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# The Vinland Map, Revisited: New Compositional Evidence on Its Inks and Parchment

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**The Vinland Map, once considered the first cartographic evidence of the North American continent, purportedly dates from the mid-15th century. In 1974 compositional evidence derived from microparticles removed from its surface led McCrone Associates to conclude that ink in the Map was made up of 20th century titanium-based pigments containing up to 50% anatase (TiO<sub>2</sub>) and that the Map was therefore a forgery. Recently at Davis, 159 multielemental PIXE (particle induced X-ray emission) analyses of the Vinland Map were performed, including spatial analyses of the parchment, 33 closely matched ink-parchment pairs, and transects across inked lines with 0.5 mm resolution. The results show that titanium and other medium and heavy elements are present in only trace amounts in the inks, with titanium reaching a maximum value of 10 ng/cm<sup>2</sup>, or about 0.0062% by weight. In the light of these results the prior interpretation that the Map has been shown to be a 20th-century forgery must be reevaluated.**

The Vinland Map of the Beinecke Rare Book and Manuscript Library at Yale University was for several years after 1965 thought to be the first cartographic evidence of North America, as well as a rather complete charting of other areas of the world, including the Far East. Extensive discussion of the possible historical setting of the Map can be found elsewhere (1, 2). Since the date of the document is purported to be the mid-15th century, it seemed to indicate a more extensive knowledge of the world than previously thought to exist in the time before Columbus. However, questions about its origins and authenticity were raised and have persisted since its discovery. For this reason, compositional studies were performed in 1974 by McCrone Associates (3, 4) on 29 microparticles removed from the surface of the Map and 25 microparticles removed from two other documents, the Tartar Relation and the *Speculum Historiale*, that are possibly associated with the Map. The results of these studies were interpreted as showing that the Map was a 20th-century forgery, made by drawing the map twice, first in a yellow-brown line and then overdrawing this line with a black ink which was partially chipped away in order to simulate antiquity. It was reported that the ink drawn first was a "firmly adhering yellow-brown substance containing up to 50% anatase, a form of titanium dioxide" (3). Since ink pigments based on crystalline TiO<sub>2</sub> became available only in the 1920s, McCrone Associates concluded the Map had to be a forgery. A critical analysis of the 1974 study by Towe (5) raised a

number of questions regarding the earlier work without challenging its conclusion.

There has been continuing interest in the Vinland Map as either an important document in cartographic history or an exceedingly clever forgery. In order to answer some of the outstanding questions concerning the Map's composition, we undertook to examine the Vinland Map, the Tartar Relation, and the *Speculum Historiale* using nondestructive techniques that do not require the removal of any material from the documents.

## EXPERIMENTAL SECTION

With the cooperation of the Beinecke Rare Book and Manuscript Library of Yale University, the Vinland Map, the Tartar Relation, and the *Speculum Historiale* were flown to the Crocker Nuclear Laboratory, University of California, Davis. The Crocker Historical and Archaeological Projects team and representatives from Yale University subjected the documents to 2 days of study and analysis. We took numerous photographs in reflected light, transmitted light, and long and short wave ultraviolet light, and obtained 32 colored microphotographs from among the over 100 locations microscopically examined on the Map. With the optical studies and earlier work as guides, we made 159 elemental analyses of the Map's parchment and ink using the proton milliprobe. In addition to the 159 analyses of the Vinland Map, we made 45 elemental analyses of the parchments and inks of the Tartar Relation and the *Speculum Historiale*.

The Davis proton milliprobe consists of a beam of 4.5-MeV protons with dimensions that can be set in the range of 0.1-25 mm<sup>2</sup>. For the present study the beam was collimated to 1.0 mm × 0.5 mm, since the width of an inked line on the Map is on the order of 0.5 mm. The energetic proton beam passes out of the vacuum system of the Crocker Nuclear Laboratory's 76" (193 cm) isochronous cyclotron, through about 3 cm of air, generates X-rays while passing through the sample, and is collected by a Faraday cup (Figure 1). A Si(Li) energy dispersive X-ray detector is placed about 2 cm from the sample, resulting in a large solid angle and absolute efficiency (6-8). The technique gives a minimum detectable limit of a few parts per million by mass of the sample in 2 min, for all elements from silicon through uranium, although rare-earth sensitivities are poorer due to common elemental interferences (9). A vital point is that the PIXE milliprobe system is completely harmless to even fragile, thermally insulating materials such as paper (10), so that small parts of large objects can be safely analyzed without the necessity of removing aliquots from their surfaces.

