The Impact of Volcanism on Reservoir Quality, Scotian Basin*

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Abstract

In magma-rich rift margins, the role of magmatism in petroleum systems is widespread and significant. In magma-poor margins, the impacts are more subtle, but nevertheless present. In the Scotian Basin, minor Aptian-Albian magmatism is associated with regional and prolonged elevated geothermal gradient, sufficient to be recognised in vitrinite reflectance. At the same time, in the western Sable Sub-basin, hydrothermal basinal fluids resulted in cementation of sandstone reservoirs by silica and carbonates. The diagenetic alteration of feldspars to albite and eventually clays and carbonate minerals took place at shallower depths in thick permeable sandstones where fluid temperatures were higher, compared with areas with lower fluid temperatures, or thinner (presumably less connected) sandstone beds. Abundant carbonate cement also appears to be favoured by the passage of hot hydrothermal basinal fluids. The presence of such late carbonate cements is the principal risk factor for reservoir quality in Late Jurassic-Early Cretaceous sandstone reservoirs of the Scotian Basin. Similar concepts on the influence of magmatism on reservoir quality may be applicable to other eastern Canadian basins where a regional volcanic phase post-dates the main extensional phase, e.g. Late Albian in the Salar Basin.

Introduction

This study aims to relate new observations on the paragenesis and spatial distribution of diagenetic minerals of importance to sandstone reservoir quality in the Scotian Basin to recent studies of volcanism and the temperatures of basinal fluids involved in diagenesis. Weirzbicki et al. (2006) argued that hot fluids that precipitated saddle dolomite in the Deep Panuke carbonate reservoirs were so hot that they could not be achieved by burial alone and were therefore hydrothermal. Karim et al. (2012) showed that similar hot fluids were associated with silica and carbonate cements in sandstone reservoirs in the western Sable Sub-basin, and on the basis of C isotopes in carbonate cements and burial history analysis, demonstrated that the temperature maximum was in the Aptian-Albian. We further explore the relationship between anomalous geothermal gradients, surface expression of volcanism, hydrothermal fluids, and development of diagenetic facies. Such concepts

would be applicable to other basins on the eastern Canadian margin (Figure 1) where there is a volcanic phase that post-dates the main extensional phase.

Methods

Diagenetic minerals in conventional core have been studied from numerous wells in the Scotian Basin by petrographic microscope, hot-cathode cathodoluminescence (CL), SEM and electron microprobe. CL allows discrimination of diagenetic from detrital quartz and feldspar. Both SEM and electron microprobe provide backscattered electron images from which diagenetic paragenesis can be interpreted and chemical analyses that permit the precise identification of diagenetic mineral phases. Hydrothermal sulphide and sulphate cements have been identified from anomalous trace elements in conventional core samples and from study of thin sections.

The stratigraphy of volcanic rocks in wells has been re-evaluated and their volcanology refined by study of cuttings and well logs, as reported by Bowman et al. (2012). More distal volcanic ash has been identified from clay mineral XRD and from bulk-rock geochemical studies. Cretaceous detrital zircons associated with detrital lithic clasts and feldspars of apparent subvolcanic origin have been dated by U-Pb laser ablation ICPMS dating (Piper et al., 2012). Analysis of homogenisation temperature of fluid inclusions in various cements has been reported by Karim et al. (2011, 2012), who fully document their methods.

The present study is based on integrating studies of diagenetic minerals with the partly published work on volcanism and on fluid inclusions. In particular, diagenetic processes of relevance to reservoir quality have been compared for those areas of the basin with and without evidence of the effects of hydrothermal fluids on cementation.

