Time to Depth Conversion and Uncertainty Characterization for SAGD Base of Pay in the McMurray Formation, Alberta, Canada*

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Search and Discovery Article #80360 (2014)*
Posted February 25, 2014

*Adapted from extended abstract prepared in conjunction with presentation at CSPG/CSEG/CWLS GeoConvention 2012, (Vision) Calgary TELUS Convention Centre & ERCB Core Research Centre, Calgary, AB, Canada, 14-18 May 2012, AAPG©2014

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Abstract

The Athabasca Oil Sands of northern Alberta are a source of vast amounts of bitumen, estimated at approximately 1.7 trillion barrels. In-situ technologies, primarily Steam-Assisted-Gravity-Drainage (SAGD), are economically viable recovery schemes for almost two thirds of these enormous resources. A key aspect of deployment of SAGD as the recovery technique is proper horizontal well placement. A very important factor in a successful horizontal well placement is accurate detection of the SAGD base of pay surface and quantification of the associated uncertainty of the reservoir conformance. In this study, the target reservoir is characterized by stacked fluvio-estuarine channels of clean sand deposited within an overall transgressive system tract, where the SAGD base of pay is often characterized by either the Devonian or the so-called “middle McMurray” composite incision surface. The primary source of data to identify the SAGD base of pay are the well tops, while seismic data that are picked in the time domain are often treated as a soft secondary source of information. The focus in this study is to apply geostatistical tools to model the SAGD base of pay by using (1) well tops only, (2) well tops and seismic patches that are often available in the first pass and prior to picking of the full surface in the time domain, and (3) well tops and the fully picked seismic surface. For this purpose, geostatistical techniques such as Ordinary Kriging (OK), Kriging with Error (KERR) and Kriging with External Drift (KED) are applied, and the calculation of a linear velocity model is exercised. The results show the range and structure of spatial correlation of error and its associated anisotropy, as well as the value of seismic data integration in reduction of uncertainty in the modeling of SAGD base of pay.

Introduction

The Athabasca Oil Sands which contain about 1.7 trillion barrels of initial bitumen in place (National Energy Board, 2000) became one of the “wonders of northern Canada” that was predicted more than 100 years ago. Current in-situ technologies aim at recovering nearly 1.2 trillion barrels of initial bitumen in place. Husky Energy will deploy SAGD In-Situ technology at its Sunrise project, located approximately 60 km northeast of Ft. McMurray (Figure 1), to extract bitumen from the Cretaceous aged fluvio-estuarine bitumen saturated sands of the McMurray Formation.

Within the Sunrise area, in general, the primary SAGD reservoir is comprised of estuarine-channel dominated sands that occur approximately in the middle part of the McMurray Formation and hence, informally called "middle McMurray sand". The secondary SAGD reservoir is dominated by fluvial channel sands within the lower part of the formation and is informally called "lower McMurray sand". In most of the study area, the lower and middle McMurray sands are separated by non-reservoir tidal flat deposits. The 'primary' SAGD base of pay, in most cases, is a composite incision surface located at the base of "middle McMurray" estuarine channels, as shown in Figure 2. This topographically irregular composite surface is a sequence stratigraphically significant surface (SSSS). However, in deeply incised areas, the SSSS can incise into the "lower McMurray" secondary reservoir sands where the "lower" and the "middle" sands are stacked. In the latter case, the (primary) SAGD base of pay is a non-stratigraphic surface at the base of stacked sands.

Predicting the irregular geometry of this combined stratigraphic and non-stratigraphic SAGD base of pay within stacked channelized systems is critical to accurately place SAGD horizontal producers where the highest possible effective well length at a lowest possible elevation near the base of a clean reservoir ensures maximum bitumen recovery. This calls for a very detailed understanding of the reservoir geometry and heterogeneity where the presence of about a meter thick mudstone can be vital. Despite the relatively higher well densities (e.g. inter-well distance of about 400 m for the vertical delineation wells), the levels of details can still be a challenge due to the relative sparsity of well data - relative to the degrees of details in the reservoir which should be reasonably elucidated for a successful well placement.

Given the challenging nature of mapping the geometry of the pay interval, especially the base of pay, as well as the intra-reservoir shale heterogeneities which may have a significant impact on the steam chamber development and the ultimate SAGD performance, the seismic data proved to be a highly valuable source of information. Although most geophysical interpretation is performed in time domain, geological features appear to be more straightforward and meaningful when maps are converted to depth domain. Therefore, accurate velocity determination is critical.

Interval velocity is typically derived from the existing wells provided that the well information markers and time picks are picked correctly. Given that the depressed areas are not sometimes seismically resolvable, miss-ties may exist between the Devonian well pick and corresponding seismic horizon pick. Therefore, the interval velocity estimation from the "upper McMurray" to Devonian is usually problematic over depressed areas. This, in turn, makes it difficult to perform a reliable depth conversion, especially for discrete seismic patches that represent parts of the SAGD base of pay which are picked prior to seismic picking of the full surface in the time domain. The delineation of the full surface in the time domain and tying it to the well markers is even more difficult and subject to uncertainties.

