Cyclodehydration of Non-aromatic Diols on Al^{III}-Montmorillonite Clay: Reactivity and Mechanism

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Al^{III}-Montmorillonite-catalysed reactions of non-aromatic diols and butane-1,4-dithiol into the corresponding heterocyclic compounds are described. Experiments with S-(+)-pentane-1,4-diol indicate a mechanism involving competitive protonation of the primary and secondary hydroxy groups, followed by S_N2 displacement of water to form the cyclic product. A comparison of the relative catalytic efficiencies of Al^{III}-montmorillonite and the corresponding alumina pillared clay suggests that the performance of the former is superior in the above acid-catalysed reactions.

Expandable layer lattice clays such as the montmorillonites exhibit Hammett acidity function (H_0) values between 1.5 and -3 in their naturally occurring forms.[1] Their acidity may be further enhanced, to levels approaching those of concentrated mineral acids, through ion-exchange treatment with aquometal

As part of a wide-ranging programme on clay chemistry,[6–8] we recently investigated the catalytic activity of Al^{III}-montmorillonite for the cyclodehydration of non-aromatic ω,ω'-diols [equations (1) and (2)].[6] Our interest in this area was stimulated by the work of Thomas and co-workers,[2–9] and


X
a; CH$_2$
b; O
c; NH
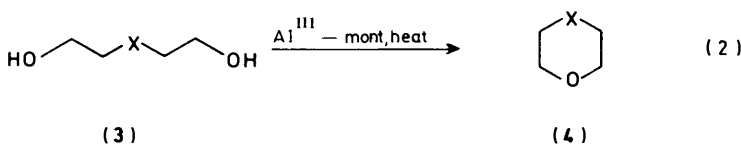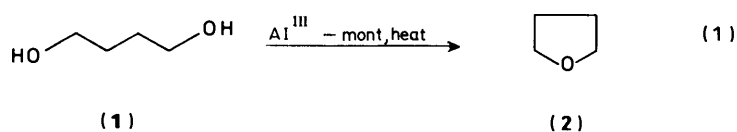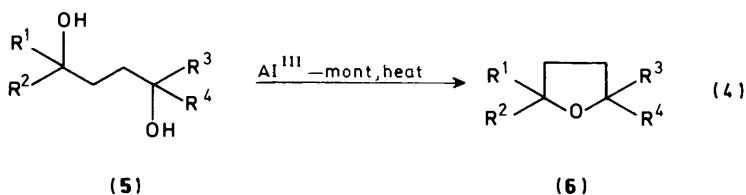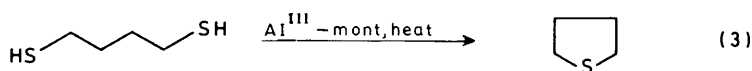
(5)   (6)
a: R^1 = R^2 = R^3 = H, R^4 = Me   b: R^1 = R^2 = R^3 = H, R^4 = Et
c: R^1 = R^3 = H, R^2 = R^4 = Me   d: R^1 = R^2 = R^3 = R^4 = Me

ions such as Al^{3+}, Cr^{3+}, and Fe^{3+}.[2–3] This high level of surface acidity, coupled with the possibility of improved reaction selectivity and other potential advantages of reactions confined in two-dimensional space,[1] have led to increasing interest in these clays as solid Bronsted acid catalysts for organic transformations. Further interest in these materials stems from their ability to function as molecular sieves, with pore sizes in the range 8—10 Å, upon 'pillaring' with polynuclear metal hydroxy ions.[4–5]