Examples

Lower Cretaceous Volcanism, Anomalous Geothermal Gradients, and Evidence for Hydrothermal Fluid Flow in the Scotian Basin

Early Cretaceous volcanism is widespread in the eastern part of the Scotian Basin, synchronous with and spatially related to the prolonged rifting between the Grand Banks and Iberia that began in the Tithonian and gave way to normal sea-floor spreading by the beginning of the Albian. Principally Hauterivian volcanic rocks on the southwest Grand Banks, and principally Aptian volcanic rocks in the Orpheus Graben are the result of Strombolian type eruptions. More extensive Hawaiian type flows have been mapped from seismic profiles on the southwest Grand Banks, derived from local volcanic basement highs with a positive magnetic anomaly, and accumulating in small Hauterivian rift basins. Subaerial basalt flows in Orpheus Graben wells are of Mid-Aptian age and extended to the paleoshoreline at the Hesper wells. They were derived from a large volcanic centre at Scatarie Bank to the north, which has a positive magnetic anomaly, dated Cretaceous mafic dykes, and seabed outcrops of Hawaiian-type lava flows.

Dating of Cretaceous detrital zircon shows two clusters of dates at ~105 and ~120 Ma, but their stratigraphic position suggests that the determined dates are ~10 Ma too young and the true ages correspond to late Aptian and Barremian. Zircon grain size (~130 μm) implies fluvial transport rather than air fall.

In the central Scotian Basin, fluid inclusions in, and the C-isotope composition of carbonate cements indicate a period of flow of hot (< 175°C and <23 wt % NaCl) basinal brines in the Aptian-Albian (Karim et al., 2012). Although no direct link with volcanism is known, the timing of these hydrothermal fluids corresponds to a period of regionally high heat flow in the Northern Appalachians that resulted in high vitrinite reflectance in the Lower Cretaceous Chaswood Formation on land and widespread paleomagnetic resetting of basement rocks. A new regional compilation of average trapping temperatures and salinities is shown in Figure 2. Regionally, temperatures are consistently higher in the western part of the Sable Sub-basin studied by Karim et al. (2012) and in the adjacent Abenaki carbonate bank at Deep Panuke (Weirzbicki et al., 2006), although precise conversion of the Weirzbicki et al. (2006) homogenization temperatures to in situ trapping temperatures has not been possible. Farther east, trapping temperatures are (for similar burial depths) rather lower at Venture and in the Abenaki sub-basin (Karim et al., 2011; Hanley, 2011).

Thermal modeling by Bowman (2010) showed that the conductive heat effects of short-lived volcanic activity in the Scotian Basin were minor and not recorded in vitrinite reflectance. However, more prolonged thermal effects result from convection of hot fluids from deeper in the basin or a period of regional high heat flow, of which the volcanism was only a surface manifestation, result in changes in vitrinite reflectance.

In the Early Cretaceous, the dominant active fault trend on land was on northeast-southwest trending strike-slip faults. It is along such faults on land that high vitrinite reflectance is found in the Chaswood Formation. It is probable that the northeast-southwest trending margin of the Abenaki carbonate bank in the western Sable Sub-basin is also represented in underlying basement by northeast-southwest trending faults, which focused hydrothermal activity and high heat-flow.

Observations on Diagenesis and Reservoir Quality and Their Relationship to Mid-Cretaceous Thermal Effects

Four main diagenetic facies control reservoir quality in sandstones in the Scotian Basin. (a) Diagenetic chlorite rims are developed in some sandstones and preserve porosity well. These are not the subject of this study – detrital supply of labile Fe derived from volcanoes and seafloor diagenesis appear to be the main processes favouring their development. (b) Locally, sandstones are strongly silica cemented. Our work on such cements is incomplete. (c) Late carbonate cements are widespread, particularly in the Sable Sub-basin, and are the principal diagenetic risk factor for reservoir quality. (d) In some sandstones, the principal cements are clays, including kaolinite (much of which appears to be early), illite and chlorite (both of which tend to be late cements).

