Geology and Thermal Features of the Sarulla Contract Area, North Sumatra, Indonesia

Richard P. Gunderson[1], Patrick F. Dobson[2], Warren D. Sharp[3], Restu Pudjianto[4] and Aidil Hasibuan[4]

[1]Unocal North Sumatra Geothermal, Ratu Plaza Office Tower - 3rd Floor, P.O. Box 1264, Jakarta 10012, Indonesia. [2]Unocal Corporation, 3576 Unocal Place, Santa Rosa, CA 95403 USA. [3]Berkeley Geochronology Center, 2453 Ridge Road, Berkeley, CA 94709 USA. [4]Pertamina Geothermal Division, Jakarta 10110 Indonesia

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ABSTRACT

Unocal has signed a contract with the Indonesian government to explore for and develop geothermal energy in the Sarulla area of North Sumatra, within the Sumatra volcanic arc and along the active Sumatra Fault System (SFS). There are no active volcanoes within the contract area, but there are extensive andesite-rhyolite lavas and dacite-rhyolite ash flow tuffs dated between 1.8 and 0.12 Ma. The area contains many surface expressions of hydrothermal activity, including fumaroles, hot springs, gas seeps, and altered rock. The hydrothermal features are clustered into four groups that are, from NW to SE: Namora-I-Langit, Silangkitang, Donotasik, and Sibualbuali; each is associated with a Quaternary volcanic eruptive center. Springs from the Silangkitang and Donotasik groups have neutral Cl waters with cation geothermometry temperatures of 270°C and 230°C, respectively. The Namora-I-Langit and Sibualbuali groups have less direct evidence of high temperature geothermal systems.

1. INTRODUCTION

In February of 1993 Unocal, Pertamina (the Indonesian state-owned oil company) and PLN (the Indonesian state-owned power company) signed a joint operations and energy sales contract enabling Unocal to explore for and develop geothermal energy in the Sarulla Contract Area, North Sumatra. The contract calls for Unocal North Sumatra Geothermal, a subsidiary of Union Oil Company of California, to act as a contractor to Pertamina for exploration and development of geothermal energy within the block. Electricity generated as a result of this exploration and development will be purchased by PLN.

The Sarulla Contract Area is approximately 15 by 63 km in dimension, elongated in a NW-SE direction, and is located between the towns of Padangsidempuan and Tarutung in the state of North Sumatra (Figure 1). Access to and within the contract area is relatively good, as the Trans-Sumatra Highway runs along its length, and local roads extend from the highway to several of the thermal areas. Physiographically, the area can be distinguished into two separate regions: the rugged, mountainous uplands of the Barisan Mountains, and the low, flat terrain within the Sarulla graben that runs along the axis of the mountains. The Batang Toru River runs along this graben through the northern and central portions of the contract area, and then cuts a gorge through the volcanic arc as it flows south and west to the Indian Ocean.

The contract area contains structural, volcanologic, and hydrothermal features that make it very attractive as a target for geothermal exploration. Pudjianto *et al.* (1991) and Hochstein and Sudarman (1993) published preliminary descriptions of the thermal features of the Sarulla area. Aspden *et al.*(1982) described the geology of the region. It is the purpose of this paper to provide more details on the geological and thermal features of the contract area, based on the results of field and lab work undertaken by Unocal geologists as a part of the initial exploration effort.

2. REGIONAL GEOLOGY

2.1 Tectonic Setting

Sumatra lies along a NW-trending sector of the Sunda Trench, at the convergent boundary between the subducting oceanic India-Australian Plate and the overriding continental Southeast Asian Plate. The convergence of these two plates in the Sumatran segment of the arc is oblique, resulting in the development of both a volcanic arc and a major transcurrent fault system. The volcanic arc and strike-slip fault are largely coincident throughout Sumatra, occurring along the axis of the uplifted Barisan Mountains. The Sarulla Contract Area is located within the Barisan Range where it intersects the southern margin of the Batak Tumor, a 125 x 250 km elliptical dome thought to be the locus of voluminous Tertiary and Quaternary crustal intrusion (van Bemmelen, 1949; Aldiss and Ghazali, 1984).

The volcanic arc in Sumatra includes eleven active volcanoes and many more that are Quaternary in age but are now considered either dormant, extinct, or in a fumarolic stage (Hochstein and Sudarman, 1993). Notable eruptive centers present along this arc include the Toba Caldera, at the center of the Batak Tumor 80 km NW of Sibualbuali, and Krakatau, located in the Sunda Strait just south of the southern tip of Sumatra. Largely coincident with the volcanic arc is the Sumatran Fault System (SFS), a right lateral strike-slip fault oriented N30-40W.

