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ANALYSIS OF SMECTITE CLAYS IN GEOTHERMAL DRILL CUTTINGS BY THE METHYLENE BLUE METHOD: FOR WELL SITE GEOTHERMOMETRY AND RESISTIVITY SOUNDING CORRELATION

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ABSTRACT

The simple, quick and inexpensive methylene-blue (MeB) dye technique long used in drilling mud analyses has been adapted to provide estimates of smectite clay content in geothermal well cuttings. Case histories from Unocal's Namora-I-Langit and Awibengkok geothermal fields in Indonesia illustrate applications of this new method to geothermal exploration and development. MeB smectite measurements can be used to constrain subsurface temperatures since smectite is unstable at temperatures over 70ºC and mixed layer smectite-illite typically becomes undetectable in porous rocks at temperatures over 200ºC. Therefore, many well casing decisions that depend on formation temperatures can be supported by well-site MeB estimates. Well-site smectite detection at formation temperatures over 200ºC can also help characterize the unstable dehydrated smectite zones that are common drilling hazards in volcanic geothermal reservoirs. Since resistivity patterns are largely controlled by the smectite distribution over and adjacent to geothermal reservoirs, MeB results can facilitate revisions of conceptual models and well targeting plans that were based on resistivity surveys. The semi-quantitative MeB smectite estimation method is applicable to both geothermal well-site geology and detailed analysis of hydrothermal alteration patterns that may be missed by the coarser sampling of well cuttings typical of more precise and expensive approaches. Since it can be carried out by the wellsite geologist during drilling, it offers immediate (real time) information regarding potential drilling hazards, mineral geothermometer temperatures, and (at least locally) changes in permeability.

1. INTRODUCTION

Smectite and smectite-illite clays are the predominant rock alteration products that form in the 50 to 200C zone over and adjacent to most high temperature volcanic-hosted, neutral pH geothermal systems (Browne, 1978). This smectite clay "cap" is an active component of the geothermal hydrology, often partially sealing the reservoir top and sides and creating perched aquifers in vadose zones that overlie high elevation geothermal reservoirs. Clay alteration within the reservoir itself is the more indurated chlorite and illite.

Geothermal alteration assemblages including smectite or mixed-layer illite-smectite are typically found at temperatures below about 200C. Jennings and Thompson (1986) and Harvey and Browne (1991) demonstrated that, in geothermal environments, pure smectite is stable only up to about 70C if there is complete water-rock interaction and an adequate supply of ions. However, incomplete water rock interaction reflecting low permeability away from fluid pathways often results in the presence of smectites in the rock matrix up to about 150C. At higher temperatures mixed-layer illite-smectite (I/S) clays with variable proportions of illite and smectite are found. These clays have increasing proportions of illite and greater order to their crystal structures with increasing temperatures. The transition to pure illite typically is observed at around 200-240C. It is common to have both illite and highly ordered I/S clays present at around 200^{o}C and, in low permeability rocks where water-rock interaction is incomplete, such I/S structures may persist over 200^{o}C. This association of clay type with temperature suggests that if smectite could be easily detected it could provide a mineral geothermometer with a lower temperature range than epidote which is usually easily detected at temperatures above about 240C.

Because of the very high cation exchange capacity of smectite and mixed layer illite-smectite clays, rocks containing them have very low electrical resistivity. Geothermal exploration programs exploit this characteristic in order to estimate resource size and target wells using magnetotelluric (MT), time-domain electromagnetic (TDEM), and other resistivity sounding methods. These geophysical methods are routinely used to map the 1 to 10 ohm-m smectite clay alteration cap that develops over and adjacent to most 5 to 100 ohm-m geothermal reservoirs.

In many of the Indonesian geothermal fields investigated by the authors, thin zones of impermeable, dehydrated, fine-grained tuffs and paleosols containing a large proportion of smectite clay are routinely found within geothermal reservoirs at temperatures ranging from 200 to 350C. Smectite in such conditions is inert but, when disturbed by drilling, rock containing it becomes physically unstable.