All Davis PIXE programs operate under formal quality assurance protocols, most of which utilize an independent research laboratory for validations (9, 11). In these studies, three standards were used: two Micromatter, Inc., thin elemental standards (Fe, Pb) and NBS-SRM 1533, a thin-film multielemental standard covering over a dozen elements heavier than silicon. Each standard was run twice to ensure consistency as well as absolute accuracy. Finally, since the technique is nondestructive, a standard parchment sample from about 1180 A.D. was analyzed at precisely the same location used on scores of previous tests since 1978. Two runs were made on the parchment. The full agreement of all analyses to within the nominal ±5% absolute accuracy was achieved before the tests were begun.

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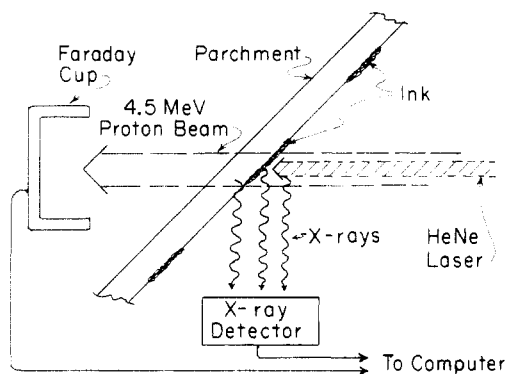


Figure 1. Schematic diagram of the Davis external PIXE milliprobe.

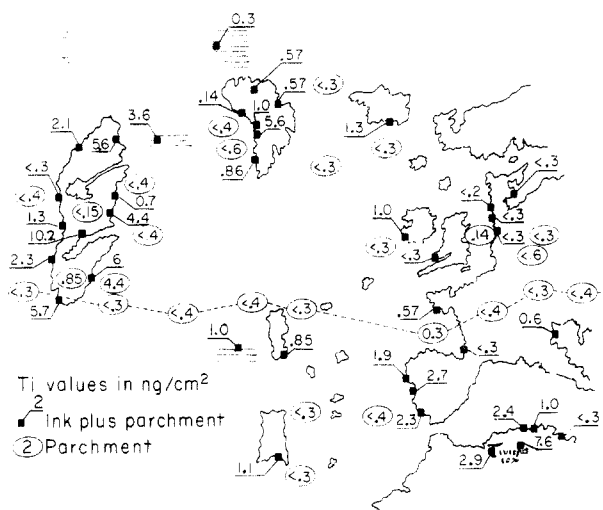


Figure 2. Titanium levels for part of the Vinland Map. The values in ellipses give titanium in  $\text{ng}/\text{cm}^2$  for the parchment, while analyses of ink, also in  $\text{ng}/\text{cm}^2$ , are underlined. Note that, while all titanium values are low, the highest values occur in "Vinland", "Algeria", and "Spain".

## RESULTS AND DISCUSSION

The full results of the study, including selected microphotographs, are included in a 75-page report to Yale University (12). The results of all elemental analyses for the 18 most common elements detected by PIXE are included in Appendix A of that report, as are internal and external quality assurance protocols.

The elemental analyses by the proton milliprobe of the Vinland Map parchment showed that it is similar to other parchments studied at Davis. We found titanium in the Vinland Map parchment in several locations (at the  $\text{ng}/\text{cm}^2$  level), along with iron, zinc, and a number of lighter elements including sulfur, chlorine, potassium, and calcium. We have detected titanium in several other early parchments in similar amounts. These include a 12th-Century Italian manuscript, a 13th-Century Oxford Bible, a 1457 Mainz Psalter, a 1470 Donatus (*Speculum*), and a 1470 Donatus (*Saliceto*). However, we found no titanium in the Tartar Relation or the *Speculum Historiale* above the minimum detectable limit. The locations of all analyses for the part of the Vinland Map that shows the North Atlantic are seen in Figure 2. Figure 3 shows transects across the parchment, first west to east, then north to south, for three common transition metals: titanium, iron, and zinc.

