Freie Universität Berlin

Reshetnikov, A., Buske, S., Shapiro, S. A.
Institute for Geological Sciences
Freie Universität Berlin
Malteserstrasse 74-100, 12249, Berlin, Germany
anton@geophysik.fu-berlin.de

# Active seismic imaging using microseismic events: results from the San-Andreas-Fault System at SAFOD

## Abstract

The analysis and interpretation of microseismic data sets is receiving increased attention, both in the exploration industry for the characterization of hydrocarbon and geothermal reservoirs as well as in academia for the general understanding of seismogenic processes at plate boundaries.

The gain in data quality due to e.g. the deployment of borehole-receiver-arrays and the meanwhile common practice of recording the full waveform of the seismic events allows to process these data sets using modern seismic imaging and inversion algorithms.

We have developed a passive seismic imaging approach which consists of two steps. Firstly, the hypocenter of the microseismic event is precisely located. Secondly, this event is treated as a "pseudo-active" seismic source and we process the reflections within the recorded wavefield using a directional migration algorithm in order to construct a high resolution image in the immediate vicinity of the hypocenter and receiver array.

Here we describe this approach and demonstrate the application to several microseismic events recorded by a borehole array in the SAFOD (San-Andreas-Fault-Observatory-at-Depth) main hole. The results are high-resolution images of different fault branches related to the San-Andreas-Fault (SAF) system in the close vicinity of the borehole. The comparison of these findings with existing surface seismic reflection images shows a good agreement. In summary our results allow to obtain a spatial characterization of the complex internal structure of the SAF and can certainly be helpful for other studies which are based on this knowledge.

## Location

In order to image reflections within microseismic data sets it is first necessary to locate the events. The accuracy and stability of the location in space and time are critical issues for a successful imaging step afterwards. Our microseismic event location procedure is similar to the one proposed by Rentsch et al. (2007) with the exception that we use the density of the back-propagated direct P-wave rays as the location criterion instead of the stacked amplitude of the image. This increases the accuracy of the location procedure and allows to take into account the quality of the obtained polarization.

