Proc. 11th New Zealand Geothermal Workshop 1989

LIFE IN GEOTHERMAL SYSTEMS
A key to sinter formation and recognition?

Keith Nicholson and Cristina G. Aquino*

Geothermal Institute, University of Auckland, Private Bag, Auckland, New Zealand.
*Present address: Philippine Geothermal Inn, PO Box 7336, Naia, Pasay City, Philippines.

ABSTRACT

Siliceous particles, typically 10-30 μm long, were collected from near-neutral-pH chloride pools in Tokaanu, Waimangu and Waiotapu geothermal fields, New Zealand. These occur in a variety of forms, described as lenticular, rectilinear, sigmoidal, rod, filament, tubule, sphere and irregular grains, and are most abundant at Tokaanu. Under the scanning electron microscope, the lenticular, rectilinear and sigmoidal forms are seen to have patterns of striations and lineations characteristic of pennate diatoms. Silica is the dominant component of the particles (75-96 wt%), as determined by semi-quantitative SEM-EDAX analysis, frequently with significant chlorine (3-19 wt%). Aluminium is commonly present in minor quantities (<1 wt%). Sodium and potassium were rarely detected. The length-width aspect ratios and silica-chlorine ratios group the forms into the following associations: lenticular-rectilinear; rod-filament and grain-sphere, with the tubule as an independent form. On the basis of morphological similarities with modern analogues, these groups are considered to be genetically distinct, representing diatoms, bacteria, inorganic particles and, possibly, filamentous algae respectively.

Textures similar to the filament and tubule forms were observed in thin sections of sinter from the Tokaanu and Waiotapu sample sites. It is suggested that biogenic matter plays an important role in the development of sinter rims and terraces, by acting as a vertical framework, and possible catalyst, for silica deposition. Recognition of such textures, and possibly the use of chlorine as part of a geochemical signature, will assist in the discrimination of sinters from other siliceous lithologies, and as such could be an important tool in epithermal gold exploration.

INTRODUCTION

Silica, both as consolidated sinter and as the loose amorphous equivalent, is a common deposit wound pools and springs discharging near-neutral-pH chloride geothermal waters. Despite the near-ubiquitous abundance of sinter, and the importance of recognising the ancient analogues of such deposits in epithermal gold exploration, the processes involved in sinter formation are not fully understood. As part of a wider study investigating this problem, particulate matter from hot pools was examined to characterise the morphology and geochemistry of the material, and to determine whether equivalent particulate matter could be identified in associated sinters. This paper describes the siliceous particles identified, and relates the findings to the role of algae and bacteria in the formation, and subsequent recognition, of silica sinter.

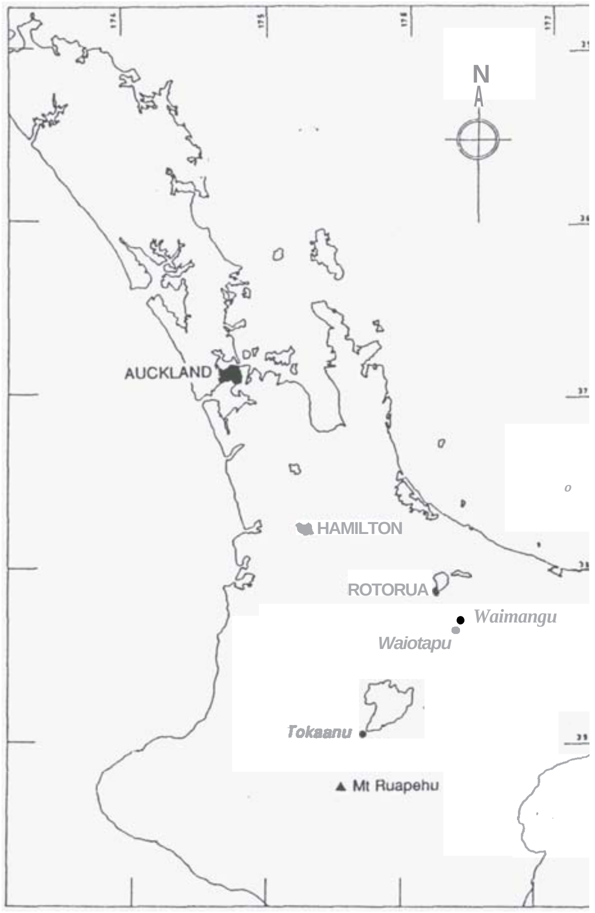

Figure 1. Location of Tokaanu, Waimangu and Waiotapu geothermal fields in the North Island of New Zealand.

