

Aluminosilicate-catalyzed oxidation of alcohols by *t*-butyl hydroperoxide

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Abstract

The catalytic abilities of commercial K10-montmorillonite and molecular sieves (4 Å and 13 X) vs. oxidation of alcohols by *t*-butyl hydroperoxide were investigated. The K10-montmorillonite-catalyzed oxidation of secondary benzylic alcohols was found to proceed in good yield and selectivity with almost all the substrates, while K10-montmorillonite Bronsted acidity induced undesired side reactions (with formation of elimination products and mixed ethers and peroxides) when an electron-donating group was present in 4-position of the aromatic ring. Structurally different aluminosilicates, 4 Å molecular sieves, showed a very close behaviour since oxidation of benzylic, linear and cyclic aliphatic alcohols occurred with comparable efficiency and selectivity. The experimental results were found to be in agreement with a mechanistic pathway involving an Oppenauer-type oxidation taking place on the edge catalytic sites (as regards K10-montmorillonite) and on the external surface (as regards 4 Å molecular sieves). In the presence of aluminosilicates, capable to accommodate the reactants in the internal cavities and channels (as 13 X molecular sieves), a very enhanced reactivity was observed, but besides the fast formation of carbonyl compounds, other competitive side reactions of oxidative fission took place. © 1999 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

Montmorillonites are crystalline aluminosilicates, characterized by a multilayered structure, whose intrinsic catalytic activity has been widely exploited in preparative organic chemistry in recent years [1].

In fact, because of their Bronsted acidity (mainly associated with the interlamellar region)

and Lewis acidity (mainly associated with edge sites) montmorillonites have been employed essentially as solid acids in a great variety of methodologies involving, for example, Diels–Alder reaction [2], formation of acetals [3] and thioacetals [4], aldol condensation [5], Friedel–Craft-type alkylation of aromatic compounds, nitration, and halogenation of aromatics [6,7].

Very interesting results have been obtained by supporting inorganic reagents on clays: for example, iron(III) nitrate (Clayfen) used for oxi-

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dition of alcohols [8], cleavage of hydrazones [9] and thioacetals [10], dehydrogenation of 1,4-dihydropyridines [10], copper (II) nitrate (claycop) for oxidative coupling of thiols [11], potassium permanganate [12] and ferrate [13] for oxidation of alcohols, thallium(III) nitrate for oxidative rearrangements of aryl alkyl ketones and alkenes [14,15].

The catalytic properties of montmorillonites can be significantly varied and enhanced by appropriate ion exchange: for example, transition-metal-exchanged (Ti^{4+} and Zr^{4+}) clays have shown to be effective catalysts for the alkylation of aromatics using halides, alcohols and alkenes [16].

Besides this diffuse catalytic activity concerning the surface of aluminosilicate layers or the interlayer region of ion-exchanged clays, there are more localized catalytic sites.

Of particular interest is the presence of coordinatively unsaturated aluminium atoms in the octahedral layer of untreated montmorillonites (deriving from isomorphous substitution of tetravalent silicon) and on the edge sites where the sheets break off.

In connection with our research efforts, devoted to the achievement of new, selective, and environmentally safe methodologies for the oxidation of organic functionalities, we propose that the combination of a suitable oxidant with hyperreactive aluminium atoms could promote an Oppenauer-type oxidation of alcohols to carbonyl compounds, according to the pathway depicted in Scheme 1.

With this in mind, the possibility of exploiting commercial aluminosilicates as selective and

safe catalysts of oxidative processes was carefully evaluated.

