A forum on microseismic technology took place on 22–24 January 2013 in Napa, California. It was the second of its kind, the first was held in April 2008 at Ucross, Wyoming, whose purpose was to bring together industry experts and capture the state of the art at the time. This year, the focus was on identifying and understanding the differences between data recorded at or near the Earth’s surface and data recorded in deep boreholes. To give the field the greatest possible impetus, attendants were selected based on their contribution potential with respect to the scope of the forum. From 160 applicants, a total of 74 attendees were selected out of which 27 presented orally and 8 presented posters. The forum’s scope was addressed over two busy days with sessions on case studies, feasibility studies, processing, uncertainties, and the road ahead. Two lunchtime presentations addressed subjects of wide interest not covered in these sessions. No proceedings were planned in order to encourage the sharing of otherwise confidential information.

Session 1: Fact finding
Julie Shemeta and Shawn Maxwell chaired the first session, in which examples of comparisons between surface and downhole monitoring were reviewed. The session also highlighted practical operational considerations and how the data is being used. Shawn Maxwell kicked off the forum with a look at a variety of microseismic monitoring programs with co-recorded surface and borehole data. The presentation culminated with an extensive microseismic monitoring program in the Fayetteville, with sensors extending from reservoir depth to the surface in one large borehole array, buried array stations and surface geophones. Maxwell’s findings included a discussion of minimum magnitudes that microseismic events must have in order to appear as visible signal in the data. Apart from the event strength, other factors such as event depth, attenuation, and transmission characteristics of the medium as well as acquisition design also influence the signal level recorded in raw records.

Kevin Smith reviewed his experience in the Haynesville play with shallowly buried and borehole arrays. Reservoir temperatures in this formation exceed the temperature limitations of typical borehole arrays. The borehole tools can be placed above the reservoir as to not exceed this limitation, but this puts the array in an unfavorable geometry for accurate event locations. One such buried array consists of 103 shallow monitor holes in a five-by-seven square-mile area, each monitor hole having a 3-level array with a total of twelve 10 Hz geophone elements. Smith reported comparable results for depth accuracy and for lateral and vertical extent of SRV from the microseismic event data from the surface and borehole arrays. These results were used to modify and optimize completion designs and to set boundaries for reservoir simulation parameters.

Rod Gertson discussed both surface and borehole microseismic results from the Arkoma Basin. He reported minimum detected magnitudes of -3.5 with borehole arrays and -2.5 with surface arrays (including signal processing and stacking) for a depth of 7800 ft. In co-recorded experiments, i.e. simultaneous recording with surface and downhole arrays, he found a reasonable match between event locations from both arrays. However, magnitude estimates for the same data set differed significantly between vendors.

Results of colocated surface and borehole arrays from Argentina were discussed by Xavier Payre. This project found the minimum detection magnitude of about -2 for surface and -2.5 for borehole microseismic monitoring. The overall goal for Total was to find a viable monitoring method that avoids the need for a monitor well, and they concluded that surface monitoring is a viable replacement for borehole monitoring. The importance of time synchronization...
between surface and borehole recording was also highlighted in this presentation.

Robin Pearson reviewed her employer’s extensive experience with surface and borehole microseismic. Pearson identified four key requirements for a successful program. First, recognize that this is a multidisciplinary effort involving the asset team, completions staff, technology groups, and microseismic contractor staff. Second, prepare a detailed project plan with clearly defined goals and plan to collect other data which will help understand the microseismic response. Third, perform careful quality control throughout the program, including validation of all support data and of the velocity model, and perform quality control of data processing. Fourth, interpret the results in the context of an integrated Earth model. She illustrated this approach with several examples where hydraulic fracturing was monitored with downhole and surface techniques and where results of the two methods can be compared. In the U.S. shale basins studied, both techniques succeeded in monitoring the well completions and showed similar overall microseismic trends in terms of lateral and vertical event distribution and event patterns in space and time. However, differences were noted between the two which are attributed to the different fields of view, acquisition geometries, and noise characteristics. Throughout all this analysis, integration with petrophysical, well completion, and production data proved to be a key step when interpreting the microseismic data in terms of the reservoir mechanical properties.