The compositional complexity of the parchment, including its titanium, and the very low levels of titanium in the ink, made efforts to isolate the composition of the ink alone more difficult than in our studies of ink on papers, for most individual sheets of paper are relatively homogeneous chemically. Since the proton milliprobe analyzes the entire sample, ink and parchment, the values for the ink are summed with the values from the underlying parchment (Figure 1). The two

Table I. Ink-Parchment Pairs (Ink-Plus-Parchment Value)/(Parchment Value), All Values in  $\text{ng}/\text{cm}^2$ <sup>a</sup>

pair	Ti	Fe	Cu	Zn	other <sup>b</sup>
1	10.2/<0.3	2.5/1.6	0.9/0.5	1.4/1.3	
2	0.3/<0.3	1.1/1.5	0.7/0.2	0.8/0.7	
3 <sup>c</sup>	5.9/2.6	1.9/2.7	0.8/0.9	3.3/8.6	
4	0.7/<0.4	1.3/1.5	0.3/<0.3	0.5/0.5	Co/-
5	3.6/<0.3	0.9/1.4	<0.1/<0.2	0.5/<0.2	
6 <sup>c</sup>	4.4/<0.3	1.6/1.5	0.4/0.5	0.6/1.1	Co/-
7	1.0/<0.5	0.6/0.9	<0.1/<0.3	0.7/<0.3	-/Mn
8	0.4/0.5	0.6/0.9	<0.1/<0.2	0.4/<0.2	-/Mn
9	1.0/<0.3	0.8/0.8	<0.1/<0.1	<0.1/<0.1	
10	<0.2/<0.2	0.7/0.9	<0.1/0.2	0.6/0.4	-/Mn
11	<0.2/<0.6	0.6/<0.5	<0.1/<0.7	0.4/<0.9	
12	5.6/<0.4	2.3/1.6	1.2/0.6	8.3/3.8	
13 <sup>d</sup>	5.6/<0.2	0.8/1.2	<0.1/0.3	0.6/2.7	
14 <sup>d</sup>	0.2/<0.4	0.7/<0.1	<0.1/<0.2	0.5/<0.2	
15	3.5/0.4	0.6/0.9	<0.1/<0.1	0.5/0.5	
16	1.9/<0.4	1.0/<0.2	<0.1/<0.2	0.5/<0.2	
17	2.1/<0.3	0.7/<0.1	<0.1/<0.1	<0.2/<0.1	
18	1.9/<0.4	0.8/<0.1	<0.2/<0.2	<0.2/<0.2	
19	0.5/<0.3	1.4/0.9	0.3/<0.1	0.7/0.4	
20	0.9/0.6	0.9/1.0	<0.1/<0.2	0.7/1.1	
21 <sup>d</sup>	0.8/<0.3	0.8/0.8	<0.1/<0.2	0.2/<0.2	
22 <sup>c</sup>	0.3/<0.3	0.8/0.9	<0.1/0.1	0.4/0.3	
23	1.9/<0.3	0.6/0.6	<0.1/<0.1	0.6/<0.2	
24	0.2/<0.3	0.9/0.9	<0.1/<0.1	0.4/0.5	
25	1.2/<0.3	0.7/1.0	<0.1/<0.1	<0.1/0.4	
26	0.4/<0.2	0.9/1.1	0.3/0.6	<0.1/0.7	
27	1.1/0.4	0.8/1.3	<0.1/<0.2	0.3/<0.2	
28	2.7/<0.3	0.8/1.4	0.2/<0.2	0.5/0.4	
29	<0.3/<0.3	0.6/<0.1	<0.1/<0.2	<0.1/<0.2	
30	0.3/<0.5	0.5/<0.8	<0.1/<1.2	0.4/<1.5	
31	1.3/<0.3	0.7/<0.1	<0.1/<0.1	<0.1/<0.2	
32	<0.2/<0.2	0.7/1.0	<0.1/<0.1	0.7/0.5	
33	1.6/<0.3	1.3/0.8	<0.1/<0.1	0.9/0.6	

<sup>a</sup>Typical uncertainties,  $\pm 0.2$ ;  $3\sigma$  minimum detection limits marked by a <. <sup>b</sup>The elements S, Cl, K, and Ca were found in every parchment analysis. <sup>c</sup>Parchment value is average of two different locations. <sup>d</sup>Ink-plus-parchment value is average of two different locations.

