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GEOCHEMICAL MUD LOGGING OF GEOTHERMAL DRILLING

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ABSTRACT

The experience and results described in the present paper were developed over nearly two decades, with a major R&D project around 1980.

The expression Geochemical Mud Logging (GML) has ill defined meaning in the geothermal industry, and ought to be specified. We refer here to GML as featuring mud and formation fluid tracer(s) and temperature as the bare essentials and with specified accuracies. Air and water logging are expected to be less demanding with regard to analysis accuracy, but are not discussed in this report.

During application of GML to several drill holes with low formation permeabilities and under conditions of high temperature and high mud weight, GML as specified, revealed unexpected influx of formation brine. Such influx was a recurring feature that has been referenced to individual fractures and reflects both fracture size and permeability. As a consequence, continuous or subcontinuous sampling of mud systems appears more cost effective than trying to keep up with cumulative changes of bulk mud composition; although, the latter approach is more sensitive to extremely low rate, steady, inflow of formation fluid into the mud system. It appears, that based on this influx of formation fluid, permeability can be estimated well before mud losses are detected and/or drill strings are stuck.

The main advantages of GML are: (1) the capability to assess formation temperature and permeability in nearly real time, resulting in (a) assessments of undisturbed formation and (b) having data in hand for holes lost during drilling operations and (2) being effective under conditions of very high temperatures where electcrical logs are very costly and less reliable.

Estimated cost for GML is $1500 per day (1982) based on assessments of R&D operations. However, extrapolating to larger scale services and to different operating conditions is indeed difficult. GML cost is probably the only significant point of controversy with regard to GML being a viable evaluation tool.

INTRODUCTION

The experience with geothermal logging outlined in this report began to build up in occasional observations in the Geysers area in the mid to late 1960's; limited geochemical logging of some drill holes followed on Basin and Range projects in the mid 1970's; a full scale project was developed during exploration geothermal drilling in the Campi Flegrei, Italy, in the late 1970's to early 1980's, with some parallel application going on in California exploration drilling marginal to the Geysers area.

The project in the Campi Flegrei was partly mud logging services, and to a major extent, research and development of new techniques. In respect to the latter, the senior author as the consultant, and the involved service and consulting company, Aquater (a ENI company) were on equal footing.

The present report furnishes an outline of: (1) definitional specifications of the developed Geochemical Mud Logging (GML) method; (2) facts established throughout the early applications outlined above; (3) techniques that were used; and (4) points that became the subject of scientific and technical controversy among the involved professionals.

A formal presentation and discussion of the GML topic took place for the first time in 1985, at a workshop held in Tirrenia, near Pisa, Italy. It was presented as part of discussions regarding means to detect and assess permeability based on data other than well testing. The workshop was set up by ENEL, and the Proceedings (available in Italian from ENEL) give a very extensive report based on tape records of discussions. The procedure and results have also been briefly outlined in lectures by Tonani, given in Strassburg, Germany in 1980.

BACKGROUND

2.1 Defining terms

Geochemical logging can be any of a great variety of procedures. Contrary to geochemical mud logging in the petroleum industry, where a well established tradition makes this a fairly specific term, such terms as geochemical logging (GL) and geochemical mud logging (GML) have hardly any specific meaning with reference to geothermal drilling. Of course, GL of air drilling (GAL), water drilling (GWL) and so forth, are entirely different from each other and from GML in specific application and techniques. Here, we shall concentrate on GML which constitutes the bulk of our work in this area.

To begin with, not any chemical monitoring of drilling air, water, or mud is to be considered a Geochemical Logging technique. Referring to chemical monitoring for, e.g., environmental purposes, the use of the term (GL) would be misleading. We shall reserve the term Geochemical Logging (GL) when referring to chemical logging aimed at gathering information on the properties of, and conditions prevailing in, the formation being being drilled through. Moreover, we shall do it with reference to properties and conditions relevant to formation and reservoir evaluation; in our case, it shall relate specifically to geothermal exploration and development drilling aimed at formation and reservoir evaluation. Requirements, hence specifications, resulting from these circumstances shall define such terms as Geochemical Logging, GML and related terminology.