Given the challenging nature of characterization of the SAGD base of pay surface, it is essential to apply geostatistical tools to ensure the (1) determination/QC of any potential inconsistencies between seismic picks and well markers, (2) delineation of uncertainty in the input data (e.g. discrete seismic patches) in time to depth conversion, (3) characterization of local uncertainty in the depth converted surface, and (4) back calculation of a linear velocity model and the associated uncertainty. In this work, a case study is presented where the value of the integration of various geostatistical tools in depth conversion of the reservoir surfaces, SAGD base of pay in particular, is discussed. The systematic reduction in the uncertainty of the final SAGD base of pay surface through the integration of seismic data at different levels is also quantified and discussed. For this purpose, first, OK is used to model a SAGD base of pay and the associated uncertainty through the use of well markers only. Then, the seismic patches that are available in the first pass of picking in the time domain are integrated after the calculation of uncertainty in their vertical position through quantification of uncertainty in the interval velocity and application of KERR, which explicitly accounts for calculated uncertainties by adjusting the Kriging weights. Finally a full time-to-depth conversion, based on KED is implemented, where the seismic amplitude in the time domain acts as an external drift and the deviations of the well markers from a trend that is constructed based on the drift is translated as uncertainty in the final output surface.

Methodology and Application

According to Deutsch and Journel (1998), kriging provides a minimum error-variance estimate of any unsampled value, and now is increasingly used to build probabilistic models of uncertainty about these unknown values. OK is a basic kriging algorithm, which is well-suited for surface modeling applications, since it does not need the prior knowledge of the local trend (or mean), while it adequately accounts for any geological anisotropies. In other words, by requiring that the kriging weights sum to one, OK filters the mean from the kriging estimator. Figure 3 shows the normalized uncertainty map for a part of the Sunrise Energy Project after applying OK with well markers only for the SAGD base of pay. The uncertainties are normalized for illustrative purposes, based on the maximum calculated uncertainty in the inter-well region calculated in the OK study before the integration of any seismic data.

As discussed above, in the Sunrise Project, the SAGD base-of-pay can be largely attributed to tidal flats at the top of the so-called ‘lower McMurray’ unit. These may appear as discrete (or locally continuous) intra-reservoir shale bodies that can be picked in the time domain. An interesting yet challenging task is to integrate these features into geostatistical surface modeling for SAGD-base-of-pay. Assuming there is no uncertainty in the time picks (in the time domain), and by quantifying the uncertainty in the upper surface (IHS Base surface which represents the base of the interbedded sand and mud at the top of McMurray Formation) and the lower surface (Devonian unconformity) and the correlation between the two, one can quantify the uncertainty in the interval velocity model (between IHS base and Devonian). This, in turn, may translate into uncertainty in the vertical position of the intra-reservoir shale bodies, which can then be integrated into surface modeling as soft secondary source of data. The well markers are treated as hard data. The algorithm used in this work is based on the proposed methodology by Deutsch et al. (2010) with minor customizations. Deutsch et al. (2010) introduced a new dimension (units of distance) to normal kriging algorithms to modify the scalar normalized distance to account for variability in measurement errors and sampling volume. They discussed the similarity of their approach to adding a constant (error variance) to diagonal terms of the kriging matrix and showed that both techniques result in a lower mean squared error and higher covariance between the estimates and the truth. In this work, the second approach was used with some provisions for accounting for the data density (frequency).

4 shows the seismic patches color-coded based on the level of uncertainty in their vertical elevations. 5 shows the normalized uncertainty in the SAGD-base-of-pay after depth conversion of seismic shale bodies. Comparing KED is a simple and efficient algorithm for integration of a secondary variable to improve the estimation of the primary variable (Deutsch and Journel, 1998), which is a simplified version of the Kriging with a Trend (KT), where the trend model is limited to two terms. The fundamental relation between the variables must make sense and the smooth variability in the secondary variable must deemed relevant to that of primary variable. The application of KED in time-to-depth

conversion is quite common (Geophysics, 2001, among others). A simple linear regression model has to be constructed to translate the seismic data picked in the time domain (external drift) to a smooth trend model in the depth domain. This has important outcomes both from a modeling point of view and from a practical prospective. From a modeling point of view, residual covariances rather than the covariances of the original variable must be used. Also, any non-zero correlation between the explicit trend and the residual has to be considered.

