Significance and Application of Velocity Derivative Gradient in Petroleum Exploration

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Key Points:

- Apply derivative gradient calculation in seismic velocity data.
- Use the anomalous values of velocity gradient to identify boundaries between different lithology, fluid, and fluid saturation.

Abstract

Velocity is one of the fundamental data obtained from seismic and it is the direct behavior of the solids and fluids in lithosphere. Here we present an analysis of the derivative gradient of seismic velocity which can help identify the featured boundary of favorable petroleum accmulations such as sedimentary facies boundary, faults, and flow unit edges. The derivative gradient can be calculated both horizontally and vertically, thus it can help discriminate favorable targets in three-dimensional. We find the application of derivative gradient to detect or enhance edge is relatively mature in gravity and geomagnetic analysis but rarely mentioned in seismic nor in petroleum exploration. We believe we can make better use of the seismic velocity data by this means as it is quite efficient in pinpointing the favorable petroleum targets in subsurface with precisions of tens-of-meter scale, depending on the horizontal resolution of seismic survey.

Plain Language Summary

Different rocks have different velocity when wave go through them. If there is water inside the rock, the velocity will be lower than in dense rock; if there is gas within, the velocity will be even lower. Based on this principle, it seems easy to differiate water, oil, and gas in rocks. We do have artificial seismic technic to measure some parameters of subsurface, in which velocity is one of the most basic and objective parameter. However, in subsurface the rocks and the fluid inside vary constantly, we can't conclude the low velocity area just as probable oil and gas targets.

In our research, we try to calculate the derivative gradients of the velocity, aiming to find where the velocity changes suddenly. The sudden change indicates the boundary or barrier between different rock, and/or the fluid. Within the same boundary it is homogenous in rock and fluid compositions, and the fluid flow is steady and continuous. We put these boundaries to the map of the production wells, then we can tell which wells are connected (within the same boundary), and if there are oil/gas areas not drilled yet. Finally we can pinpoint oil/gas targets for future production.

1 Introduction

Velocity is one of the most direct parameters we can obtain from seismic surveying. The vertical change of velocity is widely applied in time-depth conversion, significant surface (such as Moho surface) recognition, crustal structure inversion, and energy resource reservoir interpretation (eg. Domenico, 1977; Singh et al., 1993; Benites and Aki, 1994; Kern et al., 1996; Neves et al., 1996; Fruehn et al., 2008; Hustoft et al., 2009; Nishizawa et al., 2011; Simão et al., 2016). Velocity is determined by the media which the wave get through, in subsurface they are varieties of rocks and fluids within (Domenico, 1976; Wang, 1998; Hoversten et al., 2003; Sayers, 2005). Since the value of velocity is the reflection of lithology, fluid, and fluid saturation, it can always give a rough image of those features. However, we need more precision in practice of energy resource exploration, better pinpointing a small oil/gas play or even a flow unit in a reservoir especially at the late stage of exploration and production.

Driven by this urgent demand, we took a deeper look at the seismic velocity data and adopted the derivative gradient to illustrate the change of velocity horizontally. We mapped the velocity gradients for different formation surfaces and found they perfectly highlighted the boundary between different lithology and well production behaviors. We suggest the derivate gradient can be a handy and reliable tool for featured boundary identification in subsurface exploration.

2 Geological background of study area

Our research is initiated in Yakela condensate gas field in Tarim Basin, China, with an area of ~53 km^2. This gas field has been producing for more than 30 years and is pursuing another 5-10 year's steady production; thus, our aim is to locate the potential reservoirs and recoverable remaining oil. Targeted layers in this area are Lower Cretaceous Yageliemu Formation (K_1y) and Lower Jurassic (J) within the depth interval of 5300-5600 m, average thickened 47 m and 39 m, respectively. Lithology of K_1y and J include conglomerate, sandstone, siltstone, and mudstone. At the initial formation pressure of ~56 MPa and temperature of ~136 °C, the fluid in K_1y and J include brine, condensate oil, and gas.

