Base-promoted Acyloin Rearrangement of 1,8-Di-*tert*-butyldimethylsilyloxybicyclo[2.2.2]oct-5-en-2-ones

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Treatment of 1,8-di-*tert*-butyldimethylsilyloxybicyclo[2.2.2]oct-5-en-2-ones having an electron-withdrawing group such as a nitro, formyl, cyano, and imido group at C-7 with a strong base (potassium hydride, or potassium bistrimethylsilylamide, *etc.*), resulted in an acyloin rearrangement reaction accompanied by retention of two silyloxy groups to afford 1,8-disilyloxybicyclo[3.2.1]oct-3-en-2-ones.

Key words 18-crown-6; bicyclo[3.2.1]oct-3-en-2-one; bicyclo[2.2.2]oct-5-en-2-one; potassium hydride; potassium bistrimethylsilylamide; base-promoted acyloin rearrangement

The bicyclo[3.2.1]octenone ring system is contained in the basic carbon framework of various natural products such as quadrones,[1] helminthosporals,[2] and gibberellins.[3,4] Recently, in the synthesis of natural products,[5,6] bicyclo[2.2.2]-octenones have been utilized as potential bridge compounds that are convertible into bicyclo[3.2.1]octenones by means of an acid- or a Lewis acid-mediated pinacol-type transformation. The acyloin rearrangement reaction has been known as a 1,2-migration of an α-alkyl or α-aryl group on α-hydroxyketones or α-hydroxyaldehydes under acidic or basic conditions to lead to isomeric α-hydroxyketones.[7,8] Thus far this reaction has been reported in the studies of steroids[9] or other ring systems with conformational rigidity[10] and recently has been utilized for the synthesis of methyl L-mycaroside[11] and gibberellins.[12]

We have planned the construction of the bicyclo[3.2.1]-octenone ring system according to methodology using the acyloin rearrangement of bicyclo[2.2.2]octenones, which are available from the stereoselective cycloaddition of the 2-(methylsulfanyl)methylcyclohexadienes with various dienophils, directed toward the synthesis of bioactive natural products. In a previous paper,[13] we described the synthesis of 1-hydroxybicyclo[3.2.1]oct-3-en-2-ones having a methoxy or *tert*-butyldimethylsilyloxy group at the bridgehead C-1 position, *via* acyloin rearrangement of 1-methoxy- or 1-*tert*-butyldimethylsilyloxybicyclo[2.2.2]oct-5-en-2-ones by treatment with acids or tetrabutylammonium fluoride (TBAF).

Here, we describe the conversion of 1,3-di-*tert*-butyldimethylsilyloxybicyclo[2.2.2]oct-5-en-2-ones (**4**) to the 1,8-di-*tert*-butyldimethylsilyloxybicyclo[3.2.1]oct-3-en-2-ones (**5** or **6**) *via* acyloin rearrangement induced by the formation of a carbanion at C-7 using bases such as potassium hydride (KH) (method A), potassium bistrimethylsilylamide [KN-$(SiMe_3)_2$] (method B), $KN(SiMe_3)_2$ in the presence of 18-crown-6 (method C), and sodium hydride (NaH) in *N*,*N*-dimethylformamide (DMF) (method D) (Chart 1).[14]

Results and Discussion

The bicyclo[2.2.2]oct-5-en-2-ones (**4**) as the starting materials were prepared using the Diels–Alder reaction of an appropriate dienophile (**2**) with a dimer of 2,6-di-*tert*-butyldimethylsilyloxycyclohexa-2,4-dien-1-one (**1**), according to the method described by us.[13,15,16] Thus 7-nitrobicyclo-[2.2.2]oct-5-en-2-one (**4a**) was prepared by Diels–Alder reaction of nitroethene[17] with **1**. The structure of **4a** was confirmed based on the following spectral data. The infrared (IR) spectrum displayed ν (C=O) absorption at 1744 cm^{-1}, and the ^{1}H-NMR spectrum showed the characteristic signal of H-8_{endo} shifted at high field (δ 1.99) and vicinal coupling constants between H-7 and H-8_{exo} (J=9.5 Hz), showing H-8_{endo} situated over the double bond[13,18—20] and *cis* relationship with the nitro group (Fig. 1).