From a practical point of view, seismically irresolvable events (e.g. local depressions) must be identified and considered as areas with higher uncertainties. The development of the linear (or non-linear) regression model is useful since it allows for (1) calculation of residuals and their covariances, (2) close to zero correlation coefficient between the trend and residuals by construction, and (3) detection of outliers in the bivariate relationship which have to be either resolved or linked to depressed areas. 6 (left) shows a typical two-way-time versus well marker elevation cross-plot that shows two outliers that are associated with seismically irresolvable local depressions. 6 (right) shows a two-structured normalized directional experimental as well as modeled semi-variogram for the residuals that allows for appropriate representation of the locality of the depressions on the surface as well as accounting for anisotropy (if any) in the surface. 7 shows the normalized uncertainty map for a typical intra-formational surface in the McMurray Formation that shows significant decreases in the local uncertainties after a full time to depth conversion.

Conclusions

The characterization of the SAGD base of pay is a primary factor in successful horizontal well placement. Seismic data are quite valuable in delineation of the SAGD base of pay. In this work, seismic data were integrated into surface modeling at different levels, where reduction of uncertainty with integration of additional seismic data is documented and explained. The challenge of the integration of intra-reservoir shale bodies detected in the seismic time domain (seismic patches) was tackled through quantification of uncertainty in the interval velocity model and application of KERR. The value of KED process in identification of inconsistencies between seismic picks and well markers and the potential problem areas was discussed and its application in time-to-depth conversion is studied through a case study.

Acknowledgements

The authors would like to thank the management of Husky Energy Inc. for permission to publish this extended abstract.

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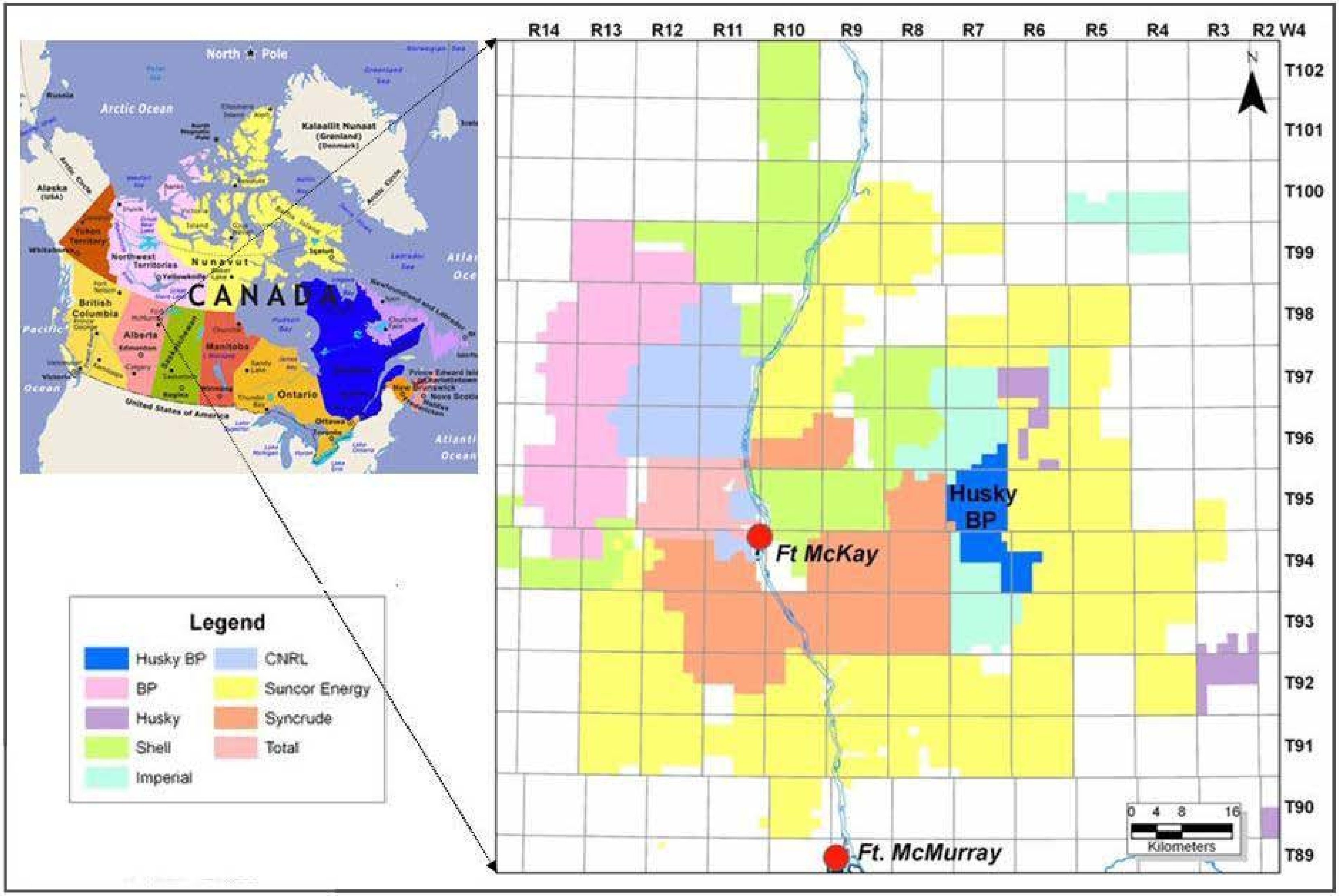

Figure 1. Husky's Sunrise project located approximately 60 km northeast of Ft. McMurray, Alberta.