STUDY AREAS AND SAMPLE SITES

Three geothermal fields in the Taupo Volcanic Zone, New Zealand, were selected for sampling: Tokaanu, Waimangu and Waiotapu (Fig. 1). These three fields were chosen since, as is described below, each provides a different hydrogeochemical background for the formation of any particulate matter. Each field has a variety of discharge features, but all the sample sites were hot pools fed by near-neutral-pH chloride water. However, despite being of the same chemical type, the water chemistry of the three sample sites is quite different (Table 1).

TABLE 1

Water chemistry of geothermal features sampled for particulate matter

(All concentrations in mg/kg)

Feature	Flow (L/s)	T°C	pH_T	Na	K	Ca	Mg	B	SiO_2	Cl	SO_4	HCO_3	Ref.
Tokaanu													
Pool 31C	<1	81	6.5	1710	147	33*	*	82	270	2723	59	46	(1)
Pool 31D	2	88	7.7	1896	161	37	0.7	97	317	3062	66	38	'(2)
Pool 105	1	82	7.5	1840	172	58	0.31	95	189	3121	69	nd	(3)
Waimangu													
Frying Pan	nd	54	3.5	497	45	7.1	1.66	6.2	389	700	247	37	(4)
Lake	120	52	4.5	514	45	4.3	1.7	7.0	389	674	242	nd	(5)
Waiotapu													
Champagne	9	75	5.7	1130	161	33	0.04	30	385	1900	100	400	(6)
Pool	nd	74	5.3	1054	150	34.2	0.06	25	433	1839	39	189	(4)

References: (1) Mahon and Klyen (1968)
(2) Robinson and Sheppard (1986)
(3) Wang (1987)
(4) Mann et al (1986)
(5) Seward and Sheppard (1986)
(6) Hedenquist (1983)

* = Combined Ca and Mg analysis; nd = indicates species not determined

Tokaanu

The Tokaanu geothermal area contains several near-neutral-pH chloride pools as well as steaming ground and acid springs. All chloride pools have well-developed sinter rims. This area was chosen because the chloride fluids discharged are the most saline of all geothermal fields in the Taupo Volcanic Zone (Robinson and Sheppard, 1986). Samples were taken from the pool 31-complex of Mahon and Klyen (1968), or more precisely from pool 105 (Figure 2).

Waimangu

In this field Frying Pan Lake has an extraordinarily large outflow rate of c. 120 L/s (Seward and Sheppard, 1986) and displays an interesting fluid chemistry, with both high chloride and sulphate concentrations (Table 1). The controls on this fluid composition have not been quantified, but may involve mixing of the chloride fluid with acid condensates or oxidation of hydrogen sulphide discharged from fumaroles within the lake. Despite the mixed nature of the waters siliceous precipitates form at the outflow of this lake, and it was here that samples were taken.

Waiotapu

The Champagne Pool was selected for sampling because it discharges deep chloride geothermal fluid at a high flow rate of 9 L/s (Table 1). This fluid has boiled but is undiluted by groundwater (Hedenquist and Henley, 1985), and therefore provides an interesting contrast with the other sample sites. Furthermore, in addition to silica sinter, the pool is rimmed with orange and yellow precipitates of amorphous antimony and arsenic sulphides.

EQUIPMENT AND PROCEDURES

Sampling Equipment. 50mL Millipore™ polythene syringes, plastic forceps, Milliporem 0.45μm filter membranes, 1L polypropylene beaker, 800mL stainless steel Zone™ sampler, screw-top polycarbonate specimen jars.

Cleaning Procedure. All plasticware was soaked for 24 hours in a 5% (v/v) Decon 90™ solution, then rinsed at least six times in distilled-deionised water, followed by a further 24-hour soak in a 10%(v/v) nitric acid solution and a final six-fold rinse in distilled-deionised water. The equipment was then oven-dried and stored in new, individual, self-sealing, low-density polythyene bags prior to