Whereas specifics will be reported in the following sections, one consequence of this report is aptly stated here: As long as consistant GML terms and methods are not established, such statements as, "GML is, or is not, effective." will be meaningless. This is of considerable consequence in regard to the commercial contracting of GML services and also has been a center of controversy in discussing even the technical success of GML.

For our GML analysis, "tracer" refers to a substance, usually a mobile one, whose concentration relates to a process; in the present case, a mixing process.

In our context, "mobility of" or "mobile" refer to the ability of the considered chemical substance (tracer) to move around some specified physical setting. It is empirically related to the chemcial ability of the considered species to concentrate in a physically mobile phase, such as in the present connection, the filterable waters of drilling muds.

2.2. Defining the specific GML method referenced in this report

GML as investigated and implemented in experimental work referred to in the introduction is defined by the following specifications. These specifications are both of a general nature and in practice may become site and project specific.

General specifications are: (1) recording temperature to within 0.1° C; (2) determining at least one mud tracer substance to within a few 0.1 percent precision; (3) determining at least one of the nonvolatile and mobile formation fluid tracers (chloride) within a few percent precision; (4) taking samples at a rate in excess of one sample every fifteenth minute.

Project specific downgrading of general specifications can be used to scale down cost as dictated by information objectives of the individual drilling projects. Site and project specific tracers must be selected according to the chemistries of the drilling target (expected formation target and formation fluids) and the drilling mud system. Specifications must be carefully tailored to the known geochemistry of the target geothermal system.

Although effective GML can be carried on with the general specification of one sample per fifteen minutes or more, recommended frequency based on presently obtain results should be increased to sampling at five minute intervals. Actual specifications for the most significant experimental work to date as reported in the referenced ENEL proceedings are listed in the next section.

OUTLINE OF PROCEDURES AND RESULTS OF GML EXPERIMENT

3.1 Procedures

Temperature. Temperature was continuously recorded to within 1° C as is usual in mud logging practice. Although this limited the quality of the results and decreased the number of cases where results were actually attainable, it did not prevent the demonstration that GML methods can estimate formation fluid enthalpy during drilling. Measurement of temperature to within 0.1 C is recommended since it is operationally feasible and hence, it is definitional in respect to the considered general GML procedure.

Frequency of sampling. Discrete sampling intervals were deemed appropriate for experimental work. Four samples per hour were used as a compromise sampling interval. This still required pumping mud samples continuously to the drill-site laboratory for efficient operations. The significance of selecting the sampling interval follows from the consideration, that the mixing of downhole drilling mud with formation fluids controls the minimum volumetric width of point like events (tracer anomolous spikes) in the mud circulation system. At mud circulation rates prevailing during these experiments (1.0 to 1.5 m^3/min), the corresponding time width of instant events resulting from formation fluid influx to the mud system was measured at approximately five minutes; e.g.; it entails a maximum frequency of sampling on the order of one sample per five minutes for detection of these instantaneous events.

Continuous sampling is recommended in principle, but is obviously not feasible, nor is as high a sampling frequency as one sample per five minutes practical with discrete sampling. Thus, sampling is not yet definitional on a practical general basis as applied to GML, in contrast to, for example, reading temperature to within 0.1° C.

Mud tracer. Nitrite ion was used as a mud tracer for the purposes of measuring formation water inflow based on mud dilution. A combination of monitoring nitrite and controlling its concentration in mud was used: nitrite would be determined in input mud, and some would be aptly added to the mud mixing system whenever appropriate.

Formation fluid tracer. Chloride was used throughout these studies to trace brine inflow into the drilling mud system. Chloride monitoring is easier and more sensitive than the use of nitrite as the mud tracer, however, to use chloride as a formation fluid tracer requires previous knowlege of brine composition (chloride concentration). In principle, by using GML procedures, an evaluation of the behavior of both mud tracer and formation fluid tracer should allow determination of the brine chemistry.