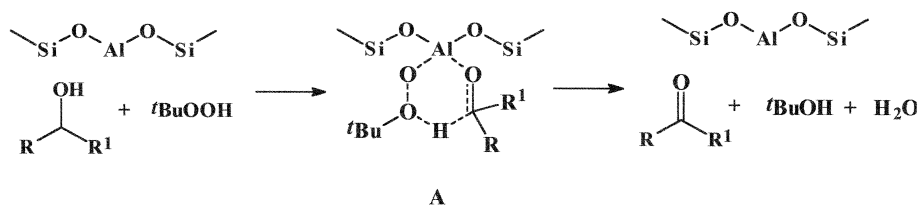
2. Experimental

2.1. General information

All linear, cyclic, and benzylic alcohols used were commercially available (Fluka or Aldrich) and were used without any previous purification. Secondary allylic alcohol **4** was prepared by routine procedure involving addition of the appropriate Grignard reagent to the corresponding α,β -unsaturated aldehyde. After purification its structure was confirmed by $^1\text{H-NMR}$. TBHP (5 M in decane solution), K10-Montmorillonite, 4 Å and 13 X molecular sieves were purchased from Aldrich. Silica gel (230–400 mesh Merck) was used for flash chromatography. Analytical thin layer chromatography (TLC) were carried out on Merck Kieselgel F₂₅₄ plates. Spots on TLC were visualized under UV light and by spraying with 2,4-dinitrophenylhydrazine (0.4% in 2 N HCl) or H_2SO_4 (10% in ethanolic solution) followed by heating. Carbonyl compounds were identified on the ground of spectroscopic data ($^1\text{H-NMR}$) by comparison with authentic samples.

2.2. General procedure for K10-montmorillonite-catalyzed oxidation of benzylic alcohols I

Commercial K10-montmorillonite (1 g), without any previous activation, was added to a solution of benzylic alcohol (1 mmol) and TBHP (2 mmol) in *n*-hexane (or CCl_4) (3 ml) under an



Scheme 1.

Table 1
K10-montmorillonite-catalyzed oxidation of 1-phenylethanol

Entry	Solvent	Temperature (°C)	Yield ^a (%)	Conversion ^a (%)
a	CH ₂ Cl ₂	40	< 10	30
b	CHCl ₃	50	25	45
c	CCl ₄	60	85	100
d	CCl ₄	60	8 ^b	8

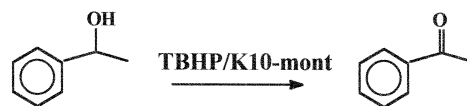
^aYields refer to isolated chromatographically pure compounds and are calculated on starting materials. Conversions are calculated on reacted 1-phenylethanol. Molar ratio alcohol/TBHP 1:2. Alcohol/solvent/catalyst 1 mmol:5 ml:1 g.

^bThis experiment was performed in absence of catalyst.

argon atmosphere in a screw-cap bottle. The reaction was monitored by TLC and prolonged, under stirring, as reported in Table 3 (or Table 2). Then, 0.1 N aqueous Na₂S₂O₃ (2 mmol) was added and the mixture was stirred for 0.5 h. The filtrated organic solution was evaporated under reduced pressure and the crude product was purified by silica gel column chromatography by elution with *n*-hexane/diethyl ether mixtures.

2.3. General procedure for 4 Å molecular sieves-catalyzed oxidation of alcohols

Commercial 4 Å molecular sieves (3 g), without any previous activation were added to a solution of alcohol (1 mmol) and TBHP (2 mmol) in *n*-hexane (1 ml) under argon atmosphere in a screw-cap bottle. The reaction was monitored by TLC and prolonged, under stirring, as reported in Table 4. Then, 0.1 N aqueous Na₂S₂O₃ (2 mmol) was added and the mixture was stirred for 0.5 h. The filtrated



Scheme 2.

organic solution was evaporated under reduced pressure and the crude product was purified by silica gel column chromatography by elution with *n*-hexane/diethyl ether mixtures.

3. Discussion

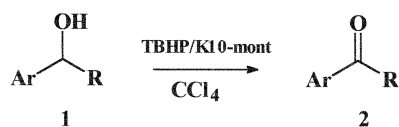
In the preliminary phase, commercial K10-montmorillonite, without any previous thermal treatment, and TBHP were, respectively, chosen as catalyst and oxidant. Then, the reactivity of a model compound, the secondary phenylmethyl carbinol, was examined under a variety of experimental conditions (Scheme 2; Table 1).