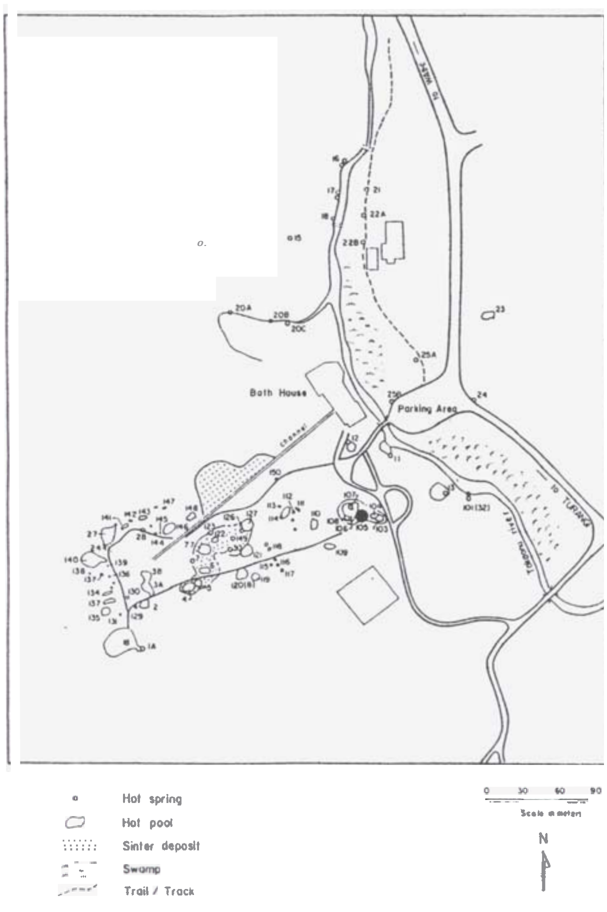

Figure 2. Tokaanu geothermal field showing principal discharge features. Sample site was pool 105.

transportation into the field. Single pre-weighed Milliporem filter membranes were placed in each of the screw-top jars. At no time in the preparatory or sampling procedures were the membranes touched by hand; all manipulation was performed using the plastic forceps.

Sampling Procedure. To ensure the material collected was not a surficial artifact, water samples were collected from a depth of 1.5 to 2m using the Zone™ sampler. The water was transferred to the 1L beaker, from which 50mL aliquots were taken into the syringe and passed through a 0.45μm filter. At each sampling site two batches of filters were collected. One batch consisted of filters through which only 50mL of water was passed, the second batch contained "saturated" membranes which had filtered a sufficient volume of water to block the pores to the extent that no further liquid could pass through. This was done to provide an estimate of the mass of solids suspended in the waters. Each filter was then retumed to its individual screw-top jar which was stored in a sealed plastic bag.

The pH and temperature of the sampling sites were recorded using a maximum thermometer and narrow-range (0.2 units) pH paper.

Analytical Procedure. Each filter was oven dried at 35°C, weighed and the mass of particulate matter per litre of water calculated. Strips of the filters were mounted onto carbon disks, carbon coated and analysed under a Philips Model 505 scanning electron microscope (SEM) equipped with an energy-dispersive X-ray analysis (EDAX) system.

RESULTS AND DISCUSSION

The results of the field measurements and particle concentration determinations are shown in Table 2. The temperatures and pH values are comparable with earlier studies except, however, for the pH of Frying Pan Lake, which is 1.5pH units more alkaline than previously recorded (Table 1). Variations in the chemistry of discharges within the Waimangu field is currently under investigation.

TABLE 2
Physical determinations on sample pools

Field/feature	date	T°C	pH_T	M_S (mg/L)
Tokaanu				
Pool 105	08/88	80	6.5	2.0
Waimangu				
Frying Pan Lake	08/88	50	6.0	10.2
Waiotapu				
Champagne Pool	08/88	74	6.0	6.0

M_S = mass of suspended solids

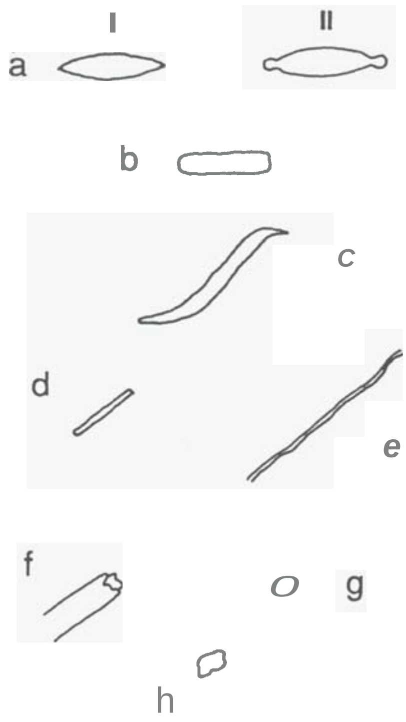

Figure 3. Outline forms of siliceous particles from Pool 105, Tokaanu geothermal field. **a:** lenticular (two varieties) **b:** rectiliner **c:** sigmoidal d: rod **e:** filament **f:** tubule **g:** sphere **h:** irregular grain

