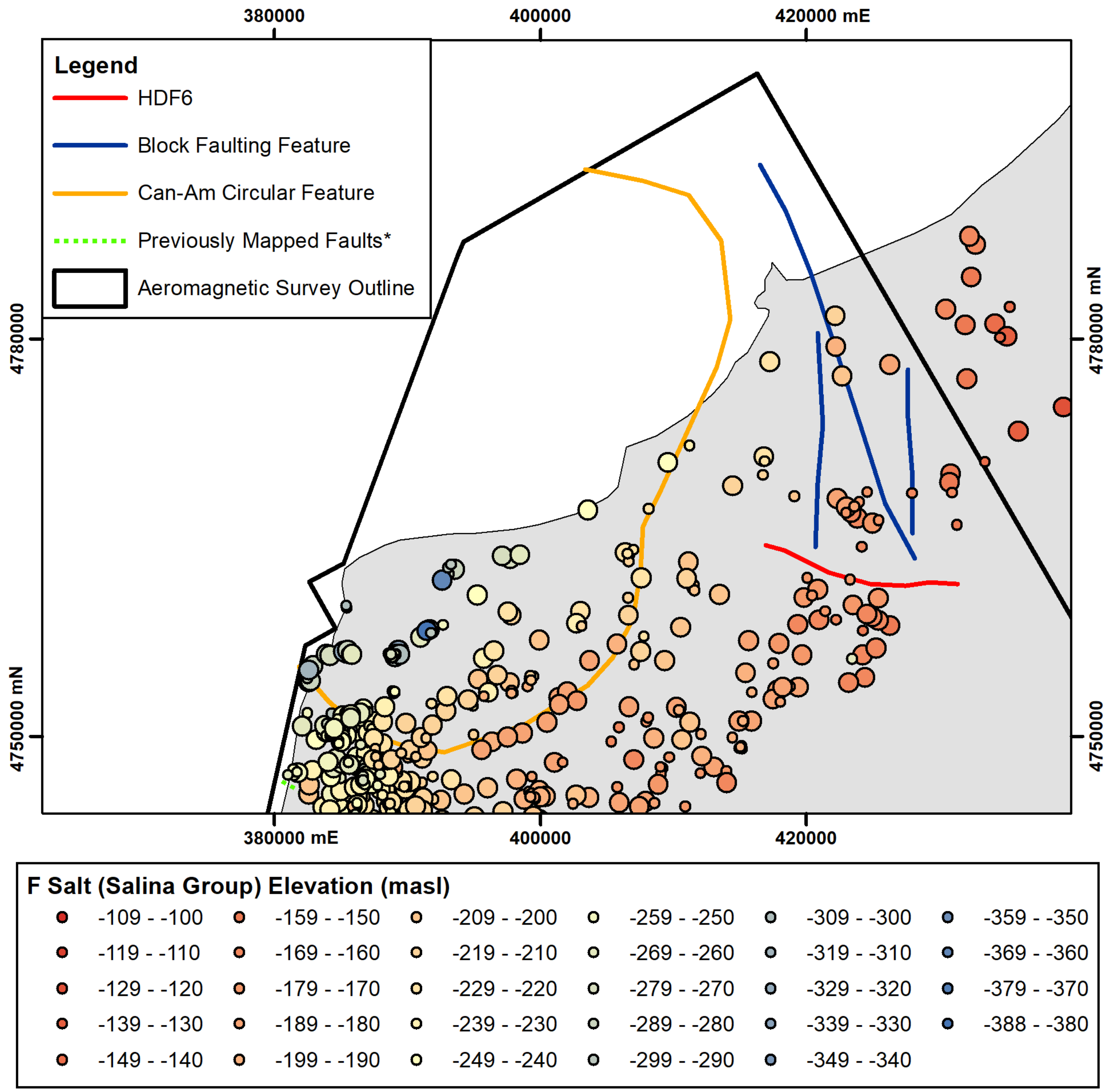

Figure 109. F Salt Unit (Salina Group) elevation around the HDF6 lineament, the Huron Domain block faulting feature and the Can-Am circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

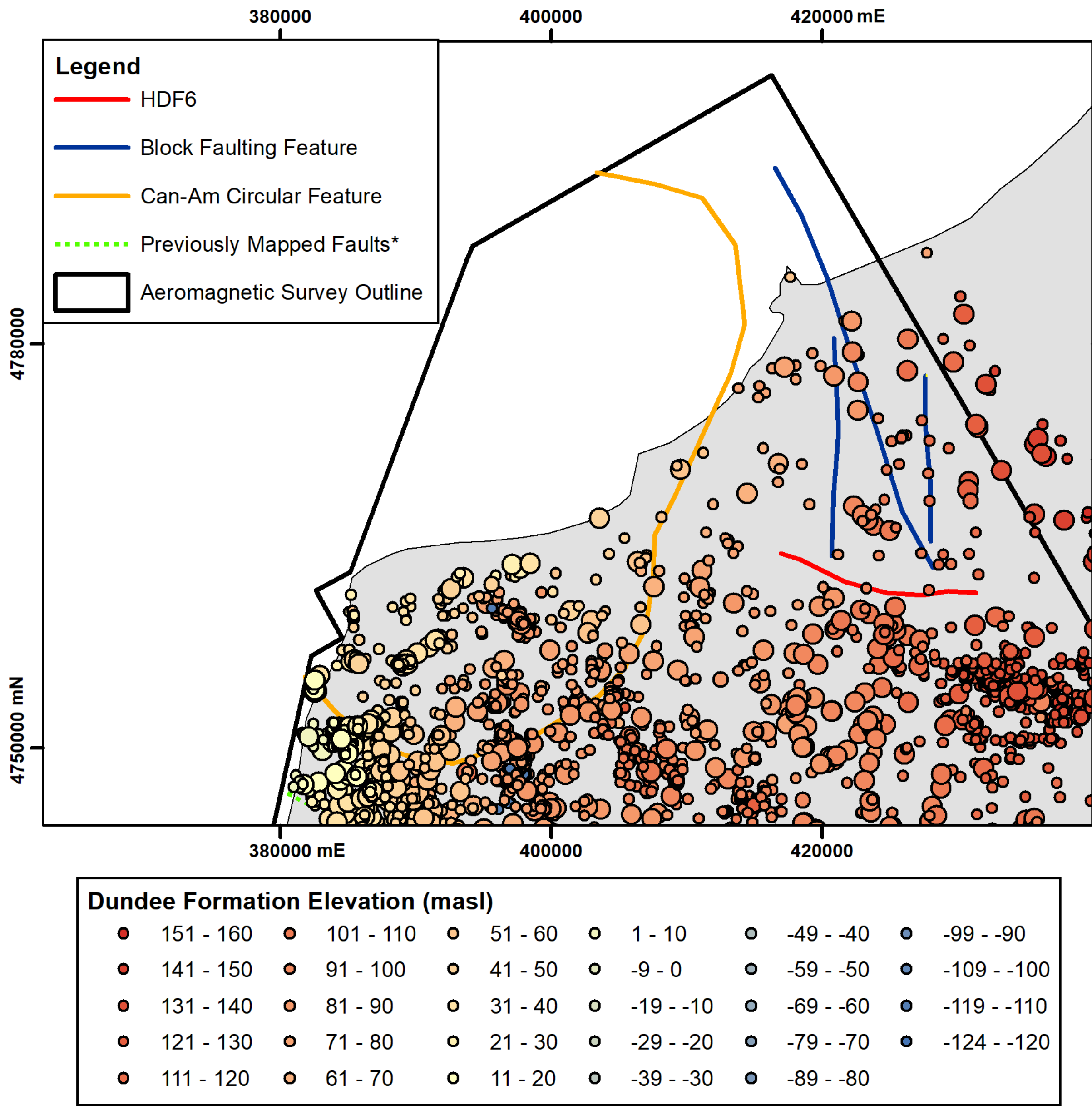

Figure 110. Dundee Formation elevation around the HDF6 lineament, the Huron Domain block faulting feature and the Can-Am circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

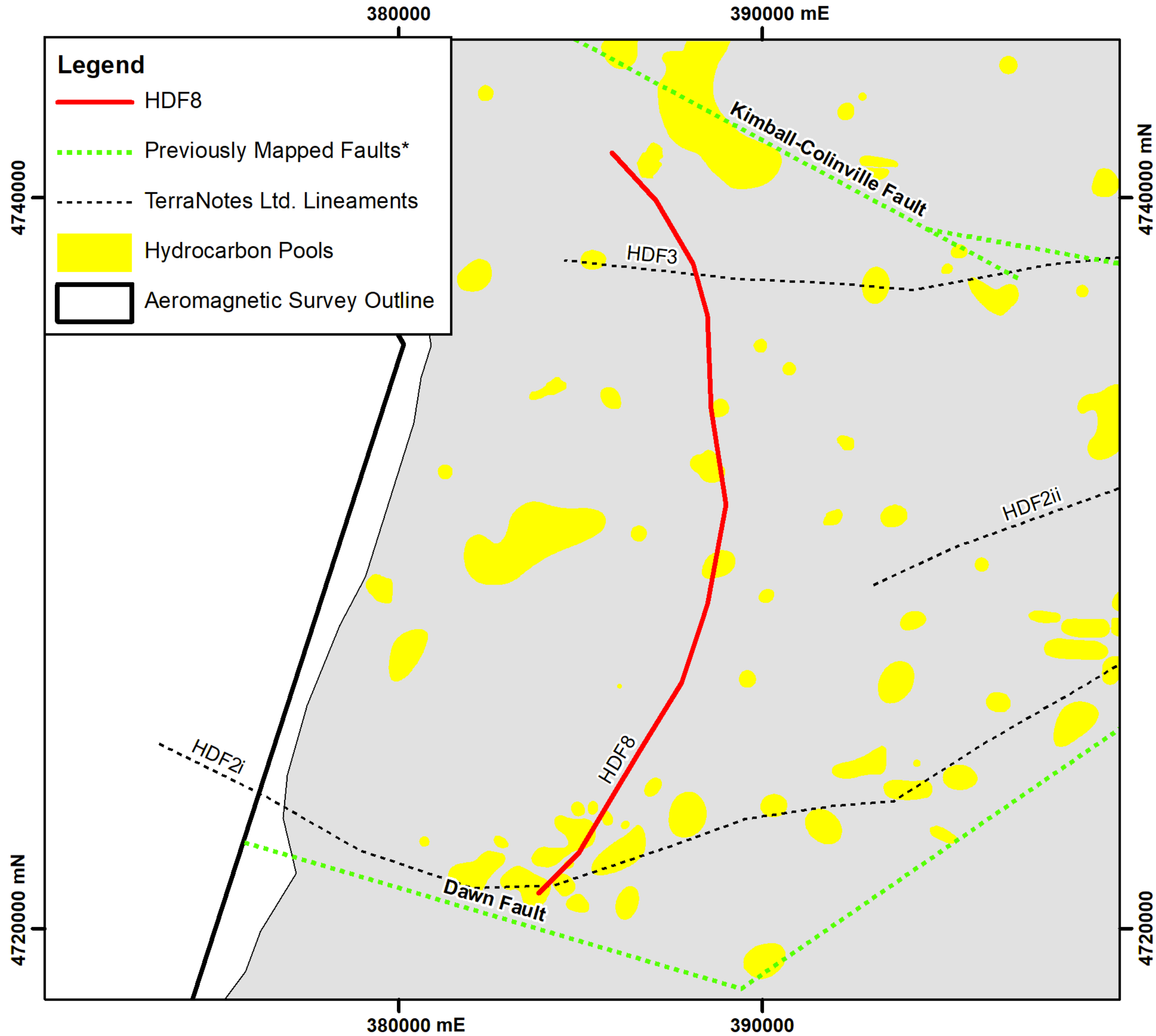

Figure 111. Location of HDF8 lineament compared to previously mapped faults, other TerraNotes Ltd. lineaments and known hydrocarbon pools. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