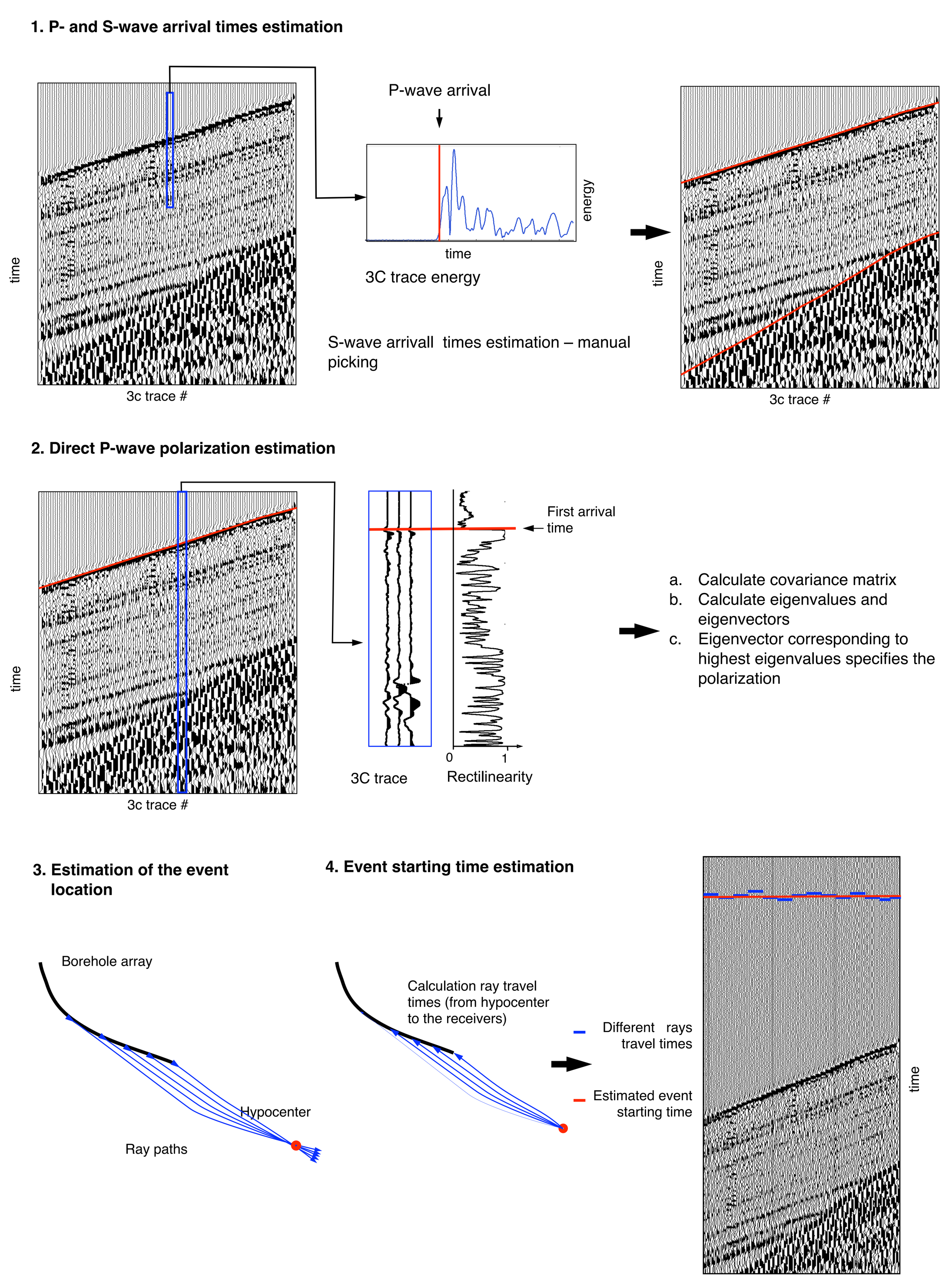


Figure 1. Diagram of location procedure.

## Imaging

In order to construct an image using located events we apply Fresnel-Volume-Migration (Lüth et al., 2005; Buske et al., 2006). This is an extension of the standard Kirchhoff migration procedure. The basic idea of this method is to restrict imaging condition to the Fresnel volume of a specular wavepath for the reflection event. The Fresnel volume can be computed from the emergence polarization of the reflected waves by dynamic raytracing (Červený, 2001). The advantage of this approach is focused imaging of the reflection events in the case of strongly limited aperture.

To perform Fresnel-Volume-Migration the polarization information is necessary. In this paper we only present PP reflections imaging. Reflection data in our case consist of complex mixture of the reflected waveforms from different reflectors. To get the emergence polarization of the reflected waves we use the following algorithm: first, we estimate the polarization for each sample of every 3C trace. Then, to each sample we assign the value of polarization corresponding to the highest rectilinearity from some time window around it. The length of the window is order of 11 ms. To exclude trace samples with unreliable polarization, we do not use the samples which correspond to windows with maximal rectilinearity less than 0.75. An example is shown in Figure 2.

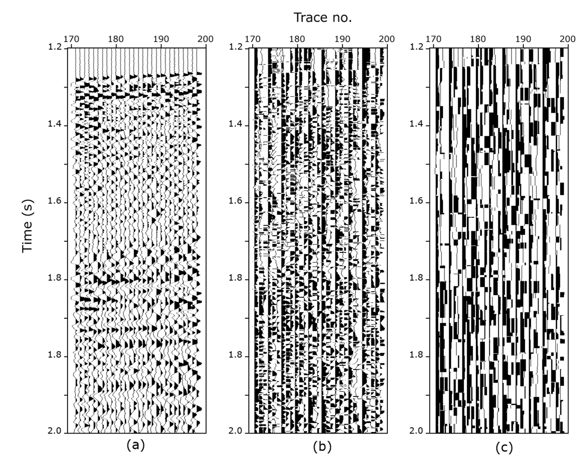

Figure 2. (a) 3C data of 5th May 2005 event. (b) Polarization. (c) Polarization calculated by means of sliding window averaging algorithm used for Fresnel-Volume-Migration.

## Application to SAFOD events

We applied our approach to a data set recorded in the SAFOD main borehole. here we present the results for five events, recorded on May 4 and May 5, 2005.