The first results obtained, performing the reaction in different halogenated solvents (where complete solubility was ensured) are reported in Table 1, and they show that, at least in CCl₄ solution (entry c), the oxidation of the alcoholic function proceeds with high yield and very satisfactory selectivity. The determining role played by K10-montmorillonite is pointed out in entry d: in fact, in the absence of catalyst, acetophenone can be recovered only in 8% yield. It has to be noted that both in chloroform and in dichloromethane solution undesired side-reactions leading to complex unseparable mixtures of elimination products, mixed and symmetrical

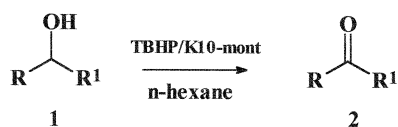
Table 2
K10-montmorillonite-catalyzed oxidation of benzylic alcohols **1** in CCl₄

Entry	R	Ar	Temperature (°C)	Reaction time (h)	Yield ^a (%)	Conversion ^a (%)
a	Me	Ph	60	18	85	100
b	Et	Ph	40	24	66	80
c	Me	4-ClC ₆ H ₄	50	18	86	100
d	Me	4-BrC ₆ H ₄	50	18	80	91
e	Me	4-NO ₂ C ₆ H ₄	60	24	63	76
f	Me	4-MeOC ₆ H ₄	r.t.	0.25	–	100

^aYields refer to isolated chromatographically pure compounds and are calculated on starting materials **1**. Conversions are calculated on reacted starting materials **1**.



Scheme 3.



Scheme 5.

ethers and peroxides took place in predominant way.

The extension of this methodology to different benzylic alcohols has generally afforded satisfactory results (Scheme 3; Table 2).

This procedure proved to be completely unsuccessful in the case of benzylic alcohols bearing an electron-donor substituent in 4-position of the aromatic ring. In fact, in entry f, under milder condition too, starting material suffered a very fast conversion into mixed *t*-butyl benzylic peroxide contaminated by variable amounts of elimination product. This result can be reasonably explained through a more favorable process involving the formation of an intermediate carbocation of type B, promoted by high Bronsted acidity of commercial K10-montmorillonite (Scheme 4).

In spite of its synthetic value, in our opinion this methodology was unacceptable from an environmental point of view because of the employment of very toxic carbon tetrachloride. Therefore, other solvents were tested and very satisfactory results have been obtained by performing the conversion $\mathbf{1} \rightarrow \mathbf{2}$ in a saturated aliphatic hydrocarbon; although most of the alcohols exhibited a not full solubility in *n*-pentane, *n*-hexane or ligroin, yields and selectivity of the oxidation resulted to be completely comparable with the ones observed in carbon tetrachloride (Scheme 5; Table 3).

In entry i the corresponding alcohol suffered the same evolution as in carbon tetrachloride solution. In agreement with the pathway pro-

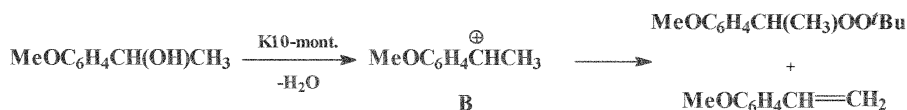
posed in Scheme 1, the oxidation of 4-methylcyclohexan-1-ol (entry j) proceeded in very poor yield: in fact, hydride abstraction from nonactivated primary and secondary alcohols is a very slow process. It is noteworthy that in the case of a propargylic alcohol (entry k) the conversion into the corresponding carbonyl compound took place with moderate yield and good selectivity (no evidence of formation of products deriving from Meyer–Schuster rearrangement could be detected).

A first attempt to confirm the pathway reported in Scheme 1 promoted an investigation on the reactivity of allylic alcohols: in fact, intermediate of type C, deriving from the coordination both of allylic alcohol and *t*-butyl hydroperoxide, by reactive Al atoms could have suffered a competitive process of epoxidation by π -electron-system attack on the polarized O–O bond (Scheme 6).

Unfortunately, under a great variety of experimental conditions, very disappointing results have been obtained: in fact, the over-enhanced Bronsted acidity of K10-montmorillonite, as confirmed by a control test performed in absence of oxidant, caused a rapid and extensive decomposition of the starting materials.

Therefore, we decided to turn our attention to other types of commercially available aluminosilicates and, in particular, to zeolites.