A regional comparison of porosity and permeability measured on conventional core plugs and petrographic description of thin sections from conventional core in the Upper Jurassic-Lower Cretaceous interval allows a comparison to be made between the western Sable Sub-basin, the region around the Venture Field, and the Abenaki Sub-basin in the eastern Scotian Basin. Clay mineral cements are most abundant in the

Abenaki Sub-basin; heavy silica cements are most common in the regional around the Venture Field, and late carbonate cements are most common in the western part of the Sable Sub-basin.

Using the porosity and permeability data from conventional core plugs from the Sable and Abenaki sub-basins, we assume that there is no sampling bias between the two subbasins, either with regard to where conventional core was cut (generally, the expected best reservoir intervals) or where plugs were taken (generally in sandstone units). Albian Cree Member samples from the Abenaki Sub-basin tend to have higher permeability at any particular value of porosity than those from the Sable Sub-basin, so that many plot on the upper left side of the cloud of data points in Figure 3. The opposite trend occurs in the Berriasian to Valanginian Middle Member of the Missisauga Formation, where Abenaki Sub-basin samples tend to have lower permeability than Sable Sub-basin samples for any particular porosity value. No particular distinction between samples from the two sub-basins is apparent in data from the Hauterivian to Barremian Upper Member of the Missisauga Formation, which is thus perhaps transitional between Cree Member and Middle Member conditions. In the upper part of the Mic Mac Formation in the Abenaki Sub-basin, the number of high porosity and permeability sandstones is disproportionally fewer than in the coeval rocks of the Lower Member of the Missisauga Formation in the Sable Sub-basin. The relatively lower permeability of samples from the Cree Member of the Sable Sub-basin appears to correlate with a greater abundance of carbonate cements compared to samples from the Abenaki Sub-basin, where carbonate cements are almost absent. The increase in abundance of carbonate cements in the Abenaki Sub-basin in the Middle Missisauga Formation and deeper samples may have negatively affected the permeability there, but does not account for the higher permeability of the Sable Sub-basin samples for the same stratigraphic interval, which also have extensive carbonate cement. It is the much greater abundance of chlorite rims in the Sable Sub-basin that is responsible for higher permeability there. The lack of late carbonate cement in the Upper Member of the Missisauga Formation and the Cree Member in the Abenaki Sub-basin does appear to correlate with the relatively low fluid entrapment temperatures measured at those stratigraphic levels in the eastern part of the Scotian Basin (Figure 2).

Feldspars are relatively abundant in the Scotian Basin sandstones, typically averaging 3-10% of framework grains. Diagenesis of these feldspars (Figure 4) has been tracked in selected samples from wells that have experienced both high temperature and lower temperature fluid flow. Diagenetic albite is much more abundant in thick sandstone units than in thin sandstone beds with interbedded mudstone, probably because such sandstones were pathways for flux of basinal fluids. It is more abundant, in the same facies and depth, in the Thebaud-Glenelg fields, where fluid inclusions in silica and carbonate cements are ~21% NaCl compared with the eastern part of the basin where fluid inclusions are ~10% NaCl and rather cooler. Dissolution of K-feldspar seems predominantly controlled by burial depth, but is most severe in permeable thick sandstone units.

In a few wells, there is evidence for Mississippi-Valley-type hydrothermal processes. Principal component analysis of bulk geochemical analyses from mudstones from throughout the basin show a few samples have high loadings for Ba, Pb and Zn. In several wells, including Kegeshook G-43 and Louisbourg J-47, macroscopic diagenetic barite and sphalerite have been indentified in thin sections.

Broader Implications

The Scotian Basin is only one of several basins offshore eastern Canada where there is evidence of volcanism tens of millions of years after the main rift phase. Extrusive volcanism may be much more limited geographically than the regional effects of high geothermal gradients.