3 Calculation results of velocity gradient

Generally, less density of rock (greater porosity) and greater gas saturation result in smaller velocity and vice versa (Domenico, 1976). We can roughly conclude this from the interval velocity distribution maps of K_1y and J (Fig. 1a, b, c): all 43 wells are drilled in the areas of low velocities indicating favorable porosity and gas saturation. We can also see from the maps that though velocity increases along depth, the distribution of velocity looks alike in the layers, making it difficult to achieve fine description of favorable reservoir and remaining oil using velocity alone.

Since the velocity represents lithology, fluid and saturation, the sudden change of velocity must reflect a big difference in those properties. We have a velocity data with the resolution of 15×15 m in horizontal which is much smaller than the averaged well spacing of ~1200 m, so we tried to calculate the velocity derivative gradient to get better estimation of inter-well areas. Derivative gradient is the function showing both the direction and extent of the changes of an irregular distributed matter or field, it has long been used for detecting or enhancing edge and evolved many advanced algorithms (Zuniga and Haralick, 1987; Tarasov, 2005). In this study we used the imbedded gradient function in Matlab. In this calculation, gradient is calculated grid by grid. A negative gradient means the velocity of calculated grid is smaller than surrounding and vice versa. By this definition, we can see that high gradient value delineates the "barriers" between wells (Fig. 1d, e, f). These barriers showing sharp increase of velocity, probably occur at the contact between porous sandstone and tight siltstone/mudstone, or between the gas and brine if lithology does not vary significantly.

The velocity gradient in the top layer of K_1y is primarily smaller than 0.5 in the gas field, indicating a relatively homogenous distribution of lithology and gas saturation, hence the lateral connectivity is good (Fig. 1d). This is consistent with the production performance that K_1y top is the most productive layer in the field with high gas saturation and few water flooding or coning.

The velocity gradient in the bottom layer of K_1y mostly ranges greater than 1.5 (Fig. 1e), indicating strong heterogeneity of lithology and gas saturation, hence the lateral connectivity is poor. Core observation and well log analysis support this conclusion as they show the K_1y bottom is coarser in grain size than K_1y top, which means the difference between the porosity of sandstone and mudstone is greater in K_1y bottom than in K_1y top. Furthermore, most areas of the K_1y bottom are below the gas-water contact, making the velocity gradient more distinct from gas to brine.

The velocity gradient in the bottom layer of J mostly ranges below 1.5 in the well regions (Fig. 1f), indicating mild-middle heterogeneity of lithology and gas saturation. Core observation and well log analysis show the lithology of this layer consists of fine grained reservoir rocks similar to K_1y top, while this layer is water flooded on the north and south sides, which may account for the high gradients at the field edge.