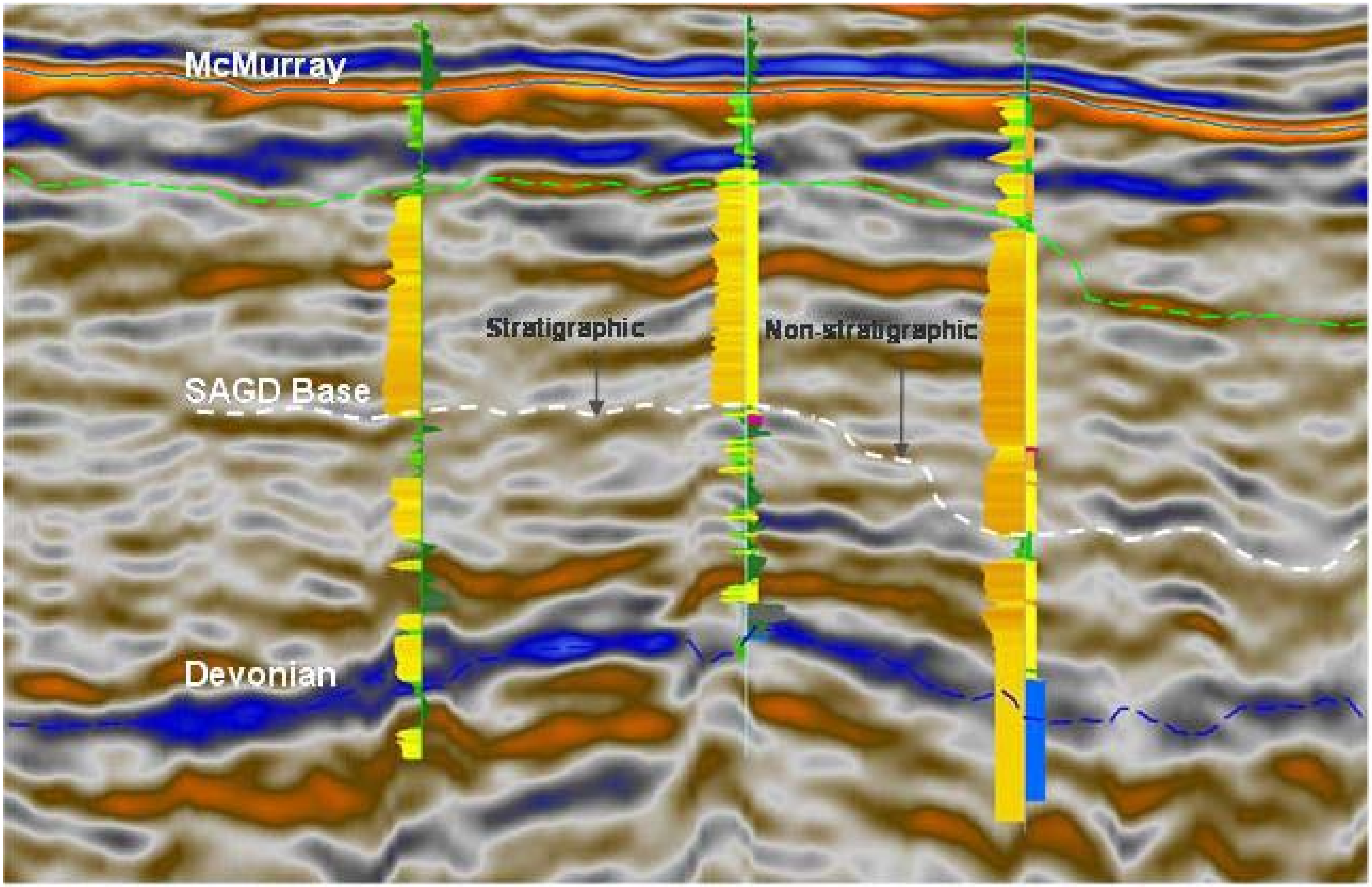

Figure 2. The primary SAGD base of pay, identified as a composite incision surface at the base of “middle McMurray” as well as other intra-McMurray stratigraphic and non-stratigraphic surfaces depicted on a depth converted seismic amplitude display.