Table II

Occurrence of Selected Elements in the Vinland Map Ink Taken from the 33 Ink-Parchment Pair Analyses

elements	frequency of occurrence	av value, $\text{ng}/\text{cm}^2$
Ti	65%	(2 $\pm$ 2)
Zn	35%	(0.7 $\pm$ 1.0) <sup>a</sup>
Fe	35%	(0.6 $\pm$ 0.2)
Cu	12%	(0.4 $\pm$ 0.2)

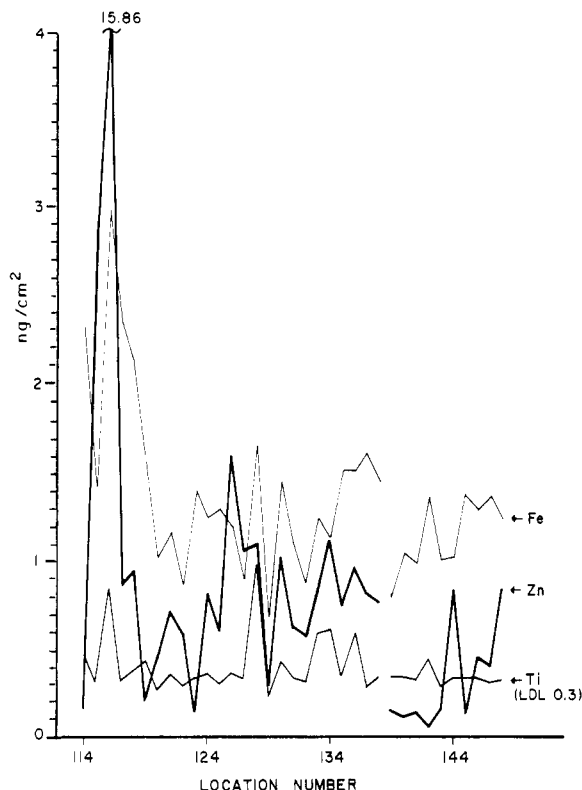
Frequency of Occurrence of More Than One Element in an Analysis

Ti and Zn	24%	Fe and Cu	9%
Ti and Fe	24%	Ti, Zn, and Fe	9%
Ti and Cu	9%	Zn, Fe, and Cu	6%
Zn and Fe	18%	Ti, Zn, Fe, and Cu	6%
Zn and Cu	6%		

<sup>a</sup>Omitting run 52 (Zn = 4.5), Zn av = 0.31  $\pm$  0.08.

methods that yielded the most satisfactory results for isolating the composition of the ink alone were as follows: first, to pair each analysis of ink-plus-parchment with an analysis of an immediately contiguous parchment location alone, and second, to make transects across inked lines.

The results of the paired analyses are given in Table I and II. About two-thirds of all ink samples showed titanium, but the highest level encountered was only 10.2  $\text{ng}/\text{cm}^2$ . The lack of uniformity in the ink is indicated by the lack of correlation between the titanium content and other transition metals, zinc, iron, and copper, which were also present in only trace



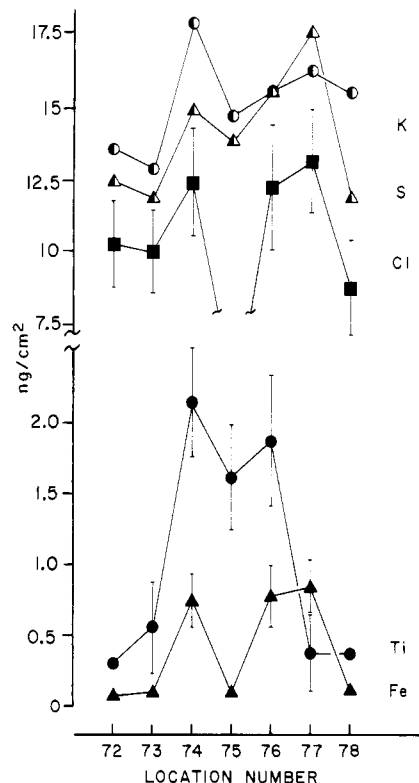
**Figure 3.** Parchment transects for titanium, zinc, and iron, in  $\text{ng}/\text{cm}^2$ . The locations 114 to 138 represent a west to east transect across the middle of the Map (the first nine locations are shown in Figure 2), while locations 139 to 149 represent a north to south transect of the "Atlantic Ocean".

amounts (Table I). Compositions tended to be similar in adjacent areas of the Map, but no clear patterns emerged. The left edge of the parchment was rich in transition metals, including titanium. Relatively high titanium readings in the ink occurred in the "Vinland" region, but also in Spain, "Tunisia", and "Japan" (Figure 4), while the low titanium values were found in "Greenland", most of Europe, and "India". Transitions in ink composition along a single line could occasionally be followed.