These basic observations imply a more or less direct application of smectite measurements in well cuttings to geothermal conceptual modeling and well targeting. If smectite measurements were available while drilling or soon after, the validity of the resistivity interpretation could be reviewed and further drilling plans adjusted. For example, this could be used to sort out as early as possible the ambiguity in a resistivity interpretation where a geothermal clay cap overlaps unrelated low resistivity basin sediments.

Some applications require that the smectite be measured in the cuttings as the well is drilled. For instance, only a near-real-time detection of reservoir smectite would have much value in characterizing a drilling problem like a stuck bit. In exploration drilling, deciding when to set well casings would have similar urgency. The shallow casings in geothermal wells must contain any shallow, high-temperature fluids and prevent them from leaking to the surface. The deeper production casing is not only designed to prevent such leaks but also to prevent water cooler than the production design temperature from entering the borehole. The temperature sensitivity of smectite can constrain both casing points, providing that the measurements are available while drilling.

Previous quantitative characterizations of the distribution of clays in geothermal reservoirs primarily relied on mud logs, x-ray diffraction (XRD) and thin-section petrography. For example, comparison plots of smectite clay in well cuttings and MT resistivity that Unocal has routinely prepared since 1983, have typically been completed a month or longer after the well was completed. These plots were usually based on coarsely spaced XRD analyses designed to generally categorize alteration types supported by very rough mud log estimates of total clay fraction in unwashed cuttings. Although it was recognized that better and more timely analyses of alteration might add value, no practical, cost-effective solution was found until 1994.

In 1994 while preparing for exploration drilling in the Sarulla Contract Area of North Sumatra, Unocal conducted a search for methods that could be used at a remote drilling location to improve mineral geothermometry and validate resistivity interpretations while drilling. Various approaches were considered, including on-site XRD and several well logging techniques. After a preliminary review, a combination of on-site petrography and analysis of rock cuttings by the methylene-blue method was pursued. One of the authors (Harvey) was contracted to develop the MeB procedure and use public materials from New Zealand geothermal fields to validate a quantitative analysis for geothermal cuttings (Table 1). The resulting technique was successfully used by Unocal during the 1994-1998 Sarulla exploration drilling program in which three new geothermal fields were discovered (Gunderson et al., 2000).

The success of this application in Sarulla led to a new project applying the MeB method to stored cuttings from wells from the 330 MW Awibengkok geothermal field. This analysis led to a better appreciation of the detailed correlation of the distribution of smectite alteration with high resolution TDEM resistivity data and the more averaged and general MT data.

The simplicity, speed, low cost and effectiveness of the MeB method of measuring smectite clay in geothermal cuttings led to its adoption as a routine measurement in Unocal exploration drilling. A brief review of the MeB analytical method is presented to validate the technique and calibration. Case histories of its application in the newly discovered Namora-I-Langit field in Sarulla, North Sumatra and the developed 330 MW Awibengkok field in West Java, Indonesia illustrate the potential value of this method in geothermal exploration and development.

2. CUTTINGS ANALYSIS BY MeB METHOD

Methylene Blue is an organic dye that shows high selectivity for adsorption by smectite clays. The dye also is adsorbed by the smectite component of mixed-layer clays, but is largely unaffected by other (even electrically conductive) common clay minerals (Table 1). This selectivity permits it to be used to estimate on a semi-quantitative basis the amount of smectite present in alteration mineral assemblages. The technique is rapid, requires very little sample and can readily be carried out by the rig geologist under relatively unsophisticated field conditions.

Because of the minor response to MeB by other clay minerals and possibly other high cation exchange minerals such as zeolites, a detection limit of 1.5 mlsMeB/g of clay has been adopted. This limit has not been rigorously tested against all minerals but appears appropriate and suitable for the fields investigated here.

Typical cation exchange capacities of commonly occurring alteration mineral assemblages in hydrothermal systems are listed in Table 1.

Table 1: Typical exchange capacities of selected minerals.