2.2 Generalized Geologic History of Sumatra

A subduction zone was first formed off the west coast of Sumatra in the late Paleozoic (Curray *et al.*, 1979). A thick sequence of Paleozoic metasedimentary rocks found throughout Sumatra and forms the basement in the contract area represents this initial period of arc construction, erosion, and sedimentation. During the Mesozoic, periods of normal arc volcanism and sedimentation appear to have been interrupted by several episodes of locally intense deformation, plutonism, and low grade metamorphism of the Paleozoic section (Page *et al.*, 1979). It is during this period when the SFS is thought to have first developed.

A relatively stable island-arc subduction regime was re-established in the Early Tertiary, when normal arc volcanism was accompanied by fore-arc sedimentation to the west, and back-arc sedimentation to the east of what are now the Barisan Mountains (Rock *et al.*, 1983). This pattern of volcanism and sedimentation continued transgressively until the Late Miocene when uplift of the Barisan Mountains began. This uplift was accompanied by (and probably in part caused by) volcanism and sub-volcanic intrusive activity. In some areas (such as Sarulla), the resurgence of volcanic activity did not begin until the Pliocene, as Pliocene basal conglomerates and lacustrine sediments overlying Paleozoic metasediments contain no volcanic detritus.

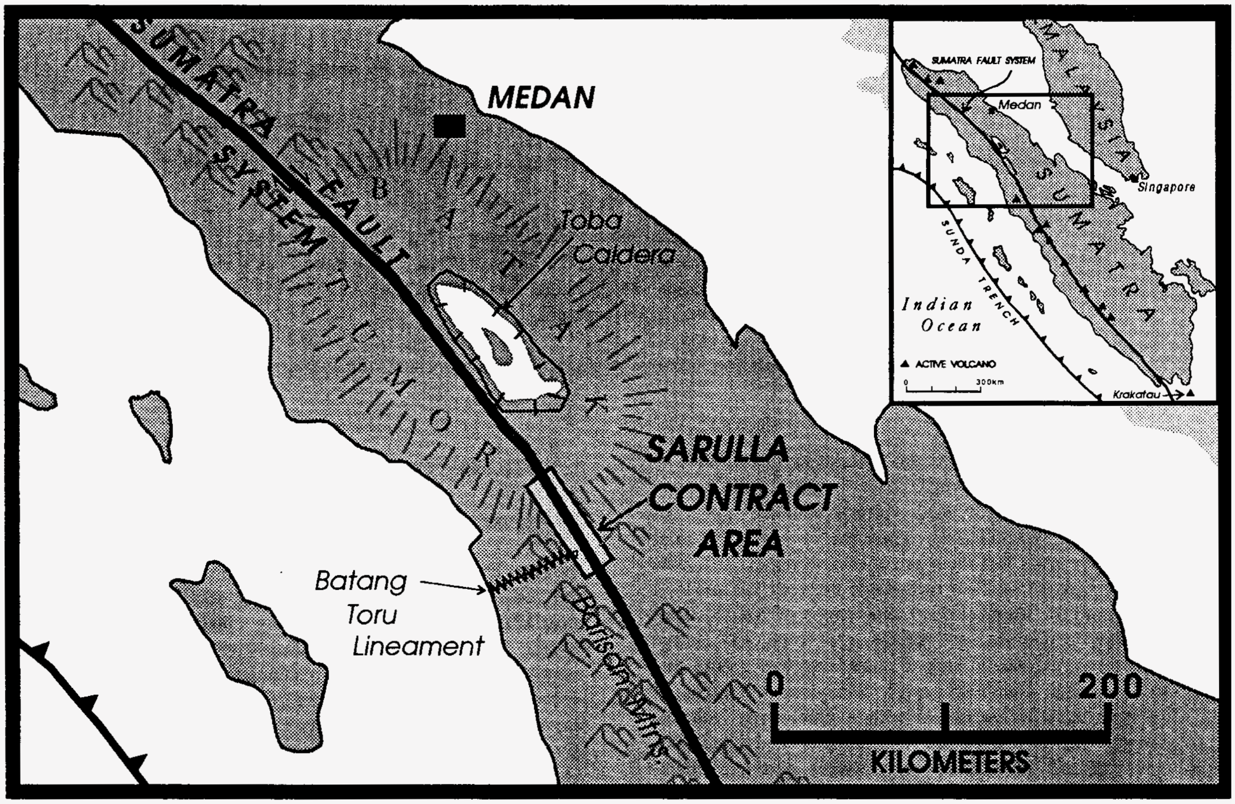

Figure 1. Regional location map of Sarulla Contract Area, North Sumatra.

