isted earlier than 10^9 years before the Cambrian. The early animals could not permanently populate the continental shelves and could not readily evolve a skeleton; thus the probability of their preservation in the fossil record would have been small. Without a Precambrian thermocline, one is forced to assume a very rapid rate of evolution for the Metazoa once the concentration of oxygen in the atmosphere was adequate for respiration (*9*). The thermocline, however, provided an extensive offshore environment between about 50 and 150 m that probably was oxygenated and within which floating and (later) swimming animals were able to evolve. The existence of a seasonally oxygenated continental-shelf environment, carpeted by algae, would have offered an adaptive advantage to organisms that evolved swimming mechanisms. Once the atmospheric concentration of oxygen became sufficient, these swimming organisms could have adapted to a benthic habit on the shelves. At this stage, density would no longer have been a problem, and the organisms could have evolved skeletons. In the early stages these exoskeletons would have provided an adaptive advantage as ultraviolet shields and would have permitted the organisms to seal themselves from the environment to survive temporary anoxia. According to my hypothesis the beginning of the Cambrian marks the first time Metazoa could permanently occupy the floors of the continental shelves.

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Gels Composed of Sodium-Aluminum Silicate, Lake Magadi, Kenya

Abstract. *Sodium-aluminum silicate gels are found in surficial deposits as thick as 5 centimeters in the Magadi area of Kenya. Chemical data indicate they are formed by the interaction of hot alkaline springwaters (67° to 82°C; pH, about 9) with alkali trachyte flows and their detritus, rather than by direct precipitation. In the process,* Na_2O *is added from and silica is released to the saline waters of the springs. Algal mats protect the gels from erosion and act as thermal insulators. The gels are probably yearly accumulates that are washed into the lakes during floods. Crystallization of these gels in the laboratory yields analcite; this fact suggests that some analcite beds in lacustrine deposits may have formed from gels. Textural evidence indicates that cherts of rocks of the Pleistocene chert series in the Magadi area may have formed from soft sodium silicate gels. Similar gels may have acted as substrates for the accumulation and preservation of prebiological organic matter during the Precambrian.*

Natural silicate gels have been reported in several localities and geologic environments (*1*). During field studies of the area of Lake Magadi, Kenya, we have encountered silicate gels containing substantial amounts of sodium and aluminum; we believe that they bear directly on the formation of authigenic zeolites in many lake beds; perhaps also on certain chert deposits.

Lake Magadi lies in the Eastern Rift Valley, Kenya, at 2°S (Fig. 1); it is a highly alkaline lake containing a large deposit of trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$). Little Magadi, or Lake Nasikie Engeda, lies 1.6 km north of Lake Magadi from which it is separated by a narrow horst. Both lakes occupy closed basins. Lake Magadi is intermittently dry, while Little Magadi is perennially saline. Inflow is predominantly from a series of hot springs around the edges of the basins. The geology and geochemistry of the area (*2*) and the silica content of the waters (*3*) have been reported.

Silicate gels were found in two locations: near the hot springs that feed Northeastern Lagoon, north of Lake Magadi (48 in Fig. 1); and north of Little Magadi, near spring 14 (Fig. 1) and where the river of hot water formed by 62 (Fig. 1) enters the lake. The gels form surficial deposits as thick as 5 cm, some of which are covered by a thin, leathery skin of algal material (Fig. 2). This algal mat does not seem to be involved directly in precipitation of the gels; rather it protects them from erosion. The gels occur in almost stagnant pools of hot water on the banks of inflow channels; at Little Magadi they cover the entire lakeshore to a width as great as 30 m; they have not been found in moving water. Near some springs, deposition is restricted to the spring orifice and the immediately adjacent area. Some of the gel above water level is covered by an efflorescent crust of sodium carbonate–bicarbonate minerals.