Sean Contenti, on behalf of Simona Costin, discussed the long history of passive seismic monitoring at the Cold Lake cyclic steam injection project in Canada. An extensive sensor network has been installed, approximately 100 borehole arrays with more than 2000 channels recording data continuously. From careful examination of the seismic records with proprietary software, they have identified characteristic events indicating casing failures, fluid movements, and heaving from reservoir dilation. This passive seismic monitoring system has become an integral part of casing integrity management and overburden monitoring during steam injection at its Cold Lake field.

During lunch, Norm Warpinski talked about verifying results from microseismic monitoring by physically inspecting the hydraulically created fractures. He showed examples from mineback experiments, the M-site, and drill cuttings injection, and explained that only a small fraction of the total injected energy appears in the form of seismic energy. He argued for ground truth experiments instead of debating how and why surface and downhole monitoring results differ. In general, he observed reasonable agreement between validation experiments and microseismic results.

The session included two posters, one from Brad Birkelo and another from Jason Hendrick.

Birkelo used a recent experiment in the Montney Shale in northeast British Columbia to show that fractures in the Upper Montney grew in the direction of maximal horizontal stress while fracture growth at this location in the Lower Montney was controlled by existing fractures, approximately oriented at 45° to the maximum horizontal stress and thus the fractures in the Upper Montney. The authors also found that the stimulated reservoir volume per stage estimated from events that occurred only during pumping time correlates well with the total amount of fluid pumped during that stage.

Hendrick described how attributes can be used when derived from a data set that was acquired from multiple observation wells. Significant progress has been made in attribute generation and analysis, including new methods of using the source mechanism information and attribute correlation. These methods are analyzed with hydraulic fracturing techniques and parameters to not only optimize deliverability, but also to estimate resource volumes and predict rock properties.

Session 2: Feasibility
Anca Rosca and Werner Heigl chaired the afternoon session of the first day, which covered topics that concerned the feasibility of microseismic monitoring surveys.

Rosca laid out a workflow for feasibility studies. She placed emphasis on using basic facts from seismology for obtaining an estimate of what to expect from a particular hydraulic fracture treatment. One example is the McGarr model that expresses the empirical fact that cumulative seismic moment is proportional to the injected volume of fluid. Because the planned volume of injected fluid is known ahead of time, one can estimate the expected magnitude distribution.

Taking into consideration source mechanisms is another example: consistent event detection and location and accurate magnitude estimation need a good sampling of the event’s focal sphere. Extensive modeling is used throughout her workflow to evaluate the potential of borehole and surface array designs to generate reliable results.

Ted Urbancic stressed the critical role of instrumentation in obtaining bandwidth with enough signal-to-noise for accurate and unbiased characterization of microseismic events. A wide-band sampling of seismicity is a necessity for determining source parameters such as magnitude (event size), source radius (fracture size), stress release, and others. To maximize the usable instrument bandwidth several aspects have to be considered. First, sensors need to be deployed properly so that ground motion is recorded with high fidelity. Poor coupling can lead both to spurious resonances and affect the transfer of useful spectral components, effectively limiting bandwidth and potentially impacting event characterization. Second, to maximize signal bandwidth, a heterogeneous network of motion sensors is preferable. It should cover a range of natural frequencies and particularly be able to record low frequencies. When such networks are employed, and the issues of sensor installation on bandwidth are well understood, an unbiased picture of the seismicity emerges. In one example from a hydraulic fracture treatment, a heterogeneous network consisting of low-frequency geophones and force-balanced accelerometers was able to accurately characterize events up to M3. It was argued that this result clearly demonstrated the need for such instrumentation to help add value from microseismic monitoring as...
accurate estimates of the size scales of fractures are important inputs to for reservoir modeling and to the due diligence aspects of seismic hazard monitoring.

Alex Goertz presented a method to forward-model the event detectability for different microseismic array configurations. Effects such as intrinsic attenuation, probabilistic description of ambient seismic noise, and the instrument noise characteristics are taken into account. The talk highlighted the importance of bandwidth on the event detectability. For a typical shale gas example, surface, buried, and downhole array configurations were compared with respect to their detection thresholds. Assuming a specific frequency-magnitude relation, the overall number of detected events can be estimated and compared for different array configurations. The modeling methodology is useful for the early identification of detectability pitfalls and could be utilized for the optimization of particular array configurations.