3. GEOLOGIC OVERVIEW OF SARULLA CONTRACT AREA

The contract area surface geology (Figure 2) is dominated by Quaternary arc volcanism and the strike-slip faulting of the **SFS.** These young features are superimposed on the uplifted, folded, and faulted crustal basement rocks, which include Paleozoic metasedimentary rocks, Mesozoic to Tertiary intrusive rocks, and Tertiary sedimentary rocks, as well as other older crustal structures.

3.1 Sub-Volcanic Basement Rocks

Metamorphosed quartzite, phyllite, and limestones interpreted to be upper Paleozoic in age (Tapanuli Group and the Kuantan Formation, Aspden *et al.*, 1982) form the local basement to the Sarulla contract area. These rocks are exposed sporadically along the uplifted eastern margins of the Sarulla and Sipirok grabens, and are also found as reworked clasts in younger sediments. They are exposed more extensively on the flanks of the Barisan Mountains, and may serve as reservoir rock for the geothermal systems within the contract area.

Marine sandstones and limestones of Miocene age (Sihapas and Telisa Formations, Aspden *et al.*, 1982) are found to the east of the contract area along the NW edge of the central Sumatran basin. However, the Barisan Mountains have been an area of uplift and erosion during much of the Neogene, and most of the sediments encountered within the contract area consist of terriginous (lacustrine and alluvial) sandstones, mudstones, and conglomerates. These sediments change in provenance from metasedimentary and granitic to volcaniclastic with the onset of volcanism in the Late Tertiary.

Exposures of hornblende granodiorite and coarse-grained biotite and two-mica granites are found within 15 km of the western boundary of the contract area. Based on limited K/Ar age dating, these intrusive rocks are interpreted to be Mesozoic to Early Tertiary in age (Aspden *et al.,* 1982). Granitic and associated homfelsic inclusions are occasionally found in volcanic rocks in the

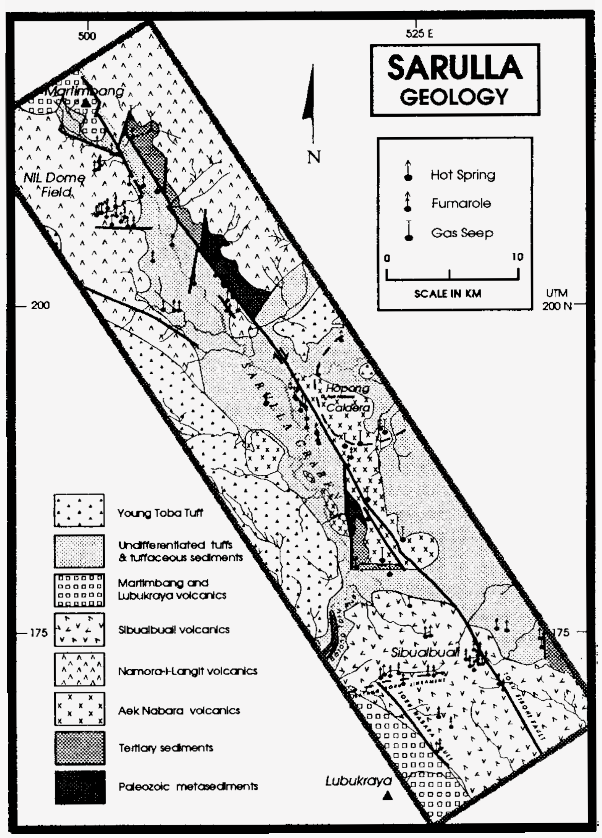

Figure 2 Geologic map of Sarulla Contract Area

Sibualbuali area, suggesting that these intrusive rocks may locally form the basement unit.