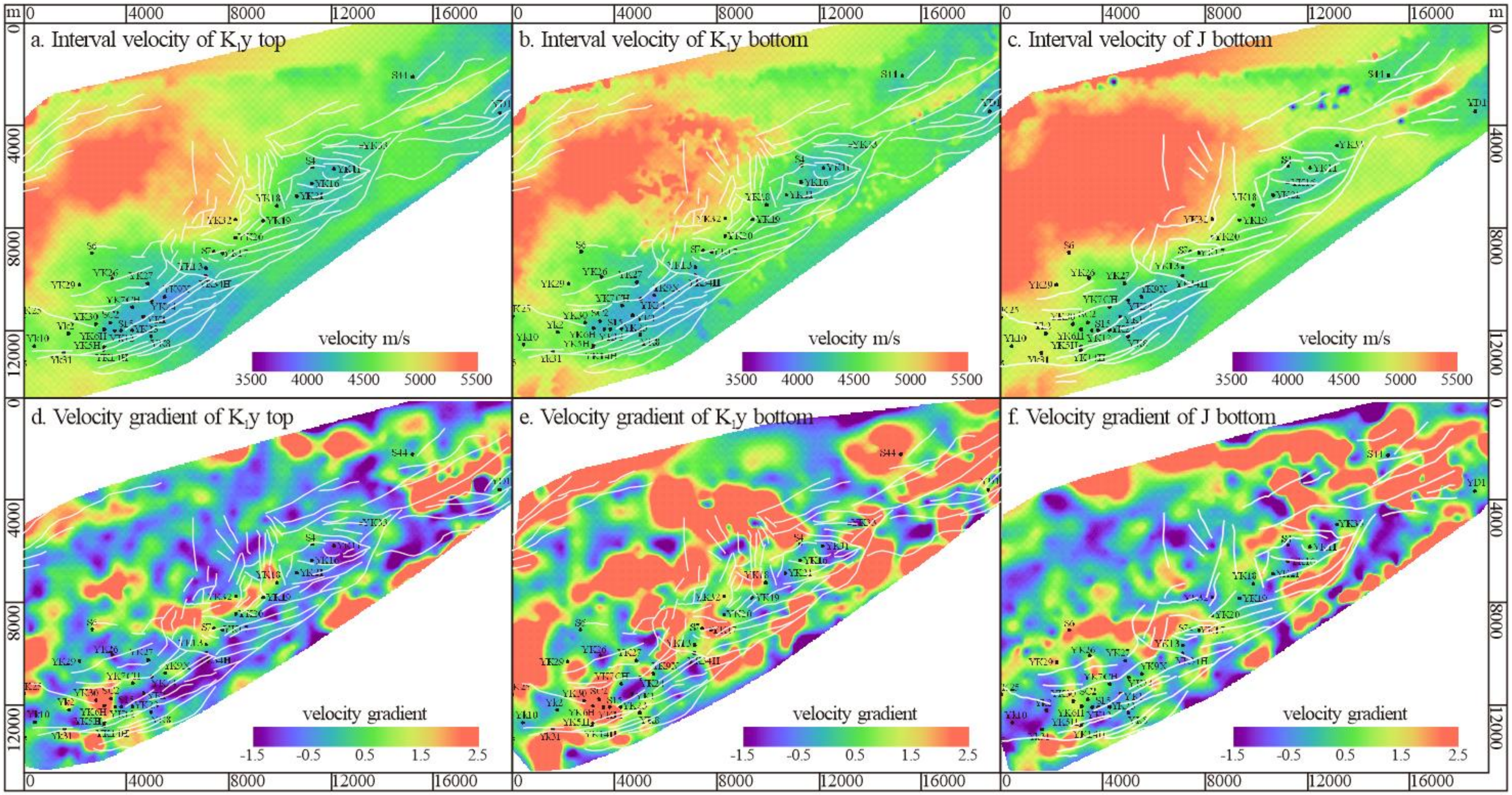

Figure 1. Maps of velocity and velocity gradient in each surface. White lines are the faults.

The derivate gradient is always subject to horizontal calculation, but we also tried it from section view. We treat a section as a map then gridded it and calculated the derivate gradient (Fig. 2). In sectional view, the high gradient barriers are obvious in each formation. They divide the formations into a series of compartments, within which the lithology and fluid saturation does not vary significantly. We suggest the sectional calculation of velocity derivative gradient can help identify in three dimensional the sweet spots with favorable lithology and fluid saturations in combination with horizontal gradient maps.

