20 April 1979, Volume 204, Number 4390 **SCIENCE**

Venice: Sea-Lagoon Exchange in a Modified Tide Regime

A black box model predicts material residence times in a simulated lagoon after entrance size reduction.

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Summary. Salinity and tide heights recorded for a month at P_0, a point in the northern section of the Venetian lagoon, are the basic experimental data used to construct a numerical model which describes the salinity variations at P_0 as a function of the tides measured at the Lido entrance. The time variation of the salinity pattern is interpreted in terms of a lagoon system in which a freshwater source of constant intensity is in a quasi-steady equilibrium with a tide-modulated sink. The mean residence time of a contaminant in this simulated lagoon is predicted from the change in the salinity pattern due to a reduction in the entrance size.

The so-called "acque alte," storm tides rising above the level of the historical center of the city of Venice (*1*), have once again in the history (*2*) of this city raised the problem of a massive artificial modification of the hydraulic system of the lagoon. In 1975 the Italian government promoted, through specific directives (*3*), the construction of "devices" designed to eliminate or at least to reduce the tides. The proposals submitted by specialized firms at the end of 1976 are at present under examination by an ad hoc committee and have not been made public.

Since the narrowing of the entrances between the sea and the lagoon would lower the tide height inside the lagoon (*4*), permanent barriers, such as would provide a constant reduction in the size of the entrances, might satisfy the directives. Such a solution gives rise to another problem, that is, to what degree a permanent narrowing of the openings would modify the exchange of material between the lagoon and the sea. The present contamination of the lagoon (*5*) and the consequent sporadic occurrence of plankton blooms (*6*) highlight the importance of this question.

A numerical calculation of lagoon water renewal as a function of the mass flux at the entrances can be obtained by various methods. Tentatively, we can speak of two lines of approach: classical hydrodynamics (*7*) and environmental physics. With the latter approach, one aims to find parameters determining sea-lagoon transport balance both by phenomenological observation and by ad hoc experiment without constructing detailed explicit models.

There have been no environmental physics approaches to the Venice problem in our national scientific community. In 1975 the Consiglio Nazionale delle Ricerche (CNR) appointed Vittori to the directorship of the Venice Laboratory and entrusted him, among other responsibilities, with the responsibility of investigating the tidal flushing of contaminants in the lagoon. So far (May 1978) Vittori has been unable to establish a large enough research group to properly deal with this problem. This explains the limitations of the approach presented here for a problem of great complexity and importance.

There exists only a limited and localized set of experimental data. We use them to describe, through a crude "black box" model, the exchange of material in a simulated portion of the Venetian lagoon and to predict changes that occur after a size reduction of the lagoon entrance.

Formulation and Purpose of the Model

Nyffeler *et al.* reported observations of the salinity S and the tide height η, recorded for 1 month at a point that we call P_0 (*8*); P_0 is located in a canal which leads from the Lido entrance to the north lagoon. A water course discharges freshwater in the vicinity of P_0.

The set of data depicts a lagoon that is periodically mixed with the sea: S is lower in the lagoon than in the open sea, and values of S increase with the flood tide and decrease with the ebb tide.

The sea ($S = S_0 = 34$ milligrams per liter) is the only source of salt at P_0, and a constant supply of inland freshwater is the only cause of a reduction of the salt concentration. The quantity S/S_0 expresses the proportion of seawater at P_0 in the lagoon, and $1 - S/S_0$ expresses the proportion of freshwater. This assumption appears realistic since the flux of inland freshwater in the lagoon is of the order of some millimeters per hour (*9*), far greater than its loss by evapora-

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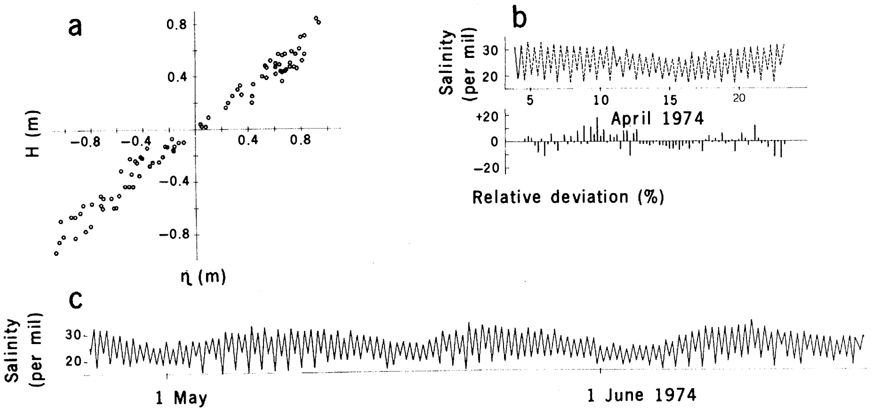