TABLE 1: SARULLA AGE DATING SUMMARY

Sample #	Rock type	UTM (E)	UTM (N)	Material analyzed	Method	Age (Ma)
Sibualbuali area						
DS-SBB1	pyroxene andesite lava	529.20	173.20	groundmass feldspar conc.	K-Ar	**0.4±0.04**
DS-SBB5	rhyolite ash flow tuff	526.75	178.30	sanidine	Ar-Ar (1)	**0.33±0.01**
SBR 91-1	bio hb rhyodacite lava	530.90	173.80	biotite	Ar-Ar (2)	**0.27±0.03**
"	"	"	"	plagioclase	Ar-Ar (2)	**0.26±0.11**
SBR 93-6	rhyolite ash flow tuff	546.83	155.86	sanidine	Ar-Ar (1)	**1.77±0.01**
SBR 93-7	lithic dacite tuff	541.75	158.79	plagioclase	Ar-Ar (2)	**0.60±0.03**
SBR 93-8	pyroxene andesite lava	532.16	172.66	plagioclase	K-Ar	**1.04±0.04**
SBR 93-10	rhyolite ash flow tuff	527.27	177.90	sanidine	Ar-Ar (1)	**0.379±0.002**
SBR 93-11	rhyolite ash flow tuff	528.56	178.29	sanidine	Ar-Ar (1)	**0.385±0.002**
SBR 93-18	pyroxene andesite lava	522.22	176.25	matrix glass	K-Ar	**0.66±0.03**
"	"	"	"	plagioclase	"	**0.61±0.03**
SBR 93-20	rhyolite tuff	521.60	177.10	sanidine	Ar-Ar (1)	**0.565±0.003**
SBR 93-35	pyroxene andesite lava	528.35	172.05	matrix glass	K-Ar	**0.37±0.02**
"	"	"	"	plagioclase	Ar-Ar (2)	**0.38±0.03**
SBR 93-45	basaltic andesite lava	521.75	169.72	matrix glass	K-Ar	**0.12±0.02**
SBR 93-51	lithic andesite tuff	520.50	170.52	plagioclase	Ar-Ar (2)	**0.49±0.01**
SBR 93-55	bio-hb rhyodacite lava	527.14	167.09	hornblende	Ar-Ar (2)	**0.10±0.03**
"	"	"	"	plagioclase	Ar-Ar (1)	**0.15±0.06**
SBR 93-62	glassy dacite lava	525.55	168.72	plagioclase	Ar-Ar (1)	**0.30±0.05**
Donotasik area						
DON-7	pyroxene andesite lava	514.79	188.44	glass	K-Ar	**0.74±0.06**
DON-14	pyroxene andesite lava	515.10	194.80	plagioclase	K-Ar	**0.89±0.07**
DON-20	rhyolite ash flow tuff	516.50	195.40	biotite	K-Ar	**1.10±0.08**
DON-24	rhyodacite ash flow tuff	516.50	186.20	biotite	K-Ar	**1.07±0.08**
Namora-I-Langit area						
NIL-10	rhyolite lava	512.45	198.41	biotite	K-Ar	**0.12±0.08**
NIL-12	dacite lava	502.34	215.51	biotite	K-Ar	**0.23±0.08**
NIL-13	dacite lava	503.30	215.45	biotite	K-Ar	**0.31±0.08**
NIL-29	andesite lava	503.30	205.20	plagioclase	K-Ar	**0.75±0.06**
NIL-33	rhyolite lava	499.50	210.65	sanidine conc.	K-Ar	**0.48±0.06**
NIL-47	andesite lava	503.62	202.50	biotite	K-Ar	**0.16±0.08**

$^{40}Ar/^{39}Ar$ age determinations of samples were conducted using two different techniques: laser fusion (1), and incremental heating (2). Ar-Ar ages determined by Berkeley Geochronology Center and Stanford University (DS-SBB5); K-Ar ages determined by IGNS and Univ. of Arizona (DS-SBBI). Analytical methods for analyses done by Sharp at the Berkeley Geochronolgy Center are as follows. Ages are referenced to the Fish Canyon sanidine irradiation monitor, with an age of 27.84 Ma (modified from Cebula et al., 1986). All samples were analyzed by laser heating, using techniques similar to those of Deino and Potts (1990) and Renne and Basu (1991) and references therein. Ages given for sanidines are the means of *3* to 5 analyses of approximately 4 grains each. Ages for plagioclase from SBR 93-55 and -62 are the means of *3* to *5* analyses of approximately 30 grains each. Ages for the remaining plagioclases and hornblende are 4 to *6* point isochrons based on incremental heating analyses

3.2 Quaternary Volcanism

There has been arc-related volcanic activity in the Sarulla area over the past **1.8** million years (see Table 1 for age dating summary). This volcanism consists of lava flows and breccias, silicic domes, and ash-flow and airfall tuffs which range in composition from basaltic andesite through rhyolite (see Table 2 for representative chemical analyses), with basalts notably absent. Prominent volcanic features in the Sarulla area include the extinct Lubukraya and Sibualbuali stratovolcanoes in the southeast, the Aek Nabara dacite domes and Hopong caldera in the center, and the Namora-I-Langit dome field and Martimbang volcano in the northwest.