Alteration Mineral	Cation Exchange Capacity (meq/100g)	Sensitivity to MeB
Smectite	80-150	V. High
Mixed-layer illite/smectite	10-150	High
Illite	10-40	Minor
Kaolinite	2-13	Minor
Chlorite	10-40	Minor
Zeolites	200-400	Minor
Vermiculite	100-150	Minor

Reference: Grim (1953),

The formula and structure for MeB are discussed in Huang and Brindley (1970). The molecule has the ability to fit in the interlayer site of expandable smectite clays, with a very high selectivity for smectite clays only. For example, Marguiles et al. (1988) reported that MeB had a binding coefficient of 10^8 in smectite clay as compared to a value of 10^0 for Na^+.

The use of MeB solutions for the determination of cation exchange capacity of swelling clays (where the MeB molecule substitutes for the exchangeable cations) has been common since the 1950's). MeB has also been used routinely by the drilling industry to estimate the percentage of bentonite mud in the circulation fluids (API RP 13B, 1974). During the 1980's the technique was successfully adapted to identify high levels of smectite in formations encountered during the drilling of exploration wells in the Philippines. Such formations were recognized to have potential for caving or slumping during drilling.

For the analysis of geothermal drill cuttings the MeB dye is essentially "titrated" into a suspension containing powdered drill cuttings until the rock is saturated with the MeB molecule. By measuring how much MeB is required to saturate the rock, the quantity of smectite clays in the rock can be calculated. The method involves the incremental addition of a known concentration of MeB solution into an acidified suspension containing a known quantity of powdered rock sample. The MeB is adsorbed by the smectite until the point where the smectite is saturated. Beyond this point there is free MeB in solution, which can be easily recognized by blotting the fluid onto standard filter paper.

Table 2: Methylene Blue, X-Ray and Temperature Data

Sample & Depth	Well Temp (°C)	Required MeB (0.75 g/l)	Swelling Clay Component	Clays Determined by XRD
WK 228 155 m	90-110	18 ml	3.6%	Minor mixed-layer I/S (50% illite)
WK 228 310 m	190-210	10 ml	2.0%	Minor mixed-layer I/S
WK 232 396 m	200-220	6 ml	1.2%	N/A
WK 233 130 m	90-100	38 ml	7.6%	Chlorite, mixed-layer I/S
WK 233 300 m	190-210	7 ml	1.4%	Chlorite, mixed-layer I/S
WK 233 360 m	210-220	5 ml	1%	Trace mixed-layer I/S
WK 233 400 m	215-225	2.5 ml	0.5%	Illite
WK 233 420 m	220-230	6 ml	1.2%	Chlorite, illite, trace mixed-layer I/S
WK 235 130 m	90-100	12 ml	2.4%	Chlorite, trace mixed-layer I/S

After Harvey and Gunderson (2000)

3. NAMORA-I-LANGIT RESULTS

The Namora-I-Langit geothermal field is located in the Sarulla contract block in North Sumatra (Gunderson et al., 2000). This area had been initially identified as prospective by the extensive fumarolic activity and acid sulfate alteration at the surface shown in Figure 1 (Gunderson et al., 1995). Four exploration wells were drilled in the field in 1997-1998, encountering a highly permeable, predominantly neutral geothermal system with production temperatures of 255-270C and maximum recorded temperature of 276C. One of the wells (NIL 1-1) was drilled in the area of extensive acid sulfate alteration. The others were drilled 0.5-1.5 kilometers away from thermal activity.

Geological, geochemical, and geophysical surveys were conducted to characterize the resource and target exploratory wells in the prospect. In particular, an extensive low resistivity layer that was exposed at the surface in the area of the thermal manifestations had been identified by the MT and TDEM surveys. This was interpreted as a clay alteration halo overlying a high temperature reservoir. The exploration wells were targeted using this low resistivity region as a proxy for the clay cap to the reservoir.

While all four Namora-I-Langit wells encountered highly productive reservoir, the near-surface environment in NIL 1-1 (drilled nearest the thermal area) was significantly different from the other three. The NIL 1-1 location is in an area of extensive acid sulfate surface alteration, whereas the other three wells all spudded in fresh, unaltered rock. In the subsurface, NIL 1-1 encountered temperatures in excess of 100C immediately below the ground surface, while the other three wells all found 30-55C temperatures in the shallow subsurface (Figure 2). The geophysical signatures of these areas were different as well. The electrical conductor at NIL 1-1 extended from the surface down several hundred meters before the rocks increased in resistivity, whereas in the vicinities of the other wells the conductor was detected several hundred meters below the surface (Figure 3).

