Geothermal anomalies associated with salt structures: application of thermochronology to petroleum exploration

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Research Results Summary

Many hydrocarbon plays on the eastern Canadian margin are associated with salt structures. Salt is thermally more conductive than other sedimentary rocks: Overlying rocks mature and cement faster whereas underlying rocks mature slower than elsewhere in a sedimentary basin. This directly impacts any basin modeling that may rely on "standard" burial history curves; thermal inconsistencies can therefore increase exploration risk. For instance, oil may be encountered during well drilling at depths where only gas is expected, and vice versa, leading to disappointing results.

This research was funded by PRAC in 2003 benefited from matching funds from the Natural Sciences and Engineering Research Council of Canada (NSERC), and in-kind contributions from Corridor Resources and Geostorage Associates. For the first time it measured the past thermal histories of rocks surrounding, above and underneath salt structures using the apatite fission-track and uranium-thorium-helium techniques, novel procedures that measure the maximum temperature attained by a rock in a sedimentary basin as well as the time and rate of its cooling within and below the "oil window", even in rocks devoid of organic matter. The facility used for these techniques is unique in Canada. Microscopic (brine and petroleum) fluid inclusions in were also studied in salt, as an additional source of thermal data.

The study focused on salt structures in the Maritimes Basin of Atlantic Canada and the Sverdrup Basin of Nunavut, where they are best exposed. Salt from the Atlantic offshore were also studied.

The results show that the thermal history of rocks in petroleum basins associated with salt are extremely variable from place to place, and not measuring and considering of these differences may lead to disappointment.

Strata above certain salt structures have been heated to much higher temperatures than regional rocks, and the thermal effect has been long-lived. In some cases, anomalous heat is transmitted not only by conduction, but by advection of fluids. Fluid inclusions in salt, many of which contain petroleum, indicate that salt deep in the basins was permeable to fluids, not an impermeable barrier as generally assumed.

The study also shows that igneous rocks in a basin may have had severe thermal effects on the petroleum system, in some cases generating petroleum, but also may have heated the rocks to temperatures above the oil window, thus destroying its capacity to further generate oil.

1.1 Brief description of the objectives of the research project as awarded

Because most giant petroleum fields are associated with salt structures, and salt is known to influence the generation and accumulation of petroleum, the primary objective of this research was to test whether it is possible:

"to determine the effects of paleothermal processes and regimes above, below and around salt structures within petroleum systems ...using thermochronology ... supported by field observations, mineralogy, and fluid inclusions microthermometry".

A significant proportion of the oil and gas resources in the East Coast offshore, as well as in the Carboniferous Maritimes Basin (New Brunswick, PEI, Nova Scotia, Magdalen Islands in Quebec) are associated with salt structures. The polar desert permitted the unequalled preservation of salt structures. Therefore half of our field work was carried out in Nunavut, and the other half was done in underground salt mines and well samples from Atlantic Canada. The main questions addressed in the proposal can be summarized as follows:

1. Can past thermal (paleo-thermal) anomalies around salt structures be detected using low-temperature thermochronology tools (e.g. apatite fission track (FT) and (U-Th)/He)? The
The answer is yes. Our data shows that low-temperature thermochronology will become an essential tool in determining the thermal effects of salt in petroleum basins.

2. **What is the significance and thermal consequence of igneous (intrusive and volcanic basaltic) rocks within or in the vicinity salt structures?** Our work demonstrates that igneous rocks in petroleum basins must be seriously considered because they can: 1) enhance rapid salt movement, 2) positively accelerate petroleum generation and 3) negatively overheat basinal rocks.

3. **Can fluid inclusions be used to constrain the thermal history within and around salt structures and what do fluid inclusions tell us about the associated petroleum systems?** The answer is yes. The presence of several generations of fluid inclusions in salt, many containing natural gas or liquid petroleum, implies that salt was not always impermeable and when deep in a basin was a conduit for hydrocarbons, not always a seal as has been assumed.

4. **What other natural resources could one find associated with salt structures?** We have encountered metallic concentrations in structures associated with salt diapirs and it is evident that in some cases salt diapirs represent long-living geothermal anomalies, which may be a potential source for geothermal energy in remote localities. Also, finely crystallized gypsum-anhydrite in many salt diapir caps or associated evaporite can be used as an alternative carving stone; welcome news in Nunavut where traditional carving stone is being imported from abroad.