We examined the acyloin rearrangement reaction of **4a** by treatment with a strong base such as KH (method A), $KN(SiMe_3)_2$ (method B), or NaH in DMF (method D). In the treatment of **4a** with KH in tetrahydrofuran (THF), or with NaH in DMF, the reaction proceeded stereoselectively, retaining both silyloxy groups, to afford 1,8-disilyloxy-7-nitrobicyclo[3.2.1]oct-3-en-2-one (**5a**), which has the *endo* arrangement of the nitro group at C-7. The IR spectrum of **5a** showed absorptions based on ν (C=C–C=O) at 1618 and 1685 cm^{-1} and no hydroxy absorption. The ^{1}H-NMR spectrum of compound **5a** showed the characteristic signals as a double-doublet at δ 7.42 due to the olefinic β-proton of the conjugated enone, and the characteristic higher field signal at δ 2.22 due to H-6_{endo} affected by the π-electron of the double bond 3(4).[13,21] The characterization of the stereochemistry of **5a** was determined by the observation of NOEs between

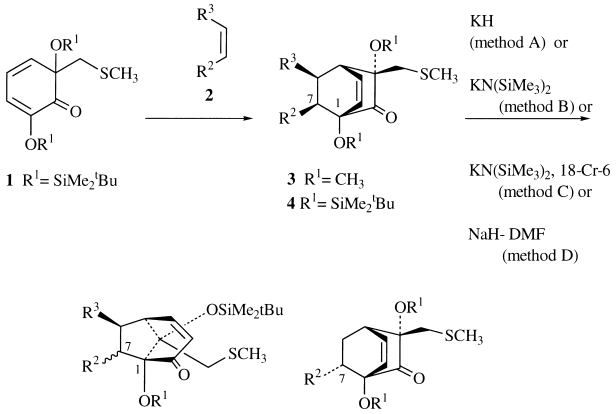

Chart 1

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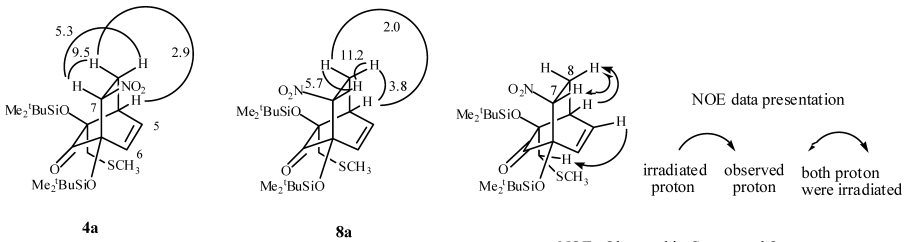
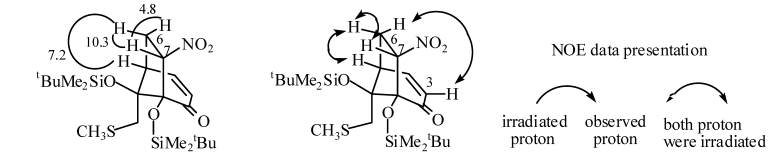


4a **8a**

Coupling Constants (Hz) in the ^{1}H-NMR Spectra of Compounds **4a** and **8a**

NOEs Observed in Compound **8a**

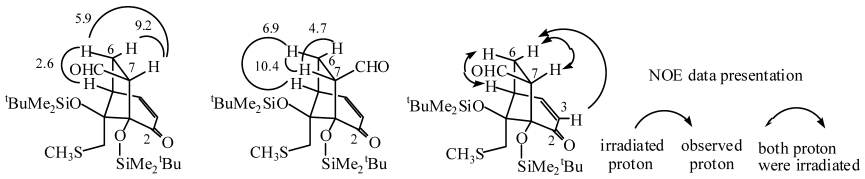
Fig. 1



Coupling Constants (Hz) in the ^{1}H-NMR Spectrum of Compound **5a**

NOEs Observed in Compound **5a**

Fig. 2



6b **5b**

Coupling Constants (Hz) in the ^{1}H-NMR Spectra of Compounds **6b** and **5a**

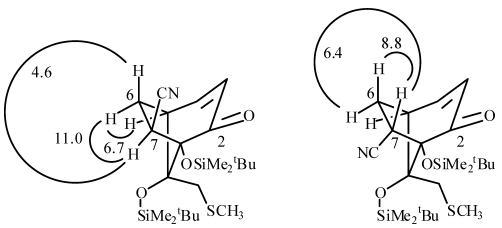
NOEs Observed in Compound **6b**

Fig. 3

olefinic H-3 and H-6$_{endo}$ and between H-6$_{exo}$ and H-7 in NOE difference spectroscopy, which showed the *cis*-arrangement of the nitro group at C-7 with H-6$_{endo}$ (Fig. 2).

On the other hand, the use of KN(SiMe$_3$)$_2$ (method B) led to epimerization at C-7 of **4a** instead of acyloin rearrangement to give its epimer **8a** in high yield. The structure was determined based on the ^{1}H-NMR spectrum, in which H-8$_{endo}$ appeared at high field (δ 2.26),[21] and *cis*-arrangement between H-7 and H-8$_{endo}$ was confirmed by ^{1}H–^{1}H vicinal coupling constants ($J_{7,8\text{-}endo}$ = 11.2 Hz), and by observation of NOEs between H-7 and H-8$_{endo}$ in the NOE difference spectrum (Fig. 1).

