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SELECTIVITY IN RING-OPENING METATHESES

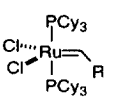
John A. Tallarico, Michele L. Randall, and Marc L. Snapper*

Department of Chemistry, Eugene F. Merkert Chemistry Center
Boston College, Chestnut Hill, Massachusetts 02167

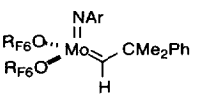
Abstract: The development of new olefin metathesis catalysts has allowed for the introduction of unique synthetic transformations. In this regard, ring-opening metathesis (ROM) offers a novel means of constructing diene-containing systems. The factors behind the chemo-, regio- and stereoselectivities of ROM are examined. The mechanistic models suggested are supported by stoichiometric studies of the unique ruthenium alkylidenes formed during the ROM of various cyclobutene-containing substrates. © 1997 Elsevier Science Ltd.

Introduction

The introduction of structurally defined, metathesis active metal alkylidenes, such as complexes **1** and **2**, offers novel opportunities for the development of new and useful synthetic methodologies.[1] For example, ring-closing metathesis (RCM) has become a proven way of generating a variety of olefin-containing hetero- and carbocycles (eq 1).[2] Recent applications of RCM in natural product synthesis provide evidence for the powerful utility of this transformation.[3] In a related fashion, cross metatheses are emerging as a new *inter*molecular method of constructing substituted olefins (eq 2).[4]



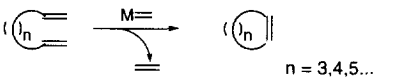
1
1a (R = Ph)
1b (R = $CHCPh_2$)



2
Ar = 2,6-diisopropylphenyl
$R_{F6}O$= $(CF_3)_2MeCO$

Similarly, ring-opening metathesis (ROM) provides a novel means of generating diene-containing systems (eq 3).[5] Whereas *intra*molecular metatheses, such as RCM can enjoy certain geometric constraints that control the outcome of the reaction, cross-metatheses, such as ROM, are not generally influenced by these factors. In this regard,

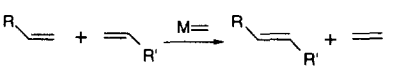
Ring-closing metathesis (RCM)



(eq 1)

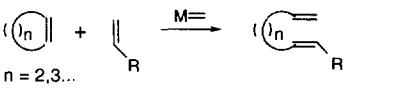
n = 3,4,5...

Cross metathesis



(eq 2)

Ring-opening metathesis (ROM)



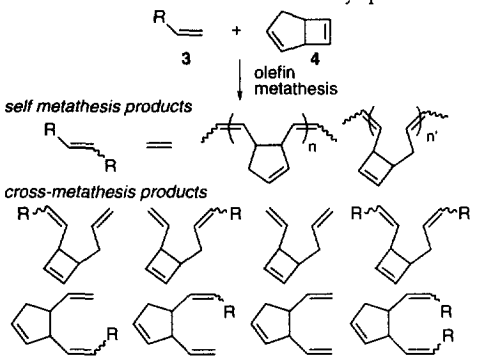
(eq 3)

n = 2,3...

understanding the steric and electronic forces that guide selectivity in cross-metatheses is an important challenge in advancing these *inter*molecular transformations to their fullest potential.

As illustrated in Scheme 1, a non-selective metathesis between terminal olefin **3** and bicyclo-[3.2.0]heptadiene **4** could generate a large number of possible products. Understanding the factors that influence the chemo-, regio-, and stereoselectivity in metathesis[6] with the aim of limiting the number of observed products is critical to the development of ROM. Among the key questions are: Which alkenes are most reactive? Will self-metathesis of the various olefins compete with the desired cross-metathesis pathway? If the reaction is cross-metathesis selective, will the reaction be regio- and/or stereoselective? Will the olefinic products of

Scheme 1. Cross-metathesis selectivity questions.



the metathesis enter back into the catalytic cycle to give starting material or new products? Mechanistic insights that allow us to answer these questions are necessary for future applications of ROM. Reported herein is our current model for ruthenium alkylidene catalyzed ROM.

Results and Discussion

We recently reported that a selective ROM occurs between terminal olefins and cyclobutenes to generate unique 1,5-diene-containing molecules (Table 1).[5a] In all cases, few if any self-metathesis products are observed. Furthermore, as long as the starting materials are present, the products of the reaction do not appear to enter back into the catalytic cycle. Of additional interest, the major product's newly formed double bond is of the Z-configuration. It is these issues that, in part, prompted a closer evaluation of the factors affecting selectivity in ROM.

Table 1. Ring-opening cross-metatheses.