The bulk cuttings of each of the Namora-I-Langit wells were analyzed by the MeB method at the wellsite as the wells were being drilled. The sampling interval was 15-30 meters. The results of these analyses are shown in Figure 2. Well NIL 1-1 found a smectite-rich layer extending from the surface at 800 meters elevation down to around 500 meters elevation. This directly reflects the abundant alteration and elevated temperatures found at this location. Each of the other wells found smectite-poor rocks from the surface down to 600-700 meters elevation, followed by 200-300 meters of smectite-rich rocks. Once again this correlates well with the shallow temperature and resistivity data. The abundance of these clays declines with depth over this interval in three of the wells, gradually settling down to background levels. The continuous layer of smectite alteration overlying the geothermal system represents this clay "cap" over the reservoir, and is largely independent of rock type. Below about 300 meters elevation all the wells have rocks nearly free of smectite clays; however occasional thin, low permeability smectite-bearing paleosols are found in all of the wells. The clay-rich rocks include intermediate to silicic lavas and tuffs, but surprisingly does not include the fine-grained sedimentary rocks interbedded with the tuffs.

Comparison of the Namora-I-Langit MeB results with the temperature profiles shows two interesting characteristics. First, as expected, rocks with a significant component of smectite clay are found at temperatures between 50 and 200C (Figure 2). This corresponds very well with the empirical thermal stability distribution derived from other geothermal fields. Additionally, essentially no smectite was found in the shallowest 200-300 meters of wells NIL 2-1, 2-2, and 3-1. This barren zone represents the cool vadose region overlying the underpressured Namora-I-Langit reservoir in which surface waters slowly downflow toward the reservoir. This contrasts strongly with the same vadose region in NIL 1-1 in which the clay cap has been breached and there is a strong upflow of steam. The distribution of clays and observed alteration patterns clearly reflect the current state of the geothermal system and its ongoing processes.

The distribution of smectite in the Namora-I-Langit wells corresponds very well with the location of the electrical conductor interpreted from the geophysical surveys. These results confirmed that the identity of the MT/TDEM conductor is a zone of clay alteration within the volcanic lavas and tuffs overlying the reservoir, and validate its northern extension as a viable target for stepout exploration.

4. AWIBENGKOK RESULTS

The initial success of the MeB technique at Sarulla led to its application to Unocal's developed Awibengkok field. In 1994, MT and TDEM data were being reviewed to plan step-out drilling for a 220 MW field expansion. Although cultural noise severely distorted all of the MT data collected at Awibengkok, data from a 1982 survey provided a key early indication that the bulk of the reservoir was offset to the west of the major thermal manifestations. Following the drilling of the first two wells in 1983, subsurface resistivity was correlated with clay fraction estimates from lithology logs. Together with sparse XRD analyses, these data confirmed that the MT was identifying the low resistivities in the smectite clay cap overlying the reservoir and that this could be used to indirectly map the reservoir structure. However, the poor quality and sparse coverage of the MT left the detailed structure of the clay cap poorly resolved. In 1994, this was a particular concern in the western field area where many new injection wells were to be targeted.

Initial interpretations of high resolution, shallow penetration TDEM acquired in 1994 suggested that the distribution of the conductive clay alteration was more complex than the MT or earlier well analyses could reliably resolve. Since a detailed MeB analysis of cuttings from all existing wells could be completed quickly and at a fraction of the cost of XRD results, this approach was used to attempt to better resolve the resistivity structure in the wells. (In fact, the cost of storage and management of the cuttings exceeded the cost of the MeB analyses).

Figure 1 shows the trace of the Awibengkok cross-section used to illustrate the MeB correlation with the resistivity and temperature data. The cross-section in Figure 3 crosses the center of the field from the deep high temperature reservoir in the west near pad A-9 to the shallow incipient steam cap close to pad A-5 near the eastern end. (Note that this section is reversed from a typical west-east orientation to facilitate comparison to the analogous Namora-I-Langit section). Despite the poor quality of the MT data, the resistivity contours generally conformed as expected to the MeB smectite estimates and to the reservoir isotherms. The MeB results were particularly helpful in sorting out the exceptions.