Laszlo *et al.*,[1–10] who have reported a number of proton-assisted reactions of organic molecules using such clay types. To extend the scope of the cyclodehydration, we have now studied the reactivity of butane-1,4-dithiol and other diol systems, in the presence of the above clay [equations (3) and (4)]. Additionally, we have carried out experiments with optically active S-(+)-(5a) to comment on the possible mechanism of the cyclodehydration process. Finally we have compared the relative catalytic efficiencies of Al^{III}-mont-
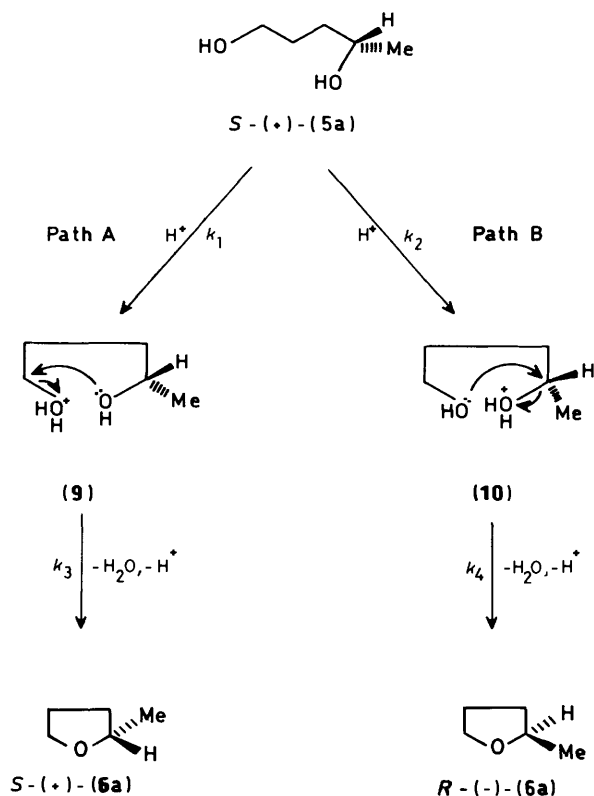
Scheme.

morillonite and the corresponding alumina-pillared clay in some of the above reactions.

Results and Discussion

Clay Catalyst.—Al^{III}-Montmorillonite is readily prepared from the exchange reaction of Na-montmorillonite* with aqueous $Al(H_2O)_n{}^{3+}$. The high Bronsted acidity of this clay presumably originates from the equilibrium process depicted in equation (5). The corresponding Al_{13}(alumina)-pillared clay

$$Al(H_2O)_n{}^{3+} \rightleftharpoons Al(H_2O)_{n-1}(OH)^{2+} + H^+ \quad (5)$$
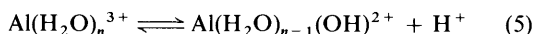
can be prepared *via* intercalation of $Al_{13}O_4(OH)_{28}{}^{3+}$, or related polynuclear Al^{III} species, and subsequent calcination of the clay at 350 °C [equation (6)].[4] It is evident from equation (6) that the latter clay would also exhibit Bronsted acidity.

$$Al_{13}O_4(OH)_{28}{}^{3+} \xrightarrow{350\,°C} (Al_2O_3)_{6.5} + 3H^+ + 12.5\,H_2O \quad (6)$$
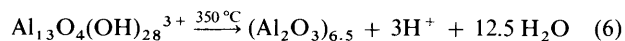
Al^{III}-Montmorillonite-catalysed Reactions.—Table 1 lists the reactions of butane-1,4-dithiol and various non-aromatic diols catalysed by Al^{III}-montmorillonite clay [equations (1)—(4)]. As can be seen from the table, the diols and dithiol are converted into the corresponding oxygen and sulphur heterocycles, respectively, in the range 140—200 °C, mass balance analyses revealing that the produ*k*ts were formed in good to excellent yields, and in high purity.

A comparison of the reactivity profiles of compounds (3a—c) (entries 8—10, respectively) indicated that ease of formation was greatest with compound (3a), no reaction being observed with compound (3c). However, the rate of formation of the

heterocycle (4a) was less than that of the corresponding 5-membered heterocycle (2).[11] Comparisons within the same class of molecules, *i.e.*, those yielding tetrahydrofuran derivatives, indicated the reactivity order (1) < (5c) < (5d) (entries 1, 5, and 6, respectively). This order suggests that the above intramolecular process is most facile for diols containing tertiary hydroxy groups, albeit with some formation of other products, and least so for the corresponding ω,ω'-diol. Curiously, this trend was not obeyed by diols (5a) and (5b) (entries 3 and 4), which exhibited reaction rates even lower than that found for (1). Comparisons between pentane-1,4-diol (5a) and hexane-1,5-diol (not shown in Table 1) indicated that while the former could be cleanly converted into compound (6a) (entry 3), reaction with the latter diol resulted in a complex mixture of products, the six-membered cyclic ether being produced in less than 40% purity. In experiments with S-(+)-(5a), a net inversion in stereochemistry of *ca.* 10% was detected in the resultant tetrahydrofuran derivative (6a).†