Julian Drew and his coauthors carried out a number of surveys with simultaneously surface, near-surface, and downhole arrays. They have observed a different noise environment in each case. In one experiment, they could track the signal from depth to surface and validate the geophysical model. As the signal arrives at the near surface, below 50 Hz the shear energy is stronger than compressional. In some areas, the noise environment at surface and near-surface can be surprisingly quiet; the intrinsic sensor and instrument noise (or sensitivity) is then a limitation in detecting signals. Array design is another way of improving signal detection. In addition to sensor technology, the authors also evaluated 2D patch arrays as a alternative to a grid-based geometry. The authors presented novel nonlinear stacking techniques, including a phase-squared technique as an alternative method to handling the signal polarity in the imaging condition.

Gregg Hofland reported on the results of field tests in the Bakken and at RMOTC. In the Bakken, they tested surface recording and found, not surprisingly, that a low signal-to-noise ratio yields biased event parameters (using a diffraction stack-based location method). At RMOTC, data were recorded with surface and buried arrays. Good results were obtained during a controlled source experiment with its high-sensitivity SM-64 geophone buried at 100 m compared to noisy surface recordings, similar to the Bakken data set. It was found that perforation shots have a moment magnitude of -1.7 to -1.5 while string shots have a magnitude of -2.2.

Ben Witten investigated the variation of signal-to-noise in the near surface. Available data confirmed the theoretically predicted signal amplification as the signal approaches the Earth's surface from below. This amplification decreases with increasing incidence angle and is stronger for S-waves than for P-waves. However, in an area with a low-velocity near surface (e.g., poorly consolidated sediments), he observed no significant increase in signal-to-noise ratio with depth. The field example S/N analysis of borehole data shows, similarly to Drew's findings, that sensor coupling affects both data and noise amplitude levels.

Doug Crice and Vladimir Grechka presented posters for this session. Crice analyzed the unique challenges that microseismic monitoring presents to designing a recording system that allows real-time delivery of data analysis to the completions engineer. He showed how technology developed in other industries can help overcome these challenges and laid out the building blocks of a feasible system.

Grechka discussed building an anisotropic velocity model from traveltime and polarization information provided by microseismic events simultaneously with locating events in that model. He showed on ray-traced synthetic that full-aperture data, typical in downhole surveys, can constrain interval stiffness coefficients of layered triclinic velocity models. However, an interplay of vertical velocity heterogeneity and azimuthal anisotropy might bias the estimates of event azimuths from the P-wave particle motions. In such a case, it is advisable to locate events solely from traveltime observations in two or more wells to avoid the polarization-related biases.

**Session 3: Processing**

Michael Thornton and Ulrich Zimmer began the second day of the forum with a session on processing.

Henry Bland discussed factors that influence the determination of the orientation of downhole geophones such as dipping layers and anisotropy. He proposed to use orientation-shots arranged in a cross-pattern to detect and correct for such factors. A case study showed that a low-cost jumping-jack soil compactor could be used to successfully calibrate a downhole array positioned 2600 m below the Earth's surface. Source locations were positioned at an offset equal to the sensor depth. A processing flow was illustrated which uses a source reference-trace to create a 400-fold stack that is suitable for orientation-analysis.

Brad Artman argued that advances in seismology should be used in exploration geophysics in general and in microseismic monitoring in particular. He emphasized modeling before acquisition, using the ray parameter curve as a measure of information content as well as appropriate aperture and constant station density. The array design should take into account aliasing and minimizing the acquisition geometry footprint. Both low and high frequencies are necessary to fully characterize an event. He also tried to disperse concerns about computationally costly algorithms as computing power (CPU and memory) is cheap and available in nearly infinite amounts.

Kit Chambers (Pinnacle) reported on progress in the development of moment tensor imaging. He highlighted that standard source imaging procedures result in an image of the source radiation pattern, which is null at the hypocenter. This is due to the fact that exactly at the origin time there is no displacement and it is therefore difficult to identify the hypocenter. He proposed to image stress instead of displacement because at the origin time there is maximum stress concentration at the hypocenter. The obtained images are images of the individual moment tensor components, and the method allows the use of multiple phases in the imaging process.

Dave Diller proposed a hybrid approach to microseismic monitoring, i.e. the simultaneous recording with surface and downhole sensors. However, GPS timing synchronization
is prone to error and need to be checked and corrected for. A patch layout reduces the total number of surface sensors needed and helps reducing the acquisition cost. He shared his experience that nonrandom patterns in the static solution are indicative of errors in the velocity model. To locate events accurately, one needs to incorporate anisotropy (at least VTI + HTI) and surface consistent statics. He also stated that more receivers don’t necessarily increase the value of results, and suggested that a sufficient number of receivers is of the order of 10^6.