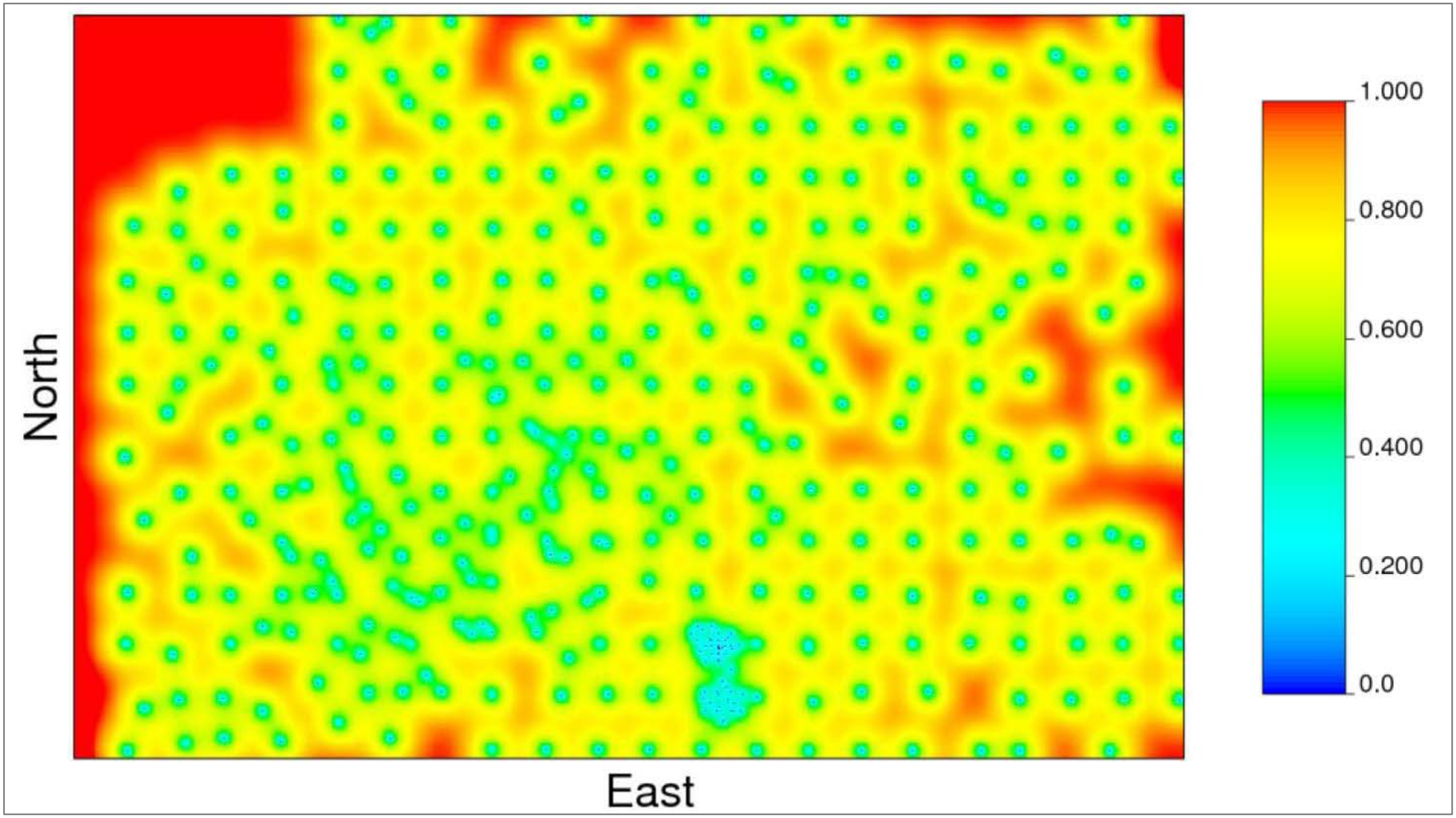

Figure 3. The normalized uncertainty map based on the application of OK with well markers only.