3.2 Obtained results

Observed facts. The rate of change of mud composition resulting from drilling mud-formation fluid exchange can, at times, be directly observed as the difference in composition of output and input mud in the circulating mud system. However, only comparatively high rates of exchange or mixing can in fact be determined by directly comparing output and input mud composition. Instead, monitoring the cumulative change of bulk mud composition utilizing longer time intervals in the system analysis, results in increasing sensitivity for detection of formation fluids. However, the trade off, is that as longer time intervals are considered in the analysis, there are larger errors resulting from mud processing operations and the consequential adjustments to the mud system.

Correcting for mud processing operations has proved difficult and depends on many factors. It is costly, in as much as it required much professional time under the conditions prevailing in the presently reported central project of consideration. Measuring steady and very low rate changes was, however, accomplished and it led to an accurate material balance sheet of bulk mud. This result was of limited direct use, however, it did provide the ground work for detecting short term input-output variations.

Transients of higher rate of change in mud composition were also observed; detecting and measuring them required increasing the frequency of sampling. Broad peaks lasting on the order of one hour as well as peaks that might be as brief as five minutes or less in duration were observed regularly. The latter features appear as individual anomalous samples in a series of samples 15 minutes or more apart. Their significance depends on how accurately the composition of the bulk mud system has been determined.

The occurrence of high amplitude peaks of mud compositional change is a persistant feature and could be definitely proved to exist. These peaks demonstrate that an influx of formation fluids does occur. This was an unexpected result based on the previously prevailing opinion regarding mud behavior and the formation of mud cake in drill holes using balanced mud systems.

By and large, rapid (spike) changes are easier to measure in many respects. Providing the baseline mud composition that is then required to detect these spikes has proved a great deal easier than monitoring the effect of mud processing and adjustment operations on absolute mud composition.

Inferred processes. Some inferences regarding the process responsible for the observed changes could be made based upon information collected during GML of several production drill holes in the Campi Flegrei. Steady, low rate, change in mud composition brought about by incorporation of formation fluids in the drill mud system as the country rock was ground by the drill bit was observed. The fairly accurate material balance sheet that was obtained in this monitoring formed the basis for further observations.

Individual anomalous change of output mud composition relative to input mud has been interpreted as the effect of short duration events lasting less than the time interval betwen discrete samples. Many of these peaks are so large amplitude compared to the admissible size of voids produced by the penetration of the drill bit (based on hole size and drill rate records), that some influx of information fluid had to be assumed in as much as these anomalies would result in estimated porosities in excess of 100%. A number of cases where such calculation was feasible indicated that formation water invades the wellbore from fractures and that this inflow must be in excess of at least several wellbore radii of influence. It seems only reasonable that the volume of each formation water influx be related to permeability.

Other, broader peaks seem referrable to washouts of the bore wall. The association of these broad peaks with compositional changes attributed to ion exchange in the mobile phase tracers was taken as evidence supporting such interpretation.

Correlation of Temperature with Chemical Change. In some cases the observed chemical peaks were accompanied by a concurrent observation of a temperature anomaly in the return mud system. These temperature anomalies were detected not withstanding the previously discussed generally below specification sensitivity of the temperature measurements. When such temperature anomalies were detected, an estimate of the enthalpy of the formation fluid influx couild also be made. Namely, the formation temperature at several points during the drilling of the San Vito #1 well were estimated. A bottomhole temperature of about 400° C and a constant temperature gradient could be inferred from GML.

SAMPLING, SAMPLE PROCESSING, AND CHEMICAL ANALYSIS TECHNIQUES USED IN EXPERIMENTAL GML

4.1 Sampling

Mud outlet samples were taken just downstream of the shaker screen and mud inlet samples were taken downstream of the mud pumps. At early stages, sample collection was essentially manual, however at later stages in the drilling, the mud samples were pumped directly to the drill-site laboratory, resulting in increased efficiency of the GML operations.

4.2 Sample processing

Throughout most of the project, plain mud filtrates were analyzed and obtained results refer to filtrate, i.e., mobile phase composition. The expression "mud composition" is used, but as discussed earlier is not definitionally quite exact.