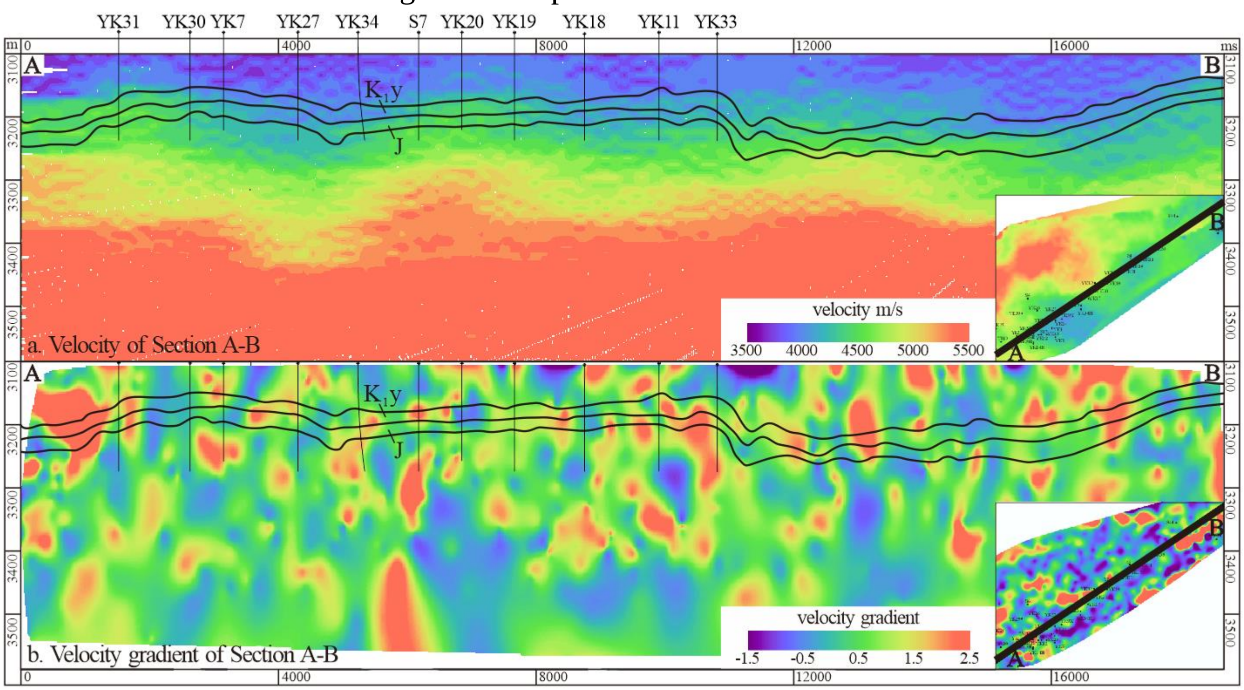

Figure 2. Velocity and velocity gradient of a section across the field.

4 Discussion on the application of velocity gradient

Regarding to the application of velocity gradient, the immediate use we propose is microfacies boundary pinpointing. Microfacies analysis is one essential work for locating favorable reservoir and remaining oil in clastic reservoir exploration and production. The averaged well spacing in the study area is ~1200 m, which is too large for conventional reservoir architecture analysis (Miall, 2006). Thus, stochastic modeling was adopted to estimate the microfacies in this area, but the model did not fit well with the well production behaviors. We have extended our work on velocity gradient by using the high gradient barrier as facies boundary to categorize the microfacies owing to its 15×15 m resolution (Fig. 3).