1.2 **Description of the progress made towards these objectives as a result of the grant**

1.2.1 **Can paleothermal anomalies around salt structures be detected above around or below them using low-temperature thermochronology tools (e.g. apatite fission track (FT) and (U-Th)/He)?**

Geothermal heat is preferentially funnelled by deeply rooted evaporite diapirs. It is widely held that most of the heat is transmitted by conduction because evaporite minerals are much better heat conductors than most sedimentary rocks (Fig. 1).

**Fig. 1** Effects of salt (stippled) on the geotherms in the Primrose Field (Scotian Basin, offshore Nova Scotia, Canada, where salt is Jurassic in age). Above salt, temperatures are expected to be higher than background, and lower than background below, a diapir, thus leading to significant changes in petroleum maturation. Keen and Beaumont (1990 based on Keen 1983 [1], but see also Nagihara 2003 AAPG Bulletin, 87, 1207–1222.

**Fig. 2** Hypothetical (scale exaggerated) cartoon to explain our working hypothesis. Light shaded indicates approximate extent of the liquid oil window, temperature range at which liquid petroleum is generated from suitable source rocks, and application range of the AFT and (U-Th)/He methods. Zircon fission tracks (ZFT) detect higher temperatures (~210-310°C). According to the diagram, apatite fission track (AFT) dates were expected to be younger (and their mean track-
lengths shorter) above a salt-anhydrite diapir (dark grey) than in the surrounding area. Conversely, where rocks are colder (under salt structures), fission track dates were expected to be older than regional dates at the same depth.

The main objective of this project was to test whether: 1) apatite fission track and (U-Th)/He thermochronology, could detect and date paleo-geothermal anomalies related to evaporite structures (Fig. 1, 2), and investigate the possible thermal role of fluids in major Canadian salt basins: A) The Maritimes Basin and offshore Atlantic Canada and B) The Sverdrup Basin of the Canadian Arctic Archipelago. The results could be extrapolated to the Atlantic offshore.

1.2.1.1. Magdalen (Maritimes) Basin

Fig. 3. Salt is mined underground in the Magdalen Islands, Quebec (Lat. 47°25’N/Long. 61°46’W), where Lower Carboniferous evaporites of the Windsor Group have risen to the surface from a depth of ca. 8 km, intrude Upper Pennsylvanian and Permian strata, and salt is in contact with Quaternary Aeolian sediments. Basaltic igneous rocks (in black) appear in rafts within the highly-deformed Windsor Group sedimentary strata. We sampled along a 100 km transect, starting from Prince Edward Island (PEI) and across the Magdalen Islands (MI). Interpretations were supplemented with our own previous regional AFT data [2]. AFT dates in Ma are shown in Fig. 4 vs track length in micrometers.

As is normal with AFT studies, only approximately half the samples collected yield age data. Time-temperature modelling confirms that the region was exhumed and cooled to AFT retention temperatures during the Triassic-Jurassic Atlantic margin break-up [e.g. 3], whereas within the diapir AFT apparent ages are Cretaceous and track lengths have been significantly shortened (Fig. 4). Time temperature modelling requires re-burial of the diapir in post Early Cretaceous times and heating of the diapir samples to higher temperatures than the regional background (Fig. 4). Fig. 4. Track-length versus AFT age plots and Monte Carlo inverse thermal history models for Magdalen Basin AFT samples using AFTINV (Willett 1997, Issler 1996). These models show that Late Cretaceous and Paleogene temperatures are predicted to have been as much as 40-45°
C higher for samples obtained close to salt (FT04-099, FT03-067) than for those that were obtained farther away (FT04-101, FT03-047). All models were done using the Laslett et al. (1987) annealing model. An initial reduction in mean length to 14.5 \( \mu \)m was introduced to minimize the inherent effects of under prediction of low-temperature annealing in the Laslett et al. 1987 model (i.e. Vrolijk et al. 1992). The upper panels show the upper and lower bounds of time-temperature solution space explored by the 250-300 acceptable model solutions (defined by a K-S goodness of fit statistic) as well as the exponential mean solution, or preferred model (thicker line). The lower panels show the measured length histograms and the exponential mean probability distributions, as well as the upper and lower bounds of the model distributions in the solution set (Note that the upper and lower bounds themselves are not solutions). 10 my time steps were used, with new populations of unannealed tracks introduced at 2 my intervals. A depositional age of 320 Ma (Mississippian) was used, and peak burial temperatures were assumed to have occurred at 300 Ma, corresponding to the regional burial maximum (Grist et al. 1995). The model was permitted heating or cooling between 120 Ma and 30 Ma, otherwise cooling-only solutions were required from 300 Ma to the present. Data and references cited in data report by Grist (2006).