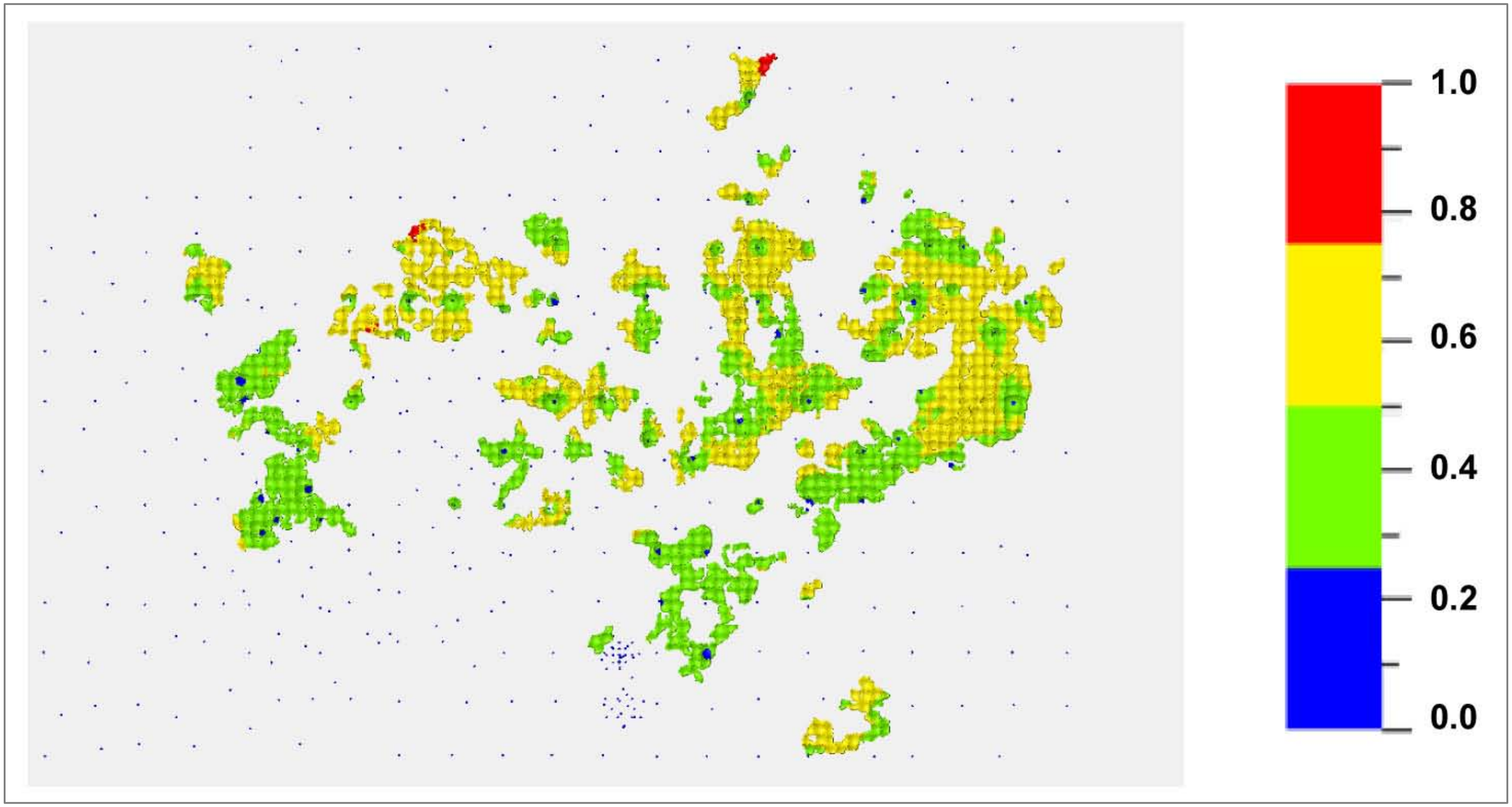

Figure 4. The depth converted intra-reservoir shale bodies that are originally picked in the time domain (seismic patches) with their associated color-coded normalized uncertainty.