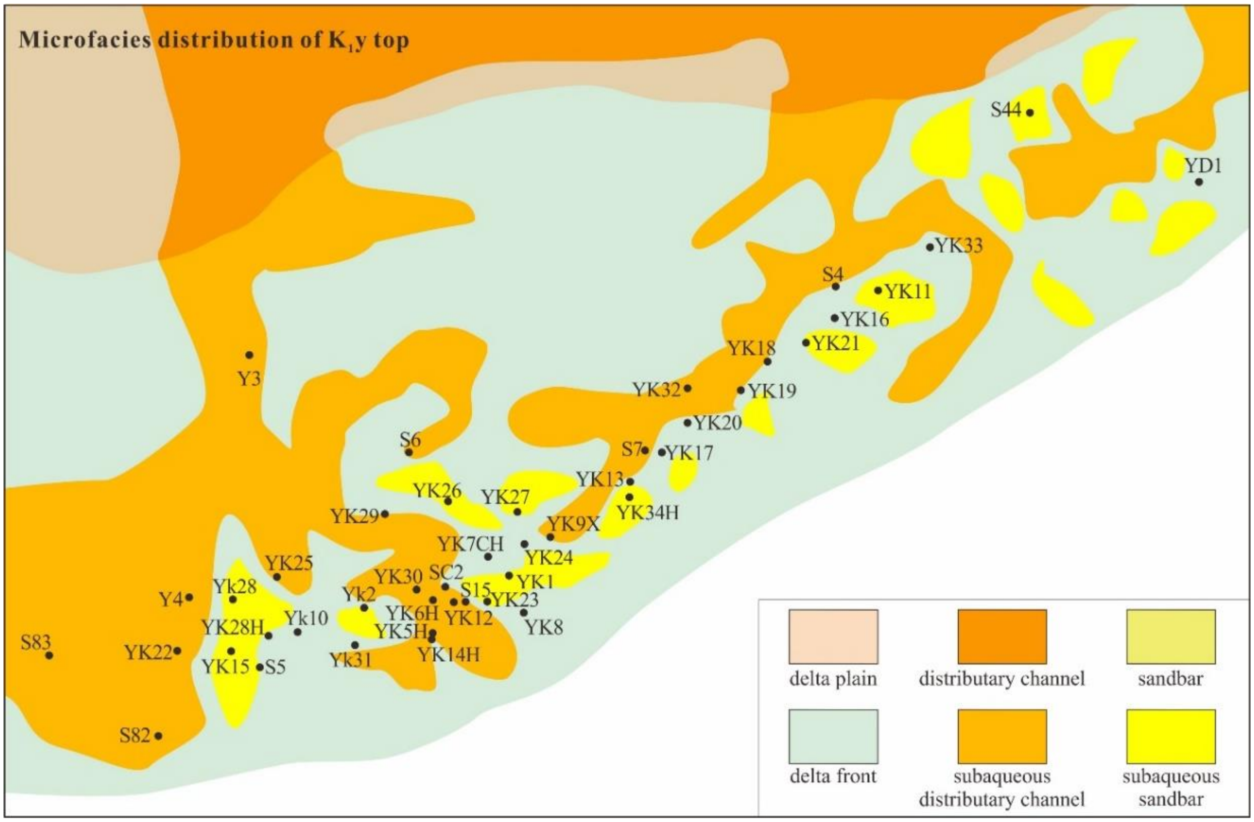

Figure 3. Microfacies mapped according to well data and seismic velocity gradient distribution.

Though the velocity gradient based microfacies estimation is more reasonable and accurate, we still note the velocity is the reflection of lithology, fluid, and fluid saturation. We suggest more works can be done on velocity derivative gradient, such as differentiating the contributions of lithology and fluid saturation, pinpointing the flow unit, calculating higher degree derivatives to see what happens, applying to geothermal exploration as temperature is also one parameter affect velocity, and experimental validations, etc.

5 Conclusions

We did find strong support to our work after we had preliminary results, but most of them are in the field of gravity or magnetic surveying (Fedi and Florio, 2001; Cooper and Cowan, 2008; Wang et al., 2008; Panet et al., 2014; Ellis et al., 2017). In one way, the literatures consolidate our confidence in the significance and application of derivative gradient in identifying featured boundaries; in another, we would like to share this work sooner with the researchers as seismic velocity is one of the fundamental data in energy resource industry and its resolution gets higher and higher. We believe we can make better use of seismic velocity data by carrying out derivative gradient analysis.

Acknowledgments

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Data Availability Statement

Due to the commercial restrictions of this research, participants of this study did not agree for the seicmic velocity data to be shared publicly. Data are available from the authors with the permission of Sinopec Northwest Oilfield Company.

References

Benites, R. & Aki, K. (1994), Ground motion at mountains and sedimentary basins with vertical seismic velocity gradient. *Geophysical Journal International*, *116,* 95-118. doi:10.1111/j.1365-246X.1994.tb02130.x

Cooper, G. R. J. & Cowan, D.R. (2008), Edge enhancement of potential-field data using normalized statistics. *Geophysics, 73,* H1-H4. doi:10.1190/1.2837309

Domenico S. N. (1976), Effect of brine-gas mixture on velocity in an unconsolidated sand reservoir. *Geophysics, 41,* 882-894. doi:10.1190/1.1440670

Domenico, S. N. (1977), Elastic properties of unconsolidated porous sand reservoirs. *Geophysics, 42,* 1339-1368. doi:10.1190/1.1440797

Ellis, S., Van Dissen, R., Eberhart-Phillips, D., Reyners, M., Dolan, J. F., & Nicol, A. (2017), Detecting hazardous New Zealand faults at depth using seismic velocity gradients. *Earth and Planetary Science Letters, 463,* 333-343. doi:10.1016/j.epsl.2017.01.038