Namora-I-Langit Dome Field

The Namora-I-Langit **(NIL)** volcanic center consists of a number of andesitic to rhyolitic domes and flows located west of the SFS at the northwest end of the contract area (Figure 2). **K-Ar** ages in this volcanic center range between 0.75 Ma for a basal andesite lava (NIL-29) to 0.16 Ma for an undissected andesite dome (NIL-47). The center is located south of Martimbang volcano, an undated but geomorphically even younger basaltic andesite cone. South of the **NIL** complex, a rhyolite dome (NIL-10) near the town of Sarulla represents the youngest volcanic feature (0.12 Ma) within the northern part of the contract area. The bulk of the **NIL** domes are dacitic in composition (DS NIL-3), and the central portion of the dome complex hosts the vigorous Namora-I-Langit fumarole field. There are also abundant silicic pyroclastic deposits, the most recent of which is the regional 74 Ka Young Toba Tuff (Chesner *et al.*, 1991), which caps most of the area. Many of these tuffs have been subsequently reworked, forming widespread, laminated volcaniclastic lacustrine deposits in the Sarulla graben.

Hopong Caldera/Aek Nabara Domes

The Hopong caldera is a previously unreported, 9 km-diameter circular volcanic collapse feature located on the eastern margin of the Sarulla graben (Figure 2). Poorly welded rhyodacitic to rhyolitic intracaldera tuffs (SCA 94-20) are found within the most deeply eroded portions of the caldera. Within the caldera, these tuffs are overlain by laminated tuffaceous lacustrine sediments, which are in turn capped by Young Toba Tuff (SCA 94-19). There are also many deeply weathered and reworked ash flow tuff deposits found in surrounding areas that are thought to have been erupted From the Hopong caldera. Overlying the Hopong ash flow tuffs along the western caldera margin are a number of dacitic to rhyolitic domes (SCA 94-2). The largest of these is the Aek Nabara dacite dome, which sits on the eastern margin of the Sarulla graben.

Sibualbuali Volcano

The Sibualbuali volcano is a deeply dissected stratovolcano at the southwest end of the Sarulla contract area that is predominantly andesitic in composition (Figure **2).** It consists of a series of andesitic to dacitic lavas and breccias with occasional interbedded

TABLE 2: SARULLA ROCK CHEMISTRY

	Sibualbuali				Donotasik				Namora-I-Langit		
Rock Type	basaltic andesite	andesite	rhyodacite	rhyolite aft	andesite	rhyodacite	rhyodacite aft	rhyolite af?	andesite	dacite	rhyolite
Sample #	SBR 93-45	SBR 93-35	SBR 93-55	SBR 93-11	DON 93-7	SCA 94-2	SCA 94-20	SCA 94-19	NIL-29	DSNIL-3	NIL-10
SiO_2	55.4	59.2	68.1	69.0	55.5	68.1	66.5	72.0	61.3	65.6	70 4
Al_2O_3	17.2	16.8	15.3	13.8	17.6	14.9	14.6	13.0	16.2	15.8	14 1
Fe_2O_3	3.86	2.63	1.47	1.70	3.45	1.68	1.12	0.99	3.26	1.60	1 15
FeO	5.5	3.5	1.2	0.4	4.3	0.9	1.1	1.2	2.7	1.6	0 5
MgO	2.86	3.12	1.02	0.80	4.29	0.74	0.80	0.55	2.67	1.35	0 49
CaO	7.58	6.56	3.01	1.56	8.09	2.22	2.39	1.38	5.95	2.97	1 82
Na_2O	3.19	3.07	4.08	2.51	2.67	3.46	2.87	2.64	3.02	2.85	3 76
K_2O	1.56	2.84	2.69	5.47	1.60	3.37	4.40	4.28	3.12	3.74	4 40’
TiO_2	1.14	0.78	0.36	0.30	0.94	0.30	0.33	0.26	0.54	0.43	0 21
P_2O_5	0.19	0.15	0.07	0.03	0.23	0.04	0.09	<0.01	0.14	0.10	0 05
MnO	0.16	0.13	0.11	0.08	0.14	0.08	0.09	0.06	0.12	0.08	0 07
LOI	0.85	1.15	2.55	4.30	0.85	4.30	5.90	3.55	0.75	3.65	3 05
Total	99.49	99.93	99.96	99.95	99.66	100.09	100.18	99.90	99.77	9977	100 01
Rb	49	103	105	259	45	130	175	201	119	220	184
Sr	293	306	208	143	342	201	221	81	291	240	177
Y	19	20	6	10	33	28	32	52	32	22	20
Zr	155	220	151	181	182	158	224	163	202	160	162
Nb	10	11	10	17	10	10	14	17	15	n.a.	12
Ba	379	432	497	468	439	463	513	397	484	560	565
UTM (E)	521.75	528.35	527.14	528.56	514.79	521.3	522.14	522.22	503.3	502.8	512 45
UTM (N)	169.72	172.05	167.09	178.29	188.44	184.39	194.97	195.28	205.2	208.4	198 41