In consistency the gels vary from soft, water-logged gelatin [resembling in texture certain material from Hawaii (*4*)] to rubber cement; they usually contain considerable amounts of organic material as well as detrital sand and silt of the unconsolidated alluvial sediment on which they are deposited. This silt and sand are rich in alkali feldspar and seem to derive predominantly from the Pleistocene alkali trachyte flows (*2*) that form the hills and scarps surrounding the basins. The springs issue directly from or from close to the bases of these flows. Total discharge

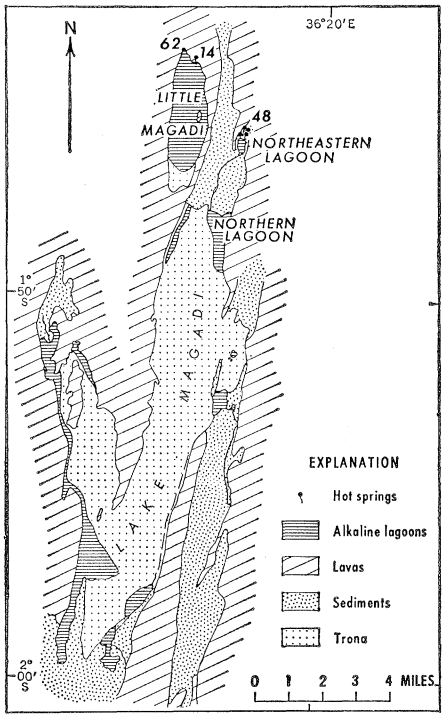

Fig. 1. Lake Magadi, Kenya; modified from Baker (*2*). Numbers (1966 numbers in Table 1) identify the hot springs with which the gels are associated.

from Little Magadi and Northeastern Lagoon springs was estimated (*2*) at 1000 liter/sec—one-third of the total spring inflow into the basins of the two lakes.

The gels are associated with only the hottest springs of the region; Stevens reported temperatures of 67°C in the springs feeding Northeastern Lagoon and 81° to 85°C for the hot-spring inflow to Little Magadi; we found similar temperatures in 1966. Stevens indicated that the composition of individual hot springs had changed very little during the 20 years preceding his report (*2*), and comparison of his results with ours (Table 1) shows that the same is true for the 34 subsequent years. Samples M14 and S20 (Table 1) are definitely from the same spring, but for the other samples one can only identify the spring group. The agreement is remarkable with respect to all constituents, the only apparent trend being increase in concentration of from 3 to 9 percent. Total dissolved solids are about 30,000 parts per million (ppm), and field *p*H values are near 9.0.

Compositional differences between the three springs are small, and anion ratios are virtually constant. The overall composition of these springs is made notable by the high molar Na^+:K^+ and HCO_3^-:$CO_3^=$ ratios, relatively abundant F^-, and paucity of sulfate and alkaline earths. Such chemical character is common in more-dilute waters associated with igneous terranes (*5*).

The chemical compositions of five purified gels, recalculated to an anhydrous basis, are given in Table 2. Water contents of the untreated gels vary greatly and range from 52 to 93 percent by weight. Even after treatment some samples still contain detrital material (sample M47H) and organic matter (M47H and M48J). The chief constituents of all samples are SiO_2, Al_2O_3, and Na_2O. In the purest samples (M48H, M48J, and M62H) K_2O is present in nearly equal amounts and the Na_2O:K_2O ratio is about 5:1; total iron as Fe_2O_3 is much higher in M48J than in the other two; M48J was not treated with heavy liquids, and finely divided opaque material may be responsible for this difference.

Figure 3 shows the gel compositions in terms of (Na_2O + K_2O), (Al_2O_3 + Fe_2O_3 + TiO_2), and SiO_2, with the sum adjusted to 100 percent. In the anhydrous gels these five constituents add to 90 to 95 percent. Their compositions lie on the sodium side of the silica-albite-analcite join. Projected from the alkali corner, they fall between nepheline and the anhydrous composition of analcite. Also plotted is the composition of nearby alkali trachyte (see Table 2).

The gels may have formed by either precipitation from the springwaters by cooling, or interaction of the springwaters with the feldspar-rich trachyte detritus. All available evidence points to the latter mechanism. Most telling are data on the silica and alumina contents, because direct precipitation of gels by cooling would require supersaturation with respect to both con-

Fig. 2. Gel deposit protected by algal mat; note the convolutions of the mat (light gray, lower right). The gel (dark gray) has been exposed by inversion of portion of the mat (left, and under the hammer head).