We have chosen these events because they are occurred within short time period. This suggests that the corresponding hypocenters are not too far away from each other which in turn implies that they will illuminate similar parts of the subsurface and the corresponding images will also be similar.

For the selected data sets was performed the event detection procedure, estimated the event positions in space and time and migrated the PP reflection for each of them. For the location and imaging we used a 3D P-velocity model (Thurber et al. 2004). To get S velocity model we used an effective Vp-Vs ratio of 1.83 (Rentsch et al. 2007). Estimated event position and ray trajectories from the receivers with directions obtained from the P-wave first arrival are shown in Figure 3, the resulting images are shown in Figure 4.

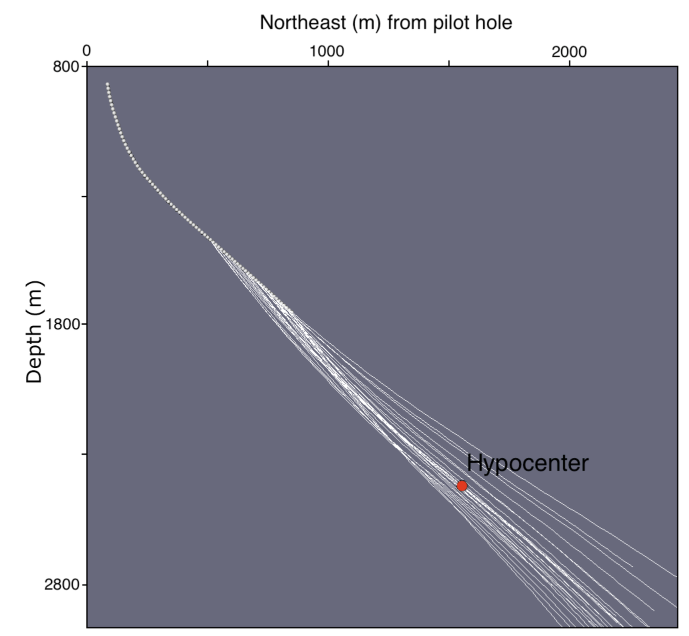


Figure 3. Estimated event position and ray trajectories from the receivers with directions obtained from the P-wave first arrival time.