Major elements reported in weight percent, trace elements in ppm. Analyses by XRF, FeO determinations by wet chemistry.

tuffs (DS SBB-1, SBR 93-18, 20, 35, 51) that range in age from −0.7 to -0.3 Ma. Following construction of the stratovolcano, younger (0.12-0.30 Ma), more silicic dacite to rhyodacite lavas and domes (SBR 91-1, **SBR** 93-55, 62) were subsequently erupted along its southwest and eastern ***flanks*** along the two major strands of the SFS. Abundant rhyolitic ash flow tuffs **(DS SBB-5,** SBR 93-10, 11) dated at 0.33 and 0.38 Ma and reworked tuffaceous sediments derived from these tuffs are present in the Sipirok graben northeast of Sibualbuali. The source of these tuffs is not known at present, although the presence near the town of Sipirok of pumice blocks up to 30 cm in length suggests a nearby source. Lubukraya volcano is the youngest eruptive center in the southern portion of the Sarulla contract area. Like the young Martimbang volcano in the north, Lubukraya primarily consists of basaltic andesites. **A** flow from Lubukraya that extends down to the southern margin of the Sibualbuali area (SBR 93-45) has been dated at 0 12 Ma.

3.3 Sumatra Fault System

The Sarulla contract area is structurally dominated by the presence of the right lateral SFS. The principal strand of the SFS within the contract area extends from the eastern flank of Sibualbuali volcano along the eastern edge of the Sarulla graben, and northwest into the Tarutung graben, the next axial graben. Near Sibualbuali volcano, a second major strand of the SFS lies along the western margin of Sibualbuali volcano (Figure 2). The principal strand of the fault appears to have numerous small subsidiary parallel and antithetic (tensional/extensional) faults, as evidenced by common minor fault scarps and sag ponds. North of Sibualbuali within the Sarulla graben, the eastern strand of the SFS is very distinct, defining the eastern edge of the valley. If a western strand exists, it is indistinct, suggesting that the Sarulla "graben" may actually be more like a half-graben structure or a large "sag" structure along the strike-slip fault. Many of the thermal features are found in close proximity to SFS-related structures, suggesting that fault-controlled upflow may play an important role in the Sarulla geothermal reservoirs.

A recent model based on interpreted focal mechanisms of Sumatran earthquakes has suggested relatively high and variable slip rates along the **SFS** that increase to the north (McCaffrey, 1991). This variability is consistent with measured fault offsets of 1.4 cm/yr around Maninjou (275 **km SE** of Sarulla) and 2.7 cm/yr near Tarutung (Sieh ***et al.***, 1991; Sieh, pers. comm., 1993). Most of the documented earthquakes in the vicinity of Sarulla are associated with subduction, but the 1892 Tapanuli earthquake (near Padangsidempuan) and the 1987 Taratung earthquake were both related to movement along the **SFS** (Newcomb and McCann, 1987; Untung and Kertapati, 1987).

4. HYDROTHERMAL FEATURES

The surface manifestations of hydrothermal activity in the Sarulla contract area include hot springs, warm springs, fumaroles, hot and cold gas seeps, and altered rock. These features, while widely distributed, can be geographically distinguished into four groups. From northwest to southeast the groups are: Namora-I-Langit, Silangkitang, Donotasik, and Sibualbuali (Figure 3 **&** Table 3). **As** expected, thermal springs at lower elevations (generally below 600 m) yield principally CI-bearing waters. Springs at higher elevations are generally more bicarbonate- and sulfate-rich. Gas seeps, fumaroles, and acid sulfate waters are found generally at the highest elevations, while evidence of hydrothermal alteration can be found at all elevations.

4.1 Namora-I-Langit

The Namora-I-Langit thermal group comprises three areas of fumaroles and acid sulfate springs, several neutral Cl-sulfate-bicarbonate hot springs, two gas seeps, and numerous warm bicarbonate springs over an area of about 50 km^2 (Figure 3). The thermal manifestations are most closely associated with the Namora-I-Langit dome field west of the SFS, but do extend east of the SFS as well.