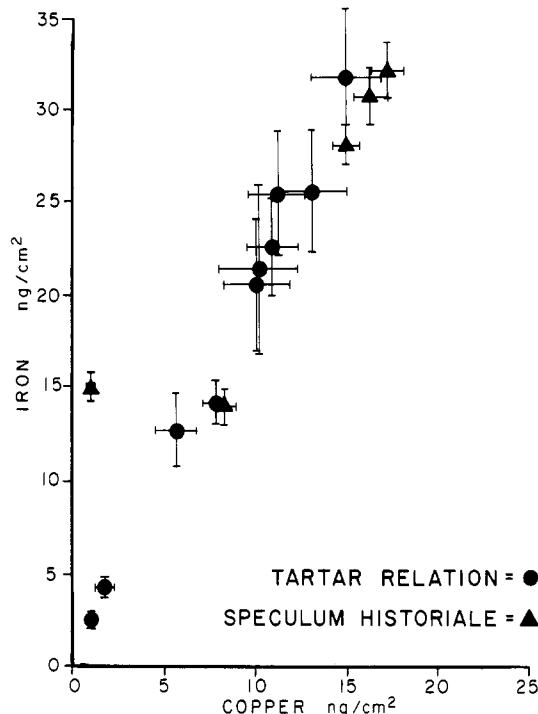
Figure 4 shows a transect across a black-inked line. In this figure, the presence of a "rimmed" ink line is shown in the elemental analyses, and microphotographs show visually that the ink trace is fainter in the center of the line than at the edge or "rim". Another transect across a dark inked line on the western coast of Europe showed relatively high iron and zinc in the ink, but no titanium above that occurring in the parchment. This further illustrates the high degree of variability in ink composition. Because of the importance of this result, the analysis was repeated, yielding results identical within an average of  $0.07 \text{ ng}/\text{cm}^2$  for iron and zinc, illustrating a precision of better than 5% at the sub-part-per-million level. Again, no titanium was found above that occurring in the parchment alone. Such variability was not unexpected by us, since in several hundred earlier analyses done at Davis on parchment manuscripts, we have had to deal with a high level of compositional variability of ink and parchment even within a single page.

The inks of the Tartar Relation and the *Speculum Historiale* were very similar to each other but different from those of the Vinland Map (Figure 5). While they have higher metallic content than the Vinland Map inks, most of their ink mass consists of elements lighter than silicon, most likely carbon and organic binders common in typical iron gall inks of the times.

**Comparison with Earlier Work.** McCrone Associates' argument is that the presence of anatase crystals of what they



**Figure 4.** Transects across a single line of ink on the coast of "Japan(?)", from east to west. Values for sulfur, chlorine, potassium, titanium, and iron show enhancement in the ink. The "rimmed" ink can be seen in all transects, since the edges are blacker than the middle. The distance from location 72 (parchment, east) to 78 (parchment, west) is about 3 mm.



**Figure 5.** Relationship of copper to iron in the inks of the Tartar Relation and the *Speculum Historiale*. Great similarities are seen in these inks, favoring a hypothesis of a common source for these two documents.

believe to be modern origin in the yellowish brown ink is proof that the Vinland Map is of 20th century manufacture. They allege that modern  $\text{TiO}_2$  was the source of the yellowish brown pigment in a separately applied underlayer on the Vinland Map. This was intended by the forger to look like the vestiges

of lines of 15th century inks that have their black layer flaked away. We found about one-third of all inked lines showed no titanium whatsoever above our minimum detectable limit of  $0.2 \text{ ng/cm}^2$  and yet the yellowish brown color is clearly visible. We therefore conclude that  $\text{TiO}_2$  could not possibly be the base of the yellowish brown pigment of the alleged underlayer. It must be noted that a yellowish brown color in an anatase-based pigment is usually due to iron impurities of a few percent. The same modern manufacturing methods that produce uniform anatase crystals also ensure that the pigment is free of impurities giving the brilliant white for which the product is so well known.