Next, we attempted the reaction of 7-formylbicyclo[2.2.2]oct-5-en-2-one (**4b**) with a base such as KH (method A) or KN(SiMe$_3$)$_2$ (method B, method C). Although the rearrangement reaction proceeded using method C to afford 1,8-disilyloxy-7-formylbicyclo[3.2.1]oct-3-en-2-ones (**5b**, **6b**) as an epimeric (1/1) mixture at C-7 in low yield, the reaction using method A or method B gave **6b** only, in which the arrangement of the formyl group at C-7 was *exo*, contrary to the case when a nitro group was at C-7 (Table 1, entry 1, 3). The structure of **6b** was determined on the basis of NMR spectra compared with the epimer **5b** at C-7 in the following manner. The ^{1}H-NMR spectrum of **6b** showed the characteristic signal of H-6$_{endo}$ at high field (δ 1.74), which was in the *trans*-arrangement with a formyl group at C-7 ($J_{7,6\text{-}endo}$ = 9.2 Hz). Furthermore, observation of NOEs between olefinic H-3 and H-6$_{endo}$ and between H-6$_{endo}$ and H-7 in the NOE difference spectroscopy of **6b** (Fig. 3) showed that the formyl group at C-7 was in the *exo*-arrangement.



5c **6c**

Fig. 4. Coupling Constants (Hz) in the ^{1}H-NMR Spectra of Compounds **5c** and **6c**

Although the reaction of 7-cyanobicyclo[2.2.2]oct-5-en-2-one (**4c**) with KH as the base (method A) failed to proceed, when KN(SiMe$_3$)$_2$ was used as the base (method B or method C) the acyloin rearrangement reaction proceeded to give 1,8-disilyloxy-7-cyanobicyclo[3.2.1]oct-3-en-2-ones (**5c**, **6c**) as an epimeric mixture at C-7. Both structures were determined based on the ^{1}H–^{1}H vicinal coupling constants between H-7 and H-6$_{endo}$ in the same manner as for **6b** (Fig. 4).

In the reaction of bicyclo[2.2.2]oct-5-en-2-one (**4d**) with KN(SiMe$_3$)$_2$ (method B), the acyloin rearrangement reaction proceeded regio- and stereoselectively at C-7 to afford 1,8-disilyloxybicyclo[3.2.1]oct-3-en-2-one (**5d**) as the sole product, although the reaction of **4d** with KH (method A) failed to proceed. The structure of **5d** was confirmed by the ^{1}H–^{1}H

vicinal coupling constants between H-5, H-6, and H-7 (Fig. 5).

The reaction of bicyclo[2.2.2]oct-5-en-2-one (**4e**), with an acetyl group at C-7, gave unidentified products when using method A, B, or C. Although the reaction of bicyclo[2.2.2]oct-5-en-2-ones (**4f**, **g**, **h**), with a carboxyl group, or lacking an electron-withdrawing group at C-7, failed to proceed using method A or B, the rearrangement reaction proceeded with the addition of 18-crown-6 (method C) to give the compound **5f** or the 1-hydroxy compounds **7g** and **7h**,[22] respectively, in poor yield.

In the reaction of 7-formylbicyclo[2.2.2]oct-5-en-2-one (**3i**), which has a methoxy group at C-1 instead of silyloxy, with the base [$KN(SiMe_3)_2$; method B], the acyloin rearrangement reaction did not proceed, but epimerization at C-7 proceeded to give only compound **9i**.[22]

The experimental results are shown in Table 1.

Based on the above results, it is thought that the base-promoted acyloin rearrangement requires a strong base such as KH or $KN(SiMe_3)_2$,[23] electron-withdrawing substituents such as a nitro group, *etc.* at C-7 for the formation of a stable carbanion, and a silyloxy group at C-1 for neighboring-group assistance.

The formation of the 1-silyloxybicyclo[3.2.1]octenones from the 1-silyloxybicyclo[2.2.2]octenones can be explained in terms of the formation of a carbanion at C-7, followed by the attack of the carbanion on the carbonyl carbon at C-2 assisted by the neighboring silyloxy group at C-1 in a concerted manner (acyloin rearrangement) (Chart 2).[24] The stereoselectivity in the reaction depends on the substituents at C-7, but the mechanism is not yet clear.

In conclusion, it was demonstrated that in the treatment of 1,8-di-*tert*-butyldimethylsilyloxybicyclo[2.2.2]oct-5-en-2-ones (**4**) that have an electron-withdrawing group such as a nitro, formyl, nitrile group, *etc.* at C-7 with a strong base [KH or $KN(SiMe_3)_2$], acyloin rearrangement proceeded to afford bicyclo[3.2.1]oct-3-en-2-ones (**5** or **6**).