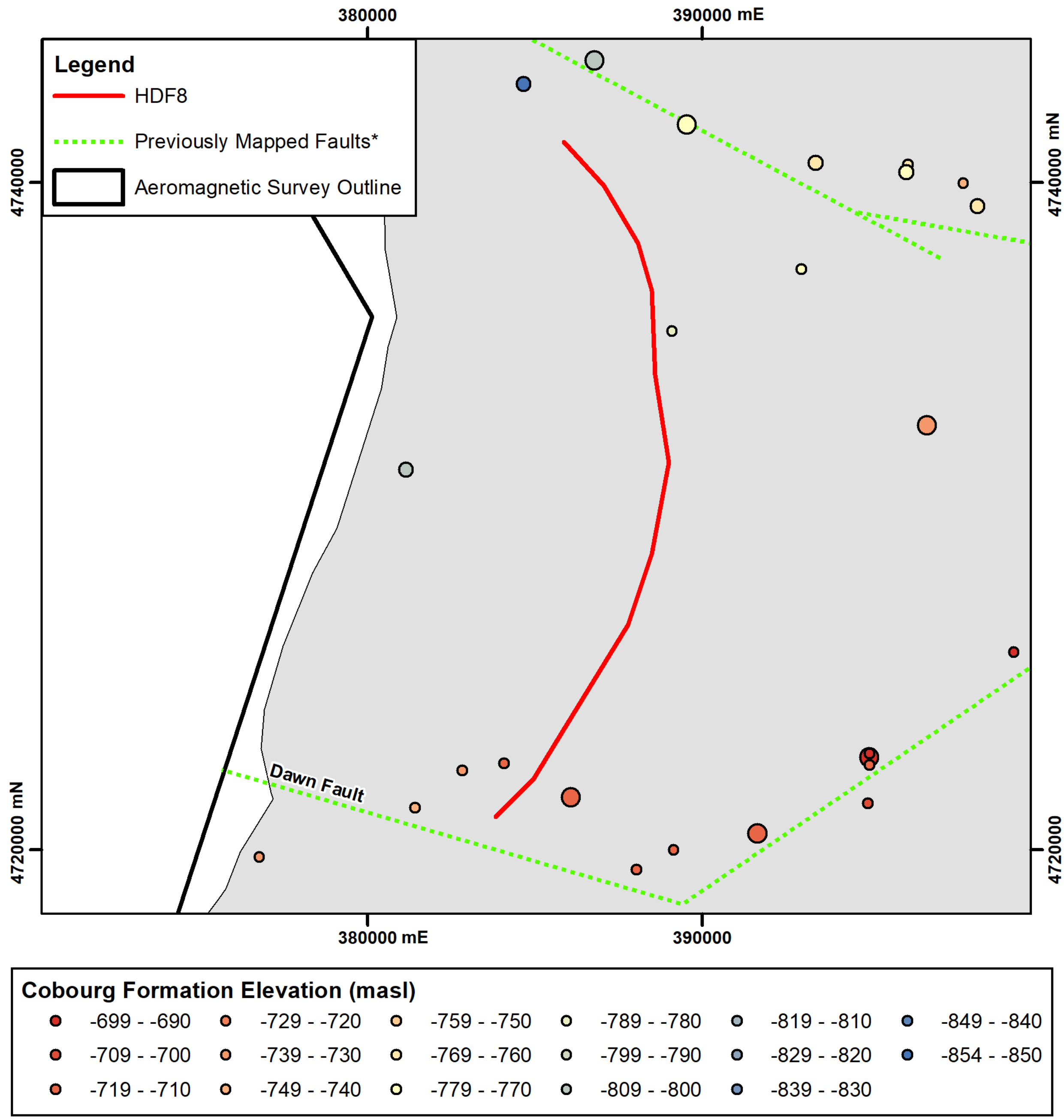

Figure 112. Cobourg Formation (Trenton Group) elevation around the HDF8 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

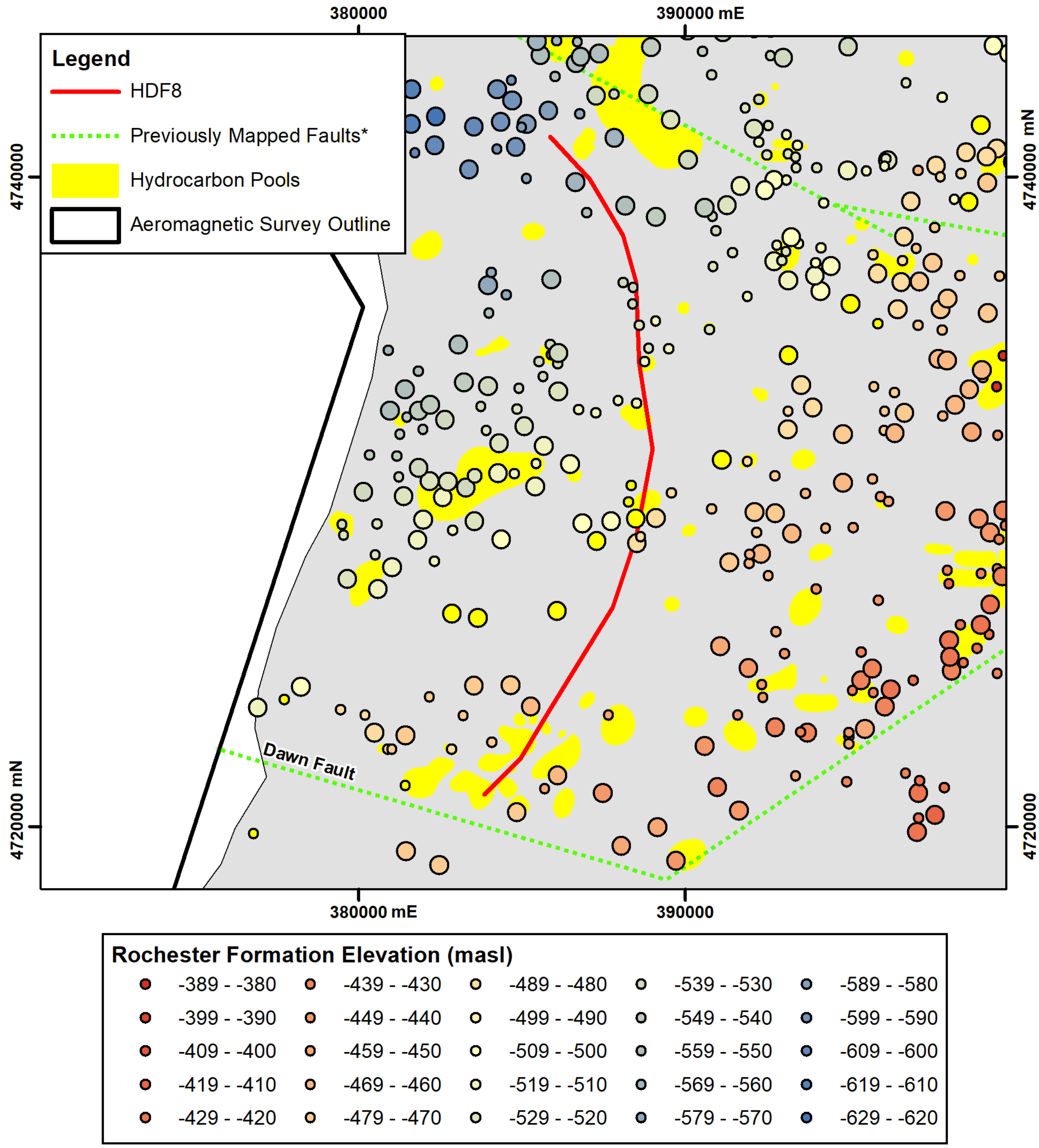

Figure 113. Rochester Formation (Clinton Group) elevation around the HDF8 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

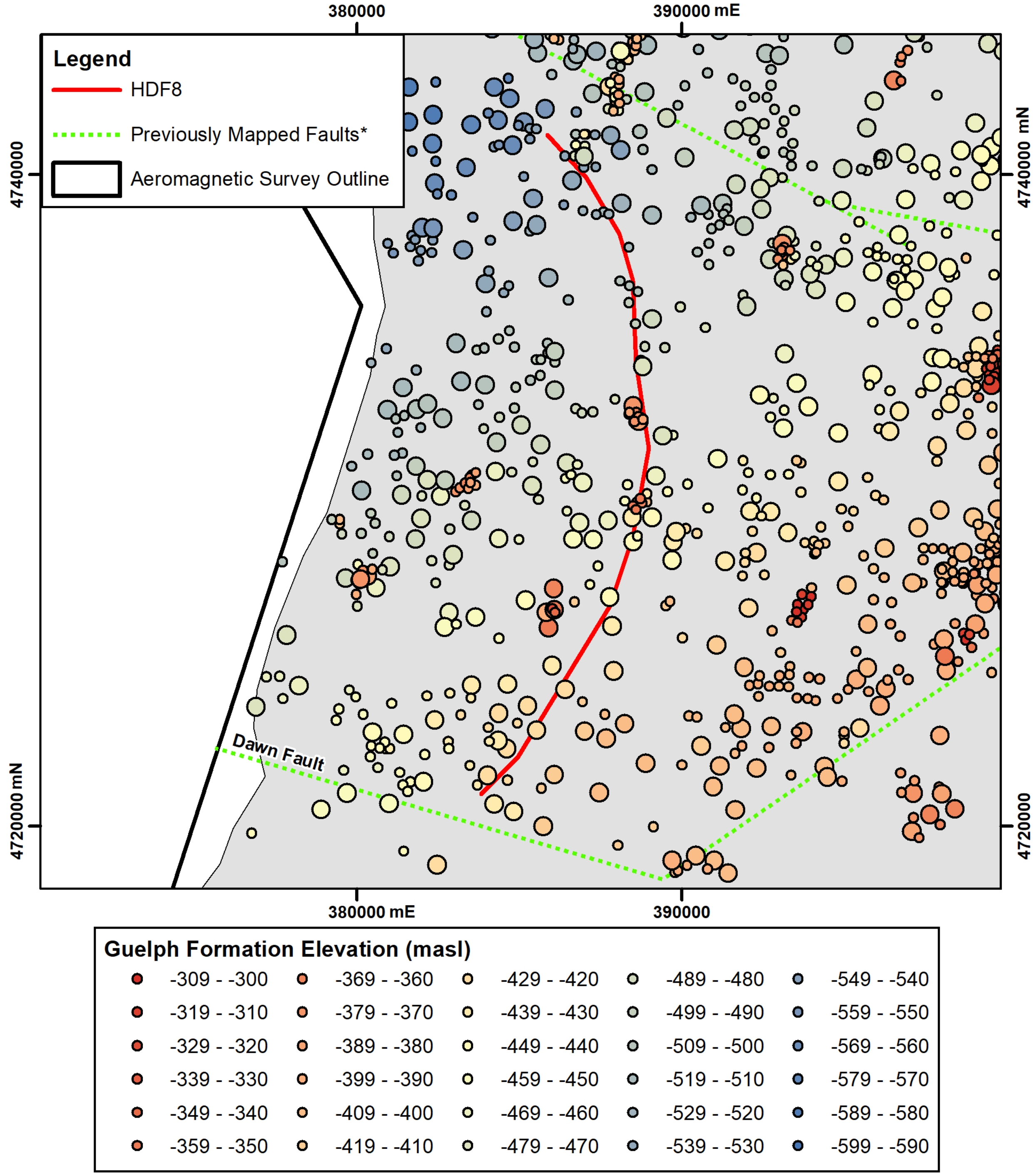

Figure 114. Guelph Formation (Lockport Group) elevation around the HDF8 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