Molecular sieves are well known in organic synthesis both for their employment as drying agents and for their intrinsic catalytic properties [17]. Furthermore, more recently, because of the



Scheme 4.

Table 3
K10-montmorillonite-catalyzed oxidation of alcohols **1** with TBHP in *n*-hexane

Entry	R	R ¹	Reaction temperature (°C)	Reaction time (h)	Yield ^a (%)	Conversion ^a (%)
a	Ph	Me	50	18	77	87
b	Ph	Et	50	18	80	80
c	Ph	<i>i</i> -Pr	60	14	55	72
d	Ph	<i>n</i> -C ₆ H ₁₃	60	7	63 ^b	76
e	4-NO ₂ C ₆ H ₄	Me	50	24	60	80
f	4-ClC ₆ H ₄	Me	50	22	75	90
g	4-BrC ₆ H ₄	Me	50	20	76	95
h	3-BrC ₆ H ₄	Me	60	7	64	81
i	4-MeOC ₆ H ₄	Me	r.t.	0.25	— ^c	100
j	4-Me-cyclohexan-1-ol		80	24	30 ^d	30
k	HC≡C–	<i>n</i> -C ₅ H ₁₁	40	48	47	54

^aYields refer to isolated chromatographically pure compounds and are calculated on starting materials **1**. Conversions are calculated on reacted starting materials **1**.

^bIn this entry elimination product was isolated in 13% yield.

^cIn this entry mixed *t*-butyl benzyl peroxide was isolated in 59% yield.

^d¹H-NMR yield. Oxidation was performed in cyclohexane.

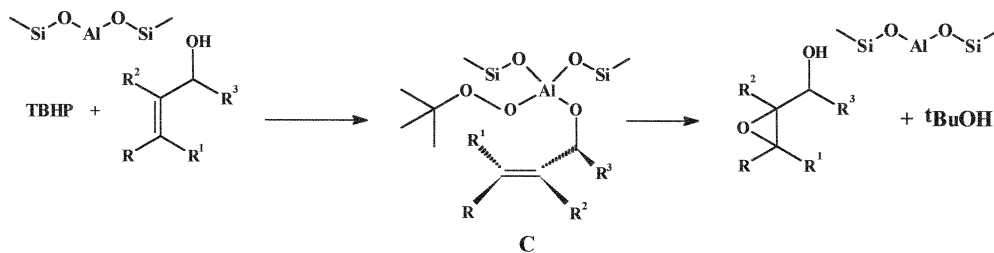
easy incorporation of transition metals (Ti, V, Cr, etc.) [18–20] into the crystalline network, doped zeolites have been widely used in efficient and selective oxidative processes.

From a structural point of view zeolites are quite different from montmorillonites, being characterized by the presence of molecular-sized intracrystalline channels and cages.

Their catalytic activity strictly depends on the resulting high internal surface area and the presence of strong Bronsted and Lewis acid sites; furthermore, the pore dimensions, limiting the access only to molecules possessing the critical diameter, are responsible of their typical shape selectivity. These factors make zeolites among

the most convenient and selective heterogeneous catalysts. Since *t*-butyl hydroperoxides certainly cannot penetrate into the pore of 4 Å molecular sieves [21] and the amount of reactive, coordinatively unsaturated Al atoms on the external surface is much more reduced in comparison with the inner ones, we propose that zeolites could be used as milder catalysts of oxidative reactions proceeding according to the pathway reported in Scheme 1.

Therefore, a model compound of type **1** (R = –Ph, R¹ = –Et) was submitted to the experimental conditions reported in Table 4 (entry a). The formation of propiophenone showed to take place in moderate yield and good selectivity; as



Scheme 6.