A few examples illustrate how the detailed MeB smectite estimates can be used to unravel details of the resistivity interpretation. The very shallow clay zone shown in A-2 is not well resolved by the MT but was detected by the TDEM. Together with data from other wells, the TDEM showed that this probably corresponds to a very thin smectite-rich hydrothermal eruption debris flow that trends across the strike of the reservoir. The poor agreement of A-10 is probably due to its 1 km offset from the line of resistivity section. The A-9 well shows minor MeB peaks in the reservoir below sea level that correspond to dehydrated smectite-rich paleosol zones that were potential drilling hazards.

The results from Awibengkok also illustrate some relevant issues for use of the method in exploration. For example, 15 meter samples, although far denser than is normally done for XRD, were not sufficiently dense to resolve all reservoir paleosols. Some wells that encountered a paleosol showed significant carry-over of smectite from that paleosol into most subsequent samples. Despite such difficulties, especially with respect to detecting drilling hazards, the Awibengkok experience confirmed the utility of MeB for clay characterization in geothermal fields.

5. CONCLUSIONS

The MeB procedure can provide valuable data when routinely used while drilling geothermal exploration and development wells. The benefits include the use of MeB smectite estimates as a mineral geothermometer to assist in setting intermediate and production casing strings. Such "real time" smectite detection can also be used to characterize drilling hazards. Either during or after drilling, the detailed picture of smectite clay distribution provided by MeB measurement, combined with local XRD analysis, can assist in preparing a field conceptual model, particularly when correlated with resistivity sounding data. Additional benefits could include calibration of geophysical resistivity measurements and potential correlation with downhole resistivity measurements and perhaps FMS logs.

The low cost and potential benefits of MeB make it a desirable method to apply in many geothermal development drilling programs and a few already drilled fields if the necessary semi-skilled manpower is available to handle the simple tasks involved.

The method has been applied to smectite and illite-smectite clays hosted in silicic to andesitic terrains. It should be equally applicable to basalt-hosted geothermal systems where mixed-layer chlorite-smectite clays may be present (Harvey and Browne 2000). The technique may also detect the smectite-illite clay transition in sediment-hosted systems.

6. REFERENCES

API RP 13B, (1974). API recommended practice standard procedure for testing drilling fluids, 9.32-9.36.

Browne, P.R.L. (1978) Hydrothermal alteration in active geothermal fields: *Ann. Rev. Earth Planet. Sci*. 6, 229-250.

Grim, R.E.(1953) *Clay Mineralogy*, McGraw Hill,384pp.

Gunderson, R.P., Dobson, P.F., Sharp, W.D., Pudjianto, R., and Hasibuan, A. (1995). Geology and Thermal Features of the Sarulla Contract Block, North Sumatra, Indonesia. *Proceedings World Geothermal Congress*, 1995, v.2, 687-692.

Gunderson, R.P., Ganefianto, N., Riedel, K.L., Sirad-Azwar, L., Suleiman, S. (2000) Exploration Results in the Sarulla Block, North Sumatra, Indonesia, *Proceedings World Geothermal Congress (this volume)*.

Harvey, C.C. and Browne, P.R.L. (2000) Studies of mixed-layer clays in geothermal systems. A review of developments and their effectiveness as mineral geothermometers: *Proceedings World Geothermal Congress (this volume)*.

Harvey, C.C. and Gunderson, R. (2000) The use of Methylene Blue adsorption to detect the presence of smectites and mixed-layer smectite clays in geothermal exploration: in press, *Applied Clay Science*.

Huang, P.T. and Brindley, G.W. (1970). Methylene blue absorption by clay minerals. Determination of surface areas and cation exchange capacities (Clay-Organic Studies XVIII), *Clays & Clay Miner.*, 18: 203-212.

Jennings, S. and Thompson, G.R. (1986) Diagenesis of Plio-Pleistocene sediments of the Colorado River Delta, southern California: *J. Sediment. Petrol.* 56, 89-98.

Johnston, C.T. (1995) Sorption of organic compound on clay minerals: a surface functional group approach in CMS short course "*Organic Pollutants in the Environment*" 2-44. Ed. B.L. Sawhney. Clay Minerals Soc. 197 pp.