Additional sub-salt samples were collected in the Sussex area (McCully Field; provided by partner Corridor Resources) from under the salt structure being mined for potash and salt. Successfully analyzed cuttings samples from the McCully Field are: McCully O-66, 2477-2546 m, McCully O-66, 2375-2447 m, and McCully J-67, 1325-1420 m. McCully O-66 gives an AFT age of 143±8 Ma and mean track length of 11.4 ± 0.6 \( \mu \)m; McCully J-67 180±9 Ma and mean track length of 12.6 ± 0.5 \( \mu \)m. These results are difficult to interpret without microprobe analysis of F/Cl and T-t modelling, which are underway. Adequate sub-salt samples have been difficult to secure.

1.2.1.2. Sverdrup Basin, Canadian Arctic Archipelago

In Axel Heiberg Island, Nunavut (Lat. 79°30’N/Long. 90°W), Upper Carboniferous – Permian evaporites have risen to the surface from a depth of 8 to 13 km and affect post-glacial Quaternary sediments. AFT samples along a >80 km transect (Fig. 5; see AFT dates in Table 1 below) demonstrate that whereas the region was exhumed and cooled to AFT retention temperatures during the Eocene (Eurekan Orogeny) [4, 5, 6], data from at least one area underlain by allochthonous salt and active perennial salt springs [7] indicate it remained warm into the Neogene (Fig. 6;
caption in next page), and accordingly, AFT apparent ages are comparatively younger and track lengths are significantly shortened (Fig. 6). Preliminary (U-Th)/He data also support this interpretation of the AFT data. Our field data indicate the diapirs are actively rising today in this Arctic desert, as presented in several conferences [e.g. 8].

Fig. 6. Monte Carlo inverse thermal history models for Sverdrup Basin AFT samples using AFTINV (Willett 1997, Issler 1996) from data report by Grist (2006). All models were done using the Laslett et al. (1987) annealing model. An initial reduction in mean length to 15 μm was introduced to minimize the inherent effects of underprediction of low-temperature annealing in the Laslett et al. 1987 model (i.e. Vrolijk et al. 1992). The middle panels show the upper and lower bounds of time-temperature solution space explored by the 250-300 acceptable model solutions (defined by a K-S goodness of fit statistic) as well as the exponential mean solution, or preferred model (thicker line). The lower panels show the measured length histograms and the exponential mean probability distributions, as well as the upper and lower bounds of the model distributions in the solution set (Note that the upper and lower bounds themselves are not solutions. For samples FT03-047 and FT03-067, 5 my time steps were used, with new populations of unannealed tracks introduced at 1 my intervals.

These models were required to find cooling-only solutions because the Sverdrup Basin was inverted during the Latest Cretaceous to Eocene Eurekan Orogeny (see Fig. 7). The 2 samples modelled are indicated on the age-length plots in Fig. 6. (U-Th)/He data on apatite in some of the same samples are compatible with the interpretations above.

We propose that the existence of active perennial salt springs (Fig. 5) in the area [e.g. 7] that have developed where the (otherwise 600 m-thick) permafrost has melted, is a focus of advective heating adjacent to the diapirs. Field work in 2005 discovered hydrothermal vein networks that may be the exposed deep roots of equivalents of today's active springs and explain the Neogene thermal effects [8].

Table 1. A summary of the apatite FT age and TL data for the Strand Fiord region. FT ages are the central age (Galbraith and Laslett 1993). Samples with a chi-square probability greater than 5 pass the chi-square test at the 95% confidence level (i.e., appear to be composed of one age population).