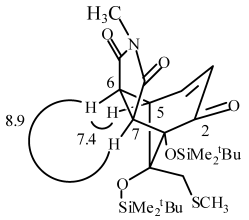


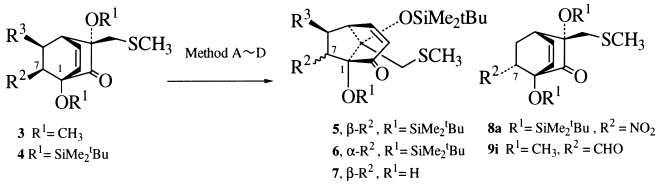
Fig. 5. Coupling Constants (Hz) in the ^{1}H-NMR Spectrum of Compound **5d**

Experimental

Spectral data were obtained using the following apparatus: IR spectra on a JASCO IR-810 spectrophotometer; mass spectra (MS) on a JEOL JMS-700 mass spectrometer by direct insertion at 70 eV; ^{1}H-NMR spectra (270 MHz) and ^{13}C-NMR spectra (67.8 MHz) on a JEOL EX-270 instrument in chloroform-d ($CDCl_3$) with chemical shifts reported in δ units from tetramethylsilane as an internal standard and coupling constants in hertz. Column chromatography was carried out on silica gel (100—200 mesh, Micro Bead 4B, Fuji-Davison Chemical Ltd.).

(1α,3*S,4α,7*S**)-1,3-Di-*tert*-butyldimethylsilyloxy-3-(methylsulfanyl)methyl-7-nitrobicyclo[2.2.2]oct-5-en-2-one (4a)** A mixture of the dimer of cyclohexadienone (**1**) (8.560 g, 10.3 mmol) and nitroethene (**2**)[17]

Table 1. Reaction of 1,3-Dimethoxy- or 1,3-Disilyloxybicyclo[2.2.2]oct-5-en-2-ones (**3** or **4**) with Base



Entry		Starting material			Product	Yield (%)	Method
		R^1	R^2	R^3			
1	**4a**	$SiMe_2{}^tBu$	NO_2	H	**5a**	78	A
2	**4a**	$SiMe_2{}^tBu$	NO_2	H	**8a**	98	B
3	**4a**	$SiMe_2{}^tBu$	NO_2	H	**5a**	76	D
4	**4b**	$SiMe_2{}^tBu$	CHO	H	**6b**	66	A
5	**4b**	$SiMe_2{}^tBu$	CHO	H	**6b**	80	B
6	**4b**	$SiMe_2{}^tBu$	CHO	H	**5b**/**6b**	35[a]	C
7	**4c**	$SiMe_2{}^tBu$	CN	H	No reaction	0[b]	A
8	**4c**	$SiMe_2{}^tBu$	CN	H	**5c**/**6c**	77[c]	B
9	**4c**	$SiMe_2{}^tBu$	CN	H	**5c**/**6c**	62[d]	C
10	**4d**	$SiMe_2{}^tBu$	$CON(CH_3)CO$		No reaction	0[b]	A
11	**4d**	$SiMe_2{}^tBu$	$CON(CH_3)CO$		**5d**	64	B
12	**4e**	$SiMe_2{}^tBu$	$COCH_3$	H	—	0[e]	A, B, C
13	**4f**	$SiMe_2{}^tBu$	CO_2CH_3	H	No reaction	0[b]	A, B
14	**4f**	$SiMe_2{}^tBu$	CO_2CH_3	H	**5f**	12	C
15	**4g**	$SiMe_2{}^tBu$	$CO_2{}^tBu$	H	No reaction	0[b]	A, B
16	**4g**	$SiMe_2{}^tBu$	$CO_2{}^tBu$	H	**7g**	10	C
17	**4h**	$SiMe_2{}^tBu$			No reaction	0[b]	A, B
18	**4h**	$SiMe_2{}^tBu$			**7h**	10	C
19	**3i**	CH_3	CHO	H	**9i**	61	B

a) **5b** and **6b** was, respectively, separated from the epimeric mixture at C-7 in 18% and 17% yields. *b*) Starting material was recovered unchange. *c*) **5c** and **6c** was, respectively, separated from the epimeric mixture at C-7 in 39% and 38% yields. *d*) **5c** and **6c** was, respectively, separated from the epimeric mixture at C-7 in 35% and 27% yields. *e*) Unidentified product was obtained.