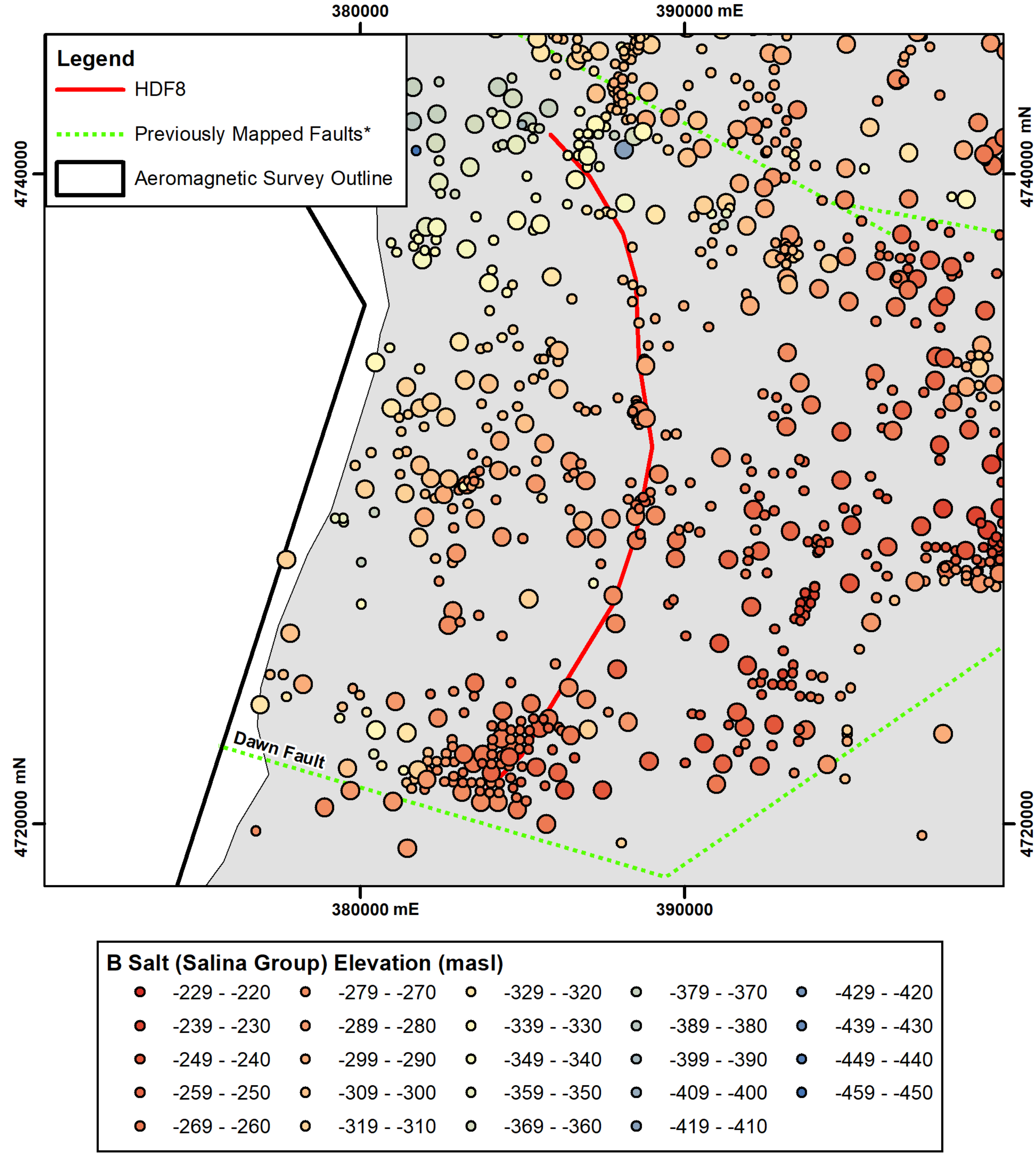

Figure 115. B Salt Unit (Salina Group) elevation around the HDF8 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

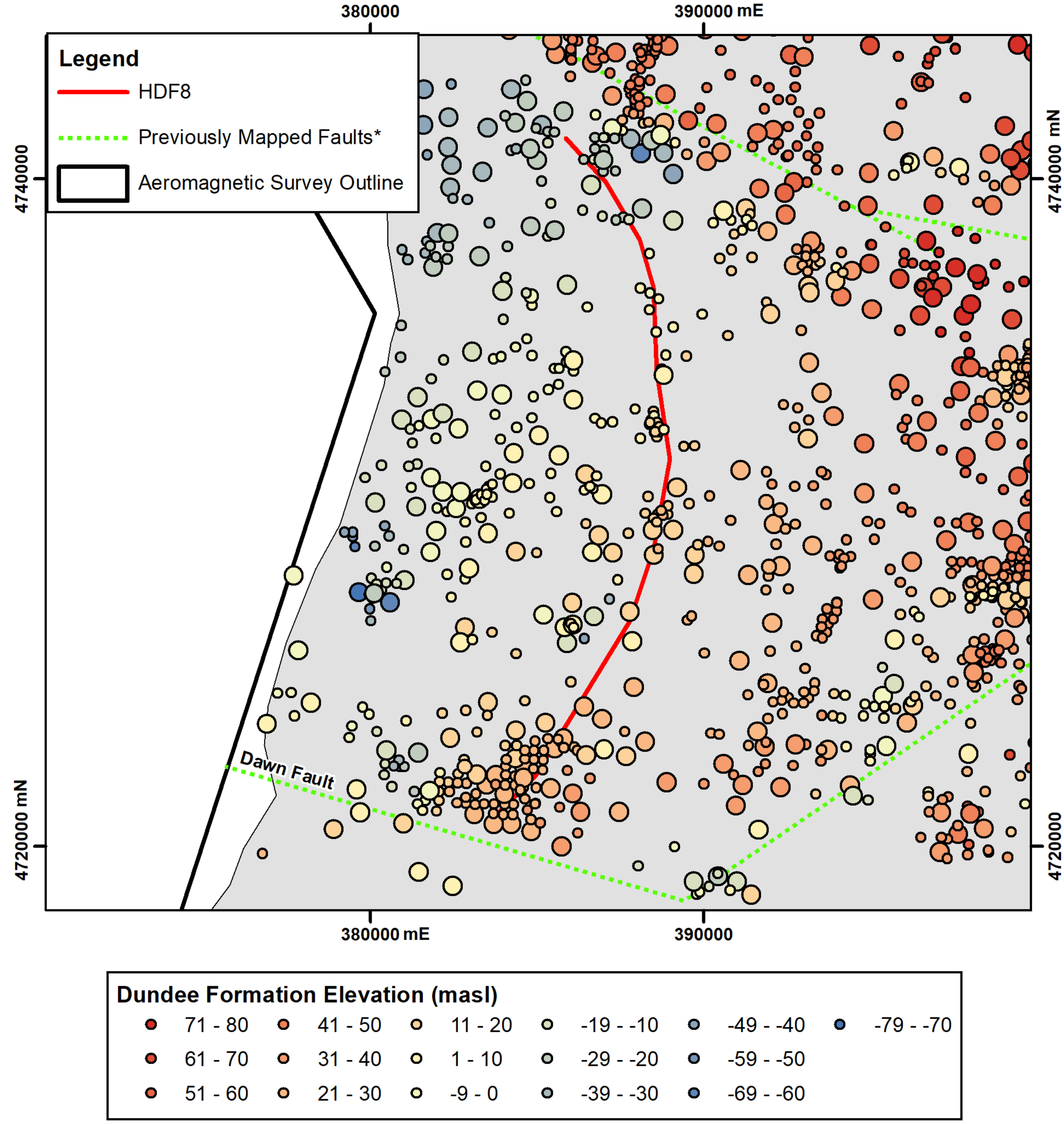

Figure 116. Dundee Formation elevation around the HDF8 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

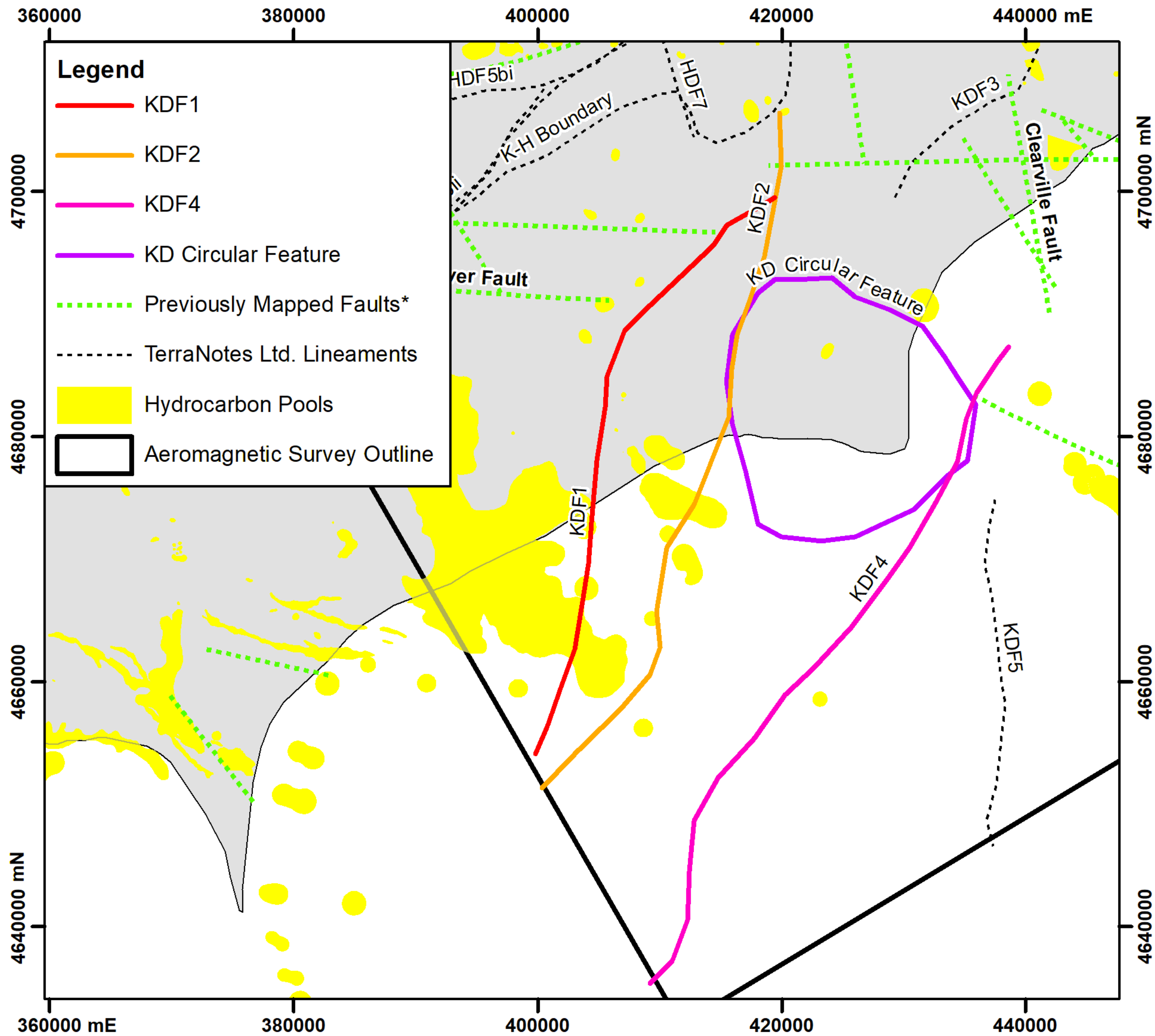

Figure 117. Locations of the KDF1, KDF2 and KDF4 lineaments and the Kent Domain circular feature compared to previously mapped faults, other TerraNotes Ltd. lineaments and known hydrocarbon pools. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