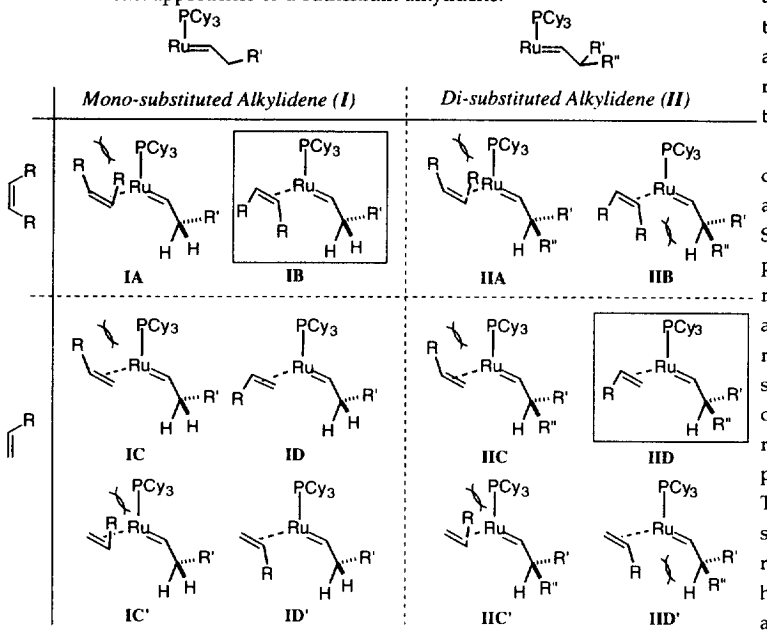
entry	olefins	products (cis:trans)	yield
1	1-octene, **5**	**6** (3.2:1)	89%
2	**5**, TBSO-pent-4-en-1-ol	**7** (2.4:1)	95%
3	1-octene, **8**	**9** (2.0:1)	96%
4	1-octene, **10**	**11** (2.2:1)	80%

Cross-metathesis selectivity: While it is not clear whether approach of an olefin to the ruthenium alkylidene or fragmentation of the resulting metallacyclobutane is the product determining event, the possible interactions in ROM can be qualitatively represented by the structures illustrated in Table 2. Although, the precise configuration of ligands about the *active* ruthenium complex in the catalytic cycle is currently unknown, NMR (*vida infra*) and other studies[7] support a ruthenium complex containing a single phosphine ligand positioned antiperiplanar to the alkyl substituent on the ruthenium-carbon double bond.

If this is the case, productive metatheses available to a disubstituted Z-olefin such as cyclobutene are limited by interactions with the large phosphine ligand[8] (transition state structures **IA** & **IIA**), as well as the 1,3-interactions with substituents on the alkylidene (**IIB**). Only the transition state represented by structure **IB** avoids these conflicts. Based on the E,Z ratios for the newly formed olefins described in Table 1, we suspect that geometry **IB** is favored over pathway **IA** by approximately 0.5 kcal/mol. That is, the cyclobutene has a small preference to react with the monosubstituted alkylidene to provide a 1,2-disubstituted Z-olefin.

The factors influencing terminal olefin metathesis, on the other hand, are less clear. Since the alkene is not symmetrical, the number of geometries that needs to be considered is doubled. Of the eight likely transition states representing a monosubstituted olefin's approach to a mono- and disubstituted alkylidene, structures **IC**, **IC'**, **IIC**, and **IIC'** can be considered less optimal because of interactions between the incoming olefin and the large tricyclohexylphosphine ligand. Likewise, the approach of an olefin to the disubstituted

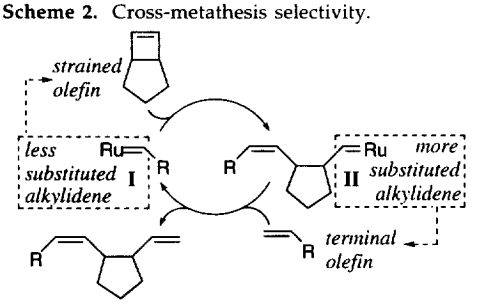
Table 2. Olefin approaches to a ruthenium alkylidene.[11]



alkylidene illustrated in **IID'** is disfavored due to 1,3-interactions. The metathesis represented by transition state **ID** can be ignored since this is a nonproductive transformation that returns the same olefin and alkylidene.[9] This leaves only transition states **ID'** and **IID** to be considered. Structure **IID** is expected to be operative in a productive cross-metathesis, while **ID'** will lead to self-metathesis of the terminal olefin. Our analysis does not provide a clear steric argument differentiating these two pathways or explain why **IB** is preferred over **ID**; however it is possible that the alkylidene formed after metathesis of structure **IID** or **IB** is electronically preferred over the ruthenium methylidene that is formed in **ID'**.[10]

The overall catalytic cycle implied in this analysis is summarized in Scheme 2. In this proposed pathway, the more reactive monosubstituted alkylidene **I** prefers to react with the more strained disubstituted olefin in a transition state represented by **IB** to provide alkylidene **II**. This more hindered, disubstituted alkylidene (**II**) reacts fastest with the less hindered terminal olefin in a transition state represented by **IID** to generate the observed product, as well as the monosubstituted alkylidene **I**. Thus, the differing reactivity of the two alkylidenes formed in the catalytic cycle provides a foundation for the cross-metathesis selectivity observed in these transformations.