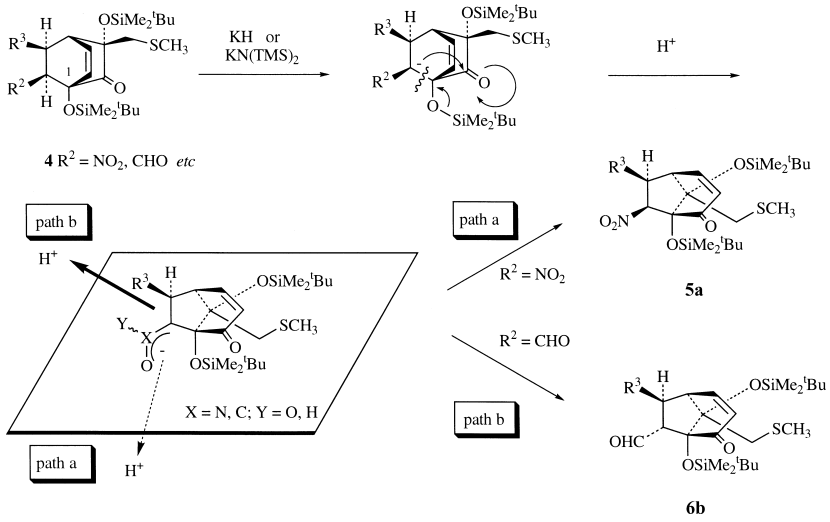


Chart 2

(15.5 ml of 2.67 M in toluene, 41.4 mmol) in dry toluene (160 ml) was heated with refluxing at 125 °C for 24 h. Removal of the solvent under reduced pressure and chromatography of the residue over silica gel (eluent: 5% ethyl acetate in hexane) furnished the adduct **4a** (7.35 g, 73%).

4a: Colorless solid (C_6H_6–hexane), mp 134—136.5 °C. IR (KBr) cm^{-1}: 1744, 1615. ^{1}H-NMR δ: 0.00, 0.02, 0.22, and 0.26 (3H×4, each s), 0.87 (9H, s), 0.88 (9H, s), 1.99 (1H, ddd, J=13.6, 5.3, 2.9 Hz), 2.07 (3H, s), 2.51 (1H, d, J=13.4 Hz), 2.84 (1H, ddd, J=13.6, 9.5, 2.9 Hz), 3.05 (1H, d, J=13.4 Hz), 3.29—3.32 (1H, m), 4.86 (1H, dd, J=9.5, 5.3 Hz), 5.95 (1H, d, J=8.6 Hz), 6.52 (1H, dd, J=8.6, 7.0 Hz). ^{13}C-NMR δ: −3.8, −3.8, −3.3, −3.0, 17.2, 18.4, 18.6, 25.6, 25.8, 29.4, 40.8, 42.5, 75.4, 83.0, 85.7, 128.9, 133.5, 201.8. FAB-MS m/z 488 (M^++1). *Anal.* Calcd for $C_{22}H_{41}NO_5SSi_2$: C, 54.17; H, 8.47; N, 2.87. Found: C, 53.94; H, 8.47; N, 2.89.

General Procedure for Reaction of 1,3-Di-*tert*-butyldimethylsilyloxy-3-(methylsulfanyl)methylbicyclo[2.2.2]oct-5-en-2-ones (4) with Base (Method A) The solution of **4** (1 mmol) in THF (5 ml) was added dropwise to the suspension of potassium hydride (30% in oil, *ca.* 200 mg) in anhydrous THF (5 ml) at −30 °C under an argon atmosphere and stirring continued for 15 h at the same temperature. Then the reaction mixture was treated with cooled diluted (*ca.* 3%) hydrochloric acid at ice-cooled temperature, and the whole mixture was extracted with ethyl ether (30 ml). The organic layer was washed with brine (1×10 ml) and dried over anhydrous $MgSO_4$. The solvent was evaporated off, and the resulting residue was chromatographed on silica gel (eluent; 10% ethyl acetate in hexane) to afford the products.

General Procedure for Reaction of 1,3-Dimethoxy- or 1,3-Di-*tert*-butyldimethylsilyloxy-3-(methylsulfanyl)methylbicyclo[2.2.2]oct-5-en-2-ones (3 or 4) with Base (Method B) To the solution of **3** (2.0 mmol) or **4** (2.0 mmol) in THF (10 ml), potassium bis(trimethylsilyl)amide (15% in toluene, 4 ml, 3 mmol) was added at −50 °C under an argon atmosphere and stirring continued for 3 h at the same temperature. Then the reaction mixture was worked up as described above for method A to afford the products.

General Procedure for Reaction of 1,3-Di-*tert*-butyldimethylsilyloxy-3-(methylsulfanyl)methylbicyclo[2.2.2]oct-5-en-2-ones (4) with Base in the Presence of 18-Crown-6 (Method C) To the solution of **4** (1.0 mmol) and 18-crown-6 (792 mg, 3 mmol) in THF (15 ml), potassium bis(trimethylsilyl)amide (15% in toluene, 4 ml, 3 mmol) was added at −50 °C under an argon atmosphere and stirring continued for 3 h at the same temperature. Then the reaction mixture was worked up as described above for method A to afford the products.