In order to compare the McCrone Associates relative values (3) to our areal mass values (mass per unit area), an estimate had to be made of the total mass of ink adhering to the parchment. We performed a short study during which three sources of titanium pigment were diluted by solvents into inks that were capable of giving fine lines similar in dimension to those on the Vinland Map. Two were oil-based artist paints (Grumbacher Titanium White and Grumbacher Quick Drying Titanium White) and the third was a modern error correction fluid (Rembrandt Opaque White). Fifteen lines were drawn on a 17th-century parchment that has an elemental composition similar to that of the Vinland Map. Line widths varied from 1.5 mm to the thinnest that could be applied, about 0.7 mm. Further, half of a 1 mm wide line was deliberately erased, to the point where no observer could, by eye, detect the presence of the line continuation. The pure white  $\text{TiO}_2$  pigments used in this test stood out even more clearly than yellow pigment on tan parchment, and thus we were assured visually that the erasure was complete.

The lines were scanned by the PIXE milliprobe as was done in the case of the Vinland Map analysis. The results show, for all pigments (Ti or Ti + Zn) and all lines measured, a mean pigment mass of  $1400 \pm 750 \text{ } \mu\text{g/cm}^2$ . The minimum value of titanium seen in the thinnest line was  $230 \text{ } \mu\text{g/cm}^2$ . When we determined the level of titanium in the erased line we found it still had  $400 \text{ } \mu\text{g/cm}^2$  of titanium. This was not unanticipated, since to make fine lines, inks had to be used that were observed under magnification to penetrate the parchment fibers. Even McCrone points out that the yellowish brown color is "in a line that tightly adheres to the parchment fibers" (13).

Thus we find it inconceivable that erasure or wear can reduce any titanium pigment from the minimum titanium value of  $230\,000 \text{ ng/cm}^2$  we see in these tests to the maximum titanium value of  $10 \pm 2 \text{ ng/cm}^2$  we see in the Vinland Map. Assuming that the entire ink mass had the composition of the particles McCrone Associates removed in the earlier study (up to 50% anatase or 30% titanium), there would be about  $69\,000 \text{ ng/cm}^2$  of titanium for the minimum value, as contrasted with our maximum observation of  $10.0 \pm 0.8 \text{ ng/cm}^2$ . Likewise, reasoning from the McCrone Associates data, the average level of titanium (12% by weight) would have been  $27\,600 \text{ ng/cm}^2$ , contrasted with  $2.0 \text{ ng/cm}^2$  that we found.

It must be realized that the McCrone Associates conclusions about the heavy concentration of anatase in the ink of the Vinland Map rests on one X-ray diffraction pattern and four electron diffraction patterns from particles less than  $8 \text{ } \mu\text{m}$  in diameter, weighing less than about  $100 \text{ ng}$  (3), plus qualitative observations of optical behavior. The McCrone Associates data also demonstrated a high degree of compositional variability from particle to particle. Our results show that it is not valid to generalize about the composition of the ink as a whole from these small aliquots. When we tested dozens of ink locations throughout the Map, we found that the amount of titanium in the ink is at most only 0.007% of the average amount estimated by McCrone Associates extrapolating from the aliquots they tested.

lating from the aliquots they tested.

McCrone Associates concluded that a forger made a double application of ink, laying a black ink over a previously applied yellowish brown ink. The results of extensive observation of the Map with a 10–15 $\times$  light microscope both at Davis and at the Beinecke Library show that the visible ink trace does in fact consist of two components. The first is a yellow-brown color absorbed into the fibers and varying considerably in intensity. The second component is a dense black film loosely adhering to the surface which has flaked away to a great extent. The darkness of the ink to the eye is largely a measure of how many of the black particles remain. McCrone Associates have suggested that the black component was separately applied and deliberately flaked off the yellow-brown underlayer to simulate age and to disguise less than perfect register between the two components (4). Our microscopic examination however, leads us to the hypothesis that the lines were a result of a single application of ink which separated into layers over time and whose black film on top chipped off, as is widely seen in vellum manuscripts. We observed excellent register throughout the Map even in the extremely fine inscriptions, typically to about 0.1 mm. The original edges of the lines can be seen clearly in nearly all parts of the Map and even in the more faded yellowish brown sections of the lines small residual black particles usually extend to the clearly defined limit of the original edge.