Table 4
Zeolite-catalyzed oxidation of alcohols **1** with TBHP

Entry	R	R ¹	Reaction time (h)	Yield ^a (%)	Conversion ^a (%)
a	Ph	Et	48	48 ^b	57
b	Ph	Et	48	70	78
c	Ph	<i>i</i> -Pr	48	59	71
d	Ph	<i>n</i> -C ₆ H ₁₃	48	79	80
e	4-NO ₂ C ₆ H ₄	Me	48	72	89
f	4-ClC ₆ H ₄	Me	48	80	94
g	4-BrC ₆ H ₄	Me	48	80	100
h	3-BrC ₆ H ₄	Me	48	60	85
i	2-BrC ₆ H ₄	Me	48	24	24
j	1-Tetralol		90	70	86
k	<i>n</i> -C ₇ H ₁₅	Me	72	35	75
l	4- <i>t</i> -butyl-cyclohexan-1-ol		90	37	65
m	5 α -cholestan-3 β -ol		48	34	45
n	Me	–CH ₂ CH ₂ OH	72	20 ^c	20
o	H	<i>n</i> -C ₁₁ H ₂₃	48	–	7
p	4-MeOC ₆ H ₄	Me	0.25	– ^d	100

^aYields refer to isolated chromatographically pure compounds and are calculated on starting materials. Conversions are calculated on reacted starting materials **1**. Molar ratio alcohol/TBHP 1:2. Alcohol/solvent/catalyst 1 mmol:5 ml:3 g.

^bIn this entry 1 g of zeolite was employed.

^c¹H-NMR yield.

^dIn this entry *t*-butyl mixed peroxide was isolated in 69% yield.

expected, oxidation proceeded with a lower reaction rate than the ones observed for K10-montmorillonite catalyzed processes (Table 4).

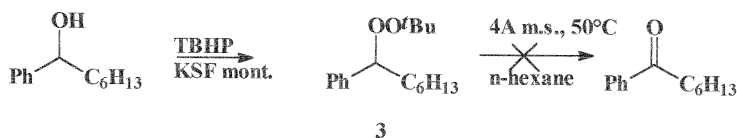
A significant improvement was obtained by performing the reaction in the presence of a threefold amount of molecular sieves (entry b).

On the basis of the data reported in Table 4, this safe methodology can be considered to be widely applicable for benzylic alcohols, both in terms of efficiency and selectivity: however, as a consequence of the enhanced steric crowding due to the proximity of the reaction centers to each other, a noticeable reduction of reaction rate could be observed (entries i and j).

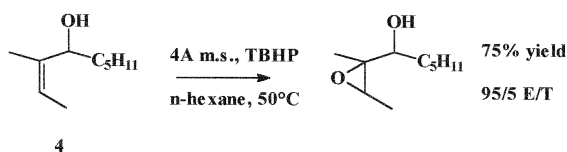
In close analogy with K10-montmorillonite-catalyzed oxidations, nonactivated alcohols have provided poor results (entries k, l, m) while

primary alcoholic functionalities proved to be completely nonreactive (entries n, o).

As previously observed, starting material involved in entry p suffered a very fast conversion into the corresponding mixed *t*-butyl peroxide. As regards the mechanistic aspects, the possibility of a different pathway, involving the previous formation of a mixed peroxide and its following conversion into a carbonyl compound through a Hoch–de La Mare-type elimination was readily excluded: in fact, peroxide **3**, readily accessible by reaction of the corresponding benzylic alcohols with TBHP in the presence of catalytic amounts of KSF montmorillonite, was recovered completely unchanged after the treatment involved by zeolite-catalyzed oxidative processes (Scheme 7).



Scheme 7.



Scheme 8.

When oxidation was carried out in the presence of 13 X molecular sieves, whose pore dimensions allowed the access of the reactants to the inner cages and channels, the much greater number of catalytic sites promoted the fast formation of the expected carbonyl compounds with lower selectivity because of the unavoidable occurrence of undesired side-reactions of rearrangements, coupling and oxidative fission of reactants and products.

A significant support to the reaction pathway depicted in Scheme 1 was furnished by an experiment performed on the allylic alcohol **4** under the usual conditions (Scheme 8).

In fact, in this case the competitive process of epoxidation resulted to be far predominant while only negligible amounts (< 5%) of the corresponding α,β -unsaturated ketone could be isolated: furthermore the observed high diastereoselectivity (95:5 erythro/threo ratio) required necessarily the contemporary coordination of the oxidant and of the allylic alcohol by Al reactive atoms.

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