Ilya Dricker explained that the general presence of correlated noise in surface microseismic data violates the assumptions inherent in location techniques that are based on seismic emission tomography. He showed that statistically optimal and adaptive algorithms are by design robust against correlated noise and their use dramatically reduces location errors. He showed tests on synthetic data and said that tests on real data are in progress.

Dennise Templeton described an empirical matched-field processing technique. It compares incoming seismicity with master events and detects more low-magnitude events than the standard STA/LTA detector. An in-house developed probabilistic event location method was tested on microseismic data from the Salton Sea geothermal field. Due in part to an instrument-constrained sample rate of 100 samples per second, the data set suffered from somewhat larger phase pick uncertainties, which were calculated to be approximately 60 ms for the P-wave and 90 ms for the S-wave. This resulted in epicenter errors of approximately 160 m and depth errors around 300 m.

Over lunch, Stewart Levin updated the audience on SEG’s efforts to modernize its SEG-Y standard in order to address various and improve its flexibility, including accommodating the needs of microseismic data types.

The session included posters from Jakob Haldorsen, David Harris, and David Einspigel. Haldorsen observed that for a point in the medium to be a viable event location the P- and S-wave fields at that point should have similar shape and be simultaneous at the origin time. Based on this imaging condition, he developed a full waveform 3D vector wavefield migration that maximizes the zero-phase bandwidth while minimizing the noise. The method is fully automatic and does not require the picking of P and S phases.

On behalf of David Harris, Templeton showed how a model-based matched-field-processing technique could be adapted to microseismic event detection and automatic focal mechanism determination in an elastic medium with no prior seismicity to act as a master event. Tomography is proposed for refining the velocity model prior to generating a library of Green’s functions that could then be used for microseismic event imaging, potentially in real time.

Einspigel tested the possibility of jointly locating events with surface and downhole data using an anisotropic velocity model. He first uses arrival times of P- and S-waves to jointly determine the hypocenter and origin times from each data set. He then tries to find an anisotropic velocity model that minimizes the difference in origin times computed from downhole and surface data. This was done by manually adjusting the coefficients of anisotropy.

Session 4: Uncertainty

The afternoon session of the second day, chaired by Ulrich Zimmer and Michael Thornton, was about the uncertainties in microseismic event locations.

Zimmer and Stephen Wilson presented a possible framework for calculating standardized and meaningful measures of event location uncertainties.

Wilson encouraged the operators and vendors in part one of the presentation to come to an agreement on definitions of precision and accuracy and to create benchmark data sets to enable this. He also stressed the importance of using more realistic estimates of location error that contain separate metrics for accuracy and precision. He reminded everyone of the difference between the two concepts, where (1) accuracy defines the bias that affects a group of events in a similar way, whereas (2) precision is a statistical measure tied to a specific event location estimate and therefore affects different events in different ways. If traveltimes can be accurately calibrated and inaccuracy reduced to a small amount, event location error can then be effectively represented as a precision-based metric using confidence intervals and probability distributions.

In part two, Zimmer reviewed the basic concepts for evaluating uncertainty in a Bayesian framework and discussed the problem of evaluating PDFs for quantities defined by complex functions of multiple parameters.

Michael Prange showed that interferometry and the double-difference method can be derived from the same probabilistic formulation. Interferometry is robust over velocity errors while the double-difference method has good precision but is not unbiased. Prange proposed a hybrid algorithm that combines the best features of the interferometry and double-difference methods in order to achieve even smaller location uncertainty.

Michael Thornton presented a poster about velocity and positional uncertainties in surface and downhole monitoring. He uses the maximum likelihood framework to show that during calibration the surface method has less velocity and origin time uncertainty than the downhole method, mostly due to larger aperture and higher fold. He also showed that the use of surface arrays result in smaller positional uncertainties in the horizontal plane but larger uncertainties in the vertical direction.

Session 5: Road ahead

Heigl led the attendees through the last session of the forum, which covered recent trends in the developing field of micro-
seismic.