Abbreviations are as follows: Ns, Ni, and Nd are the number of spontaneous, induced, and flux dosimeter (CN-5) tracks, respectively. Ro, Rho, and Rhod are the density of spontaneous, induced, and dosimeter tracks, respectively (x106/cm2). Age error estimates are at the 67% (1σ) confidence level. Mean length error estimates are at the 95% (2σ) confidence level. Apatite analyses by A.M. Grist, using a zeta of 347.8 ± 6.2 (CN-5 glass). If sufficient apatite was obtained, 2 grain mounts were made for each sample. For apatite samples marked with a cross (H) the second grain mount was subjected to a collimated 252Cf source to increase the available length data. In addition we have 14 new zircon FT dates, and 5 new (U-Th)/He dates. From data report by, and specialized references cited in Grist (2006). Similar tables are available for ZFT and (U-Th)/He dates.
1.2.2. What is the significance and thermal consequence of igneous (intrusive and volcanic basaltic) rocks within or in the vicinity salt structures, since these association is common in the Magdalen islands and the Sverdrup Basin? Did they have any interaction with the evaporite minerals as hot (>1000°C) magmas or simply only as cold, passive rafts?

In our study areas igneous rocks have probably affected the petroleum system in 2 ways: 1) accelerated the displacement of salt and evaporites, and 2) heating the source rocks to produce hydrocarbons, but at the same time exhausting their oil producing capacity. Basaltic lavas and intrusive sills and dikes coincide spatially with the deepest sedimentary piles and highest concentration of diapirs in the Sverdrup and Magdalen Basins. The abundance of diapirs Offshore Nova Scotia in the area of the enigmatic East Coast Magnetic Anomaly (ECMA), and in the Orpheus Graben, where Mesozoic volcanic rocks are present, suggests this association may be more than a coincidence. In the Maritimes Basin the basaltic intrusive and volcanic rocks are Mississippian in age, and therefore those seen at surface in the Magdalen Islands (Fig. 3) have passively risen from great depth with the (Windsor Gp.) evaporite package. They occur mainly in the basin's depocentre, and must therefore have interacted physically with the evaporite at depth, accelerated halokinesis, and probably interacted chemically, dehydrated any remnant gypsum to anhydrite (thus generating fluid overpressures), metamorphosing sediments and overheating the petroleum system. All volcanic samples yield AFT ages considerably younger (Figs. 3 & 4) than their Carboniferous depositional age. In the Sverdrup Basin we have a similar situation. Mesozoic volcanic rocks are more abundant near the depocentre and coincide with a high concentration of evaporite diapirs. Volcanism took place in one major pulse at ca. 127 Ma, and another more localized event at ca. 95 Ma (e.g. [9]). The contact metamorphic thermal effect of this magmatism is evident in having reset the zircon FT apparent ages of Triassic stratigraphic age they intrude. The threshold (track retention) temperature for ZFT is 210-310°C. Therefore the rocks that are now at the surface were heated beyond the temperature at which any petroleum source rocks could generate liquid oil.

To quantitatively test the effect of basaltic sill intrusion on the petroleum system in eastern Sverdrup Basin, we involved an NSERC summer research student Samantha Jones on modelling one representative well in Axel Heiberg. This study, carried out at the GSC-Atlantic under the co-supervision of Hans Wielens, M-C Williamson and M. Zentilli, modelled representative well L-24 Depot Point using the Petromod® software. This work resulted in an Honours thesis (Jones 2006), a presented abstract (Jones et al. 2006) and a manuscript to be submitted to the Journal of Petroleum Geology in the New Year: Jones, Wielens, Williamson & Zentilli).

![Fig. 7 Burial history of the L-24 Depot Point well, output from 1-D modelling with Petromod®. It shows that the intrusion of sills at ca. 125 Ma caused the formation temperatures to rise well beyond the oil generating window into the >200°C range, as suggested by the ZFT data. At that point in their evolution, the basinal rocks exhausted their oil generation capacity (Jones et al. 2006 & to be submitted to J. of Petroleum Geology).](image)

1.2.2.1. Volcanism, age and recent rates of diapir rise.
In 2003 we discovered basalt lava slabs with *pahoehoe* (ropy) and pillow-like structures within a diapir east of Eureka Pass (SF-55, Fig. 5). The basalt shows evidence of high-temperature (>300°C) interaction with anhydrite, with formation of epidote and amphibole. The pahoehoe indicates that the diapir was at the surface in the Cretaceous when lavas were erupted. This observation is consistent with new models of diapir emplacement, which suggest diapirs are always close to the basinal surface (refs). It is generally known that evaporitic structures rose during the compressive Eurekan Orogeny in the Paleocene-Eocene, a time of active thrust faulting. Our work points to the fact that many of the anhydrite-gypsum structures have risen tens to hundreds of meters from the glaciated valley bottoms in postglacial times, which translates in net growth rates (rise minus erosional degradation) of 1 to >5 cm/yr, thus “the fastest growing mountains in Canada”. This hypothesized rate of growth should be easily detected by InSAR methods (work in progress with Paul Budkewitsch of Canadian Centre for Remote Sensing, Ottawa).