Fedi, M. & Florio, G. (2001), Detection of potential fields source boundaries by enhanced horizontal derivative method. *Geophysical Prospecting*, *49,* 40-58. doi:10.1046/j.1365-2478.2001.00235.x

Fruehn, J., Jones, I. F., Valler, V., Sangvai, P., Biswal, A., & Mathur, M. (2008), Resolving near-seabed velocity anomalies: Deep water offshore eastern India. *Geophysics, 73,* VE235-VE241. Doi:10.1190/1.2957947

Hoversten, G. M., Gritto, R., Washbourne, J., & Daley, T. (2003), Pressure and fluid saturation prediction in a multicomponent reservoir using combined seismic and electromagnetic imaging. *Geophysics 68,* 1580-1591. doi:10.1190/1.1620632

Hustoft, S., Stefan B., Jürgen M., & Chand, S. (2009), Gas hydrate reservoir and active methane-venting province in sediments on <20? ma young oceanic crust in the Fram Strait, offshore NW-Svalbard. *Earth & Planetary Science Letters, 284,* 1-24. doi:10.1016/j.epsl.2009.03.038

Kern, H., Gao, S. & Liu, Q. (1996), Seismic properties and densities of middle and lower crustal rocks exposed along the North China Geoscience Transect. *Earth and Planetary Science Letters, 139,* 439-455. doi:10.1016/0012-821X(95)00240-D

Miall, A.D. (2006), Reconstructing the architecture and sequence stratigraphy of the preserved fluvial record as a tool for reservoir development: a reality check. *AAPG Bulletin, 90,* 989-1002. doi: 10.1306/02220605065

Neves, F. A., Singh, S. C. & Priestley, K. F. (1996), Velocity structure of upper-mantle transition zones beneath Central Eurasia from seismic inversion using genetic algorithms. *Geophysical Journal International, 125,* 869-878. doi:10.1111/j.1365-246X.1996.tb06030.x

Nishizawa, A., Kaneda, K. & Oikawa, M. (2011), Backarc basin oceanic crust and uppermost mantle seismic velocity structure of the Shikoku Basin, south of Japan. *Earth, Planets and Space, 63,* 151-155. doi: 10.5047/eps.2010.12.003

Panet, I., Pajot-Métivier, G., Greff-Lefftz, M., Métivier, L., Diament, M., & Mandea, M. (2014), Mapping the mass distribution of Earth's mantle using satellite-derived gravity gradients. *Nature Geoscience, 7,* 131-135. doi:10.1038/ngeo2063

Sayers, C. M. (2005), Seismic anisotropy of shales. *Geophysical Prospecting, 53,* 667-676. doi:10.1190/1.9781560802129.ch8

Simão, N. M., Nalbant, S. S., Sunbul, F. & Komec Mutlu, A. (2016), Central and eastern Anatolian crustal deformation rate and velocity fields derived from GPS and earthquake data. *Earth and Planetary Science Letters, 433*, 89-98. doi:10.1016/j.epsl.2015.10.041

Singh, S. C., Minshull, T. A., & Spence, G. D. (1993), Velocity structure of a gas hydrate reflector. *Science, 260,* 204-207. doi:10.1126/science.260.5105.204

Tarasov, V.E. (2005), Fractional Generalization of Gradient Systems. *Letters in Mathematical Physics, 73,* 49-58. doi:10.1007/s11005-005-8444-z

Wang, B., Krebes, E. S. & Ravat, D. (2008), High-precision potential-field and gradient-component transformations and derivative computations using cubic B-splines. *Geophysics, 73,* I35-I42. doi:10.1190/1.2953291

Wang, Z. (1998), Seismic monitoring of a CO_2 flood in a carbonate reservoir: A rock physics study. *Geophysics, 63,* 1604-1617. doi:10.1190/1.1444457

Zuniga, O. A. & Haralick, R. M. (1987), Integrated Directional Derivative Gradient Operator. *IEEE Transactions on Systems, Man, and Cybernetics, 17,* 508-517. doi:10.1109/TSMC.1987.4309068