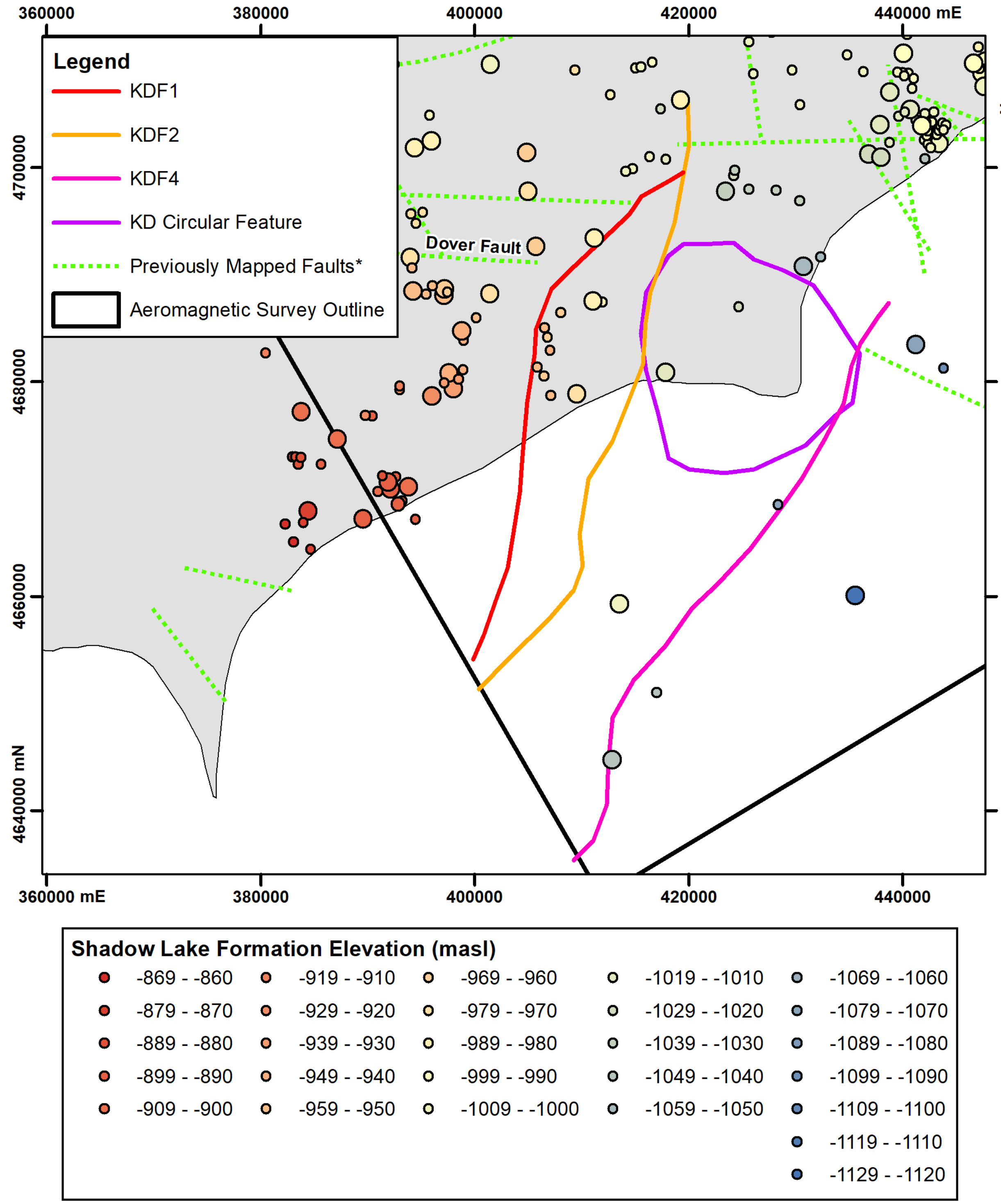

Figure 118. Shadow Lake Formation (Black River Group) elevation around the KDF1, KDF2 and KDF4 lineaments and the Kent Domain circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

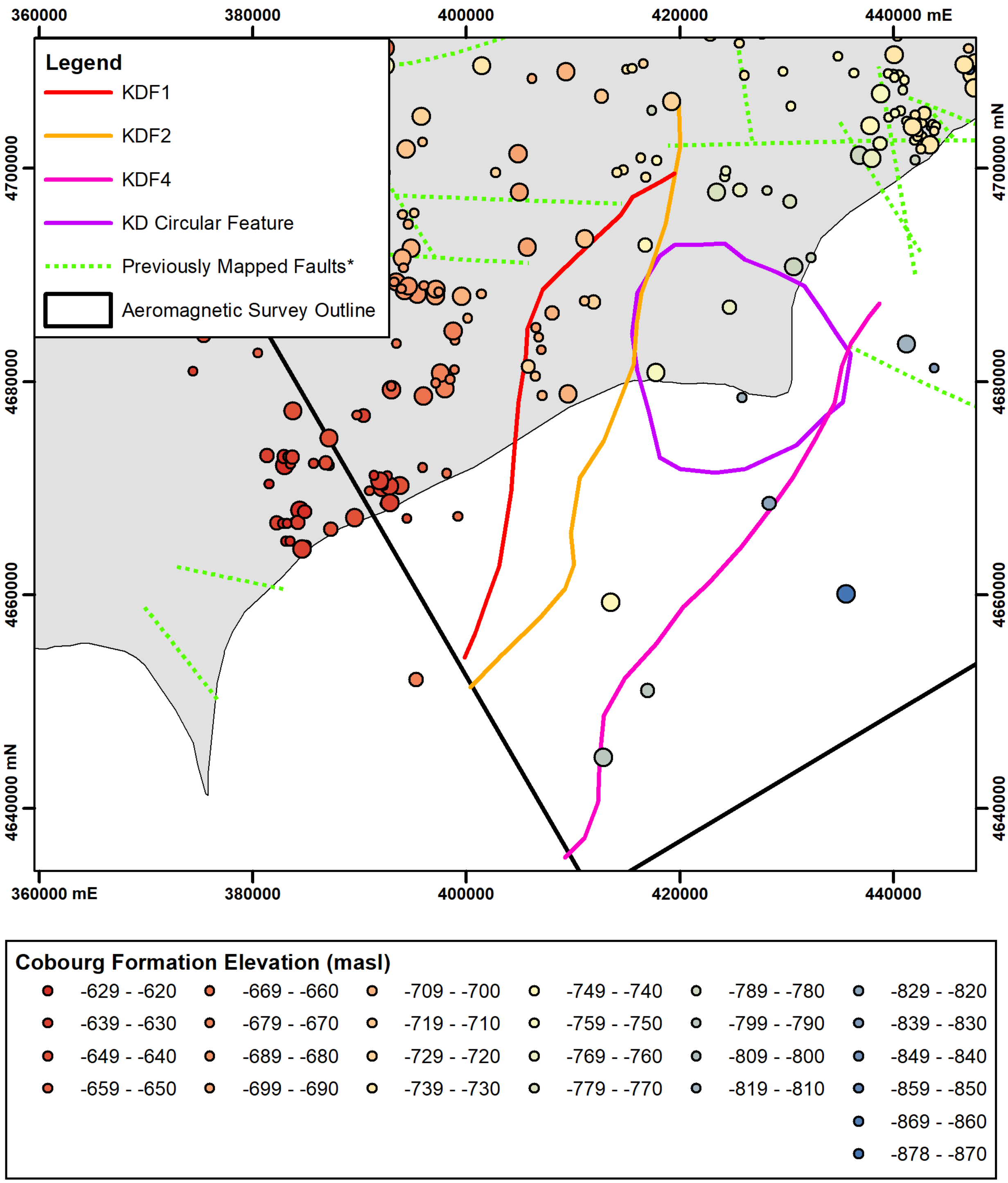

Figure 119. Cobourg Formation (Trenton Group) elevation around the KDF1, KDF2, KDF4 lineaments and the Kent Domain circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

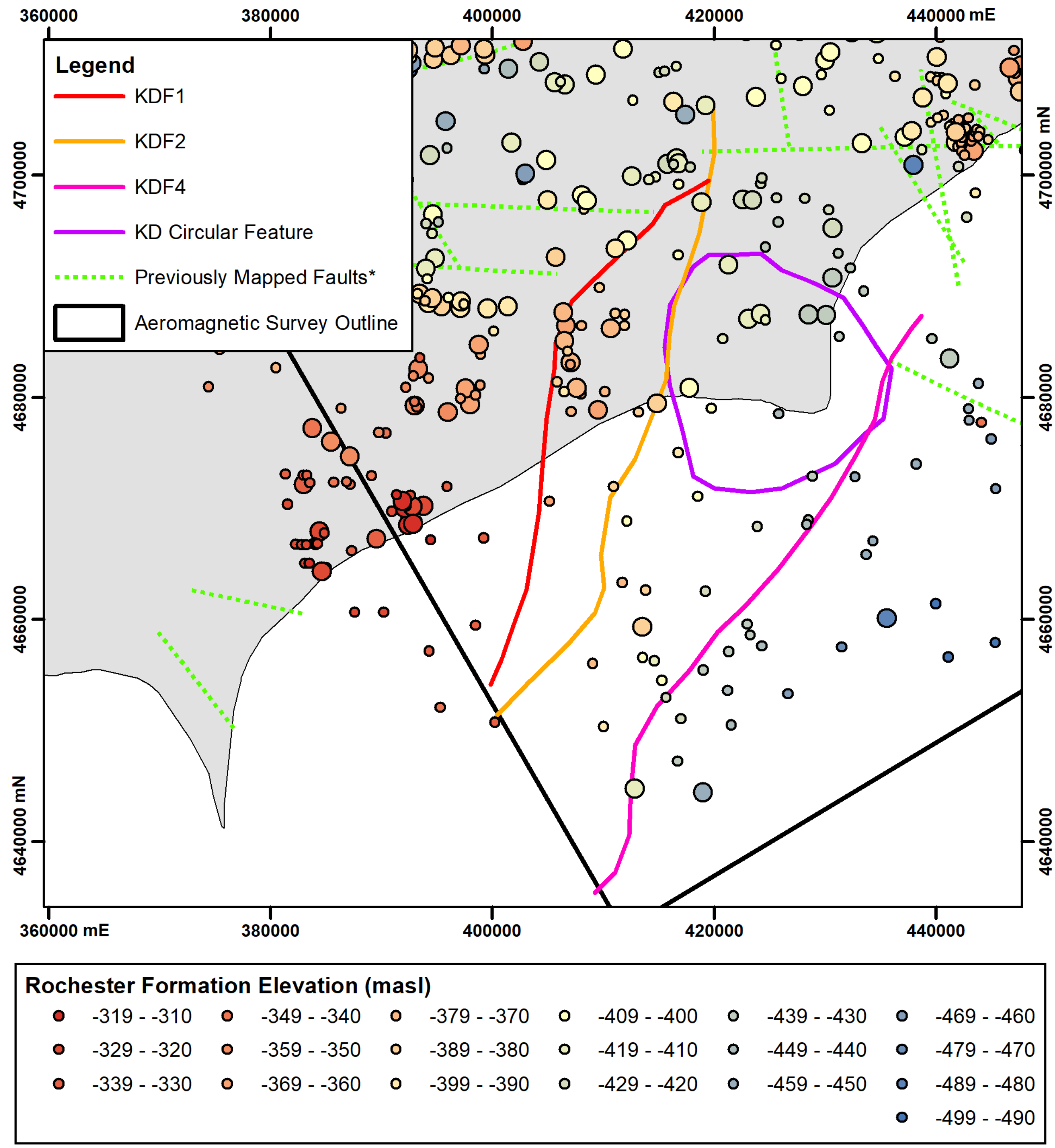

Figure 120. Rochester Formation (Clinton Group) elevation around the KDF1, KDF2, KDF4 lineaments and the Kent Domain circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

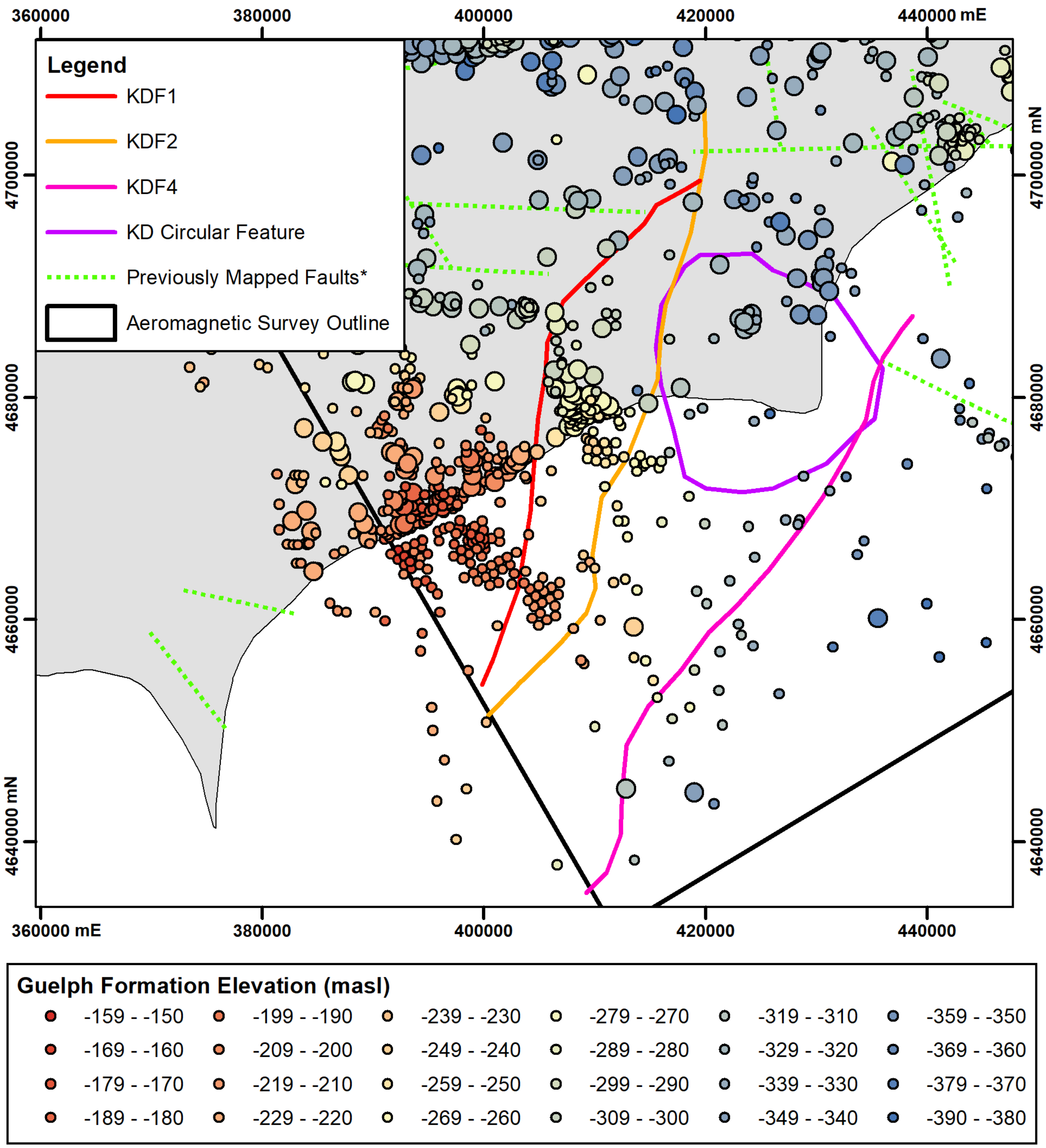

Figure 121. Guelph Formation (Lockport Group) elevation around the KDF1, KDF2, KDF4 lineaments and the Kent Domain circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