The most prominent thermal feature (in the entire Sarulla block, in fact) is an area of almost continuous fumaroles, boiling acid pools, boiling mud, acid sulfate springs, and intense acid sulfate alteration covering roughly 5 km^2 in the Namora-I-Langit dome field. The maximum fumarole temperature recorded in this area is 119°C, although most of the manifestations are only at the boiling point. The NCG content of steam from this area is generally high (10 to 45 wt.%), but one fumarole in this area has been repeatedly

TABLE **3:** SARULLA **SPRING** CHEMISTRY

	Sibualbuali		Donotasik			Namora-I-Langit					Silangkitang	
Spring Name	Somarsik	L. Aek Nabara	Sialang Jae	Donotasik	Donotasik Geyser Pool	Rihitbi-dang	W. NIL Acid Spring	Matinde	Aek Parijanan 3	Aek Alaan	Opuja-mara	Pangaloan **SW**
Sample	SMK-1	SBB92-13	**SJ-I**	DT-I	DPG-I	SRL-13	NIL92-02	N93-13	N93-6	N93-4	SG93-3	SG93-7
Date	8/2/93	7/20/92	8/16/93	8/16/93	8/16/93	6/2/90	8/24/92	7/4/93	6/25/93	6/24/93	6/27/93	6/30/93
UTM (E)	519.86	522	517 16	515.63	515.62	512 50	500 38	503 95	506.37	506 21	510.31	510.45
UTM (N)	180.87	171 92	190 42	193.03	193.30	193 00	207 35	209 48	199.80	204 92	199.78	200.55
Temp °C	68	72	82	101	92	101	97	75	80	96	96	95
pH	7.91	7.5	8 36	7.98	9.31	8 5	3 09	8 05	7.79	7 8	8.65	8.66
Li	0.59	0.69	6 51	6.7	7.41	4 41	0 05	0 28	3.31	**4** 12	6.31	6.48
Na	450.7	227	890 1	1145	1150	546 5	27 96	694 6	661.7	694 9	680.4	673.6
K	51.99	16.5	68 45	75.96	90.39	33 25	34 72	78 88	57.78	68 25	114.0	125.3
Ca	60.33	96.3	12 16	11.31	3.01	4 65	20 14	14 7	52.13	7 07	2.30	3.11
Mg	1.53	4 43	0 87	0.47	0.16	0 93	5 30	2 08	0.33	0 67	0.02	0.49
Si02	151.9	116	159 1	135.6	236.5	163 8	344 7	198 7	283.1	124 2	244.4	376.8
B	1.81	2.99	36 33	46.72	47.26	21 59	0 24	6 74	18.66	18 81	35.88	35.54
Cl	41	288	1084	1294	1310	560	7 10	48	599	580	947	980
F	0.18	0.56	1 5 8	4.24	4.6	1 8 9	0 33	0 7	1.13	1 3	7	6.1
SO4	14	57	125	348	332	142	256	24	519	393	79	68
HC03	1456	390	638	578	485	457	0	1828	312	463	126	136
NH4		0.4	2 7	0.64	0.25	1 0 6	0 3	1 2	1.12	1	0.45	0.57
TDS	2230	1200	3025	3647	3667	1937	697	2898	2509	2356	2243	2412

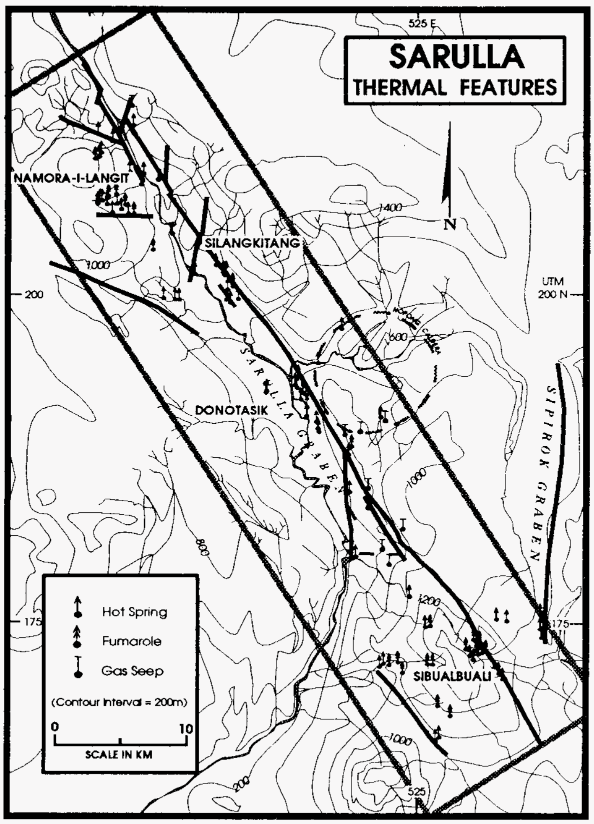

Figure 3. Thermal features of Sarulla Contract Area

measured at only 1% NCG. The other hmarolic features in the Namora-I-Langit group are considerably smaller, but also are relatively gassy.