Scheme 2. Cross-metathesis selectivity.



Strain: The proposed mechanistic model (Scheme 2) suggests that the cyclic olefin requires some form of activation to compete with the monosubstituted olefin for the less encumbered metal alkylidene (**I**). To probe the role of "strain" as an activating feature, a range of cyclic olefins was examined in ROM. The results of this study are illustrated in Table 3.

The highly strained, but hindered 2,2-diphenylcyclopropene **12**, does not undergo cross-metathesis under standard ROM conditions.[1d] Nevertheless, compounds **13**, **5**, and **15**, with an estimated release of energy upon ring-opening of -47, -40 and -32 kcal/mol respectively, are all viable substrates for a selective ROM. Cross-metathesis of cyclooctene (**17**), on the other hand, is relatively

Table 3. "Strain" in cross-metathesis.

entry	olefins	products (cis/trans)	ΔH^a (kcal/mol)	yield
1	Ph, Ph **12** 1-octene	no desired product	-57	-
2	Pr, H, O **13** ethylene	Pr, H, O **14**	-47	>60%
3	**5** 1-octene	Hex **6** (3.2:1)	-40	89%
4	**15** 1-octene	Hex **16** (1:2.3)	-32	76%
5	**17** 1-octene	Hex **18** (2.1:1)	-10	44%

[a]estimated exothermicity of ring-opening by isodesmic calculations (AM1).

nonselective. Depending somewhat on the precatalyst used, **1a** or **1b**, complete consumption of **17** is somewhat slow, and a considerable amount of tetradecene is produced during the reaction. Not surprisingly, significant amounts of disubstituted and polymeric products are also observed since the product (**18**) contains an unhindered terminal olefin that can compete with the 1-octene. Given that cyclopentene is also not a good substrate for ROM, these results suggest that the disubstituted cyclic olefin may require >10 kcal/mol of exothermicity upon ring-opening to achieve a selective cross-metathesis. Moreover, as evident in entry 5 (Table 3), the degree of allylic substitution in the ring-opened products may have a role in disfavoring subsequent undesired metatheses of the products.

Regio- and stereoselectivity: For ROM to be of synthetic value, the factors affecting regio- and stereoselectivity need to be understood. Table 4 illustrates the ROM of non-symmetrical cyclobutene-

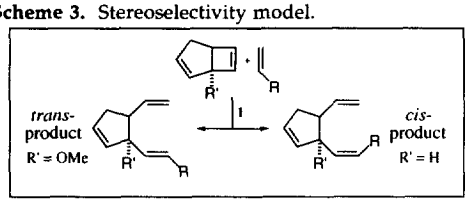
Table 4. ROM with unsymmetrical cyclobutenes.

entry	olefins	products (cis:trans)		yield
1	**4** 1,3-butadiene	viridiene	isoviridiene	87% (1:1)
2	**4** 1-butene	multifidene	isomultifidene	70% (1:1)
3	HO, Et **19** 1-decene	HO, Et, Oct **20** (2.3:1)	HO, Et, Oct **21** (1.7:1)	56% (1.3:1)
4	HO, Et **22** 1-decene	HO, Et, Oct **23** (3:1)	HO, Et, Oct **24** (2:1)	71% (2:1)
5	MeO **25** 1-octene	MeO, Hex **26** (1:9)	MeO, Hex **27** (2:1)	81% (4:1)

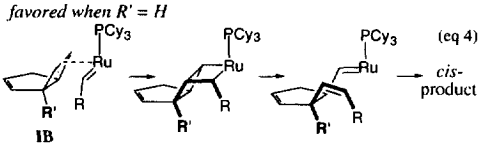
containing substrates. While no regioselectivity is observed in the syntheses of the brown algae pheromones multifidene and viridiene, a modestly regio- (**26**:**27** 4:1) and stereoselective (**26**, 9:1 *E*:*Z*) ROM is obtained with a methoxy substituted cyclobutene (**25**, entry 5). It is particularly noteworthy that in this case the larger portion of the terminal olefin (*i.e.*, 1-octene) is delivered to the more hindered side of the cyclobutene (**25**).

While there are alternative explanations, Scheme 3 provides a rationale based on sterics for the selectivity observed in this ROM. As mentioned earlier (see Table 2), the cyclobutene functionality prefers to approach the alkylidene away from the large tricyclohexylphosphine ligand (**IB**, eq 4). This usually provides the *Z*-olefin. When a substituent is introduced in the allylic position on the cyclobutene (R'≠H), the usual approach (**IB**) is no longer favorable due to a 1,3-interaction with the alkylidene. To avoid this interaction (~2 kcal/mol)[12] with the alkylidene, the cyclobutene pays the price (~0.5 kcal/mol) for approaching the ruthenium complex toward the

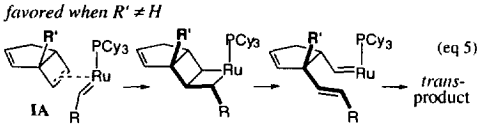