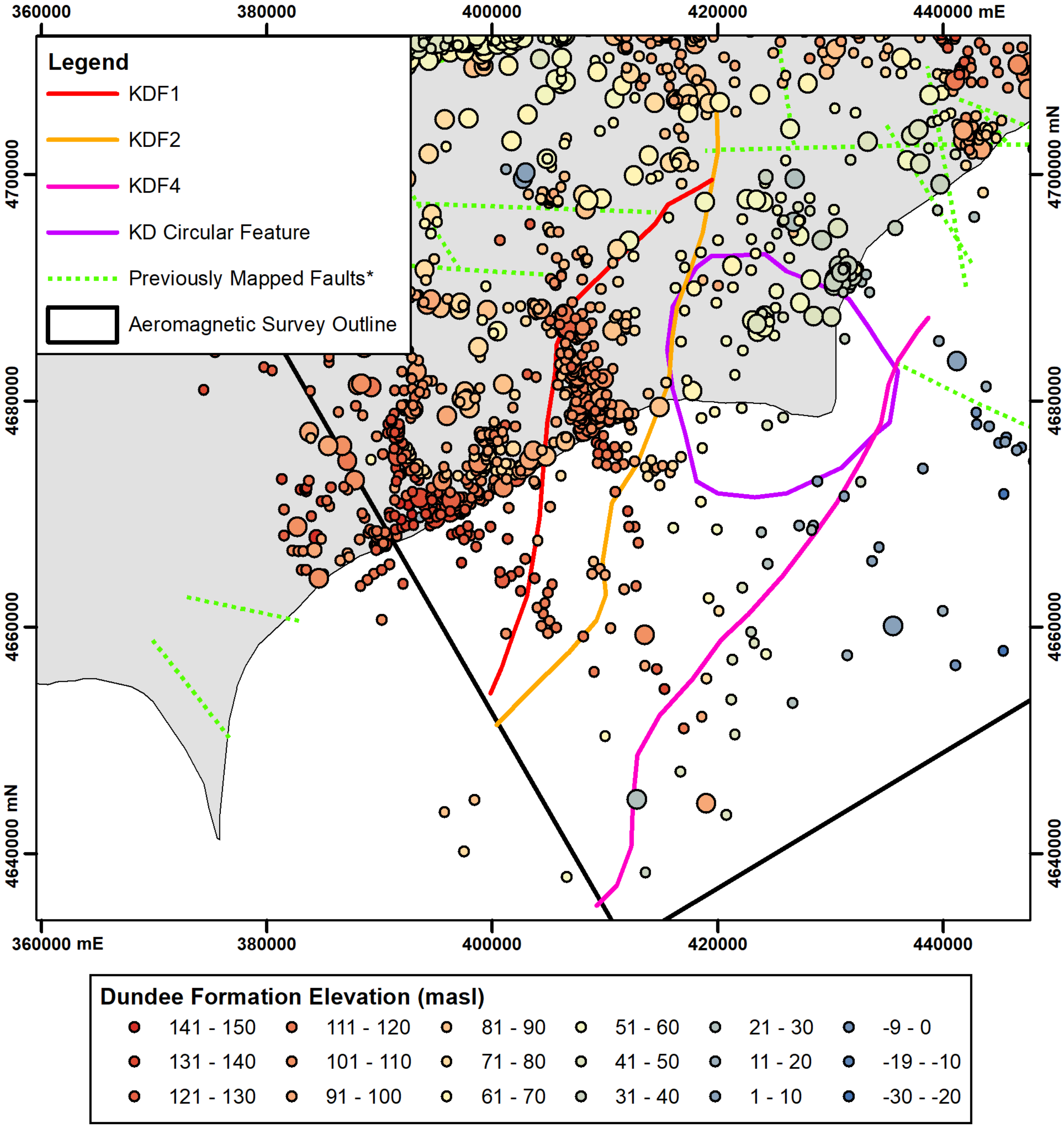

Figure 122. Dundee Formation elevation around the KDF1, KDF2, KDF4 lineaments and the Kent Domain circular feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

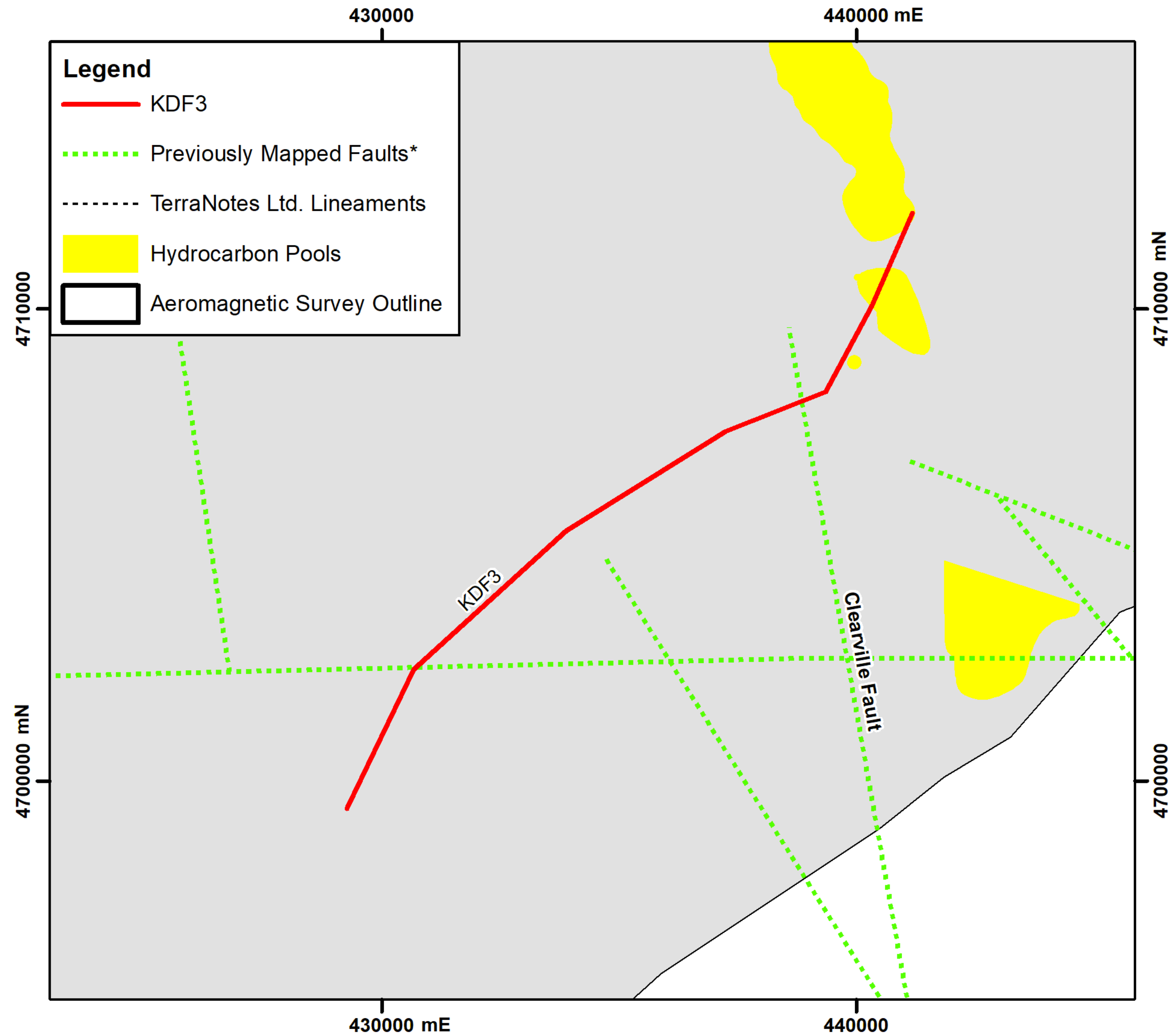

Figure 123. Location of the KDF3 lineament compared to previously mapped faults, other TerraNotes Ltd. lineaments and known hydrocarbon pools. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

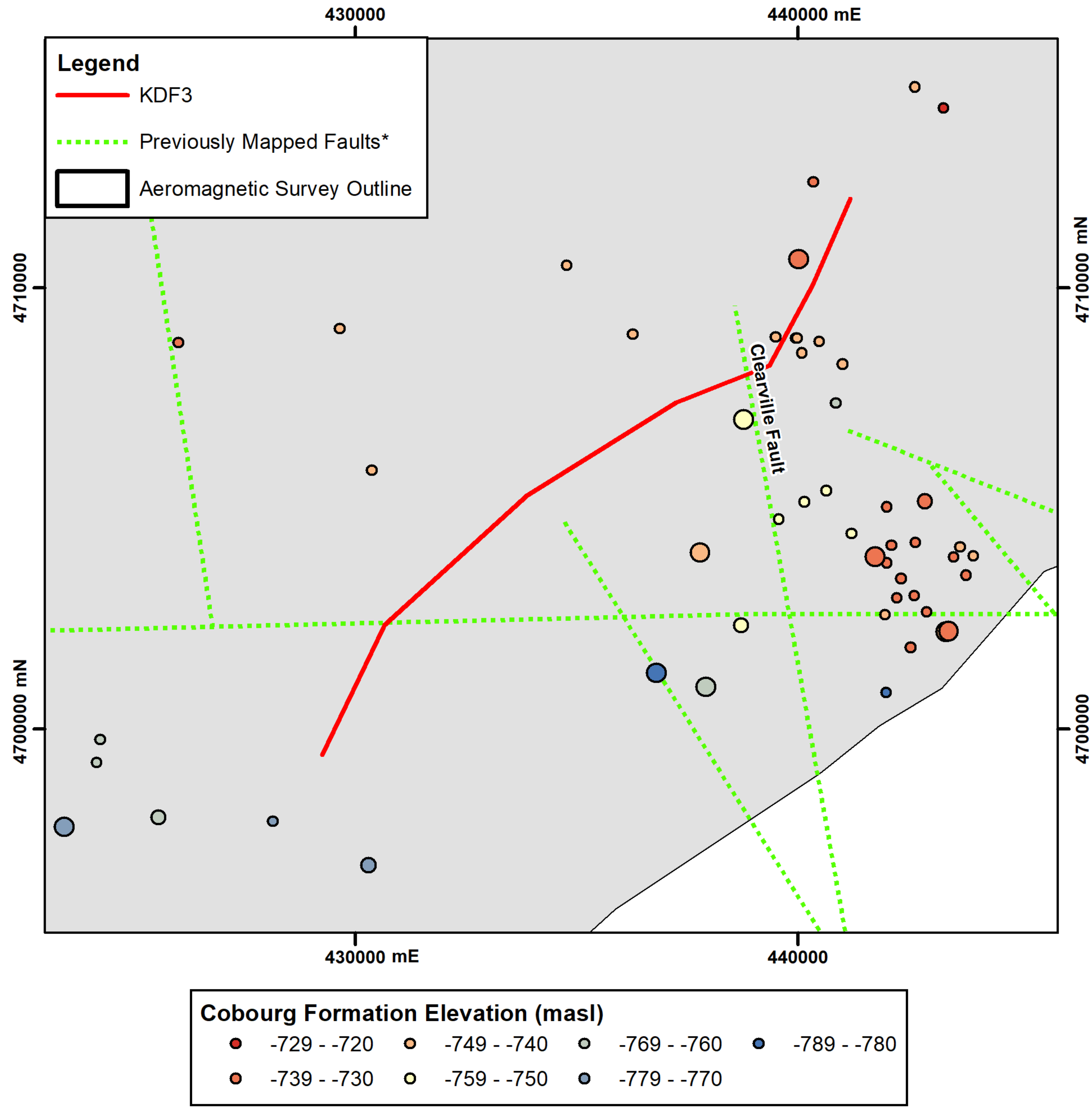

Figure 124. Cobourg Formation (Trenton Group) elevation around the KDF3 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