Marguiles, L., Rozen, H. and Nir, S. (1988) Model for competitive adsorption of organic cations on clays: *Clays and Clay Min.***36**,270-276.

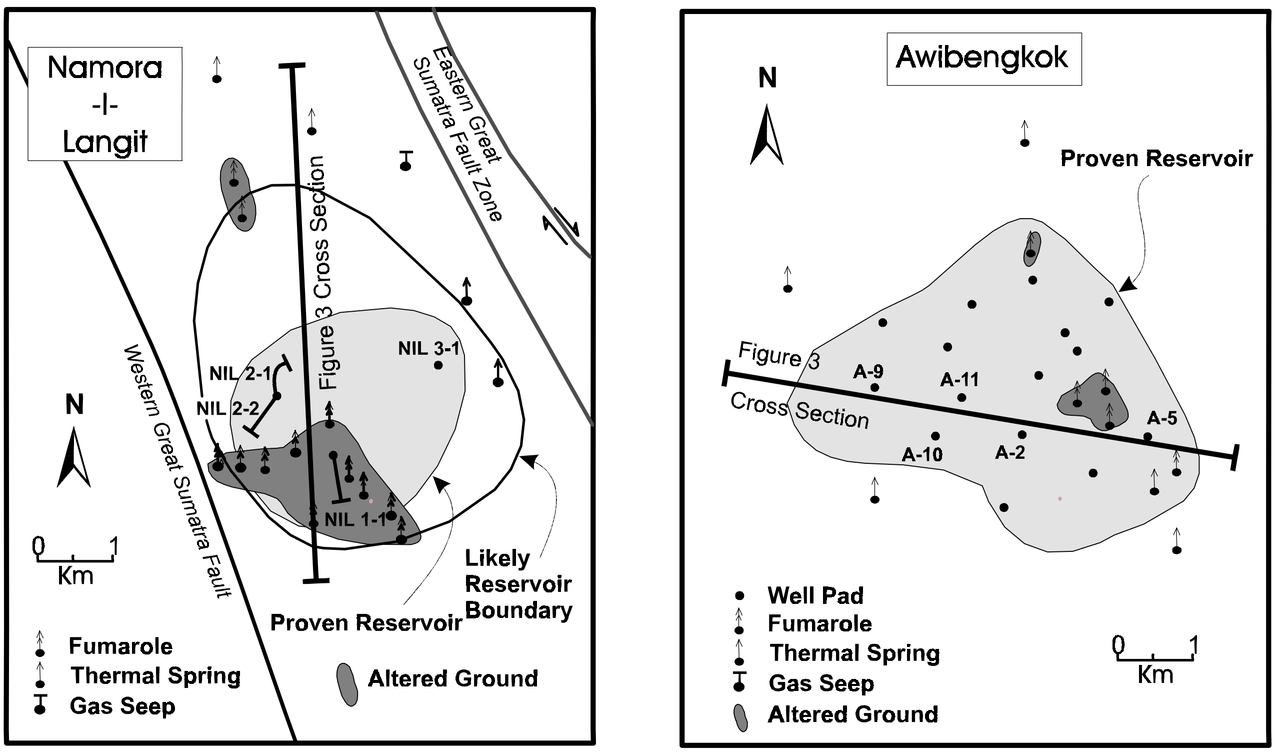


Figure 1. Sketch maps showing the distribution of thermal features, wells, and proven reservoir area for Namora-I-Langit (left) and Awibengkok (right) geothermal fields.