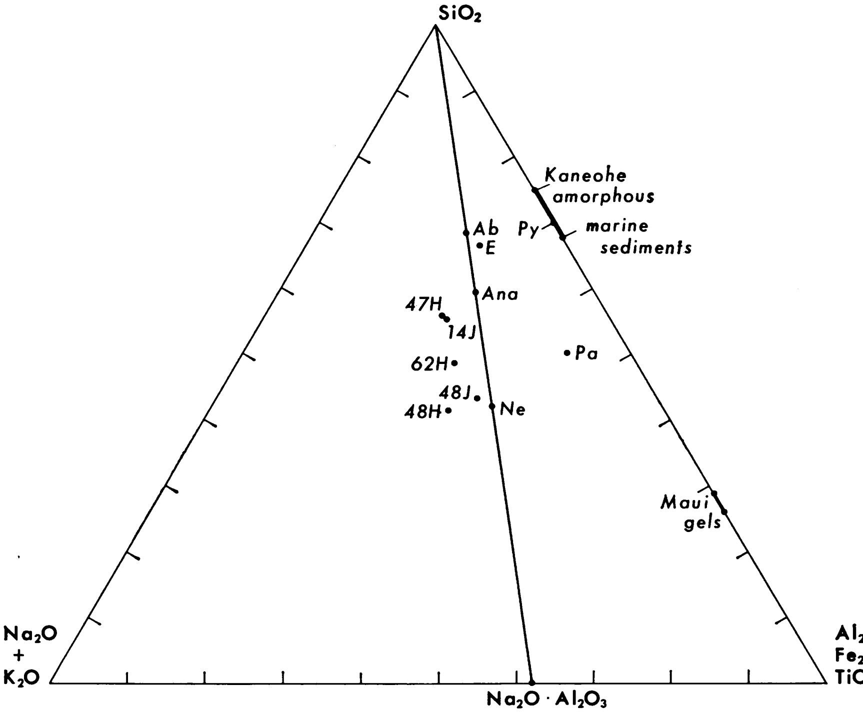

Fig. 3. Plot of anhydrous gel compositions in terms of SiO_2 + (Na_2O + K_2O) + (Al_2O_3 + Fe_2O_3 + TiO_2) = 100. Also shown are the composition of trachyte E (see Table 2), the aluminosilicate composition of allophane gels (*1*) and amorphous marine muds (*7*) from Hawaii, and idealized compositions of albite (*Ab*), analcite (*Ana*), nepheline (*Ne*), paragonite (*Pa*), and pyrophyllite (*Py*, representing montmorillonite clays).

stituents. Silica values are below saturation with respect to amorphous silica and much below those for some typical Magadi brines (*3*), and alumina analyzed by both fluorometric and gravimetric procedures is less than 1 ppm. Therefore the silica and alumina contained in the gels probably derive from decomposition *in situ* of the trachytic debris. Most of the Na_2O is contributed by the springwaters, although some of it, as well as all the K_2O, must come from the trachytic material. The chief difference between the trachyte composition and that of the purest gels is silica, indicating a significant loss of SiO_2 in the conversion. The process can be expressed in a simplified manner by

$$\text{trachyte debris} + Na_2CO_3 \text{ (in water)} \rightarrow \text{gel} + SiO_2 \text{ (in lake).}$$

Assuming that all the alumina present in the trachyte debris remains in the gel, we can draft a balance sheet for the conversion (Table 3). Reaction of 100 g of trachyte debris with the springwaters yields 65 to 75 g of anhydrous gel and releases about 35 g of SiO_2 to the lake brines; in the process, more than 9 g of Na_2O is supplied by the springwaters, and most of the iron remains in the gel. The gain or loss of iron is probably insignificant, as the trachyte specimen used for comparison comes from 1 km west of the gel locality. On the other hand, the K_2O released during the addition of Na_2O is probably real, and this exchange may be a source of K_2O now in the lake brines. Corrosion by the hot alkaline waters is dramatically demonstrated by the shapes of large trachyte boulders that have fallen into alluvial channels (Fig. 4).