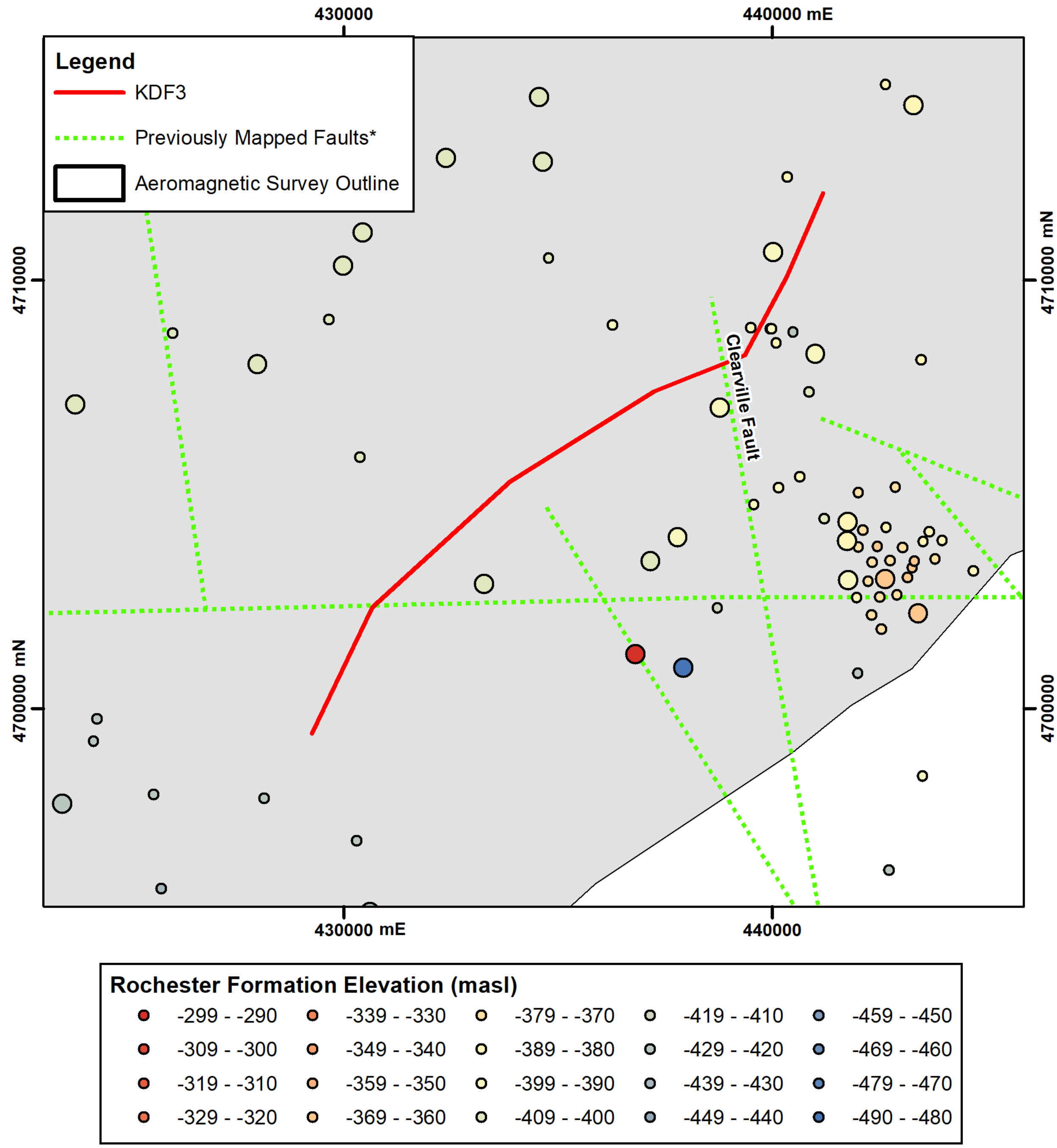

Figure 125. Rochester Formation (Clinton Group) elevation around the KDF3 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

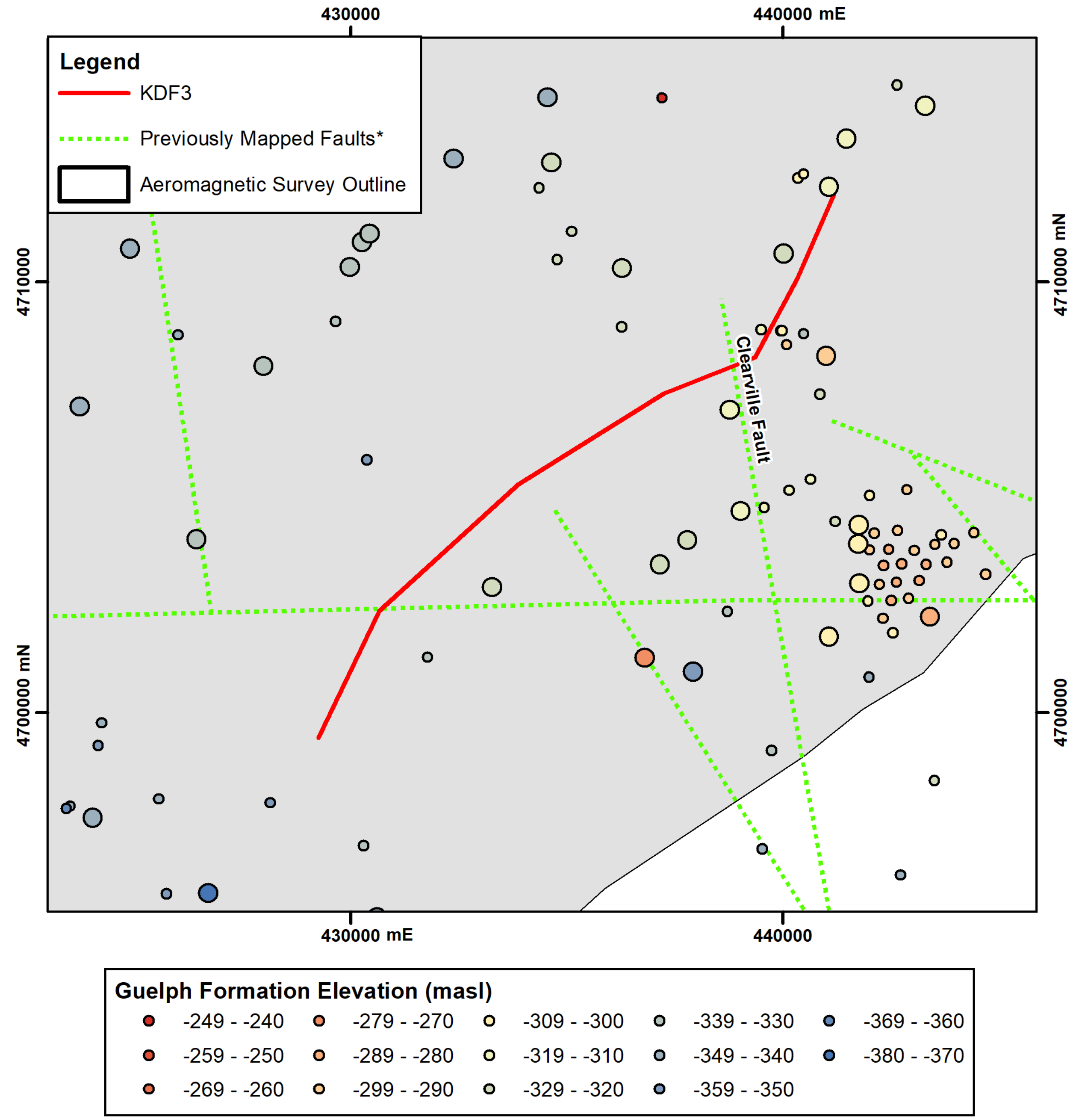

Figure 126. Guelph Formation (Lockport Group) elevation around the KDF3 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

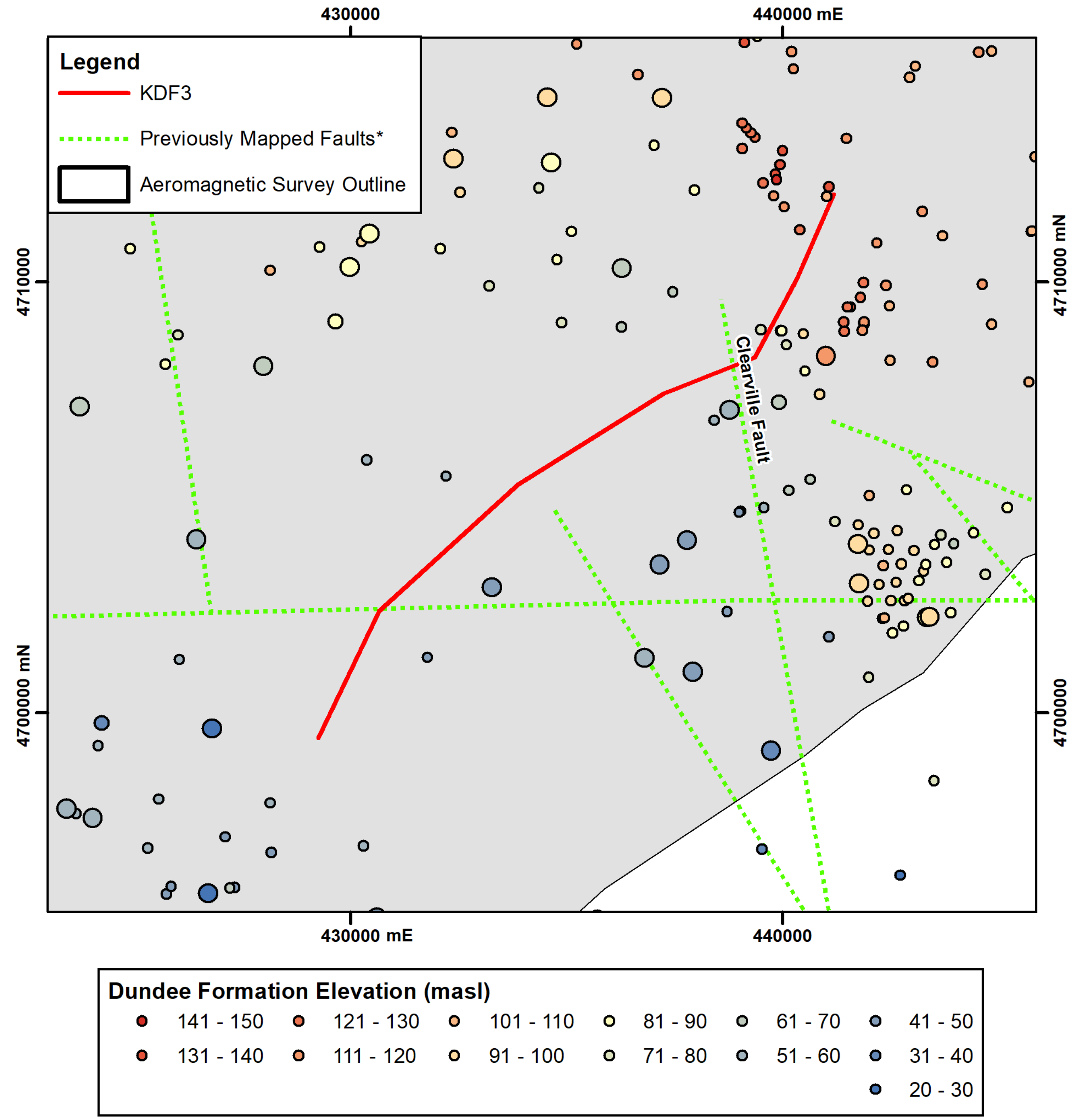

Figure 127. Dundee Formation elevation elevation around the KDF3 lineament. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