One of the research teams involved in this experimental GML used acidified mud samples which is expedient to efficient mud filtration. The obtained filtrate obviously does not represent the mobile phase in the actual drilling mud system; as a consequence, although the technique may well work and deserved testing, it cannot be taken for granted without adequate further study. The negative results reported from this type of sample processing is not conclusive, in that the followed GML procedure did not meet the same specifications reported in this paper in section 2.2 under GML specifications. Necessary information on bulk mud composition for interpreting widely spaced samples was missing. Techniques of broadly similar approach deserve further, but adequate study.

4.3 Chemical analyses

A large variety of components were tested as candidates for GML. Metal ions were determined by flame emission and atomic absorption ; anions were mostly determined by automatic colorimetry (Auto-Analyzer); chloride was determined by back-titration following a variant of the Volhard method.

Experimental work with ion specific electrodes was carried out with regard to chloride and sulphide; the former technique revealed itself to be satisfactory, and does indeed work best with untreated mud. It was developed at a late stage in the program, in preparation for continuous monitoring, and was never applied extensively. Sulphide ion determinations were abandoned after preliminary tests pointed out the lack of mobility of sulphide in the drilling mud.

The same group of scientists that carried out work with acid treated samples used ICP to determine a large array of metal ions. Although, in general, metals are less mobile than anions, they did deserve attention; however, the same comments as give in Section 4.2 above apply.

DISCUSSION AND CONTROVERSY

Thus far, according to our understanding of the viewpoints that have been expressed either formally or informally, the only meaningful controversy regards whether or not full scale GML as defined in the present report is cost-effective. There is no simple answer to such a question, as (1) there is no simple way to extrapolate from the present research and development efforts to a service company cost basis, and (2) there is no simple way to determine the potential value or worth of the information that is obtained from the cost of GML.

Some guess can be made based on the main project referred to in the present report, inasmuch as this work consisted of actually logging exploratory drilling in the then new area of Mofete (Campi Flegrei, Italy). Discussion can hardly be conclusive, however, as further controversy remains on the future of prospects in that area. Pending definitive verification of subsurface conditions in this area where our work was concentrated, the following can be concluded. The results of GML demonstrate that it can deliver decisive data regarding formation permeability (or at least its relative distribution) and temperature; that permeability information complements in essential ways the lost circulation data that usually go with commercial potential of a production well. The specific project area is likely to furnish an exemplary pattern in this respect; however, the project could not be fully developed as yet, hence it cannot be discussed in full in this report.

The main argument in favor of discontinuing the GML project was its cost. Those costs, however, were the unadjusted cost to the Research and Development project; moreover, it does not take an accountant to realize that transactions between closely related companies such as were involved in that project are hardly representative of conditions in the marketplace.

Some cost estimates were attempted based on analysis of the procedure, and on costs of partial services, personnel and so forth. This resulted in some $1500/day (1982 $) for full scale GML as defined. Such a cost compares well with similar services such as traditional mud logging and electrical logging and in our opinion, the obtained results are worth the costs.

The consideration is, that no other method gives comparable assessment of permeability, let alone in nearly real drilling time, and results reflect the undisturbed formation. A similar assessment applies to formation temperatures. In addition to such essential information, GML potentially results in a fallout of other useful information (such as fluid losses and changes of fluid chemistry with depth). An expansion on this fallout data is beyond the scope of this report, and perhaps would distort the basic contentions that GML is an effective stand alone tool within the specifications already discussed.

The fact that GML information remains available for lost drill holes and/or sections of drill holes and the entailed saving of redrilling costs, also contributes considerably to the worth of GML as defined in this report, especially, in connection with wildcats and early exploratory wells.

The above arguements are not meant to question any company's specific decisions regarding GML, as these decisions are also project specific, and possibly depend on subjective risk assessment. What is a meaningful subject of controversy is the assessment of GML's cost effectiveness as referenced to averaged conditions in the geothermal industry. The arguments presented above have, in the present case study, resulted in confusing specific company policies with general exploration strategies. Defending or refuting management decisions in this project is not an issue, (it may even lead to incorrect scientific conclusions). Such a conclusion was the case when the failure of GML was reported for the Mofete project; but, the fact that the GML program did not meet the minimum specifications as outlined above was not mentioned in the operators assessment of the GML method.