Fig. 1. Outline of the P_0 lagoon. (a) The tide height, η, at P_0 plotted against the tide height, H, at the Lido entrance of the lagoon. (b) Performance of the model: the solid line showing the first one and one-half cycles represents the experimental data inserted in the model; the broken line is the resulting predicted series. The relative deviation (in percent) between predicted and real S is shown below. (c) A sample of the simulated time S pattern in the H extended series. The record of H covers several years.

tion and far greater than its gain by rainfall since only a few hours of light rain fell during the entire sampling period (*8*). No abrupt change in the freshwater flow could be expected to occur during the dry sampling month (April 1974).

Tides drive the fluctuations in S. Changes are caused by both tide-induced transport of saline water and mixing due to turbulence (*10*). The near-uniformity of temperature and S that is found along the vertical at P_0 shows that turbulent mixing overcomes the stability resulting from the nearby freshwater inflow (*11*).

The tide height η at P_0 is proportional to the tide height H at the entrance (namely, the Lido). The experimental data give $\eta = 0.8\,H$ (Fig. 1a). The interpretation of this tide height reduction through a simplified picture of tide propagation in shallow water appears consistent with observations of the small lag between $S_{\max}$ and $\eta_{\max}$ (*12*).

If the above picture is accepted, S can be expressed as a function of the tide height now and of tide and S changes extending over several cycles in the past. We write

$$(S_{\max,i} - S_{\min,i}) = f(H_{\mathrm{f},i-k}, H_{\mathrm{e},i-k}, S_{\max,i-k}, S_{\min,i-k}) \times (S_0 - S_{\min,i}) \qquad \text{(1a)}$$

$$(S_{\min,i} - S_{\max,i-1}) = \phi(H_{\mathrm{f},i-k}, H_{\mathrm{e},i-k}, S_{\max,i-k}, S_{\min,i-k}) \times S_{\max,i-k} \qquad \text{(1b)}$$

where $S_{\max,i}$ and $S_{\min,i}$ are the maximum and minimum values of S at the ith cycle corresponding to the flood, $H_{\mathrm{f},i}$, and the ebb, $H_{\mathrm{e},i}$, values of H, respectively; k refers to the kth cycle preceding the ith; and f and ϕ are transfer functions that depend linearly on H and S.

The numerical coefficients in Eq. 1 are obtained by linear regression analysis. The following numerical relationship is obtained:

$$(S_{\max,i} - S_{\min,i}) = [0.572(H_{\mathrm{f},i} - H_{\mathrm{e},i}) + 0.317(H_{\mathrm{e},i} - H_{\mathrm{f},i-1}) - 0.012\,5(S_{\min,i} - S_{\max,i-1}) - 0.00954(S_{\max,i-1} - S_{\min,i-1}) + 0.0440 S_{\max,i-1} - 0.729](S_0 - S_{\min,i}) \qquad \text{(2a)}$$

and

$$(S_{\min,i} - S_{\max,i-1}) = 30.314(H_{\mathrm{e},i} - H_{\mathrm{f},i-1}) + 0.296(H_{\mathrm{f},i-1} - H_{\mathrm{e},i-1}) - 0.0194(S_{\max,i-1} - S_{\min,i-1}) - 0.00139(S_{\min,i-1} - S_{\max,i-1}) - 0.00739 S_{\min,i-1}]S_{\max,i-1} \qquad \text{(2b)}$$

In Eqs. 1 and 2 only the values of H and S for the preceding cycle appear. The standard stepwise procedure for determining the significance of the terms in Eq. 1 assigns significance only to these cycles.