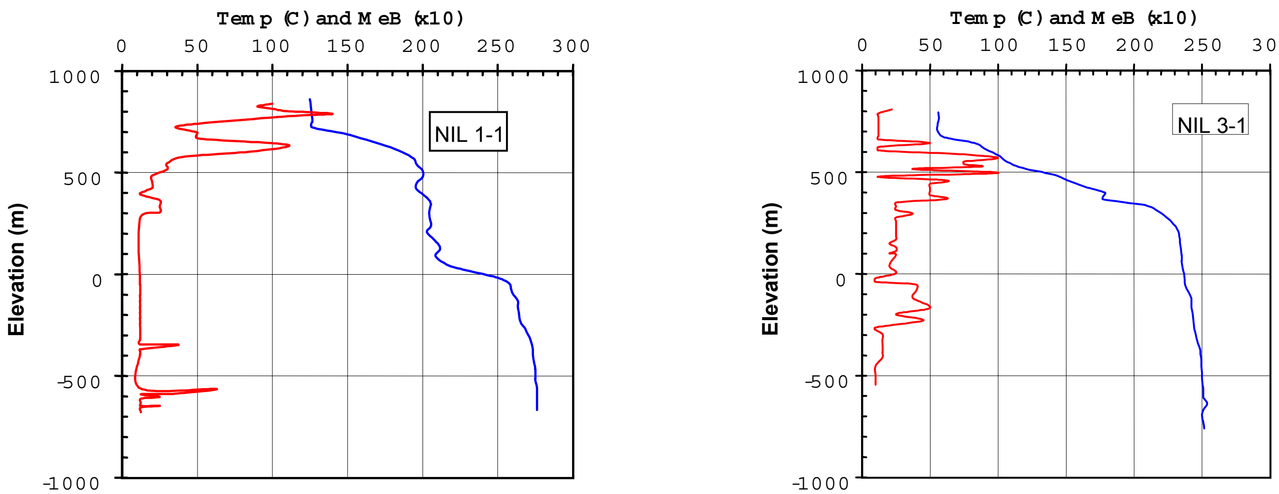
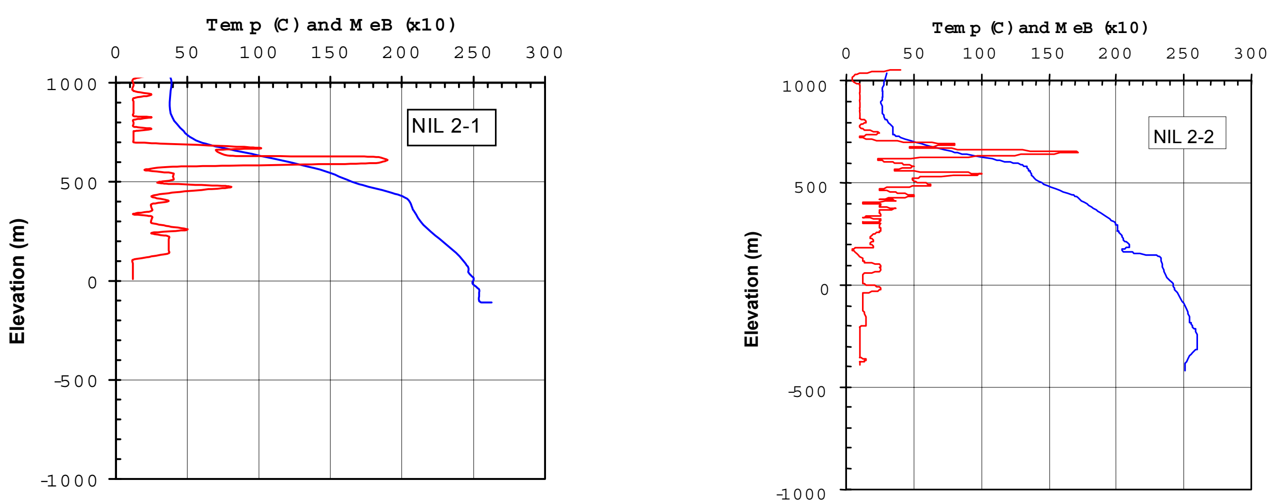


Figure 2. Plots comparing the stable temperatures (right curve) and smectite contents (left curve) from the four Namora-I-Langit wells. The smectite contents are plotted as 10 times the saturation values of MeB in the cuttings using the units “ml MeB solution per gram of



rock.” Values shown below about 1.5 ml/g are below the detection limit of the technique.