1.2.4. Inversion of the Sverdrup Basin and salt involvement.

The Stolz Thrust Fault (STF) is a ~250 km long, southwest-dipping thrust fault that locally places Carboniferous units upon Cenozoic strata, and bounds in the east the Princess Margaret Range (Fig 5), a structural and topographic high (ca. 2000m). The PMR comprises elongate, doubly-plunging folds, and faults that may be bounded at depth by a décollement within Carboniferous evaporite of the Otto Fiord Formation, which outcrops in numerous diapirs (in black in Fig. 5). Igneous and sedimentary rocks of Mesozoic age (220-120 Ma) in the hanging wall of the STF yield apatite FT ages between 65 and 52 Ma, with mean track lengths of 13.45 - 14.13 μm. The apatite FT results, assuming a geothermal gradient of ~30°C/km, suggest that diapirs occurring with the hanging wall of the STF represent a 4 to 5 km deeper level of exposure than diapirs in the footwall. This is supported by the existence of halite at surface in the Stolz Diapir, in SE AHI. The data imply that the STF started to move (to cool due to exhumation) during the earliest Palaeocene. Cyclic successions of sandstones and pebbly sandstone, probably de rived from the rising and fast-eroding STF to the west, host the famous Eocene Fossil Forests of the Geodetic Hills (Fig. 5), with *Metasequoia* and other tall tree s of Middle Eocene age, which grew at a paleolatitude of 82°N (e.g. Christie & McMillan 1991 GSC Bull 403). The sandstones yield apatite FT ages of 48-49 Ma (mean track lengths of 13.62 to 13.91 μm), indicating that the STF was still active in the Middle Eocene. The Eocene was an unusually warm period in Earth’s history; in addition to enhancing forest growth, such warm and humid climate may have accelerated denudation of the rising of the ancestral Princess Margaret Range (Fig. 5), and advancing STF. The fossil forests thus accumulated in swamps within a foreland basin to the advancing STF. This humid climate may have also dissolved any salt reaching the surface, thus further developing the diapirs’ anhydrite/gypsum caps.

1.2.5. Can fluid inclusions be used to help constrain the thermal history within and around salt structures? What do fluid inclusions tell us about the associated petroleum systems?

Our fluid inclusions (flincs) in salt indicate that the salts contain a variety of brines (e.g. Fig. 8a, Argo Salt) and hydrocarbons (Fig. 8b, Pugwash, NS). The presence of hydrocarbons is demonstrated by their fluorescence (Fig. 8d). From Kettanah et al. (2005). Analyzed samples from the Magdalen Islands salt, although fetid and physically similar to Pugwash salt, don’t contain (at least fluorescing) liquid hydrocarbons. Homogenization temperatures of flincs in salt indicate some temperatures of entrapment were higher than 100°C. Microthermometry heating measurements in flincs in salt are fraught with problems (e.g. Roedder 1984; Am.Min 69 413-439), and heating data are not considered reliable, yet various populations give consistent moderate- to high-temperature results, suggesting that the differences are real. Freezing and thawing experiments yield useful compositional data. Previous flincs studies in potash (Windsor Gp) salt from New Brunswick (e.g. Petrychenko et al. 2002; CJES 39, 157) interpret flincs to be representative of seawater from which the salts crystallized. However, we see multiple generations of flincs, and various petroleum types which were either originally contained in the salt (i.e. salt was a source rock) or, more likely, the hydrocarbons have been introduced later. Our research uncovered a body of experimental work on the dihedral angle for the halite-water system of 20
to 300°C (e.g. Holness & Graham 1991 Contr Min Pet, 108, 368-383). At depths of more than 3 km in a basin, salt will contain a stable interconnected brine-filled porosity, with permeabilities comparable to sandstones under conditions of textural equilibrium. Permeability of salt increases even further when deformed (e.g. Schenk and Urai 2004; Contr Min Pet, 146, 671-683). Experimental results are compatible with our suggestion that deep-rooted salt diapirs may act as conduits for basinal formation water and thus advective heat, leading to perennial springs and hydrothermal developments. The experimental work relates to water and salt. What about petroleum? The more unlike the solid and the liquid, the higher the angle. So hydrocarbons should have very high dihedral angles in halite. There is also a strong link between the angle and the rate at which textural equilibration occurs, with slower rates for systems with high angles (this is all related to the requirement of strong solid-liquid interactions for low angles). Dr Holness (personal communication 2006) suggests that our hydrocarbons in fluid inclusions migrated along fractures, or possibly as droplets suspended in a brine.