Morphology

A range of diverse forms of silica particles were observed under the SEM. These are described by the terms lenticular (two varieties), rectilinear, sigmoidal, rod, filament, tubule, sphere and irregular grains (Fig. 3). All morphologies were observed in the samples taken from Tokaanu which shows by far the most diverse range of forms from the pools studied, including rare examples of pollen (fig. 4). At Waimangu only grains and rare filaments were found. Grains are also the dominant form of silica at Waiotapu, with minor rods and filaments, and rare examples of the lenticular-I form. Following this initial appraisal, a more detailed analysis of particle morphology and geochemistry was performed on the Tokaanu samples.

Table 3 summarises the dimensions and the length-width aspect ratio for each of the silica forms found at Tokaanu. As can be seen, each shows a characteristic aspect ratio, with those of the lenticular and rectilinear forms being both similar and the most consistent, possibly indicating a similar origin. . Greater surficial detail was subsequently observed on SEM photographs of the lenticular forms, which revealed distinct symmetrical striation patterns and a lineation passing through the middle and length of the form (Fig. 4). Such a pattern is characteristic of the striate arrangement of punctae found on the frustuls of pennate diatoms with the central lineation representing the (pseudo)raphe (Brasier, 1980; Crawford 1981). These diatoms have a bilateral symmetry and are elliptical in valve view; a morphology which correlates with that of the lenticular forms. Further photography revealed that *striae* were also present on the rectilinear form, though in a different pattern (Fig. 4). A comparison with diatom morphologies reveals that this form probably represents the side, or girdle, view of the above diatoms, an origin which would explain the near-identical aspect ratios of the lenticular and rectilinear forms. No surface features where observed on any of the other silica forms. A biogenic origin for two of the observed forms raises the possibility of a similar origin for other morphologies. The rod and filament forms resemble bacterial structures described from iron, manganese and siliceous deposits (eg. Marshall, 1979; Chukhrov et al., 1980; Juniper and Fouquet, 1988) and are probably also bacteriological in origin. Both rod-shaped and filamentous bacteria have been found living on the margins of thermal features in New Zealand and elsewhere (Bock and Bock, 1970). The tubules show a markedly different aspect ratio (and SiO_2/Cl ratio, see below and Fig. 5) to that of the other forms, and may be of a third origin: possibly filamentous algae which have been described from geothermal areas in the Taupo-Rotorua area (Kaplan, 1956; Bock and Bock, 1970). The grains and spheres texturally resemble silica scale (e.g. Brown and McDowell, 1982) and are therefore presumed to be inorganic precipitates.

Geochemistry

The particles were analysed semi-quantitatively using the SEM-EDAX system. The irregular nature of the particle surface precluded any meaningful quantitative determinations. However, the results (Table 4) illustrate that silica is the dominant component of the particles which, interestingly, also frequently contain significant concentrations of chlorine (presumably as chloride). Aluminium is commonly present, but only in minor quantities. Sodium and potassium, despite their high concentrations in the water, were only rarely detected, and then most commonly in the spherical particles. The low concentrations of the major rock-forming elements is reassuring, since it implies that the particles are endogenic and are not entrained rock particles, an interpretation that could have easily been applied to the irregular grains.

The consistent presence of chlorine in all particle forms requires explanation. As silica has a negative surface charge under all but the most acidic conditions, the introduction of an anion into the structure by adsorption or substitution processes would not be expected. However, such inorganic processes may not be relevant to the biogenic particles which may incorporate chlorine during the life cycle. Whatever the precise mechanism, it does not appear to be a random process, since given the variable concentrations of aluminium, sodium and potassium in the particles, the silica:chlorine ratio remains remarkably constant for each form. Considering this ratio further, it clearly endorses the associations made on the basis of panicle morphology; namely, that the lenticular and rectilinear forms have a near-identical ratio (Table 4) and are almost certainly two views of the same form, while the tubules stand out as being unrelated to the other structures.