The predictive value of the model is shown in Fig. 1b. The deviations (in percent) of the predicted values from the observed values of S have a standard deviation of 5 percent. This is close to the experimental error and much less than the fluctuation (about 17 percent) of the S maximum over the period of the data, one lunar month. The interpretation of the tide attenuation at P_0 in terms of a simple frictional mechanism and the accuracy and simplicity of the predictive model give confidence in the use of the regression formula to describe S outside the period of measurement.

Assuming a freshwater source of constant intensity and a periodic sink, we now compute the mean residence time of the freshwater in the system by applying our formula iteratively, cycle by cycle, to an extended experimental time series of H. To do this it is not necessary to predict the actual S pattern. The extended S series is taken as describing the P_0 lagoon with the same boundary conditions as those existing during the sampling period.

As for the validity of the extrapolation to H outside the experimental range, it may be said that (i) the model is capable of covering a wide range of H (Fig. 1b), (ii) the extended H series has only a few terms that are outside the upper range of the experimental set, and (iii) we have no physical reasons for assuming a marked change in Eq. 2 for extrapolated H outside the experimental range.

The residence time of the freshwater in the system is then compared with that resulting from a reduction in the sizes of the lagoon entrances. For any model, an extrapolation to the tide regime as modified by entrance size reduction is necessary.

Interpreting the Extended S Series

The pattern of the extended S is shown in Fig. 1c. It is a lagoon system consisting of a freshwater source in a quasi-steady state with its sink modulated by both high (semidiurnal cycle) and low (neap-spring cycle) frequency pulses.

In the first half of a semidiurnal tidal cycle the incoming seawater reaches its minimum dilution as a result of mixing with the existing P_0 lagoon water, whereas in the second half its maximum dilution is the result of its mixing with the "local" freshwater source. The seawater mass flux increases from neap tide to spring tide and decreases in the successive inverse lunar cycle. These are the physical processes responsible for the high- and low-frequency cycles seen in Fig. 1c. Such systems can conveniently be described in terms of a mean residence time τ, defined by

$$|\bar{J}|_{\mathrm{s}} = |\bar{J}|_{\mathrm{p}} = \frac{\bar{C}}{\tau} \qquad (3)$$

where $|\bar{J}|_{\mathrm{s}}$ and $|\bar{J}|_{\mathrm{p}}$ are the mean intensities of the material source and sink, respectively, as computed through the temporal variation of the material of average concentration $\bar{C}$; τ is the mean residence time of the material in the system (*13*).

The mean residence time for the low-frequency component of $1 - S/S_0$, τ^*, expresses the renewal time of an entire homogeneous lagoon represented by the

$S_{\max}$ time series as observed at P_0. This renewal time is computed from Eq. 3 as applied to the extended S series as follows:

$$\frac{1}{nT}\sum_{i=1}^{n}(1 - S_{\max,i}/S_0)h_{f,i} - (1 - S_{\max,i-1}/S_0)h_{f,i-1} = \overline{(1 - S_{\max}/S_0)h_f/\tau^*} \qquad (4)$$

where T is the tidal period, $S_{\max,i-1}$ and $S_{\max,i}$ are the values of two successive salinity peaks, n is the number of tide events occurring in the mean interval between a spring and neap tide, and the overbar indicates an average. Since the mean depth at P_0 is about 4 meters, its change with tide (h = mean depth + η) is taken into account (h_f indicating the mean depth + $\eta_{\max}$).

The model of Ghetti *et al.* (*4*) predicts the mean tide height in the lagoon as a function of the reduction in the entrance size. We use this prediction to calculate a new series of S values from which we compute modified values of τ^* for the new steady state from Eq. 3. The quantities τ^* and $1 - \bar{S}/S_0$ can now be used as an input to other models, such as that of a biological species undergoing stresses which depend on nutrient and biochemical oxygen demand levels, both proportional to the freshwater content (*14*). The difficulty of finding a significant parameter representing a biological system (*15*) may be avoided by the use of a concentration-time formula (*16*) of the type

$$I = \int \rho f(\tau^*)\tau^*(1 - \bar{S}/S_0)d\tau^* \qquad (5)$$

where ρ is the concentration of a contaminant per unit concentration of freshwater, assumed to be constant, and $f(\tau^*)$ is the τ^* frequency distribution. This parameter has some utility in the interpretation of our results.