The above has drastic implications for salt bodies in Atlantic Canada. Our own previous AFT data on the Maritimes Basin [3,4,5] indicate that strata that are now at the surface were at depths of more than 4 km until the Triassic-Jurassic, thus the salt we now observe at surface could have been permeated by basinal brines and petroleum in the past. The same argument can be made for diapirs now exposed in the hanging wall of the Stolz Thrust in Axel Heiberg Island, Nunavut (Fig. 5).

1.2.6. What implications does the thermal history of salt structures have on engineering plans for waste and petroleum fluids (e.g. LNG) storage in salt?

Traditionally, salt has been considered extremely impermeable, and thus a perfect seal for hydrocarbons and fluids of any kind, to the point that deep cavities in salt structures have been used as repositories for hydrocarbons and proposed for high-level nuclear wastes, which can generate enormous heat. A buried salt diaper near the Canso Causeway in Cape Breton, Nova Scotia has been proposed as an adequate repository for liquefied and very cold and highly pressurized natural gas (LNG). The observation that when inclusion-riddled salt is frozen below -50°C, the inclusions expand and fracture the salt, reducing its tensional and shear strength. Experiments should be carried out to assess the effects of super cooled fluids on the strength of salt cavities and possible LNG leakage. The conclusion is that more research is needed.

1.2.7. What natural resources other than petroleum could one find associated with salt structures, such as metallic or industrial minerals and geothermal energy?

1.2.7.1. Precious metals associated to basaltic (gabbroic) intrusive rocks and evaporites.

The geological setting in the eastern Sverdrup Basin is very similar to that of another Arctic province, the giant platinoid-group-element (PGE) and Cu-Ni province of Norilsk, Siberia. Gabbroic magma has interacted with evaporites and coal beds at depth and under the right conditions produced some rich ore deposits. During field work in 2003, 2004 and 2005 we looked for evidence of mineral concentrations. Anomalous metal enrichments were documented in contact zones where basaltic magma interacted at high temperature with organic-rich shale and/or evaporite which will be described in publication.

1.2.7.2. Metals concentrated in brecciated zones peripheral to evaporite structures.

In several areas we have studied base metal concentrations in carbonate veins and stockworks associated with the peripheral zones of evaporite structures and associated faults. Some of these zones, such as one recognized at Whites Glacier in 2005, could represent the roots of perennial springs as those active in Expedition Fiord.

1.2.7.3. Use of anhydrite-gypsum as alternative carving stone.

A carver in Grise Fiord has tested the alabaster-like anhydrite and likes its characteristics. The experiment caught the attention of Nunatsiaq News, who published an article on this subject: http://www.nunatsiaqnews.com/archives/60519/news/features/60519_01.html Field work in the Magdalen Islands in 2004 uncovered the use of a similar anhydrite-gypsum “alabaster” by local craftspeople. There an unlimited source of (alternative) carving stone, salt and anhydrite in Axel Heiberg Island, Nunavut.
1.2.7.4. **Geothermal energy to heat buildings.**
This AFT study suggests that some areas overlying salt structures have been long-lived geothermal areas. In Axel Heiberg Island the thermal effect of diapirs has melted the permafrost and generated perennial salt springs. Student Lori Wrye initiated a study that shows the suitability of the Colour Peak diapir springs in Expedition Fiord as heat exchange sites. A small heat exchange unit could generate year-round heat for a research station at the site.