Resulting hydrothermal circulation has the potential to produce more rapid and complete diagenetic cementation than during normal deep-basin compaction, by acceleration dissolution and precipitation rates of diagenetic minerals. In the Scotian Basin, carbonate cementation is more widespread in the western Sable Sub-basin where the greatest evidence for hydrothermal circulation is found; notwithstanding the fact that Jurassic carbonate rocks extend beneath the sandstone reservoirs all along the length of the Scotian Basin. Similar inhomogeneity in diagenetic processes may have taken place, for example, in the Salar and Carson basins, associated with the Late Albian volcanism of the Newfoundland Seamounts, or in the Hopedale Basin, associated with reported Turonian volcanism.

Conclusions

A regional Mid-Cretaceous (Aptian-Albian) thermal event in the Scotian Basin resulted in localized hydrothermal circulation, most pronounced in the western Sable Sub-basin. The high rock temperatures brought about by prolonged fluid flow resulted in more rapid diagenetic dissolution and precipitation. This is reflected in differences between the warmer and cooler parts of the basin in the degree of alteration and dissolution of feldspars and in the abundance of carbonate cements. Similar processes may result in regional variability in reservoir quality in other east coast offshore basins.

Acknowledgements

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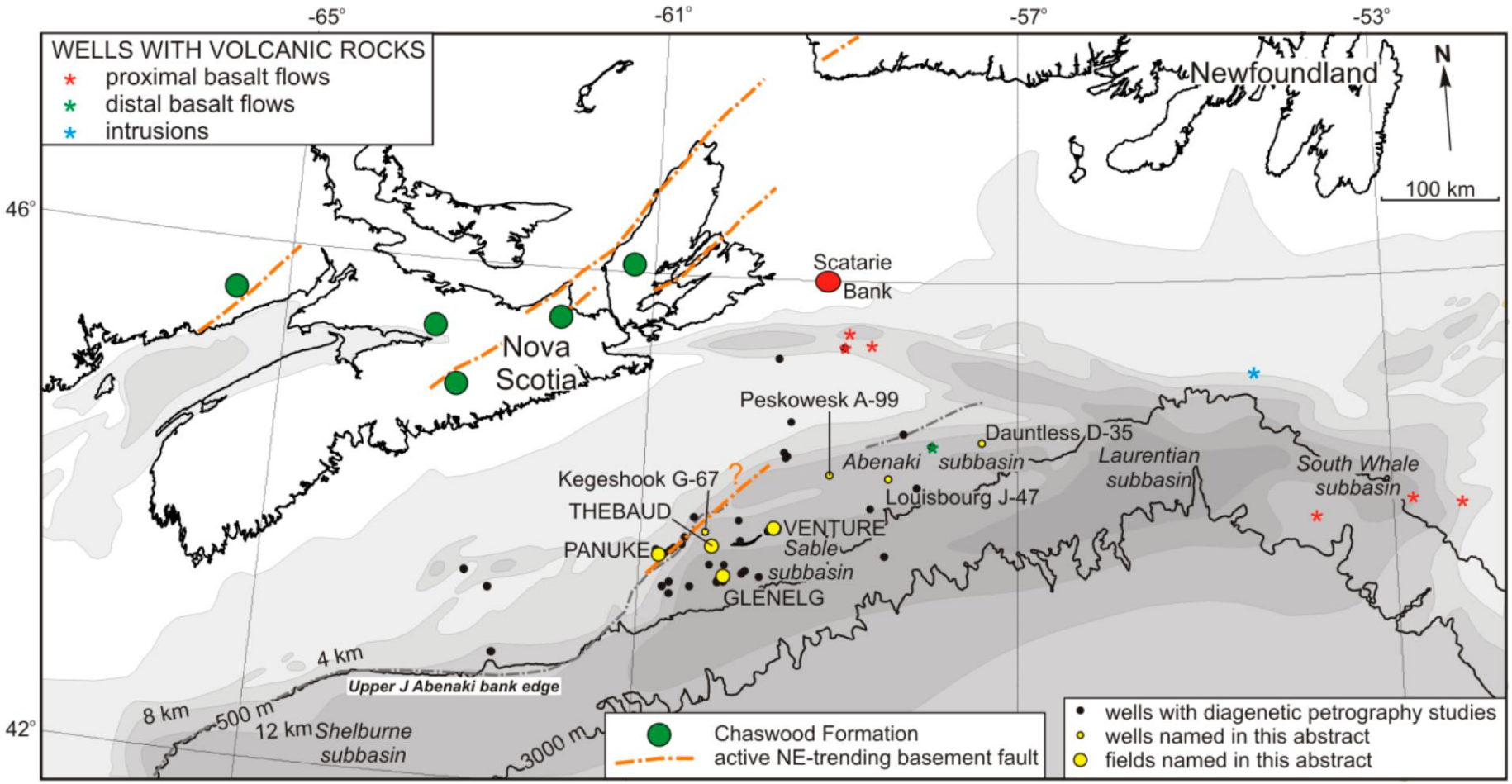