The ratio of the actual to the modified I (I_A/I_M) consequent on size reduction is given in Fig. 2. It is dominated by the contributions from high tides. The effect is marked when a certain degree of size reduction, about one-half, is reached. A reduction of this amount by permanent barriers does not affect the tide height very much; it must be exceeded to cause an appreciable reduction in the tide height (*4*). The behavior shown in Fig. 2 can be expected to apply only to very simple biological systems. Real biological systems, especially those exhibiting resilience, can be expected to react in more complex ways.

Another fundamental limit of this approach concerns the validity of the assumption $S = S_0$ in the modified tide regime. The structure of the outgoing plume could change as a result of the modified dynamics. The returning tide may contain more residues of the lagoon water. This larger content of residues should further increase the effect of size reduction.

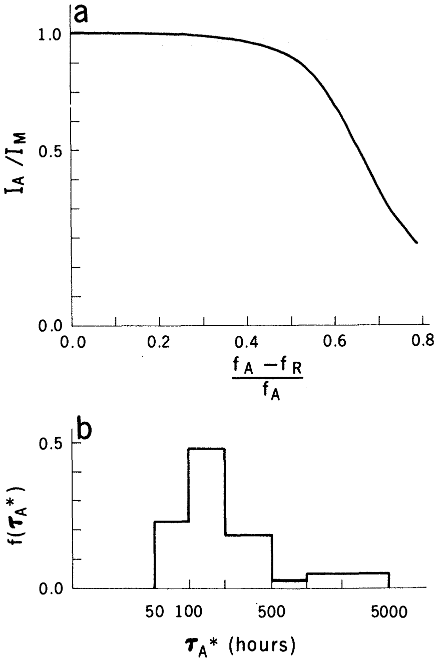

Fig. 2. (a) The ratio of the concentration-time indexes I_A/I_M (A is for actual and M is for modified) as a function of a coefficient of entrance reduction: f_A is the cross section of the actual entrance and f_R is the cross section of the reduced entrance. (b) The τ_A^* frequency distribution. The abscissa is ln τ_A^*. The shape of the spectrum is presumably affected by a seasonal periodicity in H.

Discussion and Conclusions

We are convinced, bearing in mind the complexities of the problems mentioned at the outset of this article, that we may find encouragement in Waddington (*17*) when he says that the manipulation of the variables of a (predictive) model has as its aim to answer the question: What would happen if . . .? And further when he states that the type of model that is most suitable for the analysis of a certain state of things in the real world depends on how much we know about the real world. And finally, when he affirms that, regarding this choice, we must take into consideration both the means available and the ability of the researchers.

The limits of our present results are set by the limitation of the available data and by the consequent necessity of highly simplified modeling. The data may not be sufficient to properly represent P_0. Moreover, the simulated P_0 lagoon cannot be adequately bounded, and in any case its ability for representing the real lagoon can only be conjectured.

An exhaustive approach to the problem would require an intensive campaign to collect data suitable for the computation by proper methods of exchange parameters in the entire lagoon. However, owing to the lack of such a large-scale study and the necessity for the Italian government to make a decision within a short time, we feel that it is our duty to report the present approach. It has the purpose of producing evidence that a nonlinear effect of the kind shown in Fig. 2 may occur in the sea-lagoon exchange as a consequence of a reduction in the entrance size. Moreover, it supports the action of those, in Italy and elsewhere, who require that pollution concentrations in the Venetian lagoon be quantitatively predicted before any permanent change in the lagoon tide regime is made (*18*).