Anton Reshentnikov showed results from his attempt to use micro-earthquakes as sources for imaging reflectors within the treated reservoir. The data is sorted into common receiver gathers for events from the same cluster, and only events above a certain amplitude threshold are used. A directional prestack depth migration is then applied to these gathers, taking care of event polarity such that a possible amplitude cancellation at the image point is avoided. The technique was applied to data from the Basel geothermal experiment; imaged reflectors correlate well with faults and fractures observed in borehole images. The author is currently working on imaging events from hydraulic fracture treatments of hydrocarbon reservoirs.

Estelle Rebel laid out her company’s design and workflow for acquiring and processing microseismic data obtained with a set of patches of motion sensors. Patches typically consist of about 100 sensors spread over a 150 x 150-m area, and individual patches are about 1 km apart. Twenty to thirty patches are deployed for a typical job. Data is processed by slant stacking on each patch. The example shown compares shallow buried array, broadband sensor, and patch acquisition results. The noise decrease for the patch stack is about 26 dB and the patch design provides the best S/N among the options tested.

Jared Peacock gave the field of microseismic monitoring a different twist, using magnetotellurics to monitor hydraulic fracturing. Basic idea is that changes in the Earth’s magnetic field, caused by interaction with solar wind, induces currents in the Earth, particularly in the fluid-filled crust and its sedimentary cover. Conductive bodies such a fractured and fluid-rich geothermal reservoirs change the flow patterns of these currents. These changes manifest themselves in the magnetic and electric field, which can be measured and the data inverted. The method is currently limited to the resolution of the top of a conductive body but extension to the shape and extent of such bodies is in the works. Time-lapse magnetotelluric data was used together with microseismic data for monitoring of an enhanced geothermal hydraulic stimulation.

**Concluding remarks**

Heigl concluded the forum with a summary of trends and outstanding issues he observed during the two days of presentations, posters, and discussions. In general, there is an increasing acceptance among operators of the surface-monitoring method as well as an increasing in-house expertise, which has led to more stringent quality control and the need for appropriate software. The industry is becoming aware of the important role that radiation patterns of microseismic events play in the estimation of source parameters. The characterization of microseismic events thus requires the recording of data with appropriate sensors, particularly those that have good performance at low frequencies. The blind use of the ubiquitous 10-Hz or 15-Hz geophone, commonly used in surface seismic, almost certainly leads to artifacts and biases in microseismic-monitoring results, at least for surface and near-surface data.

It was also recognized that much of the noise that contaminates microseismic data is not random but correlated and sometimes coherent. Therefore, the semblance statistic is not the most appropriate statistic to use, and some authors suggested using nonlinear stacking techniques and statistically optimal algorithms, which generally do a much better job in suppressing coherent noise.

Velocity models pose the biggest challenge in the quest for extracting accurate information from microseismic data. Extensive discussions were focused on the important topic of accurate velocity models. Particularly, the joint monitoring with surface and downhole sensors requires a model that accounts for horizontal as well as vertical P- and S-wave velocities. Depending on reservoir complexity this may in the worst case be a model consisting of layers with intrinsic triclinic anisotropy.

It is presently not clear how to handle the different frequency content of surface and downhole data and how to account for inelastic attenuation. In general, the reservoir needs to be described at smaller scales and, because surface seismic does not provide the necessary resolution, the information needed for building better velocity models has to come from the same microseismic data.

Several issues were identified that need further research. Practitioners in the field would like to deploy an optimal sensor network but what exactly constitutes an optimal sensors network is a difficult question to answer. Some argue in favor of a regular grid because it provides the most uniform array response and facilitates the use of processing techniques from surface seismic. Others responded that a regular grid requires too many sensors and that a random layout of a smaller number of sensors should give similar results because one does not know a priori where microseismic events will occur. A lot will depend on how much noise contaminates the data and how events are located. It would be desirable, from an operator’s point of view, that the reporting of location errors be standardized to allow the fair comparison of processing results from different vendors. Confidence intervals seem to be the most appropriate choice for this. However, implementing such a standardization appears to be difficult at present.

The fact that only a small fraction of the total energy injected through the pumped fluid appears in the form of seismic energy points to other phenomena happening in the reservoir during a hydraulic fracture treatment. Recording with low-frequency sensors revealed that some kind of rumbling occurs in the reservoir during treatment that is much longer in duration than microseismic events.

Several participants expressed the need for a benchmark data set against which algorithms can be tested. 

**Corresponding author:** Werner.Heigl@apachecorp.com