Figure 1. Index map of wells referred to in text. Wells with volcanic rocks are distinguished.

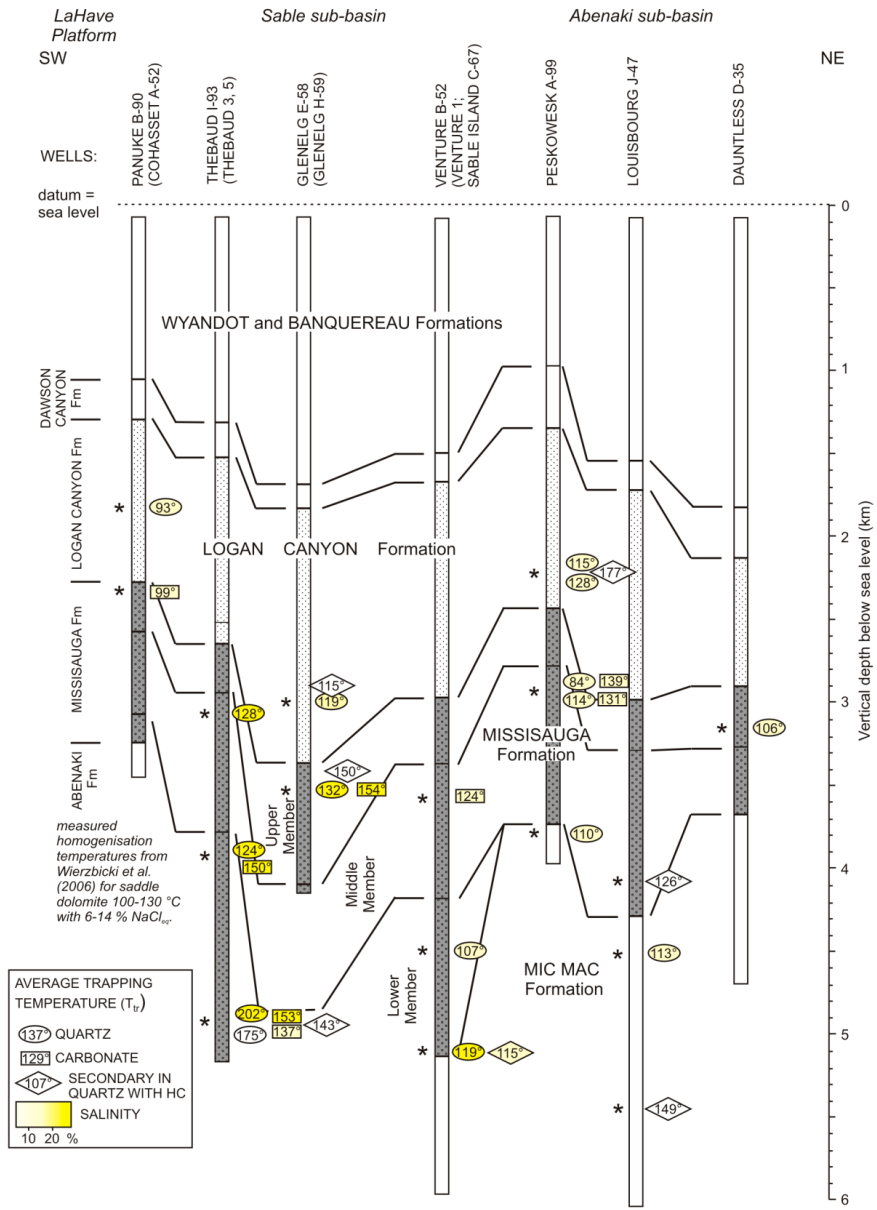

Figure 2. Synthesis of available fluid inclusion data from diagenetic cements in the Scotian Basin (based on data presented by Karim et al., 2011, 2012; Hanley, 2011; and Weirzbicki et al., 2006). * indicates samples; wells in (parentheses) have data projected into the appropriate stratigraphic level; patterns indicate Logan Canyon and Missisauga formations.