References and Notes

1. The "acque alte" are caused by storm winds and pressure fields which form in the Mediterranean area and push the water of the Adriatic Sea northward. Numerical models having as an input a proper combination of meteorological and astronomical data describe and predict them [A. Tomasin, *Comput. Phys. Commun.* **5**, 51 (1973)]. The subsidence of the city has been suggested as a further cause of the observed increased occurrence of the "acque alte" [L. Carbognin, P. Gatto, G. Mozzi, G. Gambolati, Publication No. 121 (International Association of Hydrological Sciences, Paris, 1978)].
2. E. Miozzi, *Venezia nei secoli: la laguna* (Casa Editrice Libeccio, Venice, 1968), vol. 3, pp. 73-121. *Scrittori idraulici della laguna* by R. Cessi (Officine Grafiche G. Ferrari, Venice, 1912) is a collection of original papers reporting studies of the lagoon system carried out during the period of the Venetian Republic starting from the 15th century. The ideas which in the past promoted both titanic enterprises such as the deflection of effluent rivers and smaller-scale initiatives toward the preservation of an optimum internal canal network impress the modern student as they contain implicitly the present concept that a lagoon is a "geological system" that man's presence can modify in "historical times."
3. They are fully reported in the *Gazzetta Ufficiale della Repubblica Italiana* **246** (15 September 1975). A short summary with comments is also contained in S. Cantacuzino, *Archit. Rev.* **158**, 194 (1975).
4. A. Ghetti, L. Dal Paos, R. Dazzi, in *Rapporti e studi della commissione di studio dei provvedimenti per la conservazione e la difesa della laguna della città di Venezia* (Istituto Veneto di Scienze, Lettere ed Arti, Venice, 1972), vol. 5, pp. 11-41. This study, which selects the relevant parameters of the sea-lagoon hydraulic system and establishes a numerical relationship between them, shows that a reduction in the sizes of the entrances modifies the tide characteristics of the lagoon. The internal amplitudes are decreased with respect to those observed at the entrances and as a function of the latter. The model provides a numerical relationship that predicts the modified tide height as a function of an entrance size reduction parameter.
5. R. Vendramin, in *Rapporti e studi sulla laguna* (Ministero dei Lavori Pubblici, Rome, 1973), pp. 1-146.
6. D. Voltolina, *Arch. Oceanogr. Limnol.* **18**, 19 (1973).
7. This approach aims at reproducing the system by a dynamic mathematical model consisting of a set of equations that describe water and waste movement with the appropriate boundary conditions and empirical parameters. Field measure-

ments are needed to calibrate the model. Empirical parameters to be inserted in the model and other information can also be obtained by the use of laboratory hydraulic models that reproduce on a small geometrical scale some of the nondimensional parameters of the natural system. The basic aspects of this approach are discussed in M. B. Abbott, *J. Hydraul. Res.* **14**, 271 (1976).

8. F. Nyffeler, R. Dazzi, B. Hirel, and L. Alberotanza [Technical Report No. 86 (CNR Laboratory, Venice, 1975)] give the results of an extensive experimental research program conducted in several parts of the Venetian lagoon during 1974. It also contains a map showing the position of P_0 in the Treporti canal.
9. The flow of freshwater into the lagoon varies appreciably with season and with rainfall. Data on its regime are reported in S. Cavazzoni, Technical Report No. 64 (CNR Laboratory, Venice, 1973).
10. J. Van Der Kreeke and R. G. Dean, *J. Waterways Harbors Div. Am. Soc. Civ. Eng.* **WW4**, 393 (1975).
11. The systematic samplings carried out by Nyffeler *et al.* (*8*) extended through the 4-meter depth of the canal at P_0. Only short-term pulses of vertical salinity and temperature gradients are observed to form.
12. For a tide having a progressive character, the tide height attenuation is given by $\ln(H/\eta) = \mu x$, where x is the distance from the entrance. In our case, x = 12.5 kilometers. If η is the result of a propagation with pure friction and no reflection, μ (the damping coefficient) can be computed from

$$\mu = \frac{2\Pi\,[(L_1/L)^2 - 1]^{1/2}}{L_1}$$

where L/L_1 is the relative reduction in tide wavelength experienced at x by the propagating tide. We know of no celerity measurements with which to check whether the actual $\mu = 1.7\ 10^{-2}\text{km}^{-1}$ satisfies the above conditions. However, the S and η experimental time series show that $S_{\max}$ precedes $\eta_{\max}$ by a time t_0, a little more than 1 hour. Assuming that the $S_{\max}$ coincides with the maximum tidal current, there is good correspondence between t_0 and μ. The time t by which the maximum in the current precedes the maximum in the height is given by