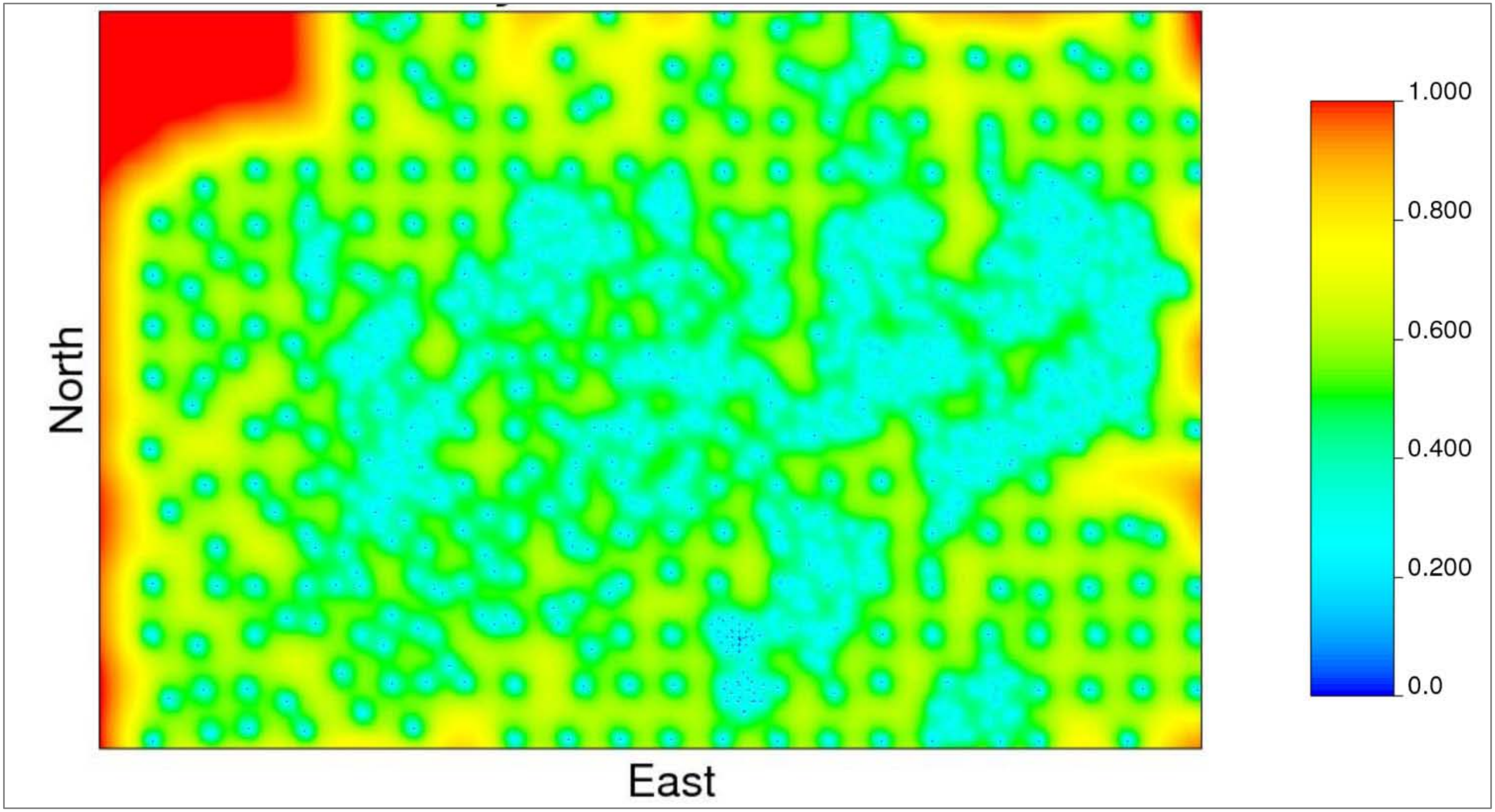

Figure 5. The normalized uncertainty map based on application of KERR with well markers as well as seismic patches.