Summary

Figure 4 summarises the associations derived from the aspect ratio and silica-chlorine ratio determinations for each form. Distinct groupings, which probably reflect similar origins for the forms, are obvious from this diagram: ie. lenticular-rectilinear, rod-filament; and grain-sphere, with the tubule as a separate form. Largely on the basis of morphological similarities with modem analogues, these groups are considered to be genetically distinct, representing diatoms, bacteria, inorganic particles and, possibly, filamentous algae respectively.

ROLE IN SINTER FORMATION AND RECOGNITION

Sinter collected from the edge of Tokaanu Pool 105 and the Waiotapu Champagne Pool was subsequently examined in thin section to search for the fossilised remains of the siliceous particles described above. Textures and individual structures which resemble, and are of the same dimensions as, both the filament and tubule forms were observed. These were cemented together and to the bulk of the sinter by fine-grained silica. These observations provide an interesting comparison with the recently-published findings of Juniper and Fouquet (1988). They describe filamentous and tubular structures in iron-silica deposits forming around active discharge vents on the East Pacific Rise and Juan de Fuca/Explorer Ridges. Similar textures were also observed by Juniper and Fouquet in cherts from ophiolite complexes, the ancient analogue of such deposits. These authors suggest that the textures are due, at least in part, to the action of "micro-organisms".

While silica sinter can undoubtably form by the accumulation of inorganic siliceous matter without a biogenic

TABLE 3
Morphology and dimensions of particulate matter from Tokaanu

Morphology	(n)	length (um)	width (um)	aspect ratio (l/w)
lenticular	22	16.8	4.0	4.2
rectilinear	20	21.2	5.5	4.0
rod	14	16.7	1.9	10.0
filament	12	30.7	1.5	22.4
tubule	6	146.7	5.3	36.9
grain	12	12.7	8.0	1.4
sphere	14	6.8	6.8	1.0

TABLE 4
Mean semi-quantitative SEM-EDAX analyses of particulate matter from Tokaanu

lenticular	14	86.1	11.1	1.0	0.9	0.3	10.2
rectilinear	10	89.8	9.9	0.3	<0.5	<0.5	10.5
rod	8	90.9	7.4	0.6	1.1	<0.5	30.6
filament	8	94.6	4.8	0.6	4.5	4.5	43.3
tubule	6	75.2	18.8	0.9	3.2	1.4	4.4
grain	12	96.0	2.9	0.9	<0.5	<0.5	38.3
sphere	8	91.7	2.5	3.2	1.4	0.9	30.0