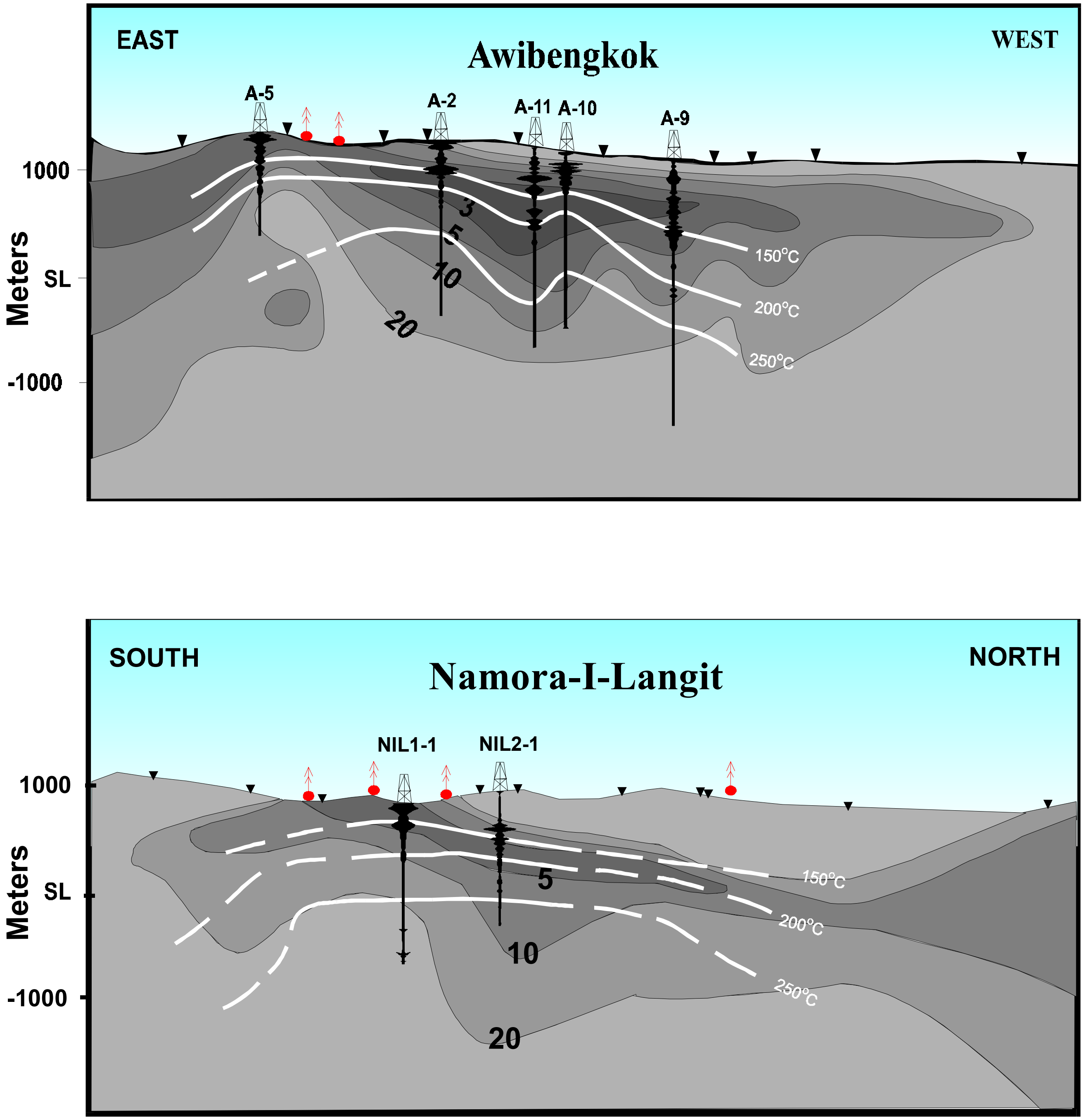


Figure 3: Comparison of resistivities integrated from MT and TDEM surveys, static temperatures derived from well measurements, and smectite contents measured using the Methylene Blue method for Awibengkok (above) and Namora-I-Langit (below). The cross section lines are those shown in Figure 1. Temperature contours are solid where measured and dashed where inferred. Resistivity contours are in ohm-m from TE-mode 1-D smooth inversions. The width of the well courses represent measured smectite abundance. No vertical exaggeration.