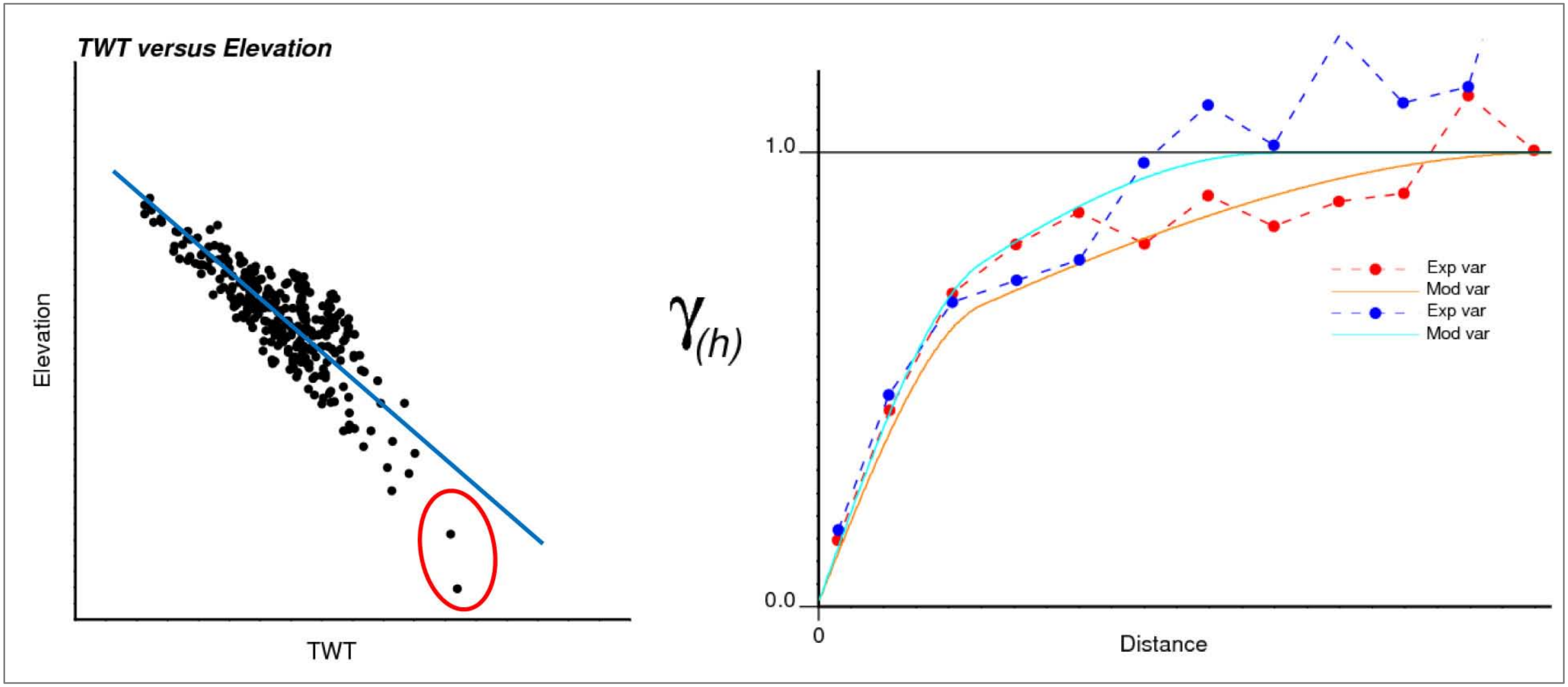

Figure 6. A typical two-way-time versus well marker elevation showing the linear regression line and the outliers (left), and typical normalized directional experimental and modeled variograms with two nested structures that show anisotropy in the spatial correlation of the residuals.

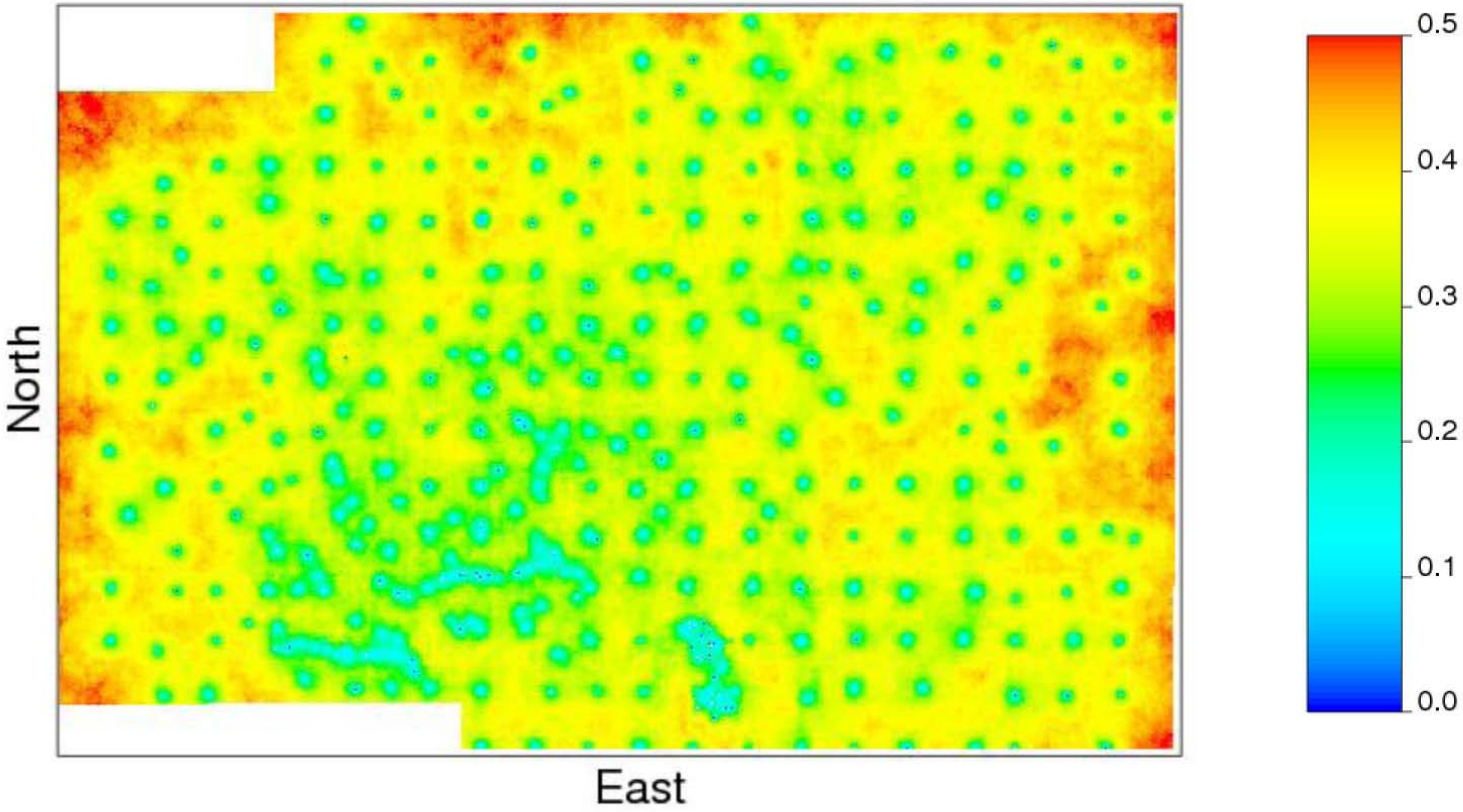

Figure 7. The normalized uncertainty map for a typical intra-formational surface in the McMurray Formation based on application of KED with well markers and the (full) seismic picks in the time domain.