Mechanism.—The reactions reported in Table 1 are catalysed by protons, *e.g.*, the reactions of compounds (1), (3c), and (3b) in the presence of mineral acids are well known.[12-14] The protons in Al^{III}-montmorillonite are located both on the external surface of the clay and within the interlayer space between clay sheets.[2] These protons are generated *via* the equilibrium process depicted in equation (5). Qualitatively, the acidity of the clay is dependent, among other factors, on its moisture content and temperature.[1]
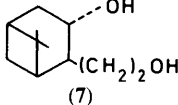
Previous work by Thomas and co-workers on intermolecular clay-catalysed reactions of alcohols, thiols, and amines indicated a mechanism involving protonation of the $OH/SH/NH_2$ functionality, followed by an S_N2-type displacement of $H_2O/H_2S/NH_3$ to the products.[9a-c] We hypothesize that the lack of reactivity of compound (3c) (entry 9) results from preferential protonation of the amino function over the hydroxy function which hinders the cyclodehydration: we note that this reaction requires forcing conditions even in concentrated sulphuric acid.[13] In our work, the reaction failed to occur even with the *N*-formyl derivative of (3c), the reactant being recovered unchanged even after prolonged heating in the presence of Al^{III}-montmorillonite. Competitive protonation between –OH and –O– in (3b) might also account for its lower reactivity compared with compound (3a) (compare entries 8 and 10). Alternatively, the slow turnover rates found with compounds (5a) and (5b) may be attributed to weaker adsorption of these molecules in the clay matrix.

The reactions of unsymmetric diols may proceed *via* 2 competing pathways. This is illustrated with the help of the Scheme, wherein the mechanism of cyclodehydration involves hydroxy protonation followed by S_N2 displacement of water.[9a] As shown in the Scheme, reaction of S-(+)-(5a) *via* path A leads to S-(+)-(6a), while R-(−)-(6a) is formed *via* path B. In the absence of side-products, the rate ratio for pathways A and B, *i.e.* k_1k_3/k_2k_4, determines the relative proportions of S-(+)-(6a) and R-(−)-(6a). From Table 1, diol (5a) was converted into compound (6a) with negligible formation of side-products, and in 10% e.e. of R-(−)-(6a); thus $k_2k_4 \gtrsim k_1k_3$. This result is in reasonable agreement with the observed cyclodehydration rates of compounds (1) and (5c), assuming that protonation of the hydroxy group is the rate-determining step in the above reactions. Such an assumption appears reasonable given the favourable thermodynamics and kinetics of five-membered ring formation, and the lack of elimination, and/or rearrangement in these reactions. A notable exception is the strained bicyclic diol

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* Na-Montmorillonite belongs to the smectite class of clays and has the unit cell formula $Na_{0.67}$ $[(Si)_8(Al_{3.3}Mg_{0.67})O_{20}(OH)_4]$.

† We have also found that S-(+)-(5b) ($[\alpha]_D^{25}$ + 9.4°, 72% e.e.) gave a slight excess of R-(−)-(6b) ($[\alpha]_D^{25}$ − 1.4°), the configuration of which was inferred from the results with S-(+)-(5a).

Table 1. Al[III]-Montmorillonite-catalysed cyclodehydration of non-aromatic diols and dithiol[a]

Entry	Reactant	Reaction conditions	Product	Yield[b] (%)	Unchanged (%)
1	(1)	160 °C, 1 h	(2)	93	0
2	(1)	180 °C, 20 min	(2)	95	0
3	S-(+)-(5a), 73% e.e.[c]	180 °C, 2 h	R-(−)-(6a), 10% e.e.[c]	55	40
4	(5b)	180 °C, 2 h	(6b)	60	37
5	(5c)	160 °C, 40 min	(6c)	94	0
6	(5d)	140 °C, 1 h	(6d)	65[b,d]	0
7	Butane-1,4-dithiol	175 °C, 1 h	Tetrahydrothiophene	66[e]	33[e]
8	(3a)	180 °C, 1 h	(4a)	94	0
9	(3c)	200 °C, 4 h	—	—	100[e]
10	(3b)	200 °C, 3 h	(4b)	75[e]	25[e]
11	(7)	200 °C, 3 h	1-Ethyl-4-isopropylbenzene (8)	45[e]	0

[a] Reactions were carried out following either procedure A (entries 1—6) or procedure B (entries 7—11) (see Experimental section). [b] The yields reported are for isolated products (94—98% pure by g.c.) except where otherwise indicated. [c] Enantiomeric excess determinations are based on maximum rotation of $[\alpha]_D$ −14.5° (c 10, CHCl₃) for (R)-(−)-pentane-1,4-diol and $[\alpha]_D$ −27.47° (neat) for (R)-(−)-2-methyltetrahydrofuran (E. R. Novak et al.,[17] D. C. Iffland et al., J. Org. Chem., 1977, 42, 4150). [d] 88% pure. [e] G.c. yield.