General Procedure for Reaction of 1,3-Di-*tert*-butyldimethylsilyloxy-3-(methylsulfanyl)methylbicyclo[2.2.2]oct-5-en-2-one (4) with Base (Method D) To the mixture of sodium hydride (60% in oil, *ca.* 100 mg) in anhydrous *N*,*N*-DMF (3 ml), the solution of **4** (0.5 mmol) in anhydrous DMF (3 ml) was added at 0 °C under an argon atmosphere and stirring continued for 2 h at the same temperature. Then the reaction mixture was worked up as described above for method A to afford the product.

(1*β*,5*β*,7*S,8*S**)-1,8-Di-*tert*-butyldimethylsilyloxy-8-(methylsulfanyl)methyl-7-nitrobicyclo[3.2.1]oct-3-en-2-one (5a)** Colorless solid (C_6H_6–hexane), mp 139—140 °C. IR (KBr) cm^{-1}: 1685, 1618. ^{1}H-NMR δ: 0.10, 0.21, 0.24, and 0.34 (3H×4, each s), 0.93 (9H, s), 0.95 (9H, s), 2.03 (3H, s), 2.22 (1H, dd, J=13.7, 4.8 Hz), 2.54 (2H, ABq, J=13.2 Hz), 2.85 (1H, ddd, J=13.7, 10.3, 7.2 Hz), 3.00—3.06 (1H, m), 5.36 (1H, dd, J=10.3, 4.8 Hz), 6.32 (1H, d, J=9.4 Hz), 7.42 (1H, dd, J=9.4, 7.5 Hz). ^{13}C-NMR δ: −2.9, −2.4, −2.3, −2.1, 17.2, 19.1, 19.3, 26.1, 26.4, 33.2, 37.9, 44.8, 91.0, 92.0, 97.4, 129.6, 152.0, 195.9. FAB-MS m/z 488 (M^++1). *Anal.* Calcd for $C_{22}H_{41}NO_5SSi_2$: C, 54.17; H, 8.47; N, 2.87. Found: C, 53.99; H, 8.62; N, 2.86. For NOE data presentation in the NOE difference spectrum, see Fig. 2.

(1*α*,3*S,4*α*,7*R**)-1,3-Di-*tert*-butyldimethylsilyloxy-3-(methylsulfanyl)methyl-7-nitrobicyclo[2.2.2]oct-5-en-2-one (8a)** Colorless solid (hexane), mp 128—130 °C. IR (KBr) cm^{-1}: 1744, 1610. ^{1}H-NMR δ: 0.03, 0.20, 0.21, and 0.33 (3H×4, each s), 0.86 (9H, s), 0.87 (9H, s), 2.07 (3H, s), 2.26 (1H, ddd, J=13.9, 11.2, 3.8 Hz), 2.53 (1H, d, J=13.4 Hz), 2.70 (1H, ddd, J=13.9, 5.7, 2.0 Hz), 3.14 (1H, d, J=13.4 Hz), 3.23 (1H, ddd, J=6.6, 3.8, 2.0 Hz), 4.72 (1H, dd, J=11.2, 5.7 Hz), 5.93 (1H, dd, J=8.4, 1.8 Hz), 6.44 (1H, dd, J=8.4, 6.6 Hz). ^{13}C-NMR δ: −3.7, −3.6, −3.2, −2.8, 17.0, 18.4, 18.8, 25.7, 25.8, 26.0, 41.2, 43.4, 76.3, 82.6, 90.3, 132.4, 135.3, 202.5. FAB-MS m/z 488 (M^++1). *Anal.* Calcd for $C_{22}H_{41}NO_5SSi_2$: C, 54.17; H, 8.47; N, 2.87. Found: C, 54.04; H, 8.53; N, 2.85. For NOE data presentation in the NOE difference spectrum, see Fig. 1.