Table 1. Values (ppm) by analyses of samples from hot springs in the Lake Magadi area. For sources of 1966 samples, see Fig. 1; for sources of 1932 samples, see Baker (*2*).

Item	M48*	S21 †	M62 *	S19 †	M14 *	S20 †
Year	1966	1932	1966	1932	1966	1932
Li	1.0		1.0		1.2	
Na	12,800	11,576	11,100	11,042	12,600	12,203
K	199		199		239	
Ca	0.0		0.0		0.6	
Mg	.0		.0		.0	
Al	.79		.56		.71	
(Al) ‡ †	(.70)		(.41)		(.41)	
SiO_2	92		90		91	
HCO_3	15,800	14,998	12,400	12,311	15,600	14,926
CO_3	3220	2757	3710	3368	3540	3340
SO_4	155	149	176	162	147	169
F	156	127	144	127	162	149
Cl	6020	5532	5240	5108	5950	5793
Br	115		158		70	
PO_4	9.2		10		11	
B	8.8		8.3		8.8	
Total solids	30,500	27,630	26,600	25,690	30,400	29,130
T (°C)	70.5	67	82.5	81.5	81	81
Field *p*H	8.98		9.13		9.50	

* Analyzed by S. Rettig. † Analyzed by J. A. Stevens. ‡ Gravimetric analysis; values in parentheses were determined fluorometrically by D. E. Donaldson, U.S. Geological Survey.

Table 2. Recalculated anhydrous compositions (percentages totaling 100 percent) of five purified gels, Lake Magadi area, Kenya. Included is trachyte analysis E (*2*), a specimen from 1 km west of the north end of Little Magadi. Samples M47H, M48H, and M62H were dried in air at ambient temperatures, washed in distilled water for removal of efflorescent crusts, and separated from detrital material by heavy liquids (bromoform plus methylene iodide); M47H was then dried at 110°C; M48 and M62H, at 600°C. Samples M48J and M14J were dispersed in water and digested in 30 percent H_2O_2 at 60°C; fractions were drawn off by settling, the final fraction (finer than 2 μ) being removed by high-speed centrifuge. Samples M47H, M48H, and M62H were analyzed by O. Von Knorring; M14J, by L. Shapiro. Values for H_2O^- are ranges obtained for gels as collected. n.d., Not determined.

Item	M47H	M48J	M48H	M62H	M14J	E
SiO_2	53.75	40.14	39.21	46.73	51.50	65.79
TiO_2	1.03	1.29	0.81	0.75	1.26	0.71
Al_2O_3 P_2O_5	11.30	18.00	21.22	19.03	10.65	14.78
Fe_2O_3 FeO	9.61	11.50	6.38	6.72	9.76	6.59
MgO	1.62	2.92	1.40	1.23	2.66	0.59
CaO	1.96	4.47	4.75	3.07	4.20	.41
Na_2O	15.67	18.24	22.54	18.50	13.98	5.85
K_2O	5.06	3.44	3.69	3.96	5.99	5.28
			H_2O^-			
	90–93	52–63	52–63	64–72	72–77	
			Loss on ignition to 900°C (purified samples)			
	61.63	45.94	2.34	2.28	n.d.	

Table 3. Balance sheet for conversion of 100 g of trachyte [recalculated from analysis E (*2*)] to anhydrous gel. The compositions of M48H and M48J have been recalculated on the assumption that the transport of alumina during the dissolution of trachyte is negligible. The balance is schematic because complete dissolution of the trachyte has been assumed.

Item	Trachyte	Anhydrous gel		Supplied by spring (+) or released to inflow (−)	
		M48J	M48H	M48J	M48H
SiO_2	66.94	33.54	27.80	−33.40	−39.14
Al_2O_3	15.04	15.04	15.04		
Fe_2O_3	6.70	9.61	4.52	+ 2.91	− 2.18
Na_2O	5.95	15.24	15.98	+ 9.29	+10.03
K_2O	5.37	2.87	2.61	− 2.50	− 2.76
			Totals		
	100.00	76.30	65.95	−23.70	−34.05

It is conceivable that during the trachyte decomposition some alkali exchange may occur between springwater and feldspar lattices. To check this possibility, we measured by x-ray techniques the composition of feldspar detritus completely enclosed in gel material. The composition was identical within our limits of accuracy with that of phenocrysts of the flow, the suggestion being that the interaction is restricted to the grain surfaces.