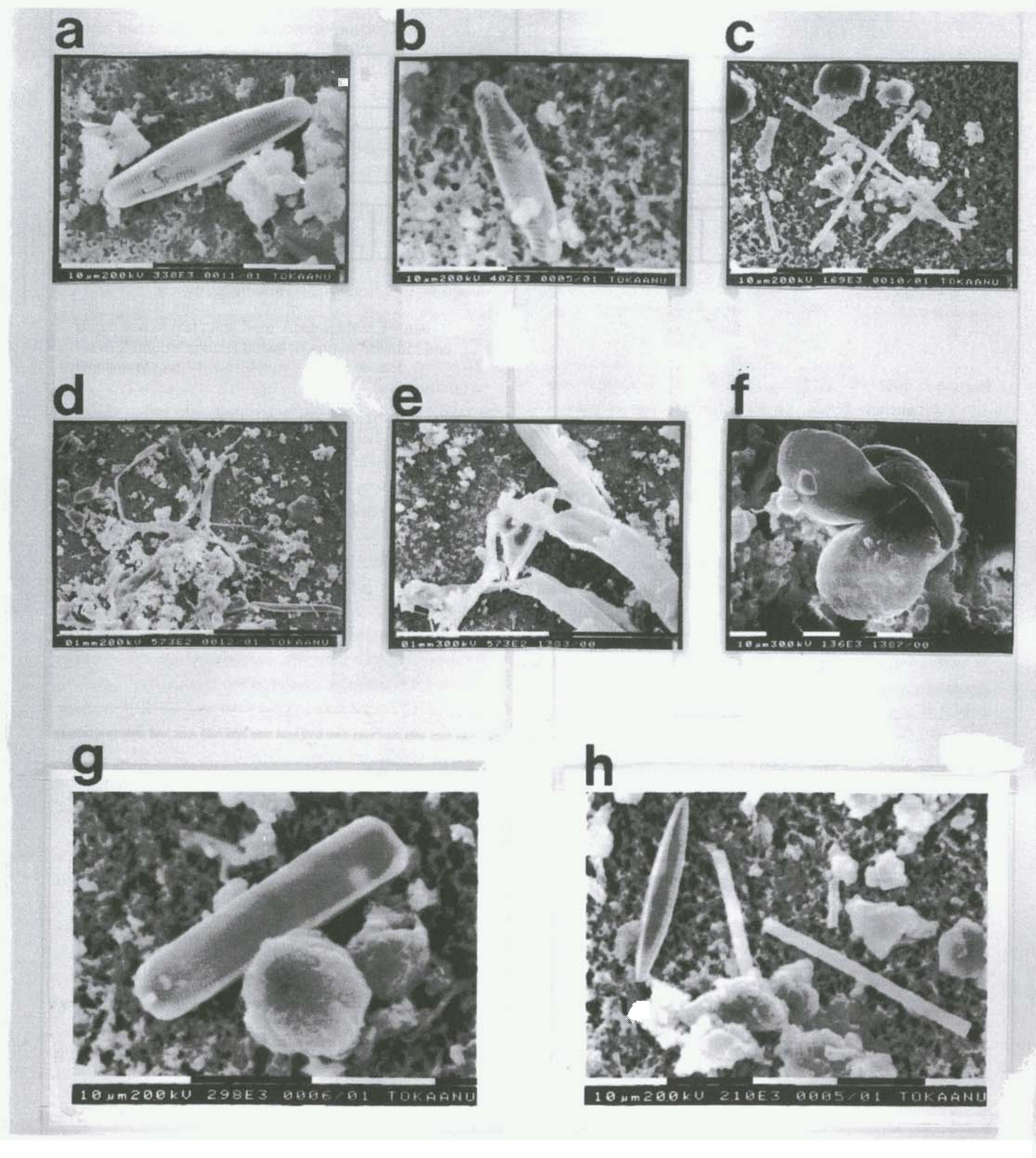

Figure 4: Particle forms under the scanning electron microscope. Scale bar is 10 µm long unless *otherwise* stated. a: diatom, lenticular-I variety . b: diatom, lenticular variety-I1 c: rods and irregular grains d: filaments and grains with a lenticular-I diatom (centre right) and a sigmoidal diatom (lower right), scale bar is 0.1 mm long. e: tubules, scale bar is 0.1 mm long. f: pollen grain (rare) g: rectilinear diatom h: rods, grains and lenticular-I diatom

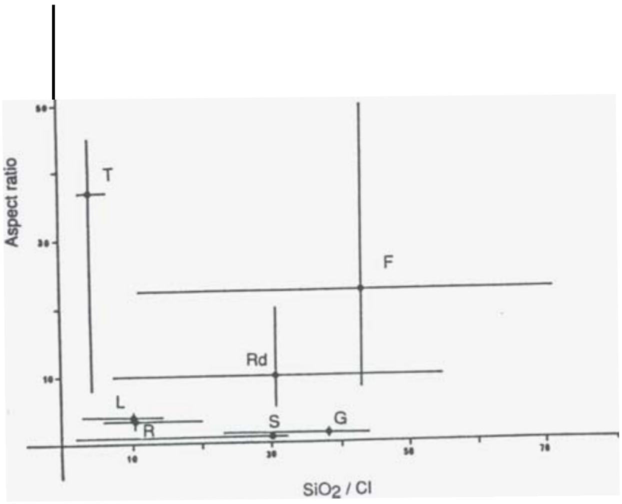

Figure 5. Plot of SiO_2 against aspect ratio for the particle forms. Bars indicate range in values. Key: L-lenticular, R-rectilinear, Rd-rod, F-filament, S-sphere, G-grain, T-tubule

contribution, perhaps the production of a well-developed thick sinter rim or terrace *is* dependant on an infrastructure of filamentous particles of an algal or bacteriological origin. Such a structure would provide a micro-framework for subsequent silica deposition and may actually catalyse deposition by providing a crystallisation substrate. By building on this biogenic scaffolding, the sinter could attain a greater thickness than otherwise possible. Providing the rate of silica deposition was not *so* great as to bury and kill the algae/bacteria, then continued biogenic growth towards the surface would permit greater sinter development. Such an origin may also explain the highly porous nature of many modern sinters.