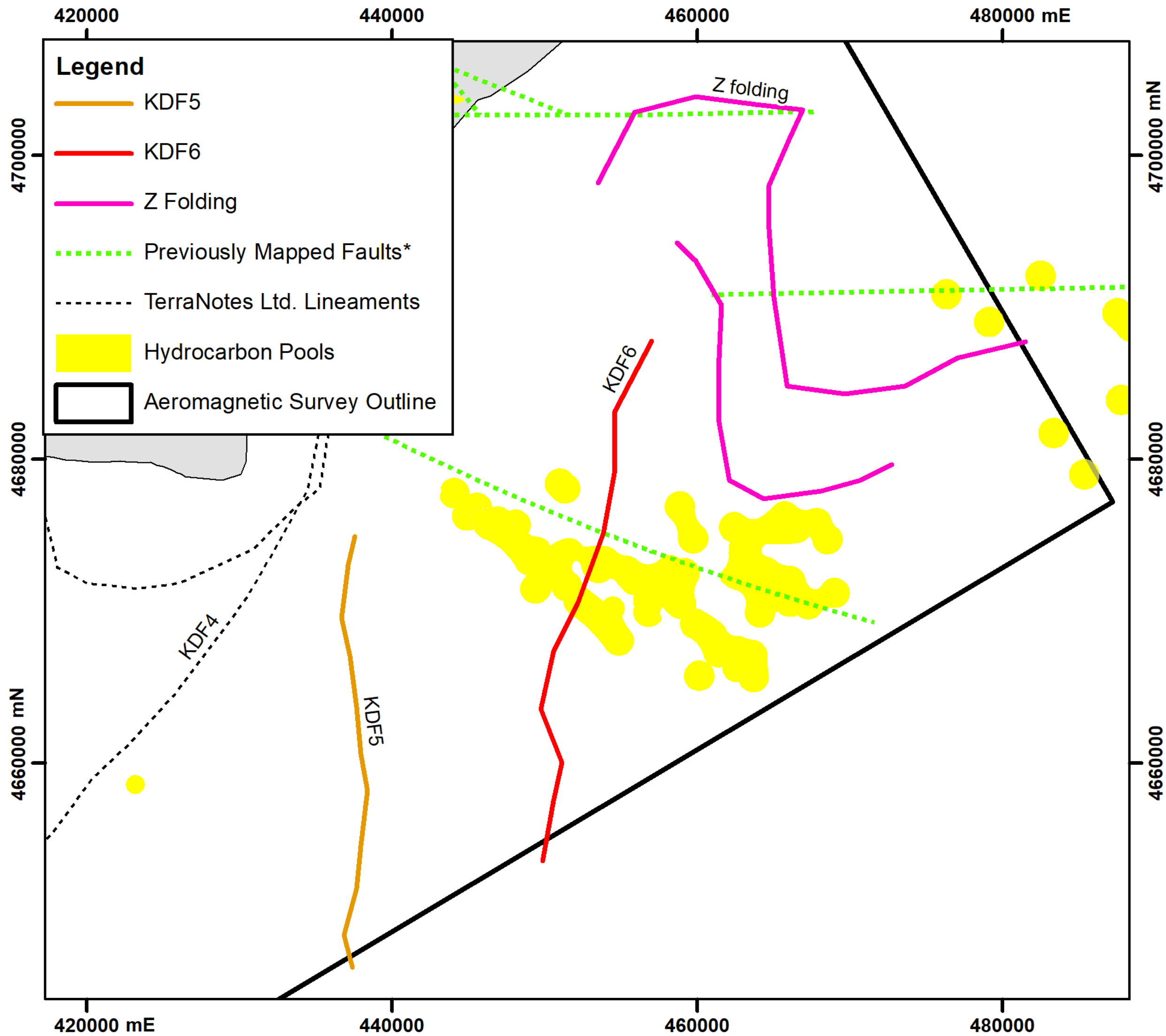

Figure 128. Locations of the KDF5 and KDF6 lineaments and the Kent Domain Z-folding feature compared to previously mapped faults, other TerraNotes Ltd. lineaments and known hydrocarbon pools. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

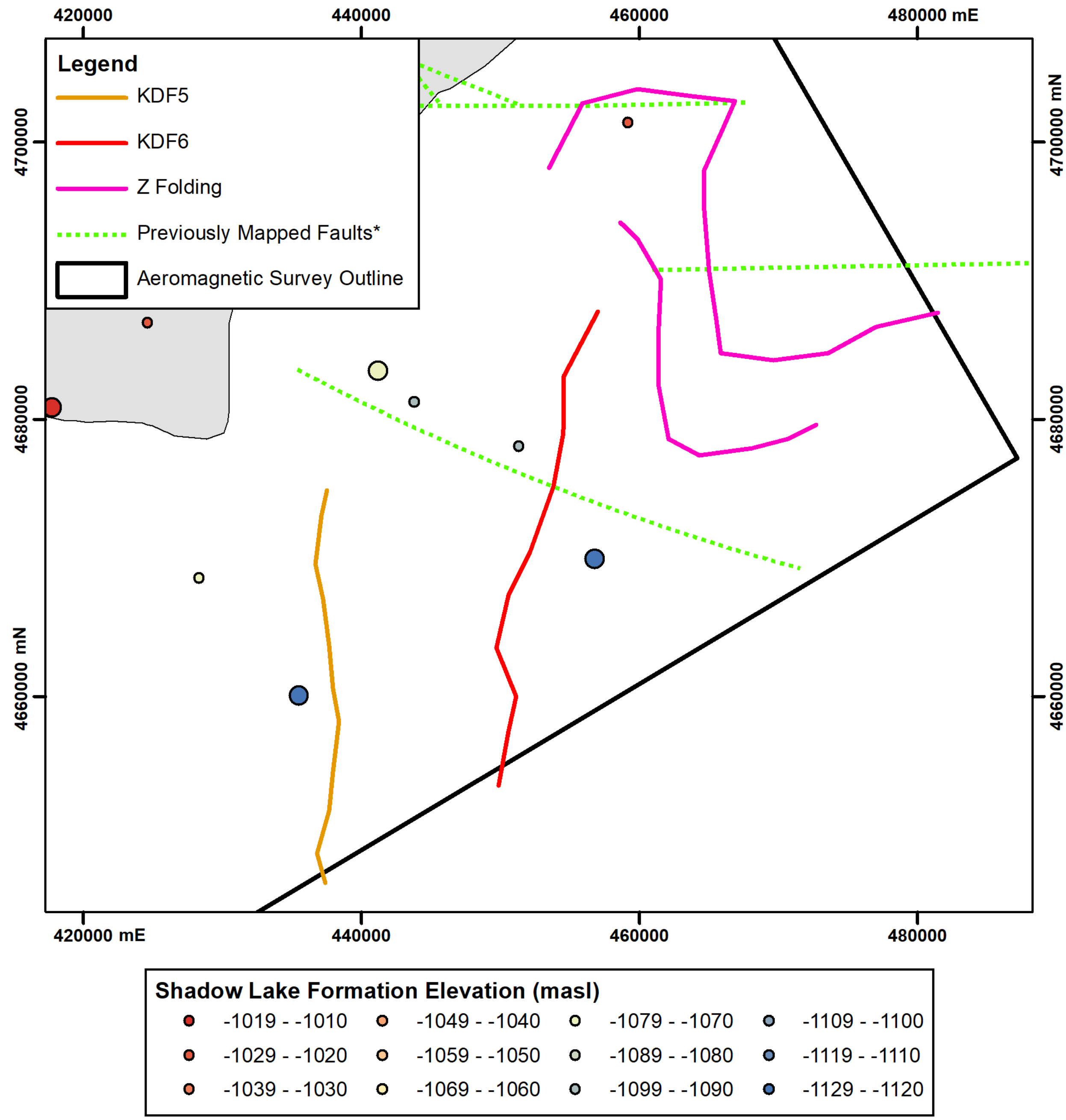

Figure 129. Shadow Lake Formation (Black River Group) elevation around the KDF5 and KDF6 lineaments and the Kent Domain Z-folding feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

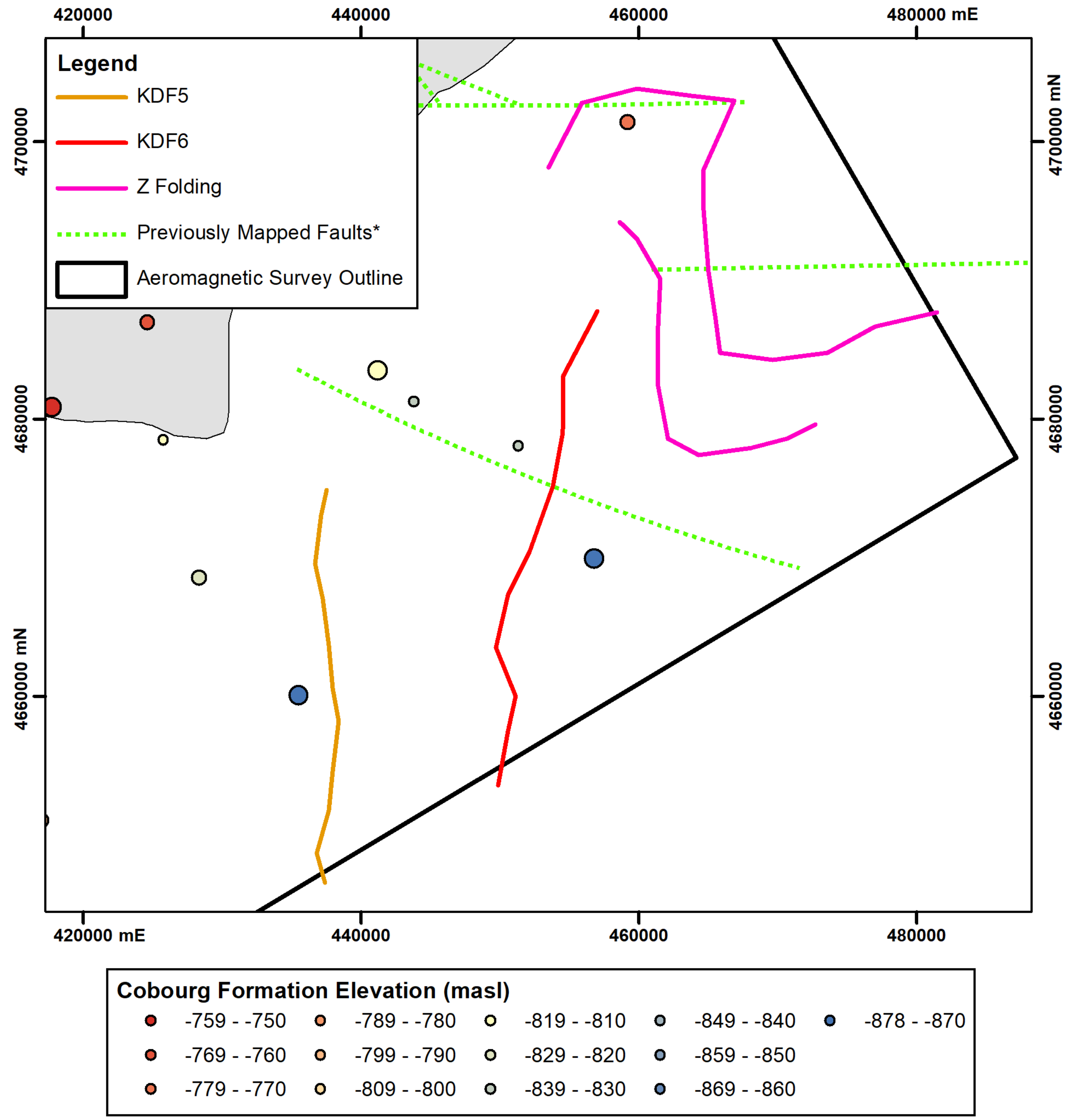

Figure 130. Cobourg Formation (Trenton Group) elevation around the KDF5 and KDF6 lineaments and the Kent Domain Z-folding feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