$$\tan(2\Pi t/T) = [(L_1/L)^2 - 1]^{1/2}$$

so that t_0 = 1 hour 20 minutes satisfactorily matches $L_1\mu/211$ (L_1 is computed from $L_1 = T\sqrt{gd}$, where T is the period = 11 hours, g is the acceleration of gravity, and d is the depth = 10 meters). See R. Silvester, *Coastal Engineering* (Elsevier, New York, 1974), vol. 2, p. 166.
13. C. Junge, *Air Chemistry and Radioactivity* (Academic Press, New York, 1963); W. G. N. Slinn, L. Hasse, B. B. Hicks, A. W. Hogan, D. Lal, P. S. Liss, K. O. Munnich, G. A. Sehmel, O. Vittori, *Atmos. Environ.* **12**, 2055 (1978).
14. B. H. Ketchum, in *Proceedings of the Symposium on Eutrophication: Causes, Consequences, and Correctives* (National Academy of Sciences, Washington, D.C., 1969), pp. 197–209.
15. O. Kinne, in *Marine Ecology*, O. Kinne, Ed. (Wiley-Interscience, New York, 1971), vol. 1, part 2, pp. 821–1023.
16. M. D. Thomas and R. M. Hendricks, in *Air Pollution Handbook*, P. L. Magill, F. R. Holden, C. Ackley, Eds. (McGraw-Hill, New York, 1956), pp. 9.1–9.44.
17. C. H. Waddington, *Tools for Thought* (Italian edition: Mondadori, Milan, 1977).
18. Prof. R. Scorer (personal communication) points out that, because of the time scale, the Coriolis force may not be negligible. The decrease in velocity that follows the size reduction of the entrances will increase the Coriolis effect. Regions of stagnant water can be created. Such an effect, he suggests, can be studied by a small rotating model.
19. We thank Dr. E. Martino (Istituto Applicazioni Calcalo, CNR) for helpful discussion and Prof. G. P. Puppi (Istituto di Fisica, University of Bologna) and Prof. B. Foraboschi (Istituto di Impianti Chimici, University of Bologna) for their advice and comments on earlier phases of this work. Thanks to the invaluable help of Dr. J. Green and Prof. R. Scorer of the Imperial College of Science and Technology, London, and Prof. J. Charney of the Massachusetts Institute of Technology, the text was given necessary clarification and a more satisfactory form.

Split Genes and RNA Splicing

Francis Crick

Summary. A number of genes in higher organisms and in their viruses appear to be split. That is, they have "nonsense" stretches of DNA interspersed within the sense DNA. The cell produces a full RNA transcript of this DNA, nonsense and all, and then appears to splice out the nonsense sequences before sending the RNA to the cytoplasm. In this article what is known about these intervening sequences and about the processing of the RNA is outlined. Also discussed is their possible use and how they might have arisen in evolution.

In the last 2 years there has been a mini-revolution in molecular genetics. When I came to California, in September 1976, I had no idea that a typical gene (*1*) might be split into several pieces and I doubt if anybody else had. By the time of the annual Cold Spring Harbor Symposium, in the summer of 1977, it was clear that there was something very strange about the arrangement of the genes in several mammalian viruses, and for this reason it seemed highly likely that some chromosomal genes would also be in several pieces. This has since been found to be the case. Even though the experimental evidence is still very patchy, it is now universally accepted that a gene in a higher organism, coding for a protein, may have other base sequences interspersed within it.

This article is not a historical account of the discovery. The earliest publications can be tracked down by consulting the Cold Spring Harbor volume on chromatin (*2*). Nor does it attempt to be a comprehensive review, both because that would take up too much space and also because experimental results are coming in all the time. I present here an overall view of the present position, fluid though it is, together with some general ideas and a few remarks about future work. A brief but very imaginative article by Gilbert (*3*), on similar lines to this one, has already appeared. Similar ideas have been presented by Tonegawa *et al.* (*4*).

The Basic Problem

It is easiest to begin by considering an imaginary example. The upper part of Fig. 1 shows schematically a length of DNA which codes for a single messenger RNA (mRNA). The lower part shows the base sequences found in that mRNA. The relation between the two is indicated by the lines connecting them. The figure shows that in this case there are two fairly long stretches of base sequence along the DNA of the gene which do not appear in the final mRNA. Such sequences are now known as intervening sequences. An alternative terminology, used by Gilbert and his colleagues (*3*, *4*) refers to the intervening sequences as "introns"; those base sequences on the DNA which do end up in the mRNA are referred to as "exons" since they are the ones which are expressed. At this stage, any terminology is likely to lead, before long, to difficulties and complications (*5*). In this article I use the intron-exon terminology, if only for want of a better one.

What possible mechanisms are there which could have produced this result? There are at least four that immediately spring to mind:

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