Table 2. Pillared Al₁₃-montmorillonite-catalysed cyclodehydration of non-aromatic diols[a]

Entry	Reactant	Reaction condition	Product	Yield[b] (%)
1	(1)	180 °C, 2 h	(2)	55
2	(5d)	160 °C, 2 h	(6d)	56

[a] Reactions carried out following procedure A. [b] G.c. yield.

(7), which yielded compound (8) as the major product, suggesting that carbocationic rearrangement may yet occur, in some cases, in preference to five-membered ring formation. Previous work on clay-catalysed reactions of alcohols had indicated that while substantial amounts of ether can be produced from primary alcohols, intramolecular dehydration to olefin is the dominant pathway in reactions with secondary and tertiary alcohols.[9a]

Pillared Clay-catalysed Reactions.—As stated above, pillared clays have been reported to exhibit Bronsted acidity and shape selectivity.[4,5] Table 2 lists the results of the cyclodehydrations of compounds (1) and (5d) on Al₁₃(alumina)-montmorillonite. These results indicate that the clay pores formed through pillaring are large enough to permit reaction even of the bulky diol (5d). While the reactivity of (5d) is higher than (1) in both clays [compare the data on (1) and (5d) in Tables 1 and 2], the cyclodehydration requires higher temperatures and longer durations in the case of the pillared clay. Indeed, the reactivity of the latter clay favours comparison with alumina catalysts, which are known to catalyse the conversion of diol (1) into tetrahydrofuran (2).[15]

Experimental

Na-Montmorillonite (grade GK 129) was obtained from the Georgia Kaolin Company and purified through further ion-exchange with NaCl (1M) followed by repeated centrifugation and washing to remove excess of salt and heavy residue. Al[III]-Montmorillonite and alumina-pillared clay[16] were prepared from the exchange reaction of aqueous Na-montmorillonite with Al(NO₃)₃ and polynuclear Al[III] (OH⁻/Al³⁺ = 2.4), respectively, followed by purification through cycles of centri-

fugation and washing. Al[III]-Montmorillonite was finally dried at 60 °C and finely crushed to a powder. Likewise, the pillared clay was also obtained as a fine powder and subsequently calcined at 350 °C. Butane-1,4-dithiol (Fluka), and compounds (1) (Koch Light), (3a) (Fluka), (3b) (SD's Lab. Chem. Ind.), and (3c) (Merck) were used as received, while (7) was prepared from Nopol (Aldrich) by hydroboration with borane–methyl sulphide in THF followed by oxidative work-up. Compound (5c) was prepared via borohydride reduction of hexane-2,5-dione, while (5d) was obtained from the reaction of the above dione with methylmagnesium iodide. S-(+)-(5a) ($[\alpha]_D^{25}$ + 10.5°, c 10, CHCl₃; 73% e.e.[17]) and S-(+)-(5b) ($[\alpha]_D^{25}$ + 9.4°, c 10, CHCl₃; 72% e.e.*) were prepared from (S)-(+)-pent-4-en-2-ol ($[\alpha]_D^{25}$ + 7.2°, neat; 74% e.e.[18]) and (S)-(−)-hex-5-en-3-ol ($[\alpha]_D^{25}$ −4.4°, neat; 72% e.e.[18]), respectively, by hydroboration with bis(3-methylbutan-2-yl)borane followed by oxidation with alkaline hydrogen peroxide.

G.c. analyses were carried out on a Pye-Unicam model 204 gas chromatograph using a 6 ft × ¼ in Porapak Q column. G.c.–m.s. analysis was conducted on a Hewlett–Packard model 5993 instrument and a 12 m long HP-101 capillary column. N.m.r. spectra were recorded on a Bruker cw 80 machine while optical rotation measurements were conducted on a Jasco DIP-140 digital polarimeter.