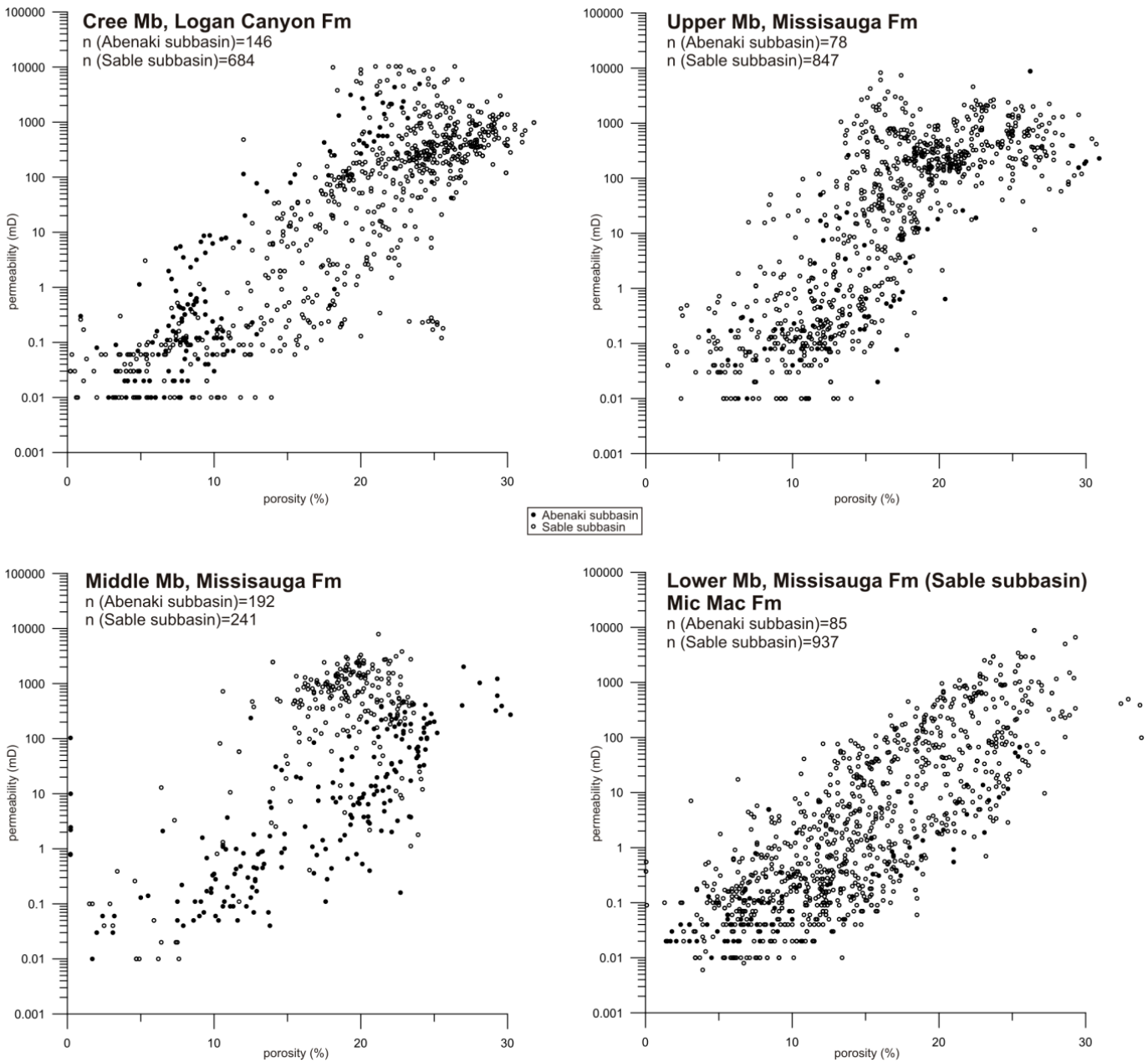

Figure 3. Plots of porosity vs. permeability for sandstone samples from conventional cores, by stratigraphic level and geography.