(1*β*,5*β*,6*R,8*S**)-5,8-Di-*tert*-butyldimethylsilyloxy-8-(methylsulfanyl)methyl-4-oxobicyclo[3.2.1]oct-2-ene-6-carbaldehyde (6b)** Colorless solid (hexane), mp 63—66 °C. IR (KBr) cm^{-1}: 1712, 1682, 1615. ^{1}H-NMR δ: 0.24, 0.26, 0.27, and 0.35 (3H×4, each s), 0.91 (9H, s), 0.92 (9H, s), 1.74 (1H, dd, J=13.0, 9.2 Hz), 2.02 (3H, s), 2.40 (1H, ddd, J=13.0, 5.9, 2.6 Hz), 2.61 (2H, ABq, J=13.2 Hz), 2.57—2.71 (1H, m), 3.00—3.02 (1H, m), 6.08 (1H, d, J=9.5 Hz), 7.34 (1H, dd, J=9.5, 7.3 Hz), 10.01 (1H, d, J=2.6 Hz). ^{13}C-NMR δ: −2.4, −2.0, −1.9, −1.5, 17.4, 19.1, 19.7, 26.2, 26.5, 29.5, 38.2, 46.5, 52.3, 77.5, 89.3, 126.6, 153.7, 198.8, 201.5. FAB-MS m/z 471 (M^++1). HR-FAB-MS Calcd for $C_{23}H_{43}O_4SSi_2$ $(M+H)^+$: 471.2421. Found: 471.2411. For NOE data presentation in the NOE difference spectrum, see Fig. 3.

(1*β*,5*β*,6*S,8*S**)-5,8-Di-*tert*-butyldimethylsilyloxy-8-(methylsulfanyl)methyl-4-oxobicyclo[3.2.1]oct-2-ene-6-carbonitrile (5c)** Colorless solid (hexane), mp 151—153.5 °C. IR (KBr) cm^{-1}: 2250, 1688, 1615. ^{1}H-NMR δ: 0.10, 0.19, 0.23, and 0.33 (3H×4, each s), 0.92 (9H, s), 0.93 (9H, s), 1.79 (1H, dd, J=12.8, 4.6 Hz), 2.03 (3H, s), 2.55 (2H, ABq, J=13.2 Hz), 2.77 (1H, ddd, J=12.8, 11.0, 6.7 Hz), 2.99 (1H, dd, J=7.3, 6.7 Hz), 3.41 (1H, dd, J=11.0, 4.6 Hz), 6.11 (1H, d, J=9.5 Hz), 7.33 (1H, dd, J=9.5, 7.3 Hz). ^{13}C-NMR δ: −2.8, −2.3, −1.9, −1.8, 17.2, 19.0, 19.2, 26.1, 26.4, 33.2, 34.3, 37.8, 45.5, 89.3, 96.2, 120.1, 128.1, 153.6, 197.0. FAB-MS m/z 468 (M^++1). *Anal.* Calcd for $C_{23}H_{41}NO_3SSi_2$: C, 59.05; H, 8.83; N, 2.99. Found: C, 58.80; H, 8.73; N, 2.96.

(1*β*,5*β*,6*R,8*S**)-5,8-Di-*tert*-butyldimethylsilyloxy-8-(methylsulfanyl)methyl-4-oxobicyclo[3.2.1]oct-2-ene-6-carbonitrile (6c)** Colorless solid (hexane), mp 114—115.5 °C. IR (KBr) cm^{-1}: 2260, 1700, 1618. ^{1}H-NMR δ: 0.16, 0.28, 0.31, and 0.36 (3H×4, each s), 1.01 (9H, s), 1.02 (9H, s), 1.96 (1H, dd, J=12.0, 8.8 Hz), 2.02 (3H, s), 2.58 (2H, ABq, J=13.2 Hz),

2.70—2.87 (1H, m), 2.85 (1H, dd, J=8.8, 6.4 Hz), 3.02—3.05 (1H, m), 6.09 (1H, d, J=9.5 Hz), 7.32 (1H, dd, J=9.5, 7.3 Hz). ^{13}C-NMR δ: −2.8, −2.2, −2.1, −1.8, 17.2, 19.0, 19.5, 26.2, 26.5, 32.2, 33.5, 37.8, 46.0, 88.9, 92.8, 118.4, 127.0, 153.6, 198.6. FAB-MS m/z 468 (M^++1). HR-FAB-MS Calcd for $C_{23}H_{42}NO_3SSi_2$ $(M+H)^+$: 468.2424. Found: 468.2406.

(1*β*,2*S,6*S**,7*β*,11*S**)-7,11-Di-*tert*-butyldimethylsilyloxy-4-methyl-11-(methylsulfanyl)methyl-4-azatricyclo[5.3.1.0^{2,6}]undec-9-ene-3,5,8-trione (5d)** Colorless solid (C_6H_6–hexane), mp 187—189.5 °C. IR (KBr) cm^{-1}: 1780, 1703, 1617. ^{1}H-NMR δ: 0.22, 0.25, 0.37, and 0.40 (3H×4, each s), 0.93 (9H, s), 0.94 (9H, s), 2.03 (3H, s), 2.53 (2H, ABq, J=13.2 Hz), 2.84 (3H, s), 3.43 (1H, dd, J=7.4, 7.4 Hz), 3.59 (1H, d, J=8.9 Hz), 3.81 (1H, dd, J=8.9, 7.4 Hz), 6.16 (1H, d, J=9.7 Hz), 7.16 (1H, dd, J=9.7, 7.4 Hz). ^{13}C-NMR δ: −2.9, −2.4, −2.2, −1.8, 17.2, 19.1, 19.2, 24.8, 26.2, 26.4, 37.8, 46.7, 47.7, 51.8, 93.9, 95.1, 130.0, 149.0, 174.8, 175.9, 193.3. FAB-MS m/z 526 (M^++1). *Anal.* Calcd for $C_{25}H_{43}NO_5SSi_2$: C, 57.10; H, 8.24; N, 2.66. Found: C, 56.85; H, 8.27; N, 2.67.