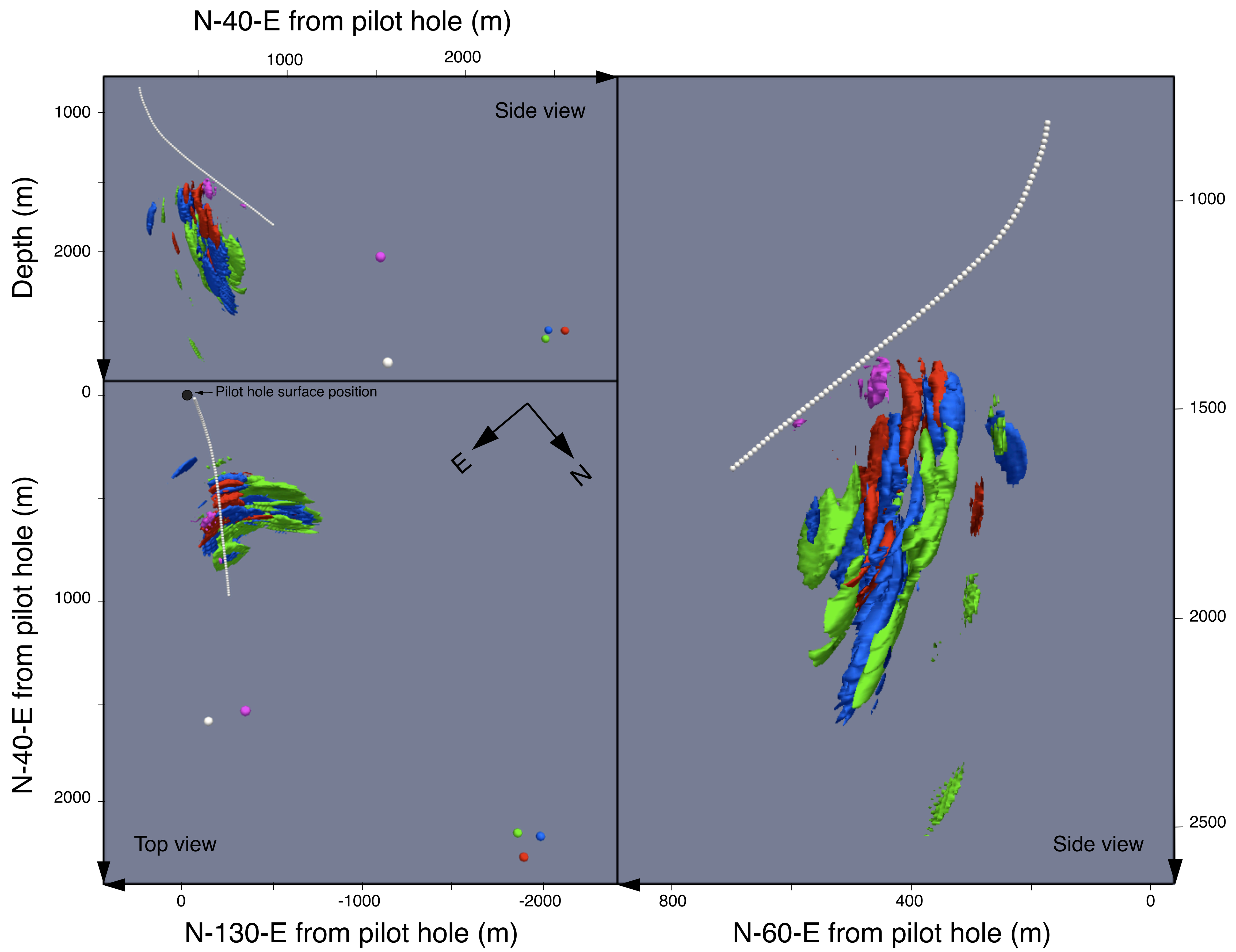


Figure 4. Combined images from three located events. Different colors of obtained reflectors corresponds to different events.

## Comparison with other results

In Figure 6 a comparison between an active surface seismic reflection image (Buske et al. 2007) and some of reflectors obtained here is shown. The comparison demonstrates quite satisfactory coincidence.