General Procedure for the Clay-catalysed Cyclodehydrations.—Procedure A. A two-necked 50 ml round-bottomed flask, fitted with a distillation assembly, was charged with the reactant (50 mmol) and catalyst (1.0 g). The reaction conditions were maintained as specified in Tables 1 and 2 and the distilled product collected in a receiver flask cooled to −78 °C. The product was then analysed by g.c. and ¹H n.m.r. The residue in the reaction flask was cooled and extracted with chloroform (2 × 25 ml). The chloroform layer was dried and evaporated and the residue then analysed for starting material by g.c.

Procedure B. A 100 ml thermostatted Parr autoclave was charged with the reactant (10 ml) and Al[III]-montmorillonite clay (0.6 g) and then heated to the specified temperature (175—200 °C) and the reaction continued until such time as a steady-state pressure was obtained. The reaction mixture was then cooled, separated from the catalyst, and analysed by g.c.

* The e.e. was inferred by assuming that the chiral centre remained unperturbed during synthesis of the diol from the corresponding enol.

Acknowledgements

References

1 P. Laszlo, *Science*, 1987, **235**, 1473; *Acc. Chem. Res.*, 1986, **19**, 121.
2 J. M. Adams, S. Elizabeth Davies, S. H. Graham, and J. M. Thomas, *J. Catal.*, 1982, **78**, 197.
3 M. M. Mortland and K. V. Raman, *Clays Clay Miner.*, 1968, **16**, 393.
4 T. J. Pinnavaia, *Science*, 1983, **220**, 365.
5 (*a*) D. Plee, L. Glatineau, and J. J. Fripiat, *Clays Clay Miner.*, 1987, **35**, 81; (*b*) J. Shabtai, *Chim. Ind. (Paris)*, 1979, **61**, 734; (*c*) K. Urabe, H. Sakurai, and Y. Izumi, *J. Chem. Soc., Chem. Commun.*, 1986, 1074.
6 D. Kotkar and P. K. Ghosh, *J. Chem. Soc., Chem. Commun.*, 1986, 650.
7 (*a*) V. Joshi, D. Kotkar, and P. K. Ghosh, *J. Am. Chem. Soc.*, 1986, **108**, 4650; (*b*) D. Kotkar and P. K. Ghosh, *Inorg. Chem.*, 1987, **26**, 208; (*c*) V. Joshi and P. K. Ghosh, *J. Chem. Soc., Chem. Commun.*, 1987, 789.
8 P. K. Ghosh, A. K. Chattopadhyay, D. N. Bhattacharya, R. S. Iyer, S. Pal, and V. Mohan Rao, Ind. Pat. Appl. No. 905/Cal/86 dated Dec. 12, 1986.
9 (*a*) J. A. Ballantine, M. Davies, H. Purnell, M. Rayanakorn, J. M. Thomas, and K. J. Williams, *J. Chem. Soc., Chem. Commun.*, 1981, 427; (*b*) J. A. Ballantine, R. P. Galvin, R. M. O'Neil, H. Purnell, M. Rayanakorn, and J. M. Thomas, *ibid.*, 1981, 695; (*c*) J. A. Ballantine, H. Purnell, M. Rayanakorn, J. M. Thomas, and K. J. Williams, *ibid.*, 1981, 9; (*d*) J. A. Ballantine, H. Purnell, and J. M. Thomas, *J. Mol. Catal.*, 1984, **27**, 157, and references therein.
10 P. Laszlo, *Synthesis*, 1985, 909.
11 D. Kotkar, and P. K. Ghosh, unpublished observation.
12 L. F. Schmoyer and L. C. Case, *Nature*, 1960, **187**, 592.
13 K. Mjos in 'Kirk-Othmer Encyclopedia of Chemical Technology,' Wiley, New York, 1978, **2**, 298.
14 W. Stumpf, 'Chemie und Anwendungen des 1,4-Dioxans,' Verlag Chemie, 1956.
15 I. G. Farbenindustrie A.-G., British Patent No. 506 674, June 2, 1939 (*Chem. Abstr.*, 1939, **33**, 9328^3).
16 D. E. W. Vaughan and R. J. Lussier, Proc. 5th International Congress on Zeolites, Naples, 1980, p. 94.
17 E. R. Novak and D. S. Tarbell, *J. Am. Chem. Soc.*, 1967, **89**, 73.
18 P. K. Jadhav, K. S. Bhat, P. T. Perumal, and H. C. Brown, *J. Org. Chem.*, 1986, **51**, 432.