Methyl (1*β*,5*β*,6*S,8*S**)-5,8-Di-*tert*-butyldimethylsilyloxy-8-(methylsulfanyl)methyl-4-oxobicyclo[3.2.1]oct-2-ene-6-carboxylate (5f)** Viscous oil. IR (film) cm^{-1}: 1740, 1700, 1615. ^{1}H-NMR δ: 0.08, 0.20, 0.22, and 0.33 (3H×4, each s), 0.92 (9H, s), 0.95 (9H, s), 1.84 (1H, dd, J=12.8, 5.1 Hz), 2.02 (3H, s), 2.54 (2H, ABq, J=13.4 Hz), 2.55 (1H, ddd, J=12.8, 10.7, 7.1 Hz), 2.90—2.95 (1H, m), 3.50 (1H, dd, J=10.7, 5.1 Hz), 3.60 (3H, s), 6.19 (1H, dd, J=9.6, 0.5 Hz), 7.31 (1H, dd, J=9.6, 7.6 Hz). ^{13}C-NMR δ: −2.9, −2.5, −2.4, −2.2, 17.1, 19.1, 19.2, 26.1, 26.4, 31.7, 38.3, 45.2, 50.3, 51.9, 90.9, 97.1, 129.0, 152.7, 174.0, 199.4. EI-MS m/z 500 (M^+), 485, 384 (base). HR-EI-MS m/z: Calcd for $C_{24}H_{44}O_5SSi_2$, 500.2448. Found: 500.2476.

(1*β*,5*β*,6*S,8*S**)-5,8-Di-*tert*-butyldimethylsilyloxy-8-(methylsulfanyl)methyl-4-oxobicyclo[3.2.1]oct-2-ene-6-carbaldehyde (5b)** A solution of the dimer of **1** (0.704 g, 1.7 mmol) and acrylaldehyde (0.959 g, 17.1 mmol) in dry toluene (50 ml) was heated in a sealed tube at 120 °C for 2 d. Removal of the solvent under reduced pressure and chromatography of the residue over silica gel (eluent: 5% ethyl acetate in hexane) furnished the adduct **4b** (0.551 g, 69%). Subsequent eluting afforded compound **5b** as the minor product (24 mg, 3%).

5b: Colorless solid (Et_2O–hexane), mp 105.5–107 °C. IR (KBr) cm^{-1}: 1734, 1688, 1610. ^{1}H-NMR δ: 0.11, 0.23, 0.28, and 0.34 (3H×4, each s), 0.95 (18H, s), 1.92 (1H, dd, J=13.2, 4.7 Hz), 2.02 (3H, s), 2.32 (1H, ddd, J=13.2, 10.4, 6.9 Hz), 2.57 (2H, ABq, J=13.0 Hz), 2.95 (1H, dd, J=7.4, 6.9 Hz), 3.44 (1H, ddd, J=10.4, 4.7, 1.5 Hz), 6.06 (1H, d, J=9.4 Hz), 7.36 (1H, dd, J=9.4, 7.4 Hz), 9.58 (1H, d, J=1.5 Hz). ^{13}C-NMR δ: −2.8, −2.2, −2.0, −1.9, 17.2, 19.2, 19.3, 26.2, 26.5, 26.8, 38.0, 45.4, 57.3, 90.4, 96.4, 127.6, 154.7, 198.9, 201.2. FAB-MS m/z 471 (M^++1). HR-FAB-MS Calcd for $C_{23}H_{43}O_4SSi_2$ $(M+H)^+$: 471.2421. Found: 471.2414.

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22) The structure of these compounds (**7g**, **7h**, **9i**) were confirmed by comparison with the spectral data of the authentic samples.[13)]
23) When using $LiN(SiMe_3)_2$, NaH, LiH, *etc.* in the place of KH, $KN(SiMe_3)_2$ the reaction did not proceed to result in the recovery of starting material except for **4a** (Table 1, entry 3).
24) Because the rearrangement reaction was promoted by the addition of 18-crown-6, we thought that the reaction required a high concentration of an effective carbanion at C-7 in the reaction mixture.