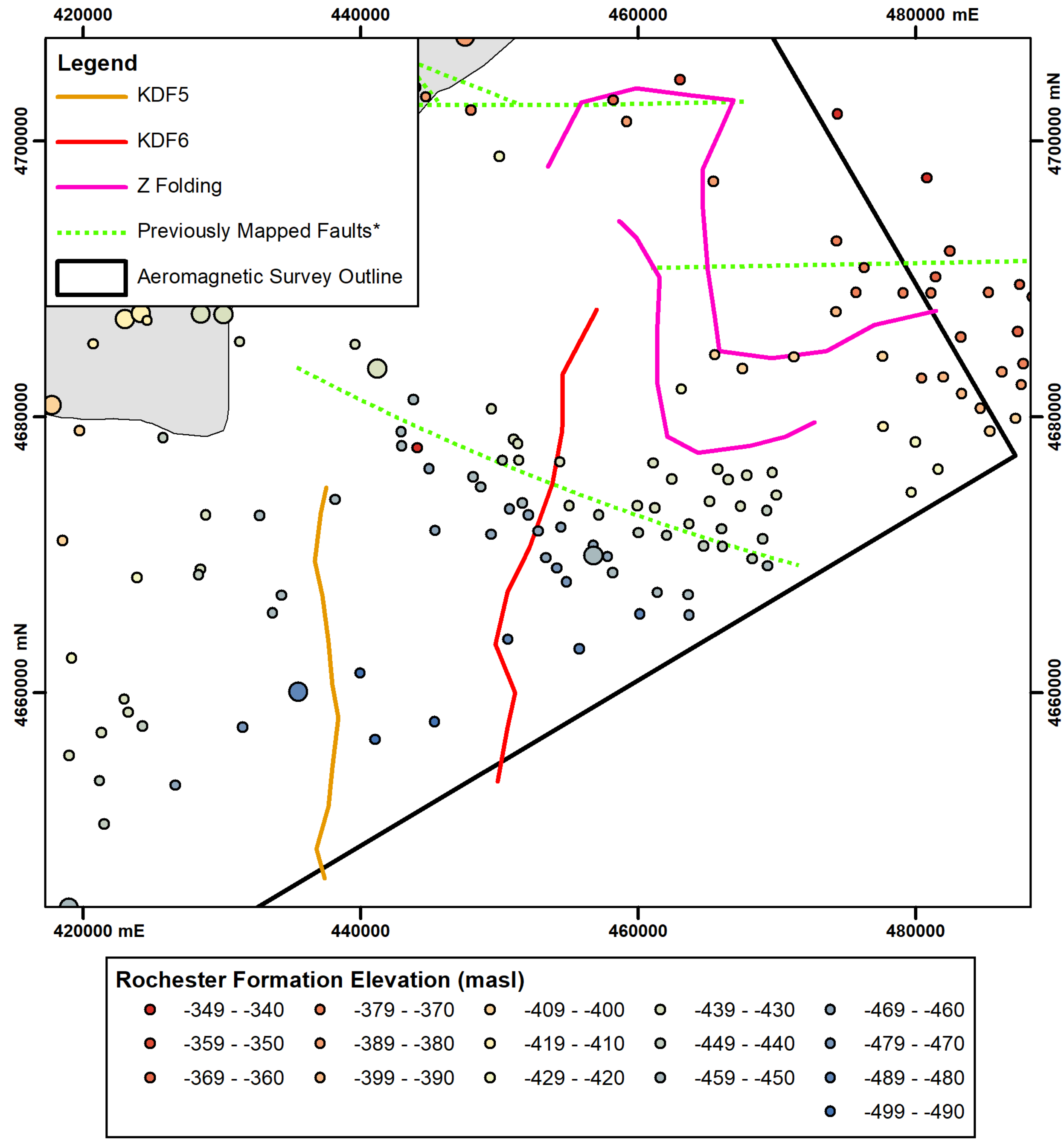

Figure 131. Rochester Formation (Clinton Group) elevation around the KDF5 and KDF6 lineaments and the Kent Domain Z-folding feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

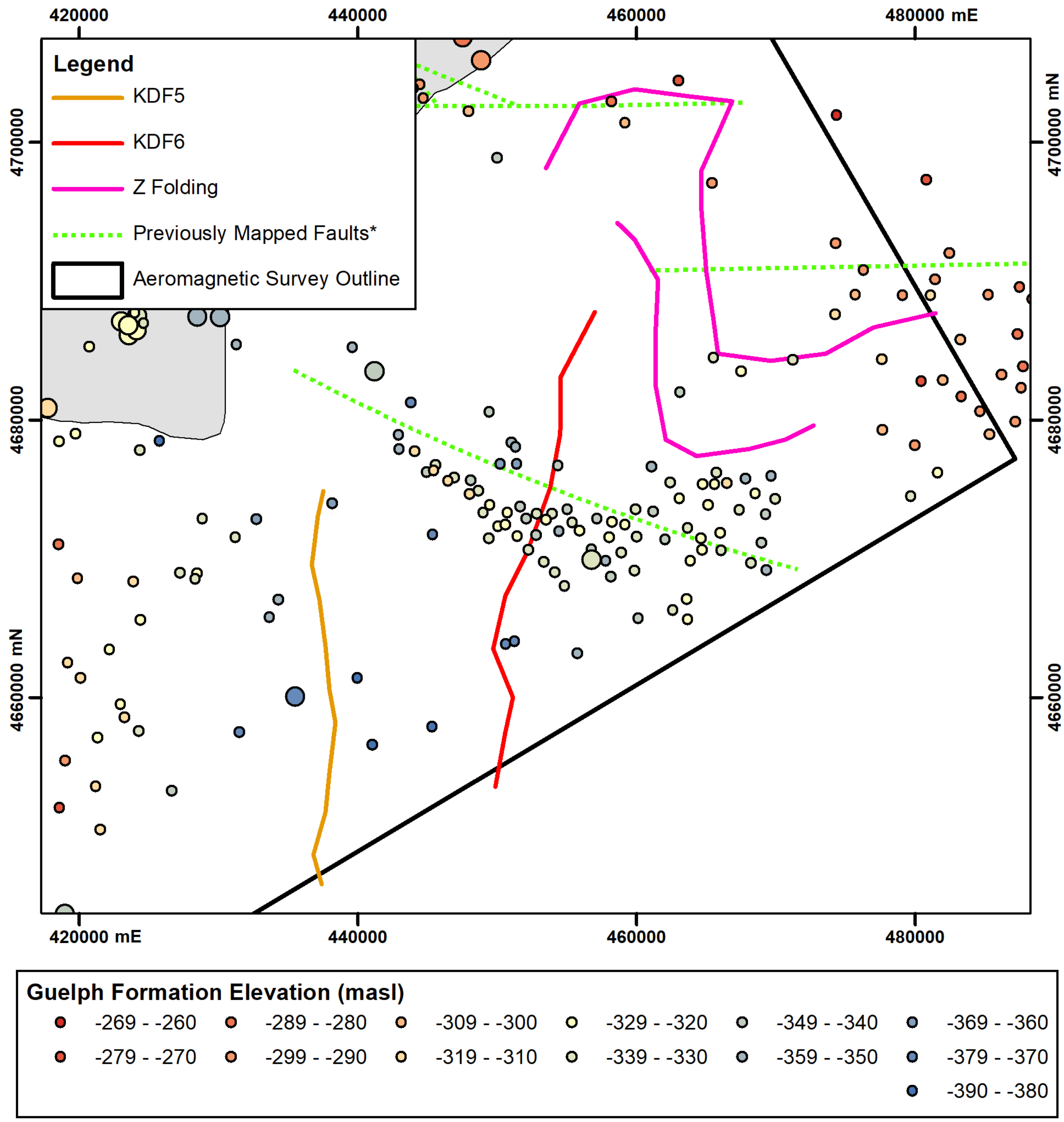

Figure 132. Guelph Formation (Lockport Group) elevation around the KDF5 and KDF6 lineaments and the Kent Domain Z-folding feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

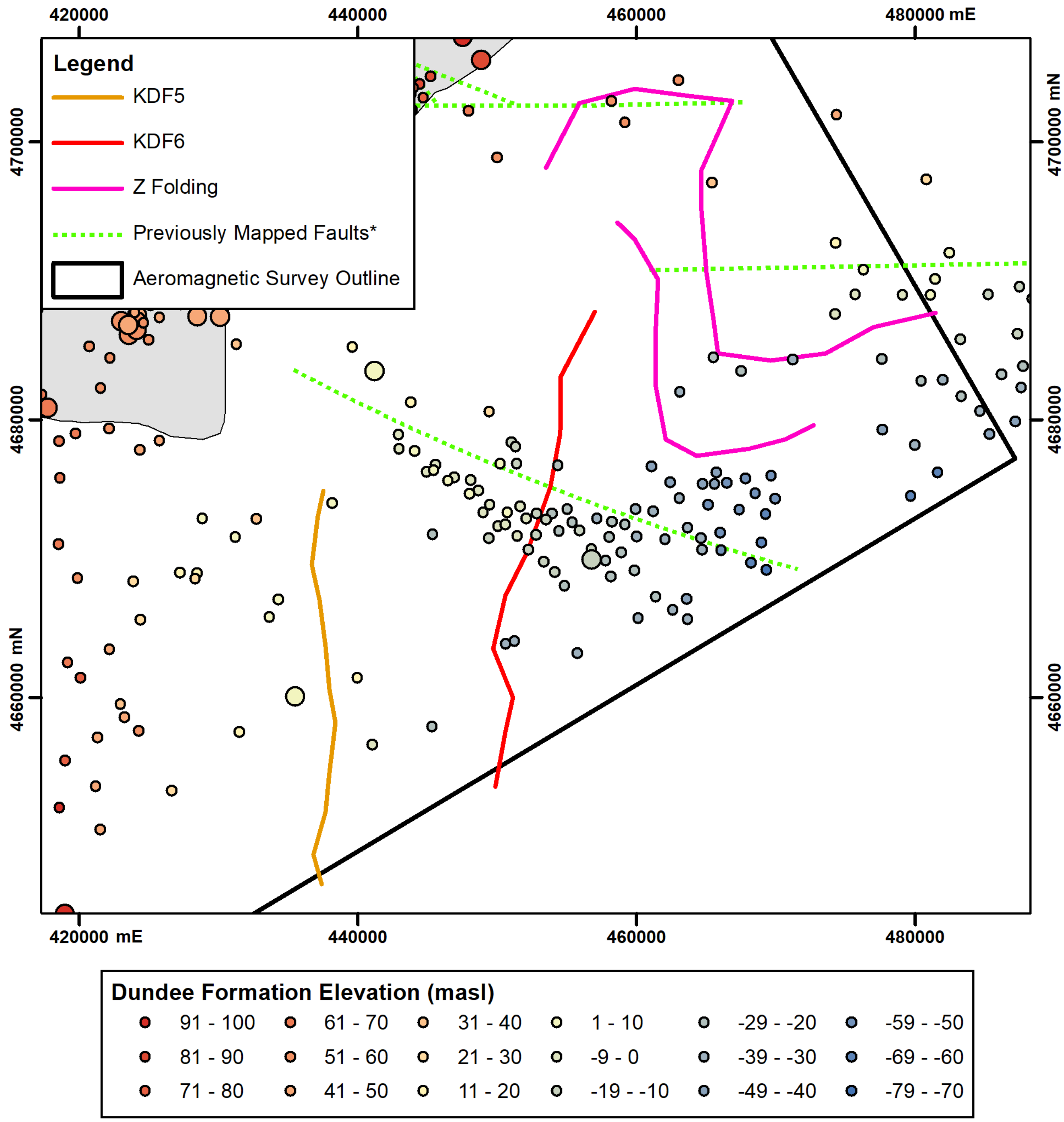

Figure 133. Dundee Formation elevation around the KDF5 and KDF6 lineaments and the Kent Domain Z-folding feature. *Previously mapped faults *from* Armstrong and Carter (2010) and *from* Brigham (1971).

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Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
		LENGTH			
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
		AREA			
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
		VOLUME			
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
		CAPACITY			
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
		MASS			
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton(short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 9**	t
		CONCENTRATION			
1 g/t	0.029 166 6	ounce (troy) / ton (short)	1 ounce (troy) / ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights / ton (short)	1 pennyweight / ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors in ***bold*** *type are exact. The conversion factors have been taken from or have been derived from factors given in the* Metric Practice Guide for the Canadian Mining and Metallurgical Industries, *published by the Mining Association of Canada in co-operation with the Coal Association of Canada.*

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