The incorporation of biogenic particulate matter into sinters may provide an important tool in the search for epithermal gold mineralisation. Recognition of micro-structures and textures of a biological origin could distinguish sinters from other siliceous lithologies. That these structures *can* be identified in modem sinters, and the preservation of similar textures in ancient cherts (Juniper and Fouquet, 1988), is particularly encouraging in this respect. The discrimination of sinter from other siliceous lithologies (? "silistones" [cf ironstones and dolostones]) will be further aided by the identification of a diagnostic geochemical signature (Nicholson, 1988). As described above, chlorine is commonly incorporated into the silica particles and therefore has potential as such a sinterdiscriminating species.

ACKNOWLEDGEMENTS

Our thanks to both Dave Stringer and Steve O'Brian for their help with the SEM analyses. We *are* also grateful to the managers of the geothermal tourist attractions at Tokaanu, Waimangu and Waiotapu for their interest and generous co-operation; and to Pat Browne for reviewing the manuscript. CGA also thanks Tom Powell and Philippine Geothermal Inc. for their support.

REFERENCES

Bock, T.D. and Bock, M.L. (1970). Micro-biological studies of thermal habitats of the central volcanic region. North Island, New Zealand. *N.Z. J. Marine and Freshwater Res.*, 5: 233-258.

Brasier, M.D. (1980). *Microfossils.* Allan and Unwin. London, 3944.

Brown. K.L. and McDowell, D. (1982). The effect of aeration on silica scaling. In: *Proc. 4ih N.Z. Geothermal Workshop,* University of Auckland. Auckland, 127-130.

Chukhrov, F.V., Gorshkov, A.I., Zvyagin, B.B. and Ermilova, LP. (1980). Iron oxides as minerals of sedimentary units and chemogenic eluvium. In: *Varentsov, I.M. and Grasselly, Cy. (eds), Geology and geochemistry of manganese,* vol. 1, E. Schweizerbartlsche Verlag., 231-257.

Crawford. R.M. (1981). The siliceous components of the diatom cell wall and their morphological variation. In: *Simpson, T.L. and Volcani, B.E. (eds), Silicon and siliceous structures in biological systems.* Springer-Verlag, Berlin, 129-156.

Hedenquist, J.W. (1983). *Waiotapu, New Zealand.* PhD thesis, University of Auckland, New Zealand (unpubl.).

Juniper, S.K. and Fouquet, Y. (1988). Filamentous iron-silica deposits from modern and ancient hydrothermal sites. *Can. Mineral.*, 26 859-869.

Kaplan, I.R. (1956). Evidence of micro-biological activity in some of the geothermal regions of New Zealand. *N.Z. J. Sci. Tech.*, 37 639-662.

Mahon W.A.J. and Klycn, L.E. (1968) Chemistry of the Tokaanu-Waihi hydrothermal area. *N.Z. J. Sci.*, 11: 140-158.

Mann, A.W., Fardy, J.J. and Hedenquist, J.W. (1986). Major and trace element concentrations in some New Zealand geothermal waters, In: *Proc. Symposium 5: Volcanism, hydrothermal sysiems and related mineralisation,* International Volcanological Congress, 61-66.

Marshall, K.C. (1979). Biogeochemistry of manganese minerals. In: *Trudinger, P.A. and Swain, D.J. (eds), Biogeochemical cycling of mineral-forming elements.* Elsevier, Amsterdam, 253-292.

Nicholson, K. (1988). Geothermal deposits in ancient terrain as a tool in epithermal gold exploration: Examples from Scotland. In: *Proc. 10th N.Z. Geothermal Workshop,* University of Auckland, Auckland. 151-153.

Robinson, B.W. and Sheppard. D.S. (1986). A chemical and isotopic study of the Tokaanu-Waihi geothermal area, New Zealand. *J. Volcanol. Geotherm. Res.*, 27 135-151.

Seward, T.M. and Sheppard, D.S. (1986). Waimangu geothermal field. In: *Henley, R.W., Hedenquist, J.W. and Roberts. P.J. (eds) Guide io active epilhermal (geothermal) systems and precious metal deposits of New Zealand.* Monograph series on mineral deposits, 26: 81-91. Gebruder Borntraeger, Berlin.

Wang, H. (1987). *Fluid and sinter chemisiry of ihe Tokaanu area.* Geothermal Institute Diploma Report 87.26. University of Auckland, New Zealand.