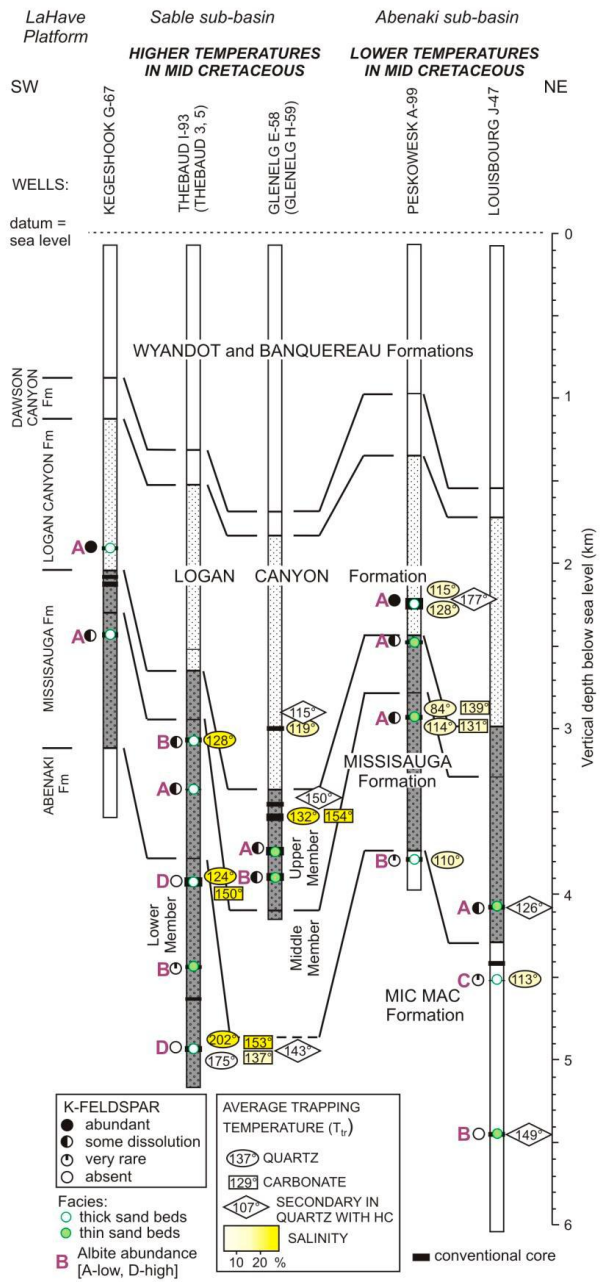

Figure 4. Relationship of degree of feldspar diagenesis to distribution of Mid-Cretaceous thermal event.