1.2.7.5. **Use of salt structures to store fluids.**
Cavities in deep salt bodies have been investigated and used for hydrocarbon storage, and that was the interest of two of our partners (Geostorage Inc. and Corridor Resources). Some concerns arise: 1) Salt mines in the study area have had water infiltration problems; 2) Salt is not homogeneous but contains layers of siltstone and brittle limestone and anhydrite, and healed breccia zones; 3) Salt contains fluid inclusions and therefore was permeable within the basin as predicted by experimental work; 4) Salt probably becomes brittle and weak when frozen to temperatures below -50°C; 5) Salt in some diapirs in Nunavut may be rising at rates of several cm per year, thus storage in them is not recommended.

1.2.7.6. **Tourism.**
Evaporite diapirs in Axel Heiberg Island are probably growing to-day, and with their associated perennial springs could be developed as spectacular tourist sites. Tourist facilities could be safely heated with geothermal heat from the salt structures.

1.3  **A description and justification for any deviations from the original objectives.**
There were no major deviations from the objectives. We seized the opportunity to work in the most amazing exposures of salt structures in the world and it paid off. From the scientific point of view, it was disappointing that samples from sub-salt situations were difficult to obtain, and results more difficult to interpret than expected.

1.4  **A description of the scientific and/or engineering significance of the results**

1.4.1. **First successful study.**
To my knowledge this is the first study that has detected and dated paleothermal anomalies related to salt using apatite fission tracks and (U- Th)/He thermochronology. The study shows that thermal history of the petroleum system in basins containing salt structures varies drastically from one place to another, and this variation must be understood to reduce risk in exploration. The thermochronology tools developed are applicable in all major salt-bearing petroleum basins worldwide.

1.4.2. **Petroleum fluid inclusions in salt.**
The presence of various generations of petroleum and brines in salt, some trapped at relatively high temperatures, is direct evidence that salt was not always impermeable in a sedimentary basin as generally assumed.

1.4.3. **Growing salt structures in Canada.**
This is the first study of the recent rate of growth of evaporate diapirs in the Sverdrup Basin. The evidence is so far geomorphologic, where soft gypsum and salt appear as small mountains where the glaciers gouged deeply even the hardest igneous rocks, but our preliminary Radarsat monitoring is also showing year to year change. Not only is this growth interesting scientifically, but should be a concern for plans of using cavities in salt to store dangerous wastes.
1.5. A brief discussion of the potential benefits to Canada.

1.5.1. We have a unique, world-class, lab in Canada and a methodology that can determine the heating effects of salt in a petroleum basin. The quantification of such thermal effects will reduce risk in exploration of sub-salt, above-salt and peripheral to salt plays. This reduced risk is

1.5.2. The identification of long-lived geothermal anomalies can be important in the supply of heating energy not only for northern communities, where hydrocarbon transport is prohibitively expensive, but also in small communities in the vicinity of salt deposits, such as the Magdalen Islands.

1.5.3. An inexhaustible source of an indigenous carving stone for Nunavut could have a positive effect on communities in the north.

1.5.4. The geothermal anomalies that produce perennial springs and can be used as a source of geothermal energy could facilitate the establishment of year-round research, tourism or sovereignty stations. The “growing mountains of Axel Heiberg Island could become managed tourist attractions”.

1.5.5. On the negative side, salt appear to have many problems as a safe repository for highly pressurized fluids and heat-producing radioactive wastes; this research points for caution in the use of same salt structures.

2. Research Team

Dr. Marcos Zentilli, Principal Investigator, thought out and proposed this project to PRAC in 2002, then to NSERC as CRD. He planned and directed all phases of the research, including participation in every phase of field work, and logistic and financial administration. He supervised PhD thesis by A.Grist and Honours BSc theses. Became Emeritus Professor upon retirement in July 2005, and continues to carry on his research as earlier.

Dr. Alexander (Sandy) M. Grist, PhD student Dalhousie University (graduated Oct 2004) and since graduation Post-doctoral Fellow; salary financed by this CRD. Analyst responsible for all fission track and (U-Th)/He dating, modelling, participated in close cooperation with PI on interpretation. Participated in field work in Atlantic Canada, and trained and co-supervised students and technicians in the lab.

Dr. Yawooz Kettanah is Adjunct Professor at Dalhousie University. He worked (part-time) on petrography, electron microprobe and fluid inclusion analyses, and contributed scientific data and literature research. He participated in field work in Atlantic Canada. Received some remuneration from this CRD.