There are two types of springs (Table 3) that carry information from depth in the Namora-I-Langit area, although neither points directly to a high temperature resource. Matinde is a bicarbonate spring **NE** of the large fumarolic area that has very low Mg contents, with Na-K-Ca, K-Mg, and SiO_2 geothermometry that agree at about 230°C. Aek Alaan and Aek Parijanan springs form a group of near-boiling CI-bicarbonate-sulfate springs distributed south and east of the large fumarolic area. These springs do not appear to represent direct outflow from a high temperature reservoir (their geothermometry indicates equilibration temperatures around 200°C), and thus they may be another indirect link to a deep reservoir The remainder of the springs in the Namora-I-Langit area have dilute bicarbonate and/or sulfate waters.

4.2 Silangkitang

The thermal features in the Silangkitang area consist primarily of fumaroles and boiling Cl springs scattered in **a** 1 by **4 km** swath along the **SFS** at the northern end of the Sarulla graben. Unlike the Namora-I-Langit springs, several of these springs yield fluid that has risen rapidly and directly from a high temperature reservoir. The chemistry of these waters (Table 3) suggests that they last equilibrated in a neutral, 260-270°C geothermal reservoir. The distribution of these springs and fumaroles along the main trace of the SFS suggest a reservoir also elongated in that direction.

4.3 Donotasik

The Donotasik group of thermal features consist primarily of boiling Cl springs on the floor of the Sarulla graben, but also includes gas seeps and fumaroles east of the valley on the slopes of the Aek Nabara domes and in the Hopong caldera. The springs are concentrated in the eastern half of the valley in low-lying, wet, marshy areas, including one large spring that flows directly into the Batang Toru river. The spring waters are generally similar to the Silangkitang waters, but all have higher Mg and equilibrated at lower temperatures. Based on the $Na\text{-}K\text{-}Mg^{1/2}$ ternary plot, most of the Donotasik waters equilibrated at 200-230°C, but have since partially re-equilibrated at lower temperatures.

4.4 Sibualbuali

There are nineteen areas of fumarolic activity spread out on and around Sibualbuali volcano. Overall, these features encompass about 45 km^2. In addition to these boiling point, acid sulfate-type features, there are numerous areas of cold alteration, as well as ten neutral-pH warm springs and three gas seeps located more distally around the periphery of the volcano.

The fumarolic areas range in size from a few hundred m^2 to about 100,000 m^2, and in temperature from 93 to 132°C. Their vigor ranges from weakly boiling mud to jet-like blasts of steam. Many of them are located near the two principal strands of the **SFS** on the volcano's eastern and western flanks. These fumaroles (e.g., Nagodan, Aek Nabara) tend to be the most superheated and vigorous. Like at Namora-I-Langit, there is a wide variation in NCG content of steam from the Sibualbuali fumaroles. Steam from vents along an E-W line across the center of the volcano (coinciding with the Batang Toru lineament) has NCG of ≤ 3 wt.%. Along this line, the NCG content decreases from west to east (3 - 0.2%). North and south of this line, NCG contents are all 3% or greater, ranging from 3 to 25%.

Most of the distal Sibualbuali springs are dilute, low to moderate flow bicarbonate springs with low Cl and high Mg contents, and represent steam-heated groundwaters. However, two of the springs shows possible evidence of deep, high temperature interaction (Table 3). First, the Lower Aek Nabara spring located west of the volcano at about 700 meters elevation contains as its principal anions about 300 ppm Cl and bicarbonate. While the low TDS and high Mg of the water indicate that it has re-equilibrated and/or mixed at low temperature, the substantial Cl content suggests that there is a significant component of reservoir brine. The aqueous geothermometers have re-equilibrated in this water, however, yielding Na-K temperatures of only 170°C. The Somarsik spring, located about 12 km NW of Sibualbuali peak, is a neutral water spring with 1450 ppm bicarbonate and low sulfate and Cl. Significantly, this spring also has low Mg and Ca, with Na-K geothermometry of about 200°C. The relatively high geothermometry and low Mg suggest that this water has risen rapidly from its source. The water from this spring may represent a deep bicarbonate reservoir, but more likely is outflow from a deep secondary steam-heated aquifer.

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