The time required for formation of the gels is difficult to estimate but must be rather short. Gel was accumulated only at the surface, and pits dug to depths of 1 to 2 m reveal no older deposits. Therefore most of the deposits are probably seasonal and insufficiently protected for preservation during the high-water stages of the rainy seasons. Hot springs and alkali trachyte flows are common throughout the Magadi basin, but gel deposits form only north of Little Magadi and in Northeast Lagoon; this restriction appears to be explained by water temperature. Springs elsewhere in the basin are considerably cooler (33° to 48°C), and their temperatures may so delay reactions that gels are prevented from accumulating. The algal mats may act as thermal insu-

Fig. 4. Corrosion of alkali trachyte boulders by hot alkaline springwaters. The water temperature is about 60°C.

lators, keeping the waters hot long enough to allow interaction with the trachyte debris.

The high alkali content of the Magadi gels seems to be unique for natural gels. However, the Si:Al ratios are similar to those of the amorphous material in average stream sediments (*6*) and amorphous marine muds (*7*) derived from weathered basalt in Hawaii. Comparison of the gels and allophane in the weathering profile of Maui (*4*) (Fig. 3) with the Kaneohe Bay muds suggests significant sorption of silica from seawater. Probably the only significant difference between the Magadi gels and the products of dissolution of volcanic rock elsewhere lies in the solutes sorbed from the alkaline springwaters.

It is possible that leaching of the Magadi gels by dilute waters may remove much of the Na_2O originally supplied by the alkaline hot springs. This process would probably result in formation of a relatively homogeneous layer of sodic montmorillonite, perhaps not unlike a bentonite bed. The transformation would be analogous to the formation of chert from magadiite (*8*). This idea is supported by the fact that the M14 gel gives very definite, though broad and asymmetric, x-ray reflections at 10.2 and 3.3 Å, the suggestion being a crude-layer silicate structure.

The Magadi gels have interesting geologic implications. If one assumes that most of the gels are washed into the lake and that annually new deposits form in the same places, a considerable accumulation of gel material may result. If incorporated into the lake beds, gels may eventually crystallize to zeolites, particularly analcite (*9*). Most analcite in lake beds forms from zeolite precursors such as clinoptilolite, erionite, or phillipsite (*10*), but some may have grown from gelatinous material.

If hot alkaline waters react with rocks very rich in alkali feldspars (about $Ab_{60}Or_{40}$) to form sodium-aluminum silicate gels, the same springwaters would produce sodium silicate gels by reaction with quartz-rich rocks. Such gels would also be plastic, but they would most likely be converted to chert through subsequent leaching of sodium; some of the Pleistocene chert-series rocks of the Magadi basin (*2*) may have originated in this way. Unlike the magadiite bed (*8*), which is probably a lake-wide chemical precipitate, the chert-series rocks must have originated from hot-spring areas similar to the ones of the areas of the gel deposits. Baker (*2*) noted the alignment of the cherts along apparent fault lines. Some of the cherts have fold textures that strikingly resemble those of the algal mats of Fig. 2; in other instances, protuberances of chert were pushed into the under- and overlying mud layers, and there are casts of mud cracks and salt crystals—probably gaylussite.

All these features indicate the soft, gelatinous nature of the original deposit. Because amorphous silica deposits are usually porcellaneous (*1*) rather than gelatinous, we postulate soft sodium silicate gels, formed by the interaction of alkaline hot-spring waters with silica-rich materials, as precursors of many of the chert-series rocks. This origin for chert deposits could be fairly common in volcanic terranes.

Alkaline springs are not very common today (*11*), but during the early Precambrian igneous terranes presumably constituted a larger proportion of Earth's surface and alkaline waters may have been more common, so that silicate gels then formed more often. Such gels may have acted as substrates for the accumulation and preservation of prebiological organic compounds (*12*). Abelson (*13*) has reasoned that an alkaline medium would be the most suitable for initial natural synthesis of organic compounds.

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