In one location on the coast of Wales there is a small discrepancy between the black and yellow which has been observed previously (5). The fact that in this one place there seems to be a double application of ink is no proof that the work was done by a forger. For comparative purposes we carried out an inspection, with 16 $\times$  magnification of many 15th and 16th century vellum manuscripts of undoubted authenticity housed at the Bancroft Library at the University of California, Berkeley. The manuscripts examined at the Bancroft Library are a mixture of vellum legal and religious documents with the following identification numbers: f2MS/A2M2/1400: 3,4,6,7,9,11,50; 1500: 1,2,4,5,6; ff2MS/A2M2/1400: 50; 1500: 8,9,10,11,14. We found that ink characteristics such as are seen in the Vinland Map are common, where the black layer of pigment is flaked off, leaving patches and specks of black on brownish yellow vestiges of lines. There are many places in these documents where the brownish yellow vestigial lines appears alone, without any trace of black on them, and other places where parts of brownish yellow lines are out of the registration completely with the blacker vestiges of lines. In any case, there is no reason for postulating that a forger made a double application of ink on the Map in the first place, since titanium cannot be the source of the yellowish brown pigmentation of the lighter lines in the Vinland Map, as we have shown.

Because our investigations have thrown the question of its authenticity open again, we recommend additional scientific investigation of the Vinland Map. One obvious step would be to determine the age of the parchment by using modern carbon-14 techniques that would require that only a few milligram sample of the parchment be used. Of course, carbon-14 analysis will have a major effect on interpretation only if the parchment is proved to be modern. It is possible that a forger could have obtained an old sheet of parchment dating from the 15th century.

In conclusion, we must stress that, while our work argues strongly against the specific McCrone Associates proof that the Map is fraudulent, we do not claim therefore that the Map is authentic. Such a judgement must be based on all available evidence, cartographic and historical as well as compositional.

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**Registry No.** Ti, 7440-32-6; Zn, 7440-66-6; Fe, 7439-89-6; S, 7704-34-9; Cl<sub>2</sub>, 7782-50-5; K, 7440-09-7; Cu, 7440-50-8.

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## Surface Acoustic Wave Devices as Chemical Sensors in Liquids. Evidence Disputing the Importance of Rayleigh Wave Propagation

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**The role of Rayleigh wave propagation in liquid-loaded ST-cut X-propagating quartz surface acoustic wave (SAW) devices with design frequencies of 10, 30, 31, and 50 MHz has been investigated. Variations of device substrate thickness combined with liquid loading experiments strongly suggest that the dominant mode of energy propagation is not due to Rayleigh waves in thin (thickness < 5 wavelengths) substrate devices. Thicker substrate devices show behavior not inconsistent with Rayleigh wave propagation at the design frequencies but are not useful as sensors at their Rayleigh wave design frequencies due to severe signal attenuation upon liquid loading. The results have implications for the design of SAW devices as chemical sensors for operation in liquid media.**

Recently, a number of reports (1-9) have appeared that describe the operation of bulk wave piezoelectric microbalances directly in a liquid environment. This has opened up exciting new possibilities for chemical sensors, since it was previously believed (10-12) that these devices could only operate in contact with the gas phase. Other recent work (13) has suggested that surface acoustic wave (SAW) devices may be superior to bulk wave devices in sensor applications mainly due to the fact that it is easy to fabricate SAW devices which operate at much higher (and more mass sensitive) frequencies

than nonovertone bulk wave devices. This perceived advantage has led to at least one report (14) on the use of a SAW device as a liquid-phase-based chemical sensor.

The operation of SAW devices has been described previously (15). Basically, Rayleigh surface acoustic waves can be generated on smooth, piezoelectric crystal surfaces with an interdigital transducer (IDT) that is microfabricated onto the active surface of the SAW device. The IDT consists of a number of interdigital "fingers" whose spacing determines its resonant frequency (and acoustic wavelength) and whose overlap aperture determines its electrical impedance. Radio frequency voltages applied to these electrodes produce a synchronous mechanical stress in the crystal. This results in an acoustic wave having longitudinal and vertical shear components that is "transmitted" bidirectionally away from the IDT, Figure 1. The Rayleigh wave can be "received" by a corresponding IDT located on the same surface since the mechanical vibrations on the piezoelectric substrate produce a voltage on the IDT experiencing the vibrations. Theoretically, an ideal SAW delay line using bidirectional IDT's will exhibit an insertion loss of 6 dB (3 dB for each IDT) when the crystal is lossless and the electrical impedances of the IDT's are perfectly matched.

It is well-known that Rayleigh waves have most of their energy confined to a region very near the "top" surface upon which they were generated. Indeed, this is what makes SAW