Dr. Marie-Claude Williamson is Research Scientist at the Geological Survey of Canada, Atlantic. She participated in field work in Nunavut in 2003 and 2004 and in the Magdalen Islands in 2005. Her interest is the involvement of volcanic rocks and their interaction with salt and the petroleum system. Contributed to supervision of students in the field and in theses. Did not receive remuneration from this CRD.

Dr. Hans Wielens is Research Scientist at the Geological Survey of Canada, Atlantic. He contributed scientifically, and analytical funds for fluid inclusions studies on salt in Atlantic Canada. He co-supervised Honours student Samantha Jones on basin modelling project using Petromod® software. Did not receive remuneration from this CRD.

Dr. Tom Martel, Corridor Resources, discussed sampling strategy and offered constructive advice.

Mr. Allan Ruffman, Geostorage Associates, discussed sampling strategy and offered useful advice.
Gilles Carrier, Mine Geologist, Mines Seleine, WindsorSalt, Magdalen Islands, collaborated in the field.

Brian Roulston, Mine Geologist, Mines Seleine, WindsorSalt, Magdalen Islands, guided us in the field.

Debra Wheeler, technician, part-time student, was trained and worked in the lab in sample preparation, literature research and graphics. Received remuneration from this CRD

Undergraduate students directly involved in the project (*received remuneration from this CRD)

Evan Brown, Summer student assistant, fluid inclusions in salt (Honours Geology st. St. Mary’s U). Received funding from Shell Canada Resources.

Samantha Jones*, BSc Honours thesis on Sverdrup Basin petroleum system (MSc st. @ U Calgary)

Lori Wrye*, summer lab assistant on thermal modelling of salt diapirs (MSc st. @ Queen's)

Andrea Mosher*, lab (sample preparation, graphics) and field (2003) assistant (MSc st. @ U Waterloo)

Christopher Hamilton, field assistant in Nunavut (2004). (PhD st. @ U Hawaii)

Emily Adams*, NSERC Summer research award, lab assistant (UG science student Dalhousie University)
3. **Selected References:**


4. Publications

Insights into the thermal history of the Nares Strait, Kane Basin and Smith Sound region in Canada and Greenland from apatite fission track and (U-Th)/He dating. GRIST, A.M. & ZENTILLI, M. (2005) Canadian Journal of Earth Sciences, 42, 1547–1569 (Although based on field work previous to this CRD project, the final version of this paper benefited from insights gained on Eurekan tectonics since 2003)

Preliminary apatite fission track thermal history modelling of the Nares Strait region of eastern Ellesmere Island and northwestern Greenland, Apatit Spaltspuren-Daten: Modellierung der thermischen Entwicklung an den Rändern der Nares Strait auf dem östlichen Ellesmere Island und in NW-Grönland. GRIST, A.M. & ZENTILLI, M. (2006) Polarforschung, 74, 1-3 (2004), 113-127 1569 (Although based on field work previous to this CRD project, the final version of this paper benefited from insights gained on Eurekan tectonics since 2003)

REFEREED JOURNAL ARTICLES (PUBLISHED/SUBMITTED)

Paleothermal effects of evaporitic structures detected by apatite fission track thermochronology: Sverdrup and Maritimes Basin, Canada, Zentilli, M., Grist, A.M. In preparation. In preparation; to be submitted to Geology.


Impact of magmatism on the petroleum system of the Sverdrup Basin, Canadian Arctic Islands, Nunavut; a numerical modeling experiment, Jones, S., Wielens, H., Williamson, M-C., and Zentilli, M. Under internal GSC review; to be submitted to Journal of Petroleum Geology.

Field and Radarsat (InSar) evidence for rising diapirs in Axel Heiberg Island, Nunavut, Zentilli, M, Budkewitsch, P., Pollard, W. In preparation, to be submitted to suitable journal

CONFERENCE PRESENTATIONS / POSTERS


Critical effects of the chronology and mode of emplacement of flood basalts on the thermal history of the Sverdrup Basin, Arctic Islands, Nunavut, M-C. Williamson, M. Zentilli, J. Dostal, and


OTHER: TECHNICAL REPORTS, NON-REFEREED ARTICLES ETC.


Fluid inclusions in minerals: petroleum in salt, Zentilli, M, October 19th, 2006. Invited oral presentation to Department of Geology, St. Mary’s University, Halifax.