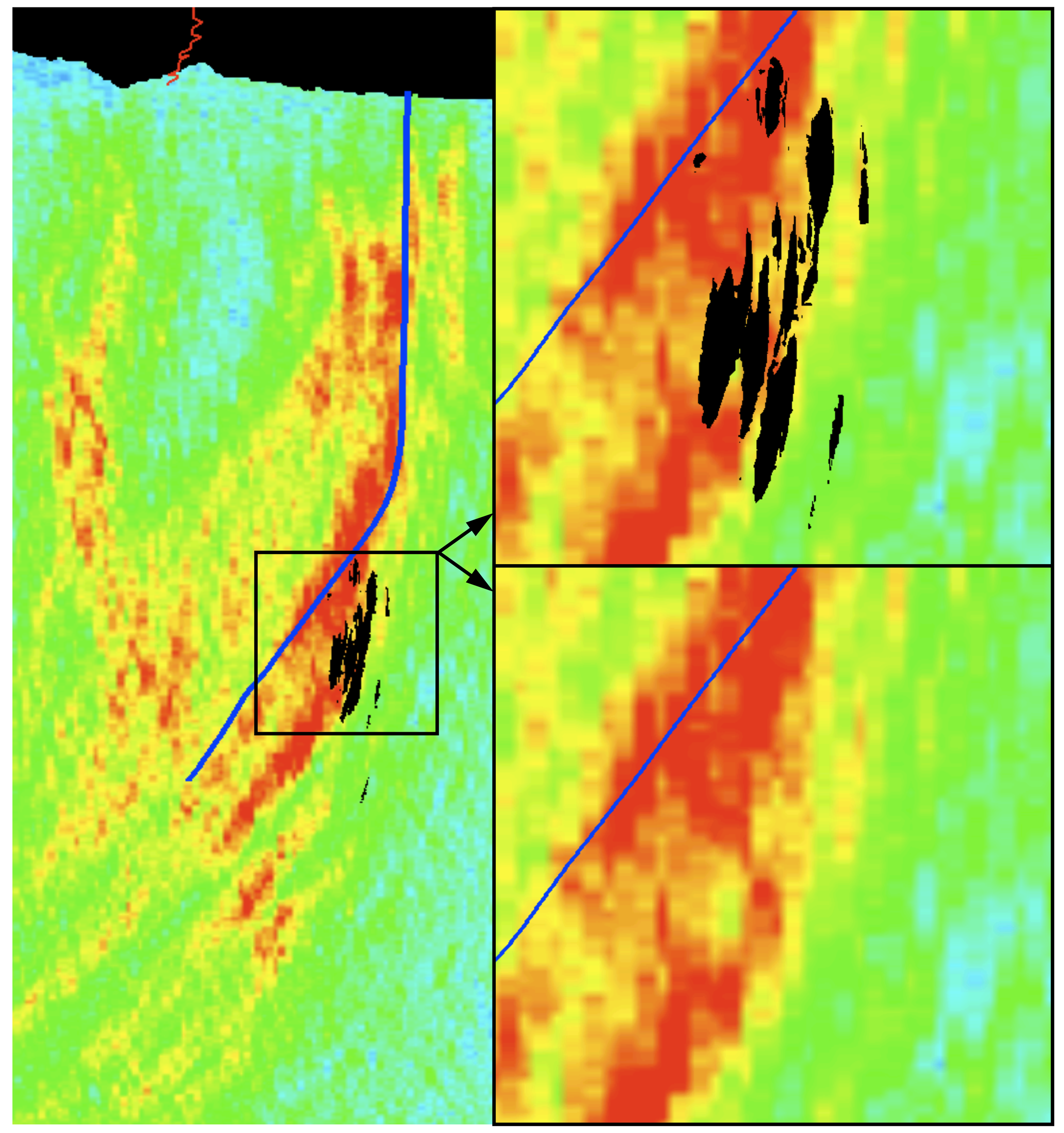

Figure 5. The comparison of obtained results with existing surface seismic reflection images.

This comparison demonstrates the good coincidence as well as the increase in resolution. Compared to the "low" resolution surface seismic image we are able to decipher the fine structure of different branches of the fault system.

## Conclusions

We have presented a procedure for microseismicity imaging. Using the obtained polarization of the first arrival the hypocenter of the microseismic event is precisely located. Then this event is treated as a "pseudo-active" seismic source and the reflections within the recorded wavefield are processed using a directional migration algorithm in order to construct a high resolution image in the close vicinity. The method was applied to three microseismic events recorded at SAFOD. The comparison of these findings with existing surface seismic reflection images shows a very good agreement and allows for better structural interpretation of the fine scale structure of the fault system.

## Acknowledgments

This work was carried out in the frame of project BU1364/4-1 of the German Science Foundation, ICDP-SPP. We would like to thank the sponsors of the Physics and Application of Seismic Emission (PHASE) consortium. We also thank PGS/I for the seismic data. We are also grateful to Susanne Rentsch for her valuable advises and comments.

## References

- Buske, S., Heigel, M. and Lüth, S., 2006, Fresnel-Volume-Migration of single-component seismic data. EAGE 68th annual meeting and technical exhibition, Vienna, Expanded Abstracts, G044.
- Buske, S., Gutjahr, S., Rentsch, S. and Shapiro, S.A., Application of Fresnel-Volume-Migration to the SAFOD2003 data set. EAGE 69th annual meeting and technical exhibition, London, Expanded Abstracts, P335, 2007.
- Červený, V., 2001, Seismic Ray Theory: Cambridge University Press, 713 pages.
- Lüth, S., Buske, S., Görtz, A. and Giese, R., 2005, Fresnel-Volume-Migration of multicomponent data. Geophysics, 70(6), S121-S129.
- Rentsch, S., Buske, S., Lüth, S., and Shapiro, S. A., 2007, Fast location of seismicity: A migration-type approach with application to hydraulic-fracturing data: Geophysics, 72, no. 1, S33–S40.
- Thurber, C., Roecker, S., Zhang, H., Baher, S., and Ellsworth, W., 2004, Fine-scale structure of the San Andreas fault zone and location of the SAFOD target earthquakes: Geophysical Research Letters, 31, no. L12S02, doi: 10.1029/2003GL019398.