

LINEAR ELUTION ADSORPTION CHROMATOGRAPHY

IX. STRONG ELUENTS AND ALUMINA. THE BASIS OF ELUENT STRENGTH

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INTRODUCTION

The role of the eluent in adsorption chromatographic separation has been discussed in previous papers¹⁻⁵. For linear isotherm separation (linear elution adsorption chromatography, LEAC), solute equivalent retention volume \underline{R}° (ml/g) varies with eluent strength (adsorption energy per unit area) ε° according to eqn. (1):

$$\log \underline{R}^\circ = \log \underline{R}_p - \alpha \varepsilon^\circ A_s \quad (1)$$

Here, \underline{R}_p is the value of \underline{R}° for elution by the standard weak eluent pentane (ε° equal 0.00), α is an adsorbent activity function, and A_s is the "effective surface volume" of the solute. A_s is normally proportional to the surface area required by the solute upon adsorption (almost all solutes for adsorption on alumina^{1, 2}, weakly adsorbed solutes on silica³ and Florisil⁴). For certain strongly adsorbing solutes on silica³ and Florisil⁴, A_s is larger than predicted because of the localization of strongly adsorbed solutes on strong adsorbent sites⁵.

With few exceptions, previous studies of the eluent role in LEAC separation have been restricted to weak eluents or eluents of intermediate strength. The behavior of very strong eluents might be expected to differ in some fundamental respects. First, the validity of eqn. (1) requires that the solution forces between non-adsorbed solute and eluent molecules be weak, so that the net loss in solution energy upon adsorption for these molecules will be small^{1, 5}. Strong eluents are for the most part highly polar solvents, for which this assumption would seem less applicable than in the case of previously studied weaker eluents. Similarly, the accuracy of eqn. (1) in previously studied chromatographic systems is believed to reflect relatively weak, non-specific (non-bonding) interactions between adsorbed eluent, solute, and adsorbent. As the strength of the eluent is increased, however, these interactions must eventually take on the character of strong chemical bonds, again with a breakdown in the reliability of eqn. (1).

A second complication in very strong eluent systems concerns solute configuration. Most chromatographic separations so far studied by us^{1, 2, 5, 6} find the solute adsorbing parallel to the adsorbent surface (flat) rather than in a perpendicular (vertical) or intermediate configuration. For elution by very strong eluents, however, certain solute types might be expected to adopt a vertical configuration because of

the competition between eluent and less strongly adsorbing parts of the solute for a place on the adsorbent surface. This has already been observed in the case of *n*-alkyl substituted solutes, where the alkyl group is largely confined to the adsorbed phase for elution by weak eluents¹, but is largely desorbed for elution by strong eluents^{2,7}. Similarly, for the elution of the diphenyl disulfides by strong eluents^{2,8}, only one phenyl ring and one sulfur atom are adsorbed, the remainder of the molecule dangling out in solution; in weaker eluents, progressively more of the solute adsorbs. In very strong eluent systems, this variability in configuration of the adsorbed solute should be much more common.

A final, experimental difficulty in elution by very strong eluents is possible in the case of water-deactivated adsorbents. The strong eluent may successfully compete with the adsorbed water for adsorption on the strong adsorbent sites, and continued elution can then lead to displacement of water from the adsorbent with a concomitant increase in adsorbent activity (as in the activation of adsorbents by solvent washing⁹). Eqn. (1) of course assumes that adsorbent activity is constant throughout separation.

The present paper is concerned with the general nature of LEAC separation in elution by strong eluents from alumina. In this connection, we propose to examine the significance of each of the above discussed effects, to acquire eluent strength data (ϵ° values) for a variety of strong eluents, and to determine the chromatographic properties of a number of strongly adsorbing solutes for the first time. Previous papers^{2,5} have presented a preliminary analysis of the dependence of eluent strength on molecular structure, one of the more challenging theoretical problems of adsorption chromatography¹⁰. In the present study, with its determination of a number of new eluent strength values to add to the considerable number already tabulated for alumina², we re-examine our original theory in an attempt to make it quantitatively compatible with experiment.

EXPERIMENTAL

Retention volume data described in the present communication were obtained essentially as in previous studies²; 2 to $5 \cdot 10^{-5}$ g/g of solute were charged to prewet columns of water-deactivated Alcoa F-20 alumina (chromatographically standardized), and each column discarded after a single \underline{R}° determination. Column linear capacity was determined for a number of representative solutes, and it appears that the above column loadings insure the linearity of presently reported \underline{R}° values. It was necessary to add up to 0.5 % water to eluents containing methyl or isopropyl alcohol, in order to prevent elution of adsorbed water. This is described in a following section. The various eluents used were reagent grade solvents, prepurified over calcined alumina. Commercial dioxane was observed to contain a strongly adsorbing impurity which was not readily removed by percolation over alumina (as evidenced by decline in retention volume for repeated elution of a given solute from the same alumina column by dioxane). Retention volume data for this eluent and its solutions are probably less reliable than for the other eluents studied.

The standardization of the adsorbents studied in the present series of investigations has been discussed in detail^{1,3,6}. It has been shown that an adsorbent activity function α and the surface area of the adsorbent (or surface volume V_a) adequately characterize adsorptive properties. For certain commercial adsorbents, whose

properties remain relatively constant from batch to batch, it has been possible to average any variation in V_a and α into a single adsorbent parameter: effective water content (% H_2O) or chromatographic activity, as inferred from the \bar{R}° value for a standard solute-eluent system (naphthalene eluted by pentane). In this respect, it appears that the last tabulation¹ of values of V_a , α , and \bar{R}° (naphthalene-pentane) *versus* % $H_2O-Al_2O_3$ (Alcoa F-20 alumina) is now somewhat in error, as a result of two effects. First, the initial calculation¹ of values of V_a gave slightly low values relative to a later procedure³, and second, the properties of Alcoa F-20 alumina acquired during the last several years seem slightly different from those of the sample originally reported on¹, and acquired in 1957. The error in the original table of V_a , α , and \bar{R}° *versus* % $H_2O-Al_2O_3$, as applied to presently available adsorbent samples, has had a negligible effect on the accuracy of predicting and correlating retention volume data in the various systems subsequently studied by us, particularly since most of these data have been measured for 3.6-4.0 % $H_2O-Al_2O_3$, where the old and new adsorbent parameter values are identical. The main limitation on these originally tabulated adsorbent parameters for Alcoa F-20 alumina occurs in the preparation of adsorbent of a certain activity by water deactivation of calcined adsorbent. Thus, addition of 2 % water to recent samples of calcined Alcoa F-20 generally gives adsorbent with a chromatographic activity equal on the old scale¹ to 1.3 % $H_2O-Al_2O_3$. A similar discrepancy occurs for most other adsorbent activities, and occasionally this has been experimentally inconvenient. Fig. 1 shows the relationship between

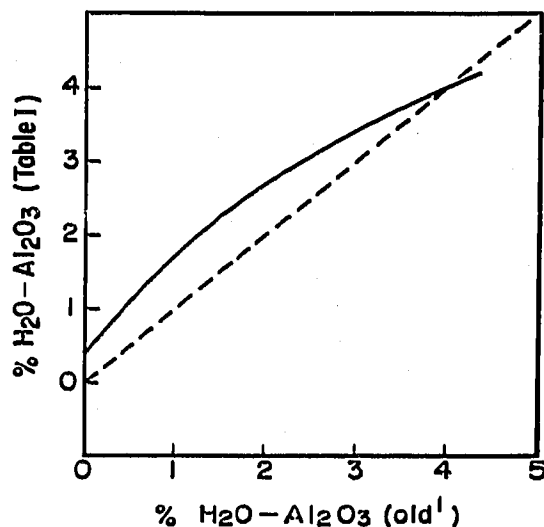


Fig. 1. Comparison of chromatographic activity as determined from old and new standard \bar{R}° values, expressed in terms of water content for equal chromatographic activity (solid curve).

chromatographic activities by the old and revised scales, and Table I summarizes the relationship between the adsorbent parameters and adsorbent water content according to the *revised* scale. Subsequent references to the chromatographically standardized water contents of Alcoa F-20 alumina samples will be based on the data given in Table I, as well as report standard \bar{R}° values (naphthalene-pentane) in order to minimize confusion in the change-over from the old standardization relationship.

TABLE I
REVISED (NEW) ADSORBENT PARAMETERS FOR ALCOA F-20 ALUMINA

% $H_2O-Al_2O_3$	V_a	$\log V_a$	α	$\underline{R}^{\circ a}$
0.0	0.054	-1.27	1.00	68
0.5	0.049	-1.31	0.90	30
1.0	0.044	-1.36	0.84	17
2.0	0.034	-1.47	0.75	7.1
3.0	0.024	-1.62	0.69	3.3
4.0	0.014	-1.85	0.63	1.3

^a Elution of naphthalene by pentane.

DISCUSSION

Relative to the weaker eluents, elution from alumina by certain strong eluents exhibits a number of new and interesting effects. These are covered in detail in the following sections. The primary purpose of the present section is to summarize the practical applications of these later sections. Additionally, previous papers in this series have developed the correlational eqn. (2) for predicting retention volume in LEAC separation over alumina:

$$\log \underline{R}_p = \log V_a + \alpha \left[\sum_i^i Q^{\circ}_i + \sum_j^j q^{\circ}_j - f(Q^{\circ}_k) \sum_{i \neq k} Q^{\circ}_i \right] \quad (2)$$

V_a is the adsorbent surface volume, α is the adsorbent activity function, Q°_i is the adsorption energy per solute group i , q°_j is a solute energy term associated with certain solute geometries, and $f(Q^{\circ}_k)$ is a solute localization function. Examples of the application of eqns. (1) and (2) to the calculation of \underline{R}° in strong eluent systems will be offered at the end of the present section, for a number of cases which reflect peculiarities in elution by strong eluents.

The use of the alcohols (or solutions of the alcohols) as eluents in separation over water-deactivated alumina results in the rapid stripping of water from the adsorbent and a resulting increase in adsorbent activity. Other eluents summarized in Table II do not appear to activate the adsorbent in this manner. Adsorbent activation during elution is an inherently undesirable phenomenon. In normal elution chromatography there is always the tendency for later eluted solute bands to broaden and \underline{R}° values to increase exponentially, thereby increasing separation time and decreasing detection sensitivity. Eluent activation increases the severity of this effect. If sufficient water is added to the eluent to effect equilibrium with adsorbent water, adsorbent activation will not occur. For the alcohols and their solutions, this usually requires addition of 0.1-0.5 % water. The determination of eluent equilibrium water content (water required in the eluent to avoid adsorbent activation) is simple and straightforward, as detailed in the immediately following section.

The eluent strengths of 9 strong eluents ($0.38 \leq \epsilon^{\circ} \leq 0.95$) were determined for the first time and are reported in Table II, along with some other properties of these solvents pertinent to their use as eluents. Data for some previously studied eluents are also included in Table II. Additional eluent strength values are predicted in Table III for another 26 eluents, most of which are strong. These latter data were

TABLE II
PROPERTIES OF THE ELUENT: ELUTION FROM ALUMINA

Eluent	ϵ°			n_D	Cut off wavelength (m μ)	Comments
	Exptl.	Calc. ^a	Calc. ^b			
<i>n</i> -Pentane	0.00	0.00	0.00	5.3	210	
Isooctane	0.01	—0.01	—0.01	7.4	210	
<i>n</i> -Hexane	0.01	0.00	0.00	6.0	210	
<i>n</i> -Octane	0.01	0.01	0.01	7.4	210	
Cyclohexane	0.04	0.03	0.03	6.0	210	
<i>n</i> -Decane	0.04	0.01	0.01	8.8	210	
Cyclopentane	0.05	0.03	0.03	5.0	210	
Carbon tetrachloride	0.18	—	—	4.4	260	
Carbon disulfide	0.26	—	—	3.0	380	
Isopropyl chloride	0.29	0.44	0.33	3.4	255	
Toluene	0.29	0.28	0.28	6.9	285	
<i>n</i> -Propyl chloride	0.32	0.44	0.33	3.4	225	
Benzene	0.32	0.31	0.31	6.0	280	
Isopropyl ether	0.28	0.43	0.32	4.7	235	e
Ethyl sulfide	0.38	0.42	0.31	4.4	290	
Phenetole	0.40	0.41	0.41	8.2	300	
Chloroform	0.40	—	—	4.4	245	
Methylene chloride	0.42	—	—	3.6	235	
Ethyl ether	0.38	0.49	0.38	4.1	210	e
Ethyl benzoate	0.48	0.41	0.50	9.5	300	
Acetone	0.56	0.55	0.55	4.0	330	
Ethyl acetate	0.58	0.41	0.50	5.5	250	
Methyl acetate	0.60	0.44	0.53	4.9	255	
Dioxane	0.63	0.73	0.62	5.5	250	
Diethylamine	0.63	—	—	—	275	d
Nitromethane	0.64	0.68	0.77	3.4	380	
Pyridine	0.71	0.73	0.73	5.6	300	d
Isopropanol	0.82	0.85	0.74	8.0 ^f	210	e
Methanol	0.95	1.05	0.94	8.0 ^f	210	e

^a Using eqns. (6a) or (6b).

^b Corrected for further localization or delocalization of large groups or small aliphatic groups.

^c $\Delta\epsilon_{es}$ values tend to be negative for solutes with strongly adsorbing groups (see Table IV).

^d $\Delta\epsilon_{es}$ values tend to be positive for solutes with potentially acidic groups (see Table XI).

^e $\Delta\epsilon_{es}$ values tend to be variable, amino groups showing generally large positive values.

^f Value is larger than predicted from area of eluent and used in calculating ϵ° values.

calculated as described in a following section. As seen from Table II, by comparison of experimental and calculated (b) ϵ° values, it is possible to predict ϵ° in most cases with a precision (± 0.03 units, average) approaching the experimental accuracy of the measured value. Together, the data of Tables II and III summarize the elution properties of more than 50 pure solvents, for ready application to experimental separation problems involving alumina as adsorbent. Since the eluent properties of any binary² or ternary¹¹ eluent mixture can in turn be calculated from the data of Tables II and III for the pure constituent solvents, the elution characteristics of a vast array of widely differing eluents can be easily obtained.

TABLE III
 PREDICTED PROPERTIES FOR SEVERAL NEW ELUENTS^a: ELUTION FROM ALUMINA

Eluent	n_b	ϵ°	Comments
Diisobutylene	7.1	0.06	
1-Pentene	5.0	0.08	
<i>m,p</i> -Xylene	7.8	0.25	
Amyl chloride	4.0	0.26	
<i>o</i> -Xylene	7.7	0.27	
Chlorobenzene	6.8	0.30	
Bromobenzene	7.1	0.31	
Ethyl bromide	3.4	0.37	
1,2-Diethoxyethane	7.4	0.43	c
Methyl isobutyl ketone	5.1	0.43	
Benzonitrile	7.2	0.44	
Triethylamine	5.8	0.48	d
1,2-Dichloroethane	5.0	0.49	
Acetophenone	7.9	0.50	
Nitrobenzene	7.3	0.52	
Nitropropane	4.1	0.53 ^b	
Benzaldehyde	7.2	0.54	
Dimethyl phthalate	12.0	0.59	
Amyl alcohol	~ 8 ^f	0.61	e
α -Picoline	6.5	0.62	d
Aniline	6.9	0.62	d
β,γ -Picoline	6.5	0.68	d
Pyrrole	5.0	0.72	e
Butyl cellosolve (C ₄ H ₉ -O-C ₂ H ₄ OH)	~ 8 ^f	0.74	
Acetonitrile	2.8 ^f	0.79	
Ethylene glycol	~ 8	1.11	e
Formamide, N,N-dimethylformamide		> 1.0	
Carboxylic acids		> 1.00	

^a Estimated from eqn. (6a) or (6b), plus correction factors.

^b Estimated from ϵ° for nitromethane.

^c $\Delta\epsilon_{es}$ values tend to be negative for solutes with strongly adsorbing groups (see Table IV).

^d $\Delta\epsilon_{es}$ values tend to be positive for solutes with potentially acidic groups (see Table XI).

^e $\Delta\epsilon_{es}$ values tend to be variable, amino groups showing generally large positive values.

^f See Table II, note f.

A preceding paper⁷ has discussed the advantages of different solvent pairs in gradient elution chromatography. In general, it is desirable that both solvents be relatively non-viscous or low boiling. Additionally, the stronger of the two solvents should have a reasonably large ϵ° value and as small a value of n_b as possible. Examination of the data of Tables II and III shows the use of the aliphatic amines and alcohols to be undesirable in this regard, while such solvents as acetone, nitromethane, and acetonitrile look especially promising. For the weaker solvent, pentane, propyl chloride, or carbon disulfide appear suitable. At first glance, the solvent pair pentane-ethyl ether might appear ideal on several counts: low viscosity, transparency in the far ultraviolet, widely differing eluent strengths, and a small n_b value for the ethyl ether. However, the failure of eqn. (1) for this system (which we will examine) results in a practical compression of the eluent strength range, and in some cases poorer separation.

Eqn. (1) breaks down in some cases involving certain strongly adsorbing eluents and solutes. This appears to be the result generally of strong interactions between eluent or solute and the adsorbent surface. Eqn. (1) predicts a constant separation order for solutes of similar size (A_s value), independent of eluent, so that two solutes of the same size which are inseparable by one eluent are predicted to be inseparable by all eluents. Consequently, the failure of eqn. (1) raises the possibility of separating such theoretically inseparable solute pairs in some cases. The ability to classify such instances and predict when they will occur is therefore of great practical interest. The breakdown of eqn. (1) in the case of specific solute-eluent combinations can be remedied by defining a solute-eluent interaction term Δ_{es} such that eqn. (3) applies exactly in all cases:

$$\log \underline{R}^o = \log \underline{R}_p - \alpha \varepsilon^o A_s + \alpha \Delta_{es} \quad (3)$$

It has been found that for given binary eluents, Δ_{es} will be essentially constant for all compositions richer than 5 % in the stronger eluent. Tables II and III summarize those cases where values of Δ_{es} are significantly different from zero (under "comments" column). One example of the failure of eqn. (1) occurs in the case of the aliphatic ethers as eluents (footnote c). Values of Δ_{es} tend to be negative for solutes with strongly adsorbing groups, so that elution by the ethers tends to speed up the elution of compounds with strongly adsorbing groups such as $-\text{COOR}$ or $-\text{N}=\text{}$. Table IV provides some experimental values of Δ_{es} for ethyl ether and isopropyl ether as eluents,

TABLE IV
 Δ_{es} VALUES FOR THE ALIPHATIC ETHERS AS ELUENTS

Strongest solute group	Q^o_k	Δ_{es}	
		Ethyl ether	Isopropyl ether
$-\text{N}=\text{}$ (3:4-benzacridine)	0.8	-0.24	-0.11
$-\text{O}-\text{R}$	1.8		-0.58
$-\text{NO}_2$	2.8		-0.01
$-\text{CO}_2\text{R}$	3.3	-0.57	-0.74
$-\text{N}=\text{}$ (quinoline)	4.1	-0.64	-0.61
$-\text{N}=\text{}$ (pyridine)	4.6	-0.89	

and various solutes containing the indicated groups. The value of Δ_{es} for a solute is determined in this case only by the single strongest adsorbing group, additional groups not affecting Δ_{es} . Thus, Δ_{es} for methyl benzoate, dimethyl phthalate, and methoxyl methyl benzoate are all predicted equal. Unfortunately, the failure of eqn. (1) in the case of the ether eluents does not appear to result in many unique separation possibilities. Separation problems in which the data of Table IV might suggest use of the ethers as eluents will frequently succumb to the use of "normal" eluents (*i.e.* for which Δ_{es} equal zero).

Another example of the failure of eqn. (1) occurs with the basic eluents such as diethylamine and pyridine (footnote d of Tables II and III). Solute which are acidic (*e.g.* phenol, carbazole) or *potentially* acidic (*e.g.* aniline) are less readily eluted by the basic eluents than by normal eluents of comparable strength. The potentially acidic solutes presumably include all compounds having a proton bonded to an

electronegative element such as oxygen or nitrogen. Δ_{es} values for the basic eluents range from +0.8 for a solute such as aniline to +2.0 for the most acidic solutes such as phenol and carbazole. For solutes of intermediate acidity, Δ_{es} parallels acid strength. This failure of eqn. (1) for basic eluents seems potentially useful for certain otherwise difficult separations.

A final example of the failure of eqn. (1) has been noted in elution by the alcohols and their solutions. With these eluents all solutes substituted by $-\text{NH}_2$ are preferentially retained relative to elution by normal eluents of comparable strength, while the phenol and carbazole type of solutes are relatively unaffected (Δ_{es} approximately zero). Insufficient data have been obtained to generalize on the solute types for which eqn. (1) fails in elution by the alcohols, but it is likely that other compound types also exhibit non-zero Δ_{es} values. For this reason, some strongly adsorbed solutes which are inseparable by "normal" eluents may be separable upon elution by one of the alcohols or its solution with a weaker eluent.

For elution by strong eluents, it has definitely been established that the phenols and substituted phenols adsorb perpendicular to the adsorbent surface (vertical), with only the hydroxyl group contained in the adsorbed phase. A_s for the phenols is therefore smaller than predicted for the molecule in the flat configuration. This effect is somewhat counteracted by a larger than normal contribution of the hydroxyl group to A_s , as in the case of the pyrrole derivatives⁶. Similarly, substituent groups on the phenols do not contribute directly to the adsorption energy of the phenol, and $\sum_i Q^{\circ}_i$ for the phenols equals Q°_i for the hydroxyl group. This does not mean that all phenols are adsorbed equally strongly on alumina, and hence have equal retention volumes. Substituents on the phenol ring change the acidity of the phenol, and hence effect the adsorption energy of the phenol group (which is increased by increased acidity). This solute geometry effect q°_j has been related to the HAMMETT σ function¹² of the substituent on the phenol ring:

$$q^{\circ}_j = 2.03 \sigma \quad (4)$$

The phenols can therefore be separated on alumina according to their relative acidity. It is believed that other acidic and hydroxylic solutes such as the thiophenols, oximes, and alcohols behave similarly to the phenols as regards configuration and response to substituents. The adsorption energy of the phenol hydroxyl is strongly affected by bulky *ortho* substituents such as *tert.*-butyl. Two such groups decrease the adsorption energy of the hydroxyl group by a factor of over 5. Table V summarizes Q°_i and a_i values for several strongly adsorbing solute groups of the present type, as well as other solute groups investigated during the present study.

In a first example of the calculation of retention volume in these strong eluent systems, consider the elution of methyl benzoate by 15 % v ethyl ether-pentane from 3.8 % $\text{H}_2\text{O}-\text{Al}_2\text{O}_3$. For elution by "normal" eluents from this adsorbent, $\log R_p$ equals 1.56 (ref. 8), and A_s can be calculated² as 9.0. The eluent strength of 15 % v ether-pentane can be calculated from eqn. (5) (following section) and Tables I and II, as 0.099. The "comments" column in Table II notes that ether is an abnormal eluent, and Table IV summarizes values of Δ_{es} for various solute groups; the strongest adsorbing group in methyl benzoate is the ester group, for which Δ_{es} equals -0.57 from Table IV. Finally, from Table I, α equals 0.64. Substituting into eqn. (3):

$$\begin{aligned}\log \underline{R}^{\circ} &= 1.56 - 0.099(9.0) + 0.64(-0.57) \\ &= 0.31.\end{aligned}$$

The experimental value was 0.25. If ether had been a normal eluent, the $\alpha\Delta_{es}$ term would be zero, and $\log \underline{R}^{\circ}$ would be higher by 0.36 units.

In a second example, consider the separation of aniline and quinoline over 3.9 % $\text{H}_2\text{O}-\text{Al}_2\text{O}_3$. These two solutes have similar $\log \underline{R}_p$ (2.29 and 2.31, respectively) and A_s (7.5 and 8.0) values^{2,8}, and elution by normal eluents would generally show little separation. For example, using an eluent for which $\alpha\varepsilon^{\circ}$ equal 0.302, we calculate from eqn. (1):

$$\begin{aligned}\text{for aniline} \quad \log \underline{R}^{\circ} &= 2.29 - 0.302(7.5) \\ &= 0.03\end{aligned}$$

$$\begin{aligned}\text{and for quinoline} \quad \log \underline{R}^{\circ} &= 2.31 - 0.302(8.0) \\ &= -0.10.\end{aligned}$$

The resulting separation (determined by difference in \underline{R}°) is seen to be poor. Use of a basic eluent, such as 20 % v diethylamine-pentane ($\alpha\varepsilon^{\circ} = 0.302$), however, will preferentially retain the aniline because of its acidic hydrogens ($-\text{NH}$). The $\alpha\Delta_{es}$ value for this solute-eluent combination is observed to be +0.53. Consequently, for aniline eluted by the latter eluent, substituting into eqn. (3):

$$\begin{aligned}\log \underline{R}^{\circ} &= 2.29 - 0.302(7.5) + 0.53 \\ &= 0.56.\end{aligned}$$

An experimental value of 0.49 was observed, *i.e.* the predicted better separation of aniline ($\underline{R}^{\circ} = 3.7$ ml/g) from quinoline ($\underline{R}^{\circ} = 0.8$ ml/g) now occurs.

In a final example, consider the elution of *m*-acetophenol by 20 % v isopropanol-pentane from 3.9 % $\text{H}_2\text{O}-\text{Al}_2\text{O}_3$. α equals 0.64 and $\log V_a$ is -1.82 (Table I). A vertical

TABLE V
GROUP ADSORPTION ENERGIES FOR VARIOUS STRONGLY ADSORBED SOLUTES

Solute group, X	Q°_i			a_i
	R)-X	Ar)-X	Ar)-X-(Ar	
-OH	6.5	7.4		6.0 ^d
		7.1 ^a		7.0 ^d
		1.3 ^b		
-SH		8.7		6.0 ^d
-CH=N-OH		7.2		6.0 ^d
-C(CH ₃)=N-OH		6.6		6.0 ^d
-CONH ₂		(6.1) ^c		2.0
-NH-CO-CH ₃ ^d		6.2		3.0
=CH-)CO-N(CH ₃)- (N-methylquinolone)			6.2	4.0
-NO ₂	5.4			2.5

^a In 2,6-dimethylphenol.

^b In 2,6-di-*tert.*-butyl-*p*-cresol.

^c Approximate value, extrapolated from isopropanol solutions; $\alpha\Delta_{es}$ estimated at 1.0.

^d For total solute ($a_i = A_s$); assumes strong eluent; vertical adsorption.

configuration of the solute is assumed, so from Table V, $Q^{\circ}_i = 7.4 = \sum_i Q^{\circ}_i$, and $A_s = a_i = 6.0$. From eqn. (4), $q^{\circ}_j = 2.03 (0.306) = +0.62$. Since no solute groups other than the hydroxyl are adsorbed, $\sum_{i \neq h} Q^{\circ}_i = 0.00$. $\alpha \varepsilon^{\circ}$ for the eluent may be calculated from eqn. (5) and Table II as 0.452. Finally, $\alpha \Delta_{es}$ for phenol (solute) and isopropanol (eluent) is +0.30. Substituting into eqn. (2):

$$\begin{aligned} \log \underline{R}_p &= -1.82 + 0.64(7.4 + 0.62 - 0) \\ &= 3.31. \end{aligned}$$

From eqn. (3):

$$\begin{aligned} \log \underline{R} &= 3.31 - 0.452(6.0) + 0.30^{\circ} \\ &= 0.90. \end{aligned}$$

An experimental value of 0.84 was found. It should be noted that $\log \underline{R}_p$ as calculated above is for a vertical configuration, whereas in the weak eluent (pentane), the molecule is undoubtedly adsorbed flat. This is of no practical consequences, however, since in any eluent system strong enough to elute this phenol at a reasonable rate, the configuration would be vertical, and the hypothetical (vertical) configuration used to calculate \underline{R}_p would be applicable.

ADSORBENT ACTIVATION BY THE ALCOHOLS AND THEIR SOLUTIONS DURING ELUTION

Adsorbent activation or the removal of adsorbed water has been accomplished in some laboratories⁹ by washing the adsorbent with certain polar solvents. *Elution* by polar solvents from water-deactivated adsorbents may therefore result in the progressive activation of the adsorbent during the course of separation. This would not greatly affect the retention volumes of the first eluted sample components, which would have left the column before appreciable activation of the adsorbent had occurred, but would increase the retention volumes of later eluted compounds. Such an effect would be disadvantageous in most separations, since it leads to inconveniently long separation times and excessive solute band broadening with loss in detection sensitivity. That is, adsorbent activation during elution would accentuate those problems inherent in normal fixed eluent elution, and which have led to the development of the gradient elution technique¹¹. For the adsorbents studied in the present investigation (3.8 to 3.0 % $H_2O-Al_2O_3$), only the alcohols and their solutions were found to give appreciable adsorbent activation during elution. The remaining solvents of Table II appear to give no problem in this respect.

Adsorbent activation by the eluent is illustrated in the data of Fig. 2 for the elution of benzaldoxime from 3.9 % $H_2O-Al_2O_3$ by 5 % v isopropanol-ethyl ether. The circles refer to \underline{R}° values determined in the usual manner: prewetting the column, charging the solute, and eluting the solute from the column. The squares refer to \underline{R}° values determined in this manner *after* initial passage of 8 ml/g of eluent through the column (for possible adsorbent activation). These \underline{R}° values are plotted *versus* the amount of water added to the eluent prior to elution, and both sets of data show \underline{R}° decreasing with increasing eluent water content. The two curves intersect at approximately 0.21 % water in the eluent, and it is presumed that for eluent of this composition the water on the initial adsorbent and in the initial eluent are at equilibrium, since no change in adsorbent activity occurs with continued elution. For

dryer eluent compositions ($< 0.21\%$ H_2O), retention volumes and adsorbent activity increase with continued elution, since the eluent is water-poor with respect to starting adsorbent, and hence can remove water and increase activity. This dependence of \bar{R}° on eluent water content and extent of pre-elution is just that expected for adsorbent activation (and deactivation) during elution by a polar solvent.

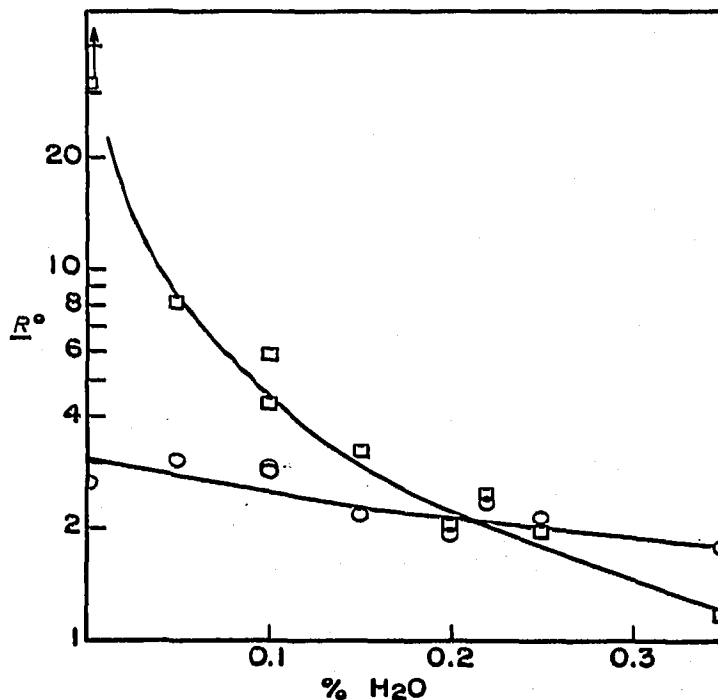


Fig. 2. Activation and deactivation of the adsorbent during elution, *versus* eluent water content. Elution of benzaldoxime by 5% v isopropanol-ethyl ether from 3.9% $\text{H}_2\text{O}-\text{Al}_2\text{O}_3$. O = simple column pre-wetting (1 ml/g pre-elution); □ = pre-elution by 8 ml/g of eluent.

Preservation of the adsorbent activity at its initial value requires the addition of a certain amount of water to the eluent (0.21% in the system of Fig. 2). The amount of water needed will vary with the adsorbent activity and eluent composition, and may be determined by experiment as in Fig. 2. In normal separation, and particularly in theoretical investigations such as the present one, it will be important to use water-equilibrated eluent whenever the eluent is capable of stripping water from the column. In some separation systems, however, it might prove advantageous to use higher than equilibrium water content so as to effect the gradual deactivation of the adsorbent during separation. Practically, this would confer some of the advantages of gradient elution separation without use of the special equipment normally required. Because of the limited solubility of water in most of the weaker eluents, this technique would be limited to separations with strong eluents or eluents of intermediate strength.

The addition of water to the eluent might be expected to change its effective strength (ϵ°) as an eluent, as well as prevent adsorbent deactivation. The data of Fig. 2 suggest that this effect will be small, inasmuch as the \bar{R}° data for 1 ml/g pre-elution (circles) show little dependence on water content (about what could have been expected from adsorbent activation and deactivation, from comparison with the 8 ml/g pre-elution data). The small amounts of water required in eluent equili-

bration (0–0.5 %) and the great strength of the alcohols and their solutions as eluents appear to explain the lack of dependence of eluent strength on water content in studies such as that of Fig. 2.

Previous studies of elution from alumina have not involved the alcohols as eluents, and hence have not been subject to the adsorbent activation effect. A later study will show that adsorbent activation occurs much more readily with silica as adsorbent, although prior studies with silica are not thereby in error (because of the measuring technique used, equivalent to simple prewetting data of Fig. 2, and the less polar solvents employed as eluents).

ANOMALIES IN ELUTION FROM ALUMINA BY STRONG ELUENTS

For elution from alumina by eluents of weak or intermediate strength, the role of the eluent in determining solute retention volume (eqn. 1) has been thoroughly tested^{1, 2, 6, 7}. The only separation variables that contribute to an eluent effect in these cases are eluent strength ϵ° (or adsorption energy per unit area) and solute effective area (or surface volume A_s). The applicability of eqn. (1) in given situations suggests two corollary conclusions: (a) solution effects are relatively unimportant, or the solubility of the solute in the eluent plays no major role in determining its retention volume; (b) strong chemical bonds between specific adsorbent sites and reactive eluent atoms on groups are absent. As the polarity and adsorption strength of the eluent increase (these two eluent properties are roughly related), however, the validity of the latter two conclusions becomes progressively more suspect, and eqn. (1) should become less accurate for elution by the strongest eluents. Previously reported data on the applicability of eqn. (1) have been largely restricted to eluents whose strengths ϵ° lie between pentane (0.00) and methylene chloride (0.42). Such data as have been reported for stronger eluents² do in fact suggest a lesser accuracy in the application of eqn. (1).

A large number of data for elution by strong eluents were obtained in the present investigation, leading to the expanded eluent strength scale of Table II. In the course of acquiring these data, it has become apparent that eqn. (1) as it stands is in many cases a poor approximation for elution in these strong eluent systems. While this complication of the simple eluent theory (eqn. 1) may appear lamentable from the standpoint of comprehending adsorption chromatographic separation, the number of separation possibilities are greatly increased in separations using strong eluents or their binary solutions. The use of strong eluents (or their solutions in weaker eluents) therefore complicates the task of the theoretical chromatographer but simplifies the work of the practical chromatographer. The value of simple eluent theory (eqn. 1) in these more complex strong eluent separations is as a tool for the recognition, quantitation, and classification of strong eluent anomalies (for eventual exploitation in new separation schemes), and as a necessary preliminary to the development of a satisfactory theory of adsorption chromatography in strong eluent systems.

The "ether anomaly"

One type of strong eluent anomaly or failure of eqn. (1) is illustrated by the data of Tables VI and VII for elution of a number of solutes from 3.8 % $\text{H}_2\text{O}-\text{Al}_2\text{O}_3$ by several

ether-pentane binary eluents. If values of $\alpha\epsilon^\circ$ are calculated from these R° values by means of eqn. (1) and plotted *versus* eluent composition as in Fig. 3, the resulting plot scatters badly. This means that $\alpha\epsilon^\circ$ for these binary eluents appears to be a function of both eluent composition and solute type, whereas for normal eluents $\alpha\epsilon^\circ$ is independent of solute type. The dark circles of Fig. 3 for the non-hydrocarbon

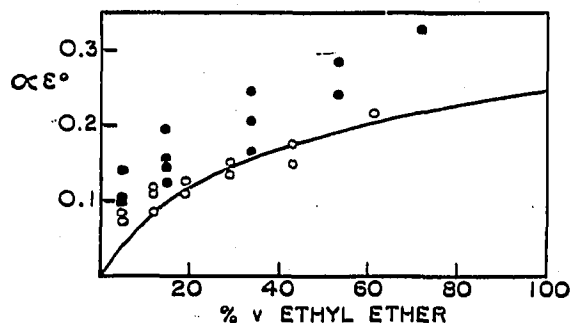


Fig. 3. Experimental eluent strength data *versus* eluent composition and solute type. Elution of solutes of Tables VI and VII by ether-pentane solutions from 3.8% $H_2O-Al_2O_3$. O = experimental data for hydrocarbon solutes; ● = experimental data for non-hydrocarbon solutes; — calculated from eqn. (5) and data of Table II for ethyl ether.

solutes lie consistently above the data for the hydrocarbon solutes (open circles). If we assume that the hydrocarbon $\alpha\epsilon^\circ$ values of Table VI represent the "true" eluent strengths of these binaries (as previously²), it is possible to calculate values of $\log R^\circ$ for the non-hydrocarbons of Table IV by means of eqn. (1), and the differences $\alpha\Delta_{es}$ between experimental and calculated $\log R^\circ$ values by means of eqn. (3). Values of Δ_{es} are shown in parentheses in Table VII. For those solutes in Table VII which have the eluent varied over a wide range of compositions (*e.g.* quinoline, pyridine), values of $\alpha\Delta_{es}$ are seen to be essentially independent of eluent compositions. This is particularly true if the $\alpha\Delta_{es}$ values for the most dilute ether-pentane eluents ($\leq 5\%$) are excepted. This lack of dependence of $\alpha\Delta_{es}$ on eluent composition strongly suggests that solution effects (preferential solubility of the solute in different eluents) are *not* responsible for the anomalous behavior represented by the large $\alpha\Delta_{es}$ values of Table VII. Rather, some peculiarity in the interaction of solute and eluent with the adsorbent is suggested, since for ether concentrations in excess of 10% the adsorbent

TABLE VI

ELUTION OF HYDROCARBON SOLUTES FROM 3.8% $H_2O-Al_2O_3$ BY ETHYL ETHER-PENTANE BINARY ELUENTS

Solute	$\log R_p$	$\log R^\circ$ for indicated eluents ^a						
		2.0	5.0	12.0	19.0	29.0	43.0	61.0
Phenanthrene	1.14	0.64	0.31	—0.04				
Chrysene	1.90	1.46	1.05	0.59				
Picene	2.58			1.42	1.05	0.72	0.51	
Benzocoronene	3.75				1.61	1.20	0.81	0.08
$\alpha\epsilon^\circ$ exptl.		0.043	0.077	0.103	0.118	0.141	0.160	0.216
calc. ^b		0.017	0.039	0.085	0.114	0.144	0.176	0.205

^a % v Ethyl ether-pentane.

^b Eqn. (5), data of Table II.

TABLE VII
 ELUTION OF NON-HYDROCARBON SOLUTES FROM 3.8% H₂O-Al₂O₃ BY ETHYL ETHER-PENTANE BINARY ELUENTS

Solute	log R_p	Q^*k	log R^* for indicated eluents ^a							an. αA_{eg} ^b	
			5.0	15.0	34.0	53.0	72.0	100.0			
3:4-Benzacridine	2.15	0.8	1.75 (0.00)	0.67 (-0.22)	0.19 (-0.08)						
Methyl benzoate	1.56	3.3	0.68 (-0.19)	0.25 (-0.35)							-0.15
1,2,4-Tricarbomethoxy- benzene	4.31	3.3									-0.35
Quinoline	2.30	4.1		1.45 (-0.38)	1.06 (-0.38)	0.67 (-0.46)	0.38 (-0.47)		0.24 (-0.37)		-0.37
6-Methoxyquinoline	2.99	4.1							0.12 (-0.40)		(-0.41)
Pyridine	2.26	4.6	1.40 (-0.38)	1.09 (-0.53)	0.79 (-0.53)	0.56 (-0.54)	0.32 (-0.62)		0.15 (-0.63)		-0.40 (-0.57)
αE° (best values)			0.077	0.107	0.156	0.193	0.220		0.247		

^a % v Ethyl ether; parentheses refer to experimental log R^* values minus calculated values (eqn. 1), αA_{eg} .

^b Exclusive of data for 5% ether solutions.

surface is covered primarily with ether, and hence the composition of the adsorbed phase does not vary much over the eluent composition range of 10–100% ether. If the averaged values of $\alpha\Delta_{es}$ for each solute are plotted *versus* the adsorption energy Q_k° of the strongest solute group k , as in Fig. 4, an approximate correlation is noted, indicative of localization effects as in the adsorption of strong solute groups on specific adsorbent sites⁸.

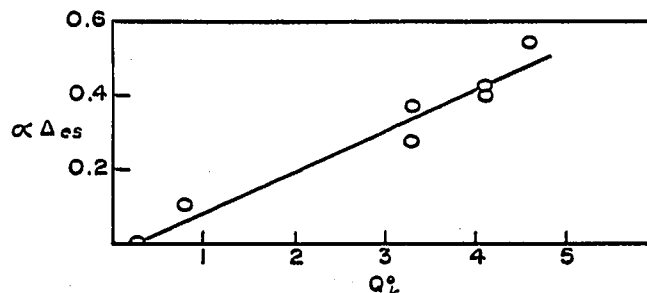


Fig. 4. Dependence of $\alpha\Delta_{es}$ on adsorption energy of strongest adsorbing solute group. Ethyl ether–pentane binary eluents, 3.8% $\text{H}_2\text{O}-\text{Al}_2\text{O}_3$.

The eluent anomaly which occurs in the case of ethyl ether and its solutions cannot be recognized in a solvent without obtaining extensive experimental data of the type given in Tables VI and VII. Additionally, the experimental analysis of the “ether effect” becomes almost impossible for eluents stronger than ethyl ether (or of comparable strength and with n_b larger). A simpler procedure is therefore required for assessing the importance of this “ether anomaly” in other strong eluents. We will now show that the dependence of non-hydrocarbon $\alpha\varepsilon^\circ$ values on binary eluent composition can be used to detect the presence or absence of the “ether anomaly” in the strong eluent.

The strength of an eluent binary ε°_{AB} has previously² been related to the strengths of the constituent eluents A (weak) and B (strong):

$$\varepsilon^\circ_{AB} = \varepsilon^\circ_A + \frac{\log [X_B \cdot 10^{\alpha n_b(\varepsilon^\circ_B - \varepsilon^\circ_A)} + 1 - X_B]}{\alpha n_b} \quad (5)$$

X_B is the mole fraction of B in the binary mixture, and n_b is the eluent surface volume (equal to its value of A_s for the eluent considered as solute). ε°_A and ε°_B are the strengths of the two pure eluents A and B. The values of n_b in Tables II and III differ slightly from previous values^{2, 5}, reflecting improvements in the calculation procedure (as for analogous A_s values⁵).

Eqn. (5) accurately correlates (solid line) the $\alpha\varepsilon^\circ$ values of Fig. 3 for the hydrocarbons, and satisfactory correlations of the same type have been noted for many “normal” eluents and both hydrocarbon and non-hydrocarbon solute types². Attempts to fit the non-hydrocarbon data of Fig. 3 by means of eqn. (5) do not give a good fit, even when the value of ε° for ethyl ether is permitted to vary. If the value of n_b for ethyl ether is permitted to vary too, however, rather than being restricted to the real, calculated value (4.1), the non-hydrocarbon data of Fig. 3 can be brought into good agreement with eqn. (3). The deviation of experimental (6.0, optimized) and calculated (4.1) values of n_b then provides a direct, quantitative measure of the failure of eqn. (5) for these non-hydrocarbon data. The form of eqn. (5) and of the

deviations from eqn. (1) in Table VII suggests that deviations between experimental and calculated n_b values can be used to evaluate the presence or absence of an "ether anomaly" for other eluents.

Table VIII summarizes a number of eluent strength data for elution of both hydrocarbons and non-hydrocarbons by binary eluents previously reported or described for the first time in Table VI. These data were fitted by least squares to a best value of n_b (± 0.5 units) by comparison with calculated values of $\alpha\epsilon^\circ$ from eqn. (5). For the first nine binary eluent systems, the average deviation of experimental and calculated n_b values is only ± 0.7 units, within the variability of the $\alpha\epsilon^\circ$ determinations. Where the difference between experimental and calculated n_b values exceeds 0.5 unit, the experimental value is invariably negative, as might have been expected from the crowding of eluent molecules on the adsorbent surface, with reduction in the area required for adsorption. In the last five binary eluent systems, the experimental n_b values for the non-hydrocarbon data are all greater than +1.5 (although normal for the hydrocarbon data), suggesting the possible existence of an "ether anomaly" effect for these three strong eluents (ethyl sulfide, ethyl ether, and diethylamine). The remaining strong eluents of Table VIII appear quite normal in this respect.

These various observations on the "ether anomaly" effect suggest a fairly detailed picture of its origin. The effect is associated with the adsorbed, rather than solution, phase; it is most prominent in the case of strongly adsorbed solute groups, implying some peculiar interaction between strong adsorbent sites, solute, and/or eluent, and it seems to occur for the strongly adsorbing, saturated, aliphatic eluents (ethyl sulfide, ethyl ether, diethylamine), rather than for aromatic counterparts (e.g. phenetole) or unsaturated aliphatics (e.g. acetone). The adsorption of ethyl ether on the alumina surface is visualized in Fig. 5A. It is presumed that the primary

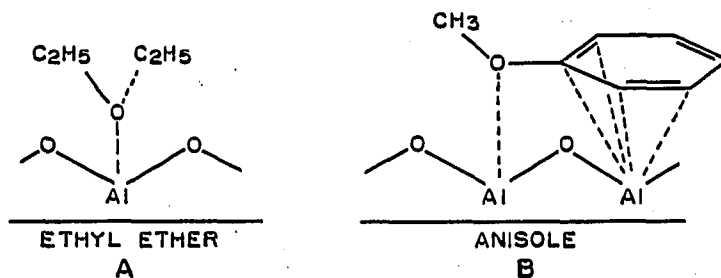


Fig. 5. Origin of the "ether anomaly". Configuration of adsorbed ethyl ether and anisole.

interaction is between the basic oxygen atom and an acidic aluminum atom, as in the adsorption of the basic nitrogen derivatives⁶. The geometry around the oxygen atom in ethyl ether favors the formation of a localized, strong bond, in contrast with the adsorption of the "normal" eluent anisole, shown in Fig. 5B. Thus, the concomitant adsorption of the phenyl ring in the latter eluent requires that the oxygen atom of anisole remain at a greater distance from the alumina surface than in the case of the ethyl ether oxygen group. The energy required to desorb the ether oxygen in these two situations will clearly be greater in the case of the ethyl ether molecule. More important, because of the proximity of oxygen and aluminum atoms which is possible in the adsorption of ethyl ether, the resulting interaction will assume the

TABLE VIII
 BINARY ELUENT STRENGTH AND THE "ETHER ANOMALY"

Binary eluent system ^a	Adsorbent activity ^b	%vB	$\alpha\epsilon^\circ$	^{n_b}		$(n_b)^c - (n_b)^d$	Reference
				Exptl. ^c	Calc. ^d		
(1) CCl ₄ -pentane (H)	2.0	5	0.016	3.5	4.4	-0.9	13
		10	0.028				
		25	0.059				
		50	0.083				
CCl ₄ -pentane (NH)	3.8	10	0.028	3.5	4.4	-0.9	2
		25	0.044				
		50	0.072				
(2) Benzene-pentane (H)	0.0	1.5	0.095	6.5	6.0	+0.5	2
		5.0	0.141				
		15	0.194				
		30	0.235				
		70	0.293				
(3) CH ₂ Cl ₂ -pentane (NH)	3.8	5	0.052	2.5	3.6	-1.1	2
		10	0.084				
		25	0.146				
		50	0.206				
(4) Phenetole-pentane (NH)	3.9	30	0.178	7.0	8.4	-1.4	Table IX
(5) Acetone-pentane (NH)	3.9	10	0.170	4.0	4.0	0.0	Table IX
		25	0.259				
		50	0.316				
(6) Dioxane-pentane (NH)	3.8	10	0.242	5.0	5.5	-0.5	2
		25	0.307				
		50	0.357				
(7) Pyridine-pentane (NH)	3.9	0.4	0.132	4.5	5.6	-1.1	Table IX
		1.0	0.155				
		4.0	0.238				
		10	0.274				
		25	0.356				
		50	0.417				
(8) Nitromethane-benzene (NH)	3.9	3	0.233	3.5	3.4	+0.1	Table IX
		8.3	0.266				
		25	0.328				
(9) Ethyl sulfide-pentane (NH)	3.9	10	0.100	6.0	4.4	+1.6	Table IX
		30	0.164				
(10) Ethyl ether-pentane (H)	2.0	10	0.139	4.0	4.1	-0.1	14
(11) Ethyl ether-CCl ₄ (H)	2.0	25	0.240	5.0	4.1	+0.9	14
(12) Ethyl ether-pentane (H)	3.8	(2-61)		2.5 ^e	4.1	-1.6	Table VI
Ethyl ether-pentane (NH)	3.8	(5-72)		6.0	4.1	+1.9	Table VII
(13) Diethylamine-pentane (NH)	3.9	5	0.233	7.5	4.4	+3.1	Table IX
		20	0.302				
		50	0.368				

^a Strong eluent (B) given first; (H) refers to data for hydrocarbon solutes, (NH) to non-hydrocarbons.

^b % H₂O-Al₂O₃ (chromatographic).

^c Least squares fit to eqn. (5).

^d Calculated from molecular dimensions of molecule as in ref. 5.

^e Assumes ϵ° value calculated from non-hydrocarbons.

TABLE IX

RETENTION VOLUME DATA FOR CALCULATING ELUENT STRENGTH IN SOME STRONG ELUENT SYSTEMS; 3.9% H₂O-Al₂O₃

Eluent	$\log R^o$										
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Ethyl sulfide			0.29					0.67			
10% v ethyl sulfide-pentane			1.51								
30% v ethyl sulfide-pentane			1.00								
Nitromethane								0.67			
3% v nitromethane-benzene								0.34			
8.3% v nitromethane-benzene								-0.28			
25% v nitromethane-benzene								-0.04			
Ethyl benzoate								0.52			
Phenetole			0.27								
30% v phenetole-pentane			0.89								
Acetone								1.30		0.54	
10% v acetone-pentane								0.41		1.04	
25% v acetone-pentane								-0.21			
50% v acetone-pentane											
Ethylamine											0.60
5% v ethylamine-pentane		0.01	0.26						0.59		1.56
20% v ethylamine-pentane			-0.37						-0.05		1.02
50% v ethylamine-pentane											0.23
Pyridine											
0.4% v pyridine-pentane		0.63	1.04	1.06							
1% v pyridine-pentane		0.40	0.79	0.83							
4% v pyridine-pentane				0.06		0.51	0.67				
10% v pyridine-pentane					0.20	0.10	0.40				
25% v pyridine-pentane										1.04	
50% v pyridine-pentane										0.43	

	Solute	$\log R_p$	Solute	$\log R_p$	
I	acetophenone	1.76	VII	6-methoxyquinoline	2.95
II	methyl 1-naphthoate	2.05	VIII	m-nitroaniline	3.00
III	quinoline	2.31	IX	dimethyl phthalate	3.33
IV	1-acetonaphthone	2.47	X	2,3-diaminonaphthalene	4.46
V	phenanthridine	2.68	XI	1,10-phenanthroline	4.60
VI	isoquinoline	2.73			

character of a strong chemical bond, and the disruption of this bond upon adsorption of a solute will clearly require a good deal more energy than is required on less active sites. Consequently, the adsorption of solutes with strongly adsorbing groups k , which have a preference for adsorption on the strongest sites (localization), will suffer most when ether or similar solvent is eluent, because the ether-site bonds tend to be stronger than for normal eluents, which are incapable of forming strong bonds with strong adsorbent sites. The localization of ether molecules on strong adsorbent sites thus appears to explain the basis of the "ether anomaly".

Strongly adsorbing aliphatic eluents such as acetone do not exhibit the "ether anomaly", presumably because the p electrons of the ether oxygen atom favor the formation of a strong, directed bond to aluminum while the more diffuse π electrons of acetone do not. Other strongly adsorbing aliphatic eluents capable of the "ether anomaly" can be predicted: aliphatic halides, other ethers, alkyl sulfides and alkylamines. Additional data for the first three eluent types were obtained to evaluate this possibility, and these are summarized in Table X. Comparison of hydrocarbon and non-hydrocarbon $\alpha\epsilon^\circ$ values in Table X shows the *absence* of the "ether anomaly" in the case of ethyl sulfide and propyl chloride, and confirms its presence in the case of isopropyl ether. Values of $\alpha\Delta_{es}$ for isopropyl ether and various solute groups are quite similar to corresponding values for ethyl ether, as seen in the averages of Table IV. The absence of an "ether anomaly" in the case of the chlorides and sulfides need not be surprising since, the "ether anomaly" must be a function of the bonding energies of the localizing eluent group and aluminum atom, the sensitivity of this energy to the distance of separation, and the steric environment around the localizing eluent group. The presence or absence of the "ether anomaly" in eluents as strong as diethylamine cannot be directly verified and is therefore not of much practical importance; the experimental ϵ° value for this eluent in Table II includes the effect of Δ_{es} terms.

The "basic eluent anomaly"

The data of Table IX for elution by diethylamine and pyridine include no R° values for solutes possessing either N-H or O-H groups (*i.e.* acidic hydrogens). Table XI summarizes a number of such experimental R° values, along with values of $\alpha\Delta_{es}$ in parentheses calculated as previously, using the $\alpha\epsilon^\circ$ values of Table VIII for the pyridine and diethylamine solutions. As in the elution of non-hydrocarbons by the ethers, we find large values of $\alpha\Delta_{es}$ for these solutes, which are essentially independent of eluent composition. This suggests, as in the case of the "ether anomaly", that some peculiar interaction in the *adsorbed* phase is occurring. We also note in Table XI that the values of $\alpha\Delta_{es}$ are invariably positive, and generally increase with the acidity of the N-H or O-H group. Thus, the acidity of the aniline derivatives increases in the order shown in Table XI (aniline weakest, nitroaniline strongest), paralleling the increase in σ^{12} for the substituent group on the aniline. Similarly, acidity should increase in the order aniline, carbazole, phenol. To the extent that acidic solute groups interact with these basic eluents in *solution*, increasing acidity of the solute group should decrease adsorption and hence lead to *negative* $\alpha\Delta_{es}$ values. It is therefore clear that the effect arises in the adsorbed phase, in agreement with the constancy of the $\alpha\Delta_{es}$ terms as eluent composition is varied. It is proposed that this "basic eluent anomaly" arises from a complex interaction of adsorbed eluent

TABLE X

TEST OF THE "ETHER ANOMALY" FOR PROPYL CHLORIDE, ETHYL SULFIDE, AND ISOPROPYL ETHER; 3.9% H₂O-Al₂O₃

Solute	log K_p	log R^c											
		<i>n</i> -Propyl chloride-pentane binaries ^a		Ethyl sulfide-pentane binaries ^b		Isopropyl ether-pentane binaries ^c							
		10	25	50	100	10	10	30	100	10	25	50	100
Chrysene	1.85	1.20	0.70	0.15						1.08	0.69	0.29	
1:2;4:5-Dibenzopyrene	3.10				0.14	0.62		0.71			1.08	0.41	
3:4-Benzacridine	2.10					1.09		0.31		1.29	0.84		
Dimethyl phthalate	3.33									(-0.04) ^d	(-0.10) ^d		
Quinoline	2.31				0.68	1.51		1.00	0.29		1.75	1.32	0.62
<i>m</i> -Nitroaniline	3.00										(-0.42) ^d	(-0.43) ^d	(-0.56) ^d
<i>p</i> -Diethoxybenzene	1.53								0.67		1.11	0.83	0.56
<i>m</i> -Dinitrobenzene	2.28										(-0.42) ^d	(-0.42) ^d	(0.32) ^d
α^e exptl. (hydrocarbons)		0.054	0.096	0.142	0.204	0.103	0.159			0.064	0.097	0.133	0.179
calc. (non-hydrocarbons)		0.052	0.101	0.150	0.204	0.091	0.155	0.242	0.242	0.078	0.126	0.175	0.223
					(0.204)	0.074	0.145	(0.242)	(0.242)	0.038	0.076	0.121	(0.179)

a % v Propyl chloride.

b % v Ethyl sulfide.

c % v Isopropyl ether.

d $\alpha\Delta_{cs}$

TABLE XI

THE "BASIC ELUENT" ANOMALY FOR PYRIDINE AND DIETHYLAMINE AS ELUENTS; 3.9% $\text{H}_2\text{O}-\text{Al}_2\text{O}_3$

Solute	$\log R_p$	$\log R^0$				50% v Pyridine-pentane
		Diethylamine-pentane solutions ^a				
		5	20	50	100	
$a\epsilon^0$		0.233	0.302	0.368	0.400	0.417
Carbazole	2.64	1.22 (0.78)				
Phenol	2.93				1.60 (1.07)	
Aniline	2.29	1.15 (0.60)	0.49 (0.47)	0.05 (0.52)		
<i>p</i> -Fluoroaniline	2.33		0.81 (0.76)			
<i>p</i> -Chloroaniline	2.36		0.85 (1.06)			
<i>m</i> -Chloroaniline	2.36		0.74 (1.05)			
<i>m</i> -Nitroaniline	3.00		1.14 (1.16)	0.50 (1.18)	0.24 (1.24)	0.19 (1.36)

^a % v Diethylamine.

and solute, as shown in Fig. 6 for the adsorption of aniline from diethylamine solutions. The amino group of the aniline is first assumed to localize on a strong adsorbent site (aluminum atom) with electron transfer⁶. This greatly increases the acidity of the N-H group in the aniline molecule, and the proton on the aniline nitrogen can then interact by hydrogen bonding or proton transfer with an adjacent amino group. Since not all eluent molecules can localize on strong adsorbent sites (see discussion of following section), the amine to which hydrogen bonding occurs is presumed to be non-localized, with little loss in its normal basicity. Similarly, the amine displaced by the aniline nitrogen upon adsorption is less acidic than the corresponding aniline amino group, so that competitive interaction between two eluent groups, as in Fig. 6 between an eluent and a solute, is less favored.

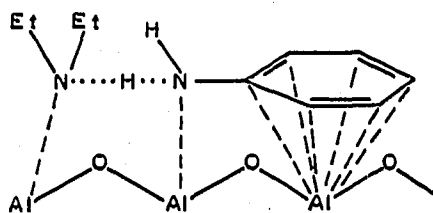


Fig. 6. Origin of the "basic eluent anomaly". Configuration of adsorbed aniline-diethylamine complex.

The magnitude of the "basic eluent" effect is similar for both diethylamine and pyridine solutions, and this may be true of other basic eluents as well. The "basic eluent anomaly" can be used to great advantage in the separation of solutes differing in the possession of N-H or O-H groups, but not in other chromatographic properties

(A_s , R_p). It is important to realize that the acidity of the solute *in the adsorbed phase* determines the magnitude of the "basic eluent anomaly", rather than the more familiar solution acidity of the substance. Thus, phenol is certainly a stronger acid than *p*-chloroaniline, yet the values of $\alpha\Delta_{es}$ in each case are identical. Presumably, the strong, electron transfer interaction of the aniline nitrogen with an adsorbent aluminum atom results in an appreciably greater increase in the aniline acidity than occurs for the phenol upon adsorption.

The alcohols and their solutions as eluents

The alcohols and their solutions represent a limiting case as eluents, being among the strongest useful eluents*, and giving rise to the strongest solution interactions. Additionally, specific adsorbent-solute-eluent interactions as in Fig. 6 can be readily conceived. It might therefore seem unlikely that eqn. (1) could have more than qualitative significance in systems using the alcohols as eluents. Table XII summarizes R^o data for elution of various solutes by several isopropanol binaries. Varying amounts of water were added to the eluent as needed to preserve adsorbent activity at its initial value. Using 1,10-phenanthroline as standard solute, values of $\alpha\epsilon^o$ were calculated for the 1 to 35 % isopropanol-pentane solutions, and these $\alpha\epsilon$ values in turn used to calculate values of $\alpha\Delta_{es}$ for most of the remaining solutes. For the first seven solutes, these values of $\alpha\Delta_{es}$ are appreciable, but apparently randomly distributed as a function of solute structure; the average of the $\alpha\Delta_{es}$ values for the 1 to 10 % isopropanol solutions, where sufficient solute data are available for a valid comparison of experimental values with those calculated from eqn. (1), is ± 0.15 log units. This is reasonably small considering our previous remarks. The last four solutes of Table XII show much larger values of $\alpha\Delta_{es}$, and it may be significant that each of these solutes possesses an amino group. This suggests interaction of adsorbed solute and eluent, similar to that shown in Fig. 6 for the basic eluents. The relative constancy of these $\alpha\Delta_{es}$ values for each amino-substituted solute confirms the importance of interactions in the adsorbed rather than solution phase. The model of Fig. 6 fails for the other acidic solutes of Table XII (azaindole, acetylindole, phenol), which should also be strongly retained (large positive $\alpha\Delta_{es}$ values) if a "basic eluent anomaly" were operating in elution by the alcohols. While there are insufficient data in Table XII to permit any firm conclusions as to the origin of these alcohol eluent $\alpha\Delta_{es}$ values for the amino-substituted solutes, the following qualitative explanation may have some merit.

The two indole derivatives of Table XII and phenol have a relatively acidic hydrogen in each case, and it is believed (ref. 6 and following section) that the principal contribution to the adsorption energy of these solutes arises as a result of proton transfer from solute to the surface oxygen atoms of the alumina. For elution by basic eluents, such as the amines and pyridine, the basic eluent competes favorably with the surface oxygen atoms for proton transfer from the solute, and the adsorption energy for the solute is enhanced by proton transfer to the eluent, as in Fig. 6. For eluents such as the alcohols, the alcohol oxygen atom is considerably less basic, and it is postulated that interactions such as those of Fig. 6 are insufficiently strong to pre-empt the primary proton bonding between solute and surface

* The aliphatic acids are stronger, but chemically alter the alumina adsorbent and do not appear to constitute useful eluents.

TABLE XII
ISOPROPANOL-PENTANE BINARY ELUENTS; 3.9% H₂O-Al₂O₃

Solute	log <i>K_p</i>	log <i>R_f</i> ^a							CH ₂ Cl ₂	Dioxane
		1	2	5	10	20	35	100		
7-Azaindole	3.36		0.35 (-0.35)	0.02 (-0.35)	-0.26 (-0.38)					
3-Acetylpyridine	3.02	0.25 (-0.26)	0.02 (-0.17)							
3-Acetylindole	4.61		1.38 (0.13)	0.90 (0.07)						
Dimethyl phthalate	3.33	-0.44								
N-Methylquinolone	3.69		0.29 (0.14)	0.04 (0.33)					1.02	-0.46
1:10-Phenanthroline	4.60	1.44	1.05	0.62	0.29	-0.01	-0.24			0.59
Phenol	2.92									
Benzyl alcohol	2.33 ^b		0.66	0.90 (0.36)	0.59 (0.25)	0.34 (0.18)	0.30 (0.27)			
Benzamide	3.23 ^c		1.43	1.29			0.26			
2-Aminopyridine	3.04	1.58 (0.79)	1.16 (0.78)	0.73 (0.68)	0.39 (0.62)	0.09 (0.51)	-0.13 (0.46)			0.03
Aniline	2.16	0.34 (0.53)								
m-Nitroaniline	3.00	1.18 (1.32)	0.70 (1.24)	0.64 (1.62)	0.31 (1.62)	0.02 (1.63)				
2,3-Diaminonaphthalene	4.46							1.19 (2.05)	0.77	
$\alpha\epsilon^d$		0.314	0.354	0.398	0.431	0.461	0.484			0.522 ^e

^a % v Isopropanol.
^b Assumes *A_s* equal 6.0, αA_{es} equal 0.3.
^c Assumes *A_s* equal 8.0, αA_{es} equal 1.0.
^d Calculated from 1,10-phenanthroline data.
^e Calculated from 2,3-diaminonaphthalene data.

oxygen atoms. Furthermore, the alcohols themselves are believed selectively adsorbed by proton transfer to the surface oxygen atoms, which in turn selectively restricts the adsorption of acidic solutes such as the indoles and phenols. Solute such as aniline do not adsorb principally by proton transfer, and any additional adsorption energy contributed by interactions of the type shown in Fig. 6 should increase the adsorption energy of the anilines and hence give positive values of $\alpha\Delta_{es}$. While this explanation of the data of Table XII is qualitatively satisfactory, the $\alpha\Delta_{es}$ values for the amino derivatives of Table XII tend to be higher than comparable values in Table XI, whereas the present theory requires that they be lower. Undoubtedly, the actual situation is considerably more complex than we have represented it.

If the $\alpha\varepsilon^\circ$ values of Table XII for the isopropanol-pentane binaries are correlated by means of eqn. (5), it is found that a very poor fit results with the calculated n_b value (3.2), but a reasonable fit is obtained for n_b equal 8. This is similar to the case of diethylamine as eluent, and may reflect the existence of an "ether anomaly" effect with the alcohols.

An ε° value for pure isopropanol may be calculated from the data of Table XII, equal to 0.82. The pure alcohols do not appear suitable as eluents since they tend to wash out the smaller adsorbent particles, which usually is experimentally inconvenient. Retention volume values for methanol-ethyl ether binaries (25 and 50 % v) and 2,3-diaminonaphthalene as solute ($\log R^\circ$ equal 0.33 and 0.10, respectively) suggest an ε° value for pure methanol equal to 0.95.

THE RELATIONSHIP OF ELUENT STRENGTH TO MOLECULAR STRUCTURE

The relative strength of the eluent in adsorption chromatography has been investigated by a number of workers, as reviewed by LEDERER AND LEDERER¹⁵, and more recently by STRAIN *et al.*¹⁶. Previous studies have led to eluent strength series generally similar to that of Table II, although there has been occasional disagreement about the relative elution efficiency of certain solvents. Such differences of opinion are scarcely surprising, in view of effects such as the "ether anomaly" and "basic eluent anomaly", which if ignored lead to eluent strength series which depend upon the solute studied. The importance of such effects in previous studies has been magnified by the tendency of previous workers to study only a limited number of solutes, as well as by past ignorance of the theoretical relationship between binary eluent strength and eluent composition (eqn. 5).

The theoretical basis of the relationship between eluent strength and molecular structure has long been an important problem in the theory of adsorption chromatography. Early workers noted the general dependence of eluent strength on "polarity" (dipole moment, dielectric constant, etc.), but such relationships have never been found to be more than rough correlations with numerous exceptions. The eluent has been generally assumed to achieve its elution power by competitive interactions with solute in both adsorbed and non-sorbed phases¹⁶. The importance of net solution interactions in this respect, however, is contradicted by the general applicability of eqn. (1) for the weaker eluents, and the association of deviations from eqn. (1) for the stronger eluents (*e.g.* ethyl ether, ethylamine, isopropanol), with adsorbed phase interactions. Direct comparison⁵ of the magnitudes of solution and adsorption

terms in typical chromatographic systems also challenges the importance of solution interactions in affecting adsorption chromatographic separation. Consequently, a reasonable theory of the dependence of eluent strength on molecular structure must emphasize the interactions in the adsorbed phase.

Eluent strengths of pure solvents

An earlier paper² in the present series has suggested that the strength of a compound used as eluent (ϵ°) can be related to the adsorption energy of the same compound when considered as solute. Specifically, it was predicted that ϵ° would be determined by the adsorption energy of the solute S° per unit area A_s :

$$\epsilon^\circ = \frac{S^\circ}{A_s} = \frac{\sum^i Q^\circ_i + \sum^j q^\circ_j - f(Q^\circ_k) \sum^{i \neq k} Q^\circ_i}{A_s} \quad (6)$$

Eqn. (6) completely ignores solution energy terms. Application of eqn. (6) to a number of eluents of known strengths² showed good agreement between calculated and experimental ϵ° values for a number of weak and moderately strong eluents, but calculated values for the stronger eluents were generally high by a factor of at least two. This was originally rationalized in terms of localization effects. Solute with strongly adsorbing groups tend to localize upon adsorption⁸, with the strongest adsorbing solute group fixed to a strong adsorbent site. Eqn. (6) takes solute localization into account, but localization of the adsorbed eluent would be expected to differ markedly from localization of the adsorbed solute, because of greater competition for adsorbent sites among eluent molecules. The failure of the *average* eluent molecule to adsorb on a strong adsorbent site would lead to a lower energy of adsorption of the eluent than predicted by eqn. (6), as is in fact observed.

The actual adsorption energy per eluent molecule can be estimated if we assume that localization is absent in the average adsorbed eluent molecule, an assumption which appears realistic since the average strong adsorbent sites appear widely separated⁶. The various group adsorption energies Q°_i (and solute geometry terms q°_j) of eqn. (6) must then be replaced by $[1 - f(Q^\circ_k)]Q^\circ_i$, the energy per non-localized group in the eluent as solute⁸. $f(Q^\circ_k)$, the localization function for the strongest adsorbing solute group k , has been previously defined⁸. The resulting relationship between eluent strength and structure is then given by:

$$\epsilon^\circ = \frac{[1 - f(Q^\circ_k)] [\sum^i Q^\circ_i + \sum^j q^\circ_j]}{A_s} \quad (6a)$$

Before applying eqn. (6a) to eluent strength calculations, however, two additional complications must be recognized. First, previous treatments of solute adsorption energy (and tabulations of Q°_i values) ignore the delocalization of benzene rings attached directly to a localizing group k . Since the benzene ring is delocalized in the eluent considered as solute, it cannot undergo further delocalization when the solute is considered as eluent. Consequently, for aromatic eluents eqn. (6a) assumes the alternate form:

$$\epsilon^\circ = \frac{n_a Q^\circ_c + [1 - f(Q^\circ_k)] [\sum^i Q^\circ_i + \sum^j q^\circ_j - n_a Q^\circ_c]}{A_s} \quad (6b)$$

Here, n_a refers to the number of aromatic carbon atoms (usually six) in the ring attached to the group k , and Q°_c is the value of Q°_i for an aromatic carbon atom (0.31 for alumina).

A second correction is required for eluents where k is attached to alkyl carbon. In this case, the localization function calculated from aromatic solutes does not apply, again because of the convention of ignoring the delocalization of the benzene ring attached to the localizing group k . That is, if delocalization of the aromatic ring in such solutes as anisole had been originally considered, the calculated net adsorption energy of the benzene ring would have been less, and the Q°_i value of the methoxy group (k) larger. This would in turn have led to a larger calculated value of $f(Q^{\circ}_k)$ in such solutes as dimethoxybenzene. Fig. 7 summarizes the complete re-interpretation

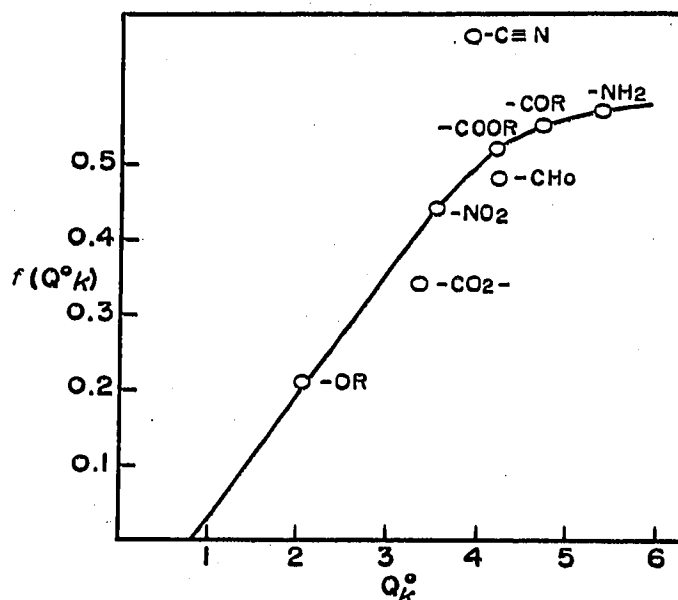


Fig. 7. Revised localization function for both aromatic and aliphatic solutes and eluents (delocalization of attached ring considered).

of Table VI of ref. 8 (where the localization function was first derived) in terms of a model assuming the delocalization of the benzene ring attached to each localizing group k , as well as delocalization of other groups. As expected, the revised relationship between $f(Q^{\circ}_k)$ and Q°_k differs from the previous relationship (Fig. 2, ref. 8) based on non-delocalization of one aromatic ring. The localization function of Fig. 7 could be used with the revised Q°_k values (also noted in Fig. 7) to calculate the adsorption energies of aromatic solutes with a precision equal to the previous treatment⁸. Alternately, these same Q°_k and $f(Q^{\circ}_k)$ values of Fig. 7 could be used in eqn. (6 a), rather than the original values in eqn. (6 b), to calculate the eluent strengths of aromatic eluents. For purposes of convenience and consistency, however, we will retain the former convention of ignoring ring delocalization for the aromatic solutes and eluents. The revised function of Fig. 7 has the unique merit of permitting eluent strength calculations for *any* solvent according to eqn. (6 a), since the new localization function (Fig. 7) is of general applicability.

Values of A_s for the various eluents of Tables II and III were calculated from the estimated configuration of adsorbed eluent and the known molecular dimensions

and Van der Waals radii, as previously in the calculation of solute group area values⁵. For alkyl groups longer than methyl, the contribution to A_s was taken from experimental data for alkyl-substituted solutes (obtained by eluent variation studies¹¹). ε° values for 24 of the 29 eluents of Table II could then be calculated using either eqn. (6a) for aliphatic eluents, or (6b) for aromatic eluents, and Q°_i and q°_j values from the present study (Table V) or a previous tabulation⁸. Five of the eluents of Table II could not be treated by eqn. (6a) or (6b), either because unknown Q°_i values were involved (carbon disulfide, diethylamine), or more than one strongly adsorbing group was attached to the same carbon atom (carbon disulfide, CH_2Cl_2 , CHCl_3 , CCl_4), with resulting serious steric and electronic interaction (of unknown magnitude) among these strong eluent groups.

The agreement between experimental and calculated (no correction) ε° values in Table II is semi-quantitative, the average deviation being ± 0.06 units for a total range of $0.00 \leq \varepsilon \leq 0.95$. Seven eluents deviate from the calculated value by more than 0.10 unit. Several sources of error in this calculation can be recognized, apart from possible inadequacies in the theoretical development. Several of the Q°_i values for aliphatic eluents ($\text{R-CO}_2\text{R}$, R-Cl , R-O-R) are estimates, based on extrapolated data⁸. In other cases (R-OH), the Q°_i values are relatively uncertain for other reasons. The various A_s values can hardly be more accurate than $\pm 10\%$. Finally, the calculation of the localization function in Fig. 7 is somewhat ambiguous; a previous communication⁶ has observed that the localization of aromatic rings and of single groups (e.g. nitro, amino, etc.) has a fundamentally different basis, and that the resultant localization functions are only fortuitously equal for certain solute types. The delocalization of a ring attached to a strongly adsorbing group may in fact be somewhat greater than assumed in Fig. 7. With these considerations in mind, the uncorrected correlation of Table II is in fact seen to be quite reasonable. Since we have ignored solution interactions completely in this treatment, this is excellent additional evidence for the general unimportance of such interactions in determining the properties of an eluent.

It is worth while to consider one additional contribution to eluent strength, particularly as it permits an approximate correction of the ε° values calculated above. We have already observed the special ability of ethyl ether to adopt a preferred adsorbed configuration (as in Fig. 5A), and it has been previously postulated⁸ that all monatomic adsorbing groups have a greater than average localization function because of their ability to form a single strong bond with an adsorbent site. If the eluents capable of ether-like interaction with the adsorbent are considered separately (8 compounds in Table II of the general type R-X or R-X-R , where X is monatomic exclusive of hydrogens, and R is alkyl), it is found that the calculated values are high by an average of 0.11 ± 0.04 units. This would have been predicted if localization of the eluent molecule (as solute, but not as eluent) as in Fig. 5A occurs, since the true delocalization function is then effectively higher. It also suggests a correction (-0.11 units) for the calculated ε° values of eluents of this type. The second column of calculated ε° values in Table II (corrected) have been corrected in this fashion. Similarly, it seems possible that eluents which contain a tri-atomic k group (exclusive of hydrogen) might tend to have *smaller* than normal localization functions, because of the more diffuse interaction of the group k with a point adsorbent site, and resulting greater freedom (lesser delocalization) of the remainder of the solute to adopt an

optimum configuration on the adsorbent surface. In confirmation of this expectation, the four eluents of this type in Table II (nitromethane, ethyl benzoate, methyl acetate, ethyl acetate) show calculated ϵ° values which are *low* by 0.09 ± 0.08 units. It therefore seems that eluents which possess strong groups containing three or more atoms will generally show ϵ° values higher than calculated, and that the calculated values should be corrected by adding 0.09 units. The second column of calculated ϵ° values in the Table II (corrected) have been corrected in this fashion.

The 24 calculated ϵ° values of Table II, corrected in the above fashion, deviate from the experimental values by an average of only ± 0.03 units with only one calculated ϵ° value in error by more than 0.10 unit. This correlation of experimental and calculated ϵ° values is better shown in the plot of Fig. 8. Considering the range

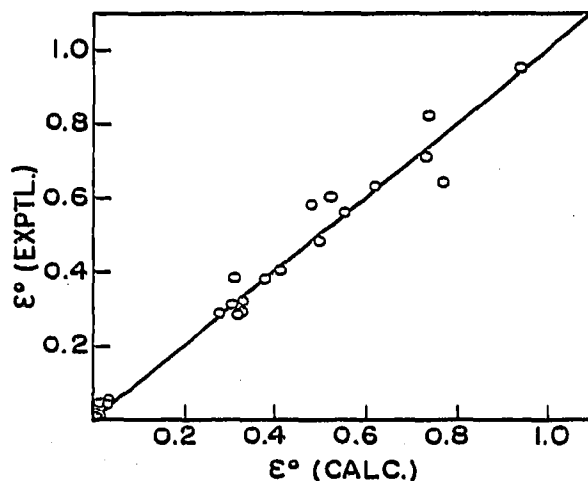


Fig. 8. Comparison of experimental *versus* calculated (corrected) ϵ° values for the eluents of Table II.

in eluent strengths and properties, the numerous approximations represented in the Q°_t and A_s values, and the simplicity of the theoretical derivation, this is a surprisingly good fit of experiment and theory. Fig. 8 confirms that the major aspects of the role of the eluent in adsorption chromatography now rest upon a firm fundamental basis. Only the more general problem remains of relating *solute* adsorption energies to structure in terms of fundamental interactions between adsorbate and adsorbent.

A recent approach¹⁷ to the relationship between eluent strength and structure deserves brief comment; it has been suggested that eluent strength can be correlated with surface tension *versus* water. While this correlation appears experimentally more satisfactory than previous correlations on eluent dielectric constant or dipole moment, it seems clear that only a qualitative, empirical relationship is involved, which cannot apply to all systems.

Eqns. (6a) and (6b) can be used to predict the strengths of a number of eluents for which ϵ° values have not yet been measured. Table III summarizes several such values. In most cases these calculated ϵ° values should be accurate within ± 0.1 units. The value for nitropropane was estimated from the experimental value for nitroethane, in view of the large error in the calculated value for that eluent.

Eluent strengths of binary mixtures

For molecules which localize on the adsorbent surface, the adsorption energy differs

depending upon whether the molecule functions as an eluent or a solute. As an eluent, the entire adsorbent surface is covered by the localizing molecule, the competition for strong adsorbent sites is keen and most molecules are incompletely localized, and average adsorption energy is low. As a solute, very little of the adsorbent surface is covered by localizing molecule, there is *no* competition among solute molecules for strong adsorbent sites, and average solute adsorption energy is high. In binary eluent solutions of the localizing molecule and a weaker adsorbing solvent, the average adsorption energy of the localizing molecule (as eluent) approaches that of pure eluent at high surface coverages, and that of the molecule as solute at low surface coverages. Eqn. (5) should therefore be most accurate at high concentrations of the strong eluent.

Similarly, in binary eluents containing a strong eluent which exhibits "ether" or "basic eluent" anomalies, $\alpha\Delta_{es}$ has been observed to be constant as eluent composition varies. This can only be true at relatively high surface coverages, however, $\alpha\Delta_{es}$ eventually approaching the value applicable to the weaker binary eluent as the concentration of the strong eluent in solution and adsorbed phases decreases. Adsorbent surface coverage by the strong eluent in a binary eluent system can be calculated as previously², and compared with experimental $\alpha\varepsilon^\circ$ and $\alpha\Delta_{es}$ values in selected systems, in order to evaluate the importance of these effects. Such comparisons can also offer additional evidence in behalf of the present theory of eluent localization in the adsorbed phase.

In Fig. 9a, $\alpha\varepsilon^\circ$ values for dilute ethyl ether-pentane solutions are plotted *versus* eluent composition. These are taken from the hydrocarbon solute data of Table VI, plus a similarly determined value for 2% ether-pentane. The lower solid line ("eluent") of Fig. 9a is calculated from eqn. (5), using the ε° value for ether as eluent.

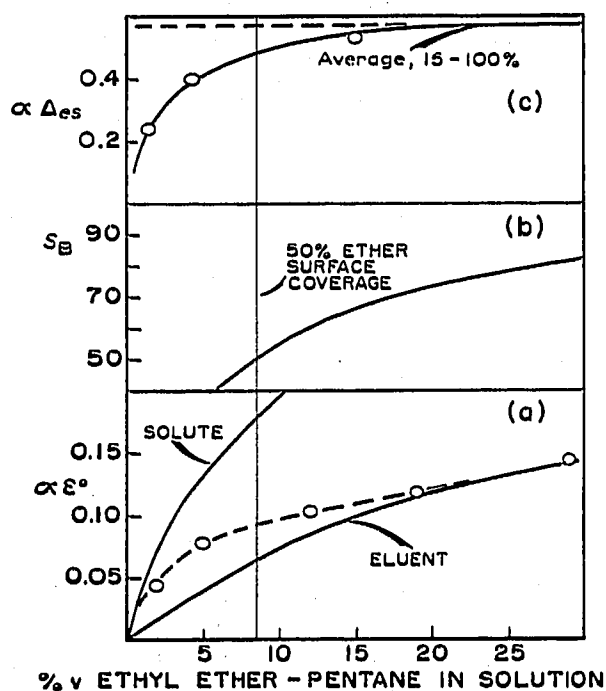


Fig. 9. Eluent strength and the "ether anomaly" in dilute solutions of ethyl ether-pentane. 3.8% $\text{H}_2\text{O}-\text{Al}_2\text{O}_3$. (a) $\alpha\varepsilon^\circ$ data for hydrocarbon solutes (see Table VI); (b) % surface coverage S_B by ether, calculated from eqn. 6, ref. 2; (c) $\alpha\Delta_{es}$ values for pyridine as solute (see Table VII).

The upper solid line of Fig. 9a ("solute") is calculated from eqn. (5), using a calculated ϵ° value (eqn. 6) for ether at low surface coverages (as solute). As seen, the experimental data follow the "eluent" curve at higher ether concentrations, and approach the "solute" curve at low ether concentrations. In Fig. 9b, calculated surface coverage, S_B , by ether (eqn. 6, ref. 2) is plotted *versus* ether solution concentration. As ether surface coverage drops to about 50%, we might expect the ether adsorption energy to change from that characteristic of the eluent to that characteristic of the solute. Fig. 9a confirms this, the $\alpha\epsilon^\circ$ data falling about midway between the "eluent" and "solute" curves when ether surface coverage is 40–50%.

Similarly, for the plot of $\alpha\Delta_{es}$ *versus* ether concentration in Fig. 9c, the $\alpha\Delta_{es}$ values are essentially constant for ether surface coverages above about 70%, and begin to drop significantly when ether surface coverage approaches 50%. It is seen that the breakdown of eqn. (5) and the dependence of $\alpha\Delta_{es}$ on eluent composition first occurs in the system of Fig. 9 at ether concentrations of 5–10%. Since other localizing eluents are generally as strong or stronger than ethyl ether, have bigger n_b values, and the adsorbent of Fig. 9 is relatively deactivated, it may be anticipated that *effects of the type shown in Fig. 9 (failure of eqn. 5, variation of $\alpha\Delta_{es}$ with % strong eluent) will in general not be important when the strong eluent concentration in a binary exceeds 5%.*

THE PHENOLS AND RELATED COMPOUNDS AS SOLUTES

Whereas most solutes are adsorbed on alumina in a parallel (flat) configuration, the adsorption of the phenols is commonly assumed¹⁰ to give a perpendicular (vertical) configuration. These two possible orientations of the adsorbed phenol molecule are illustrated in Fig. 10. It is of both practical and theoretical interest to confirm the true configuration of the adsorbed phenols at low surface coverages.

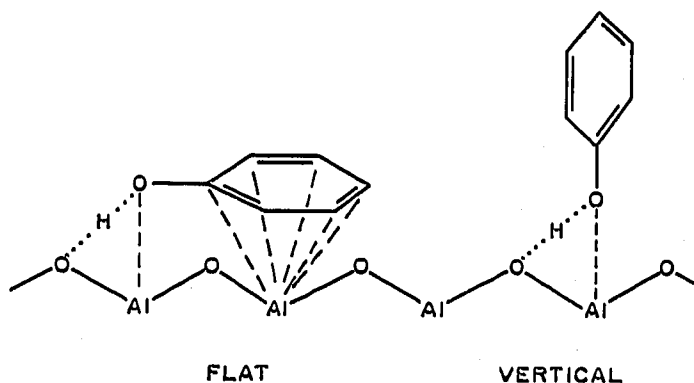


Fig. 10. Possible orientations of adsorbed phenol on adsorbent surface.

Tables XIII and XIV summarize a number of retention volume data for various substituted phenols and some related compounds. The variation of R° with changing eluent can in principle provide a value of A_s and hence specify solute configuration². This procedure is not particularly applicable to the data of Table XIII (phenol, dimethylphenol) because of the lesser accuracy of eqn. (1) in strong eluent systems. Additionally, it appears that the A_s values of acidic solutes (such as carbazole) are higher than calculated⁶, further confusing the interpretation of such data. An alter-

TABLE XIII

 RETENTION VOLUMES FOR MISCELLANEOUS STRONGLY ADSORBING SOLUTES; 3.9% H₂O-Al₂O₃

Solute	log R°							20% IPA-P ^c	log R_p
	P ^a	50% M-P ^b	10% D-P ^c	CH ₂ Cl ₂	Ethyl ether	25% D-P ^d	Dioxane		
Phenol ^f			1.58			0.98	0.53	0.34	2.93
2,6-Dimethylphenol ^g		1.35	0.88	0.85	0.78	0.17	-0.12		2.64
2,6-Di- <i>tert.</i> -butyl- <i>p</i> -cresol	0.20								
Thiophenol ^h								1.12	3.7
Benzaldoxime ^h								0.23	2.8
Acetophenone oxime ^h								0.20	2.4
αs°		0.210	0.235	0.267	0.293	0.298	0.401	0.461	

^a Pentane.

^b 50% v Methylene chloride-pentane.

^c 10% v Dioxane-pentane.

^d 25% v Dioxane-pentane.

^e 20% v Isopropyl alcohol-pentane.

^f Assumes A_s equal 6.0.

^g Assumes A_s equal 7.0.

^h Assumes A_s equal 6.0, αA_{es} equal +0.30.

native analysis is offered by the variation of R° among the substituted phenols, using a single system, as in Table XIV. From eqns. (1) and (2), and the R° value for phenol, R° values for the substituted phenols may be calculated if we ignore the (unknown) geometry term $\sum_j q^{\circ}_j$. The difference between experimental and calculated experimental values Δ_f is then equal to the solute geometry term. This calculation assumes flat adsorption of the phenols. Alternatively, for vertical adsorption, $\sum_j q^{\circ}_j$ or Δ_v is simply the difference between the experimental values of R° for the substituted phenol and

TABLE XIV

 RETENTION VOLUMES OF *m*- AND *p*-SUBSTITUTED PHENOLS; 3.9% H₂O-Al₂O₃, 20% v ISOPROPANOL-PENTANE ELUENT

Solute	log R°	Δ_v	Δ_f	σ^{18}
<i>p</i> -Methoxyphenol	0.30	-0.04	0.26	-0.268
3,4-Dimethylphenol	0.15	-0.19	0.71	-0.239
<i>p</i> -Methylphenol	0.27	-0.07	0.38	-0.170
3,5-Dimethylphenol	-0.03	-0.37	0.53	-0.138
Phenol	0.34	0.00	0.00	0.000
<i>m</i> -Methoxyphenol	0.40	0.06	0.36	0.115
<i>p</i> -Chlorophenol	0.75	0.41	0.80	0.227
<i>m</i> -Acetophenol	0.84	0.50	0.10	0.306
<i>m</i> -Chlorophenol	0.70	0.36	0.75	0.373
<i>p</i> -Acetophenol	1.54	1.20	0.80	0.874 ^a
<i>p</i> -Formylphenol	1.93	1.59	0.87	1.126 ^a
<i>p</i> -Nitrophenol	> 2.00	> 1.64	> 1.87	1.27 ^a

^a σ^{18} Values for reactions of anilines and phenols.

phenol. In either case, these $\sum q_j^{\circ}$ values should be linearly related to the HAMMETT σ parameter¹² since phenol acidity is so related, and the adsorption of the phenols on alumina is assumed to be an acid-base type reaction¹⁰. The best correlation of $\sum q_j^{\circ}$ on σ should therefore indicate the actual configuration of the adsorbed phenols. Table XIV and Fig. 11 summarize these two possibilities. As clearly seen in Fig. 11, for the vertical adsorption case, this configuration gives a quite satisfactory correlation on δ , whereas the correlation for the horizontal adsorption case in Fig. 11b is very poor. It is therefore concluded that the phenols are adsorbed in the vertical configuration from the solvent of Table XIV. The correlation of Fig. 11a also permits $\sum q_j^{\circ}$ for the substituted phenols to be related to σ (eqn. 4).

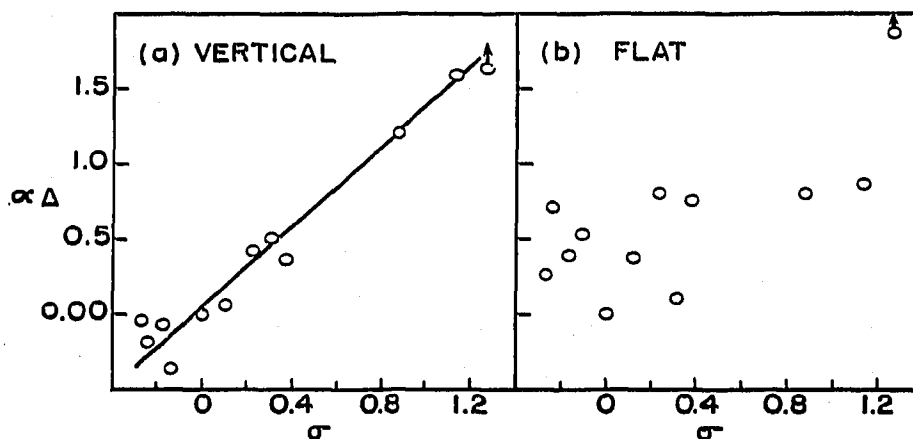


Fig. 11. Correlation of phenol Δ values for flat and vertical configurations *versus* HAMMETT σ values.

A vertical configuration for phenol can be used to calculate a value of A_s equal 3.5, *versus* 7.0 for the horizontal configuration. Similarly, 2,6-dimethylphenol should have an A_s value of 4.3 in the vertical configuration. The data of Table XIII actually suggest A_s values for phenol and dimethylphenol of about 6 and 7, respectively. The higher values can presumably be ascribed to an effect similar to that encountered in the pyrrole derivatives⁶, where the acidic nitrogen group requires an apparent area of adsorption (A_s value) some 2.5 units higher than calculated. Assuming a similar increase in A_s for all the solutes of Table XIII, the indicated $\log R_p$ values can be calculated, and are the basis of the values of Table V. The data taken from the 20% isopropanol-phenol solution were arbitrarily reduced by 0.3, the value of αA_{es} for phenol in this solvent.

Without a doubt, as eluent strength is decreased from that of 20% isopropanol-pentane toward that of pentane, at some point the phenol molecule changes from a vertical to a flat configuration. The condition for this configuration transformation has been considered previously²: it should occur at that eluent strength where the adsorption energies for each configuration are equal. Conversely, configuration in a particular case may be decided from adsorption energy calculations on both flat and vertical configurations. The configuration giving the greatest energy or R° value is the preferred one. As an example, the A_s values for flat and vertical phenol are calculated as 9.5 and 6.0 units. The adsorption energy of the benzene ring is given by

$f(Q^{\circ k}) \sum_{i \neq k} Q^{\circ i}$ for the flat configuration (1.02), taking the normally neglected delocalization of the ring attached to k into account, while that for the vertically adsorbed phenol ring is 0.00. At an eluent strength ϵ° equal to 1.02/3.5, or 0.29, phenol should pass from a vertical configuration to a horizontal one. Similarly, we can estimate the configuration of *p*-acetophenol in the system of Table XIV. A_s for the flat and vertical configurations is calculated at 11.5 and 6.0, respectively, and the net adsorption energy $\alpha f(Q^{\circ k}) \sum_{i \neq k} Q^{\circ i}$ to be gained in the flat configuration is 1.94. $\alpha \epsilon^{\circ}$ is 0.461 and it is calculated that the vertical configuration is favored by 0.60 units, *i.e.* by a substantial margin. Since *p*-acetophenol is the most likely of the phenols in Table XIV to adsorb in the flat configuration (the aceto group has the largest adsorption energy), this calculation supports our prior conclusion: all of these phenols adsorb vertically.

GLOSSARY OF TERMS

A_s	Solute surface volume, approximately proportional to area required by solute upon adsorption
a_i	Contribution of solute group i to A_s ; $A_s = \sum a_i$
$f(Q^{\circ k})$	Solute localization function ⁸
n_a	Number of aromatic carbon atoms in eluent molecule
n_b	Value of A_s for the strong eluent in a binary eluent solution
$q^{\circ j}$	Solute geometry parameter
$Q^{\circ i}$	Solute group adsorption energy parameter
\underline{R}°	Linear equivalent retention volume (ml/g)
\underline{R}_p	Value of \underline{R}° for pentane eluent
S°	Solute dimensionless adsorption energy from pentane onto calcined adsorbent (defined by relationship $\log \underline{R}_p = \log V_a + S^{\circ}$)
S_B	Fraction of adsorbent surface covered by eluent B where binary eluent (A-B) is used
V_a	Adsorbent surface volume (ml/g)
X_B	Mole fraction of strong eluent B in eluent binary (A-B)
α	Adsorbent activity function
Δ_{es}	Eluent-solute interaction parameter, for application to "anomalous" eluents; defined by eqn. (3)
ϵ°	Eluent strength parameter
ϵ°_{AB}	Eluent strength of binary solution (A-B)
$\epsilon^{\circ}_A, \epsilon^{\circ}_B$	Eluent strengths of solvents A and B
δ, δ^*	HAMMETT substituent constants ^{12,18}

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SUMMARY

Experimental data are reported for elution of a number of solutes from alumina by several very strong eluents. A number of these strong eluents (the ethers, amines,

alcohols, pyridine) exhibit unique elution characteristics, leading to a number of new separation possibilities. A quantitative theory has been developed for the relationship between elution strength and eluent constitution. For elution from alumina, the eluent properties of almost any common solvent or solvent mixture can now be accurately predicted. Whereas most solutes adsorb parallel to the adsorbent surface (flat), it is shown that the phenols adsorb in a perpendicular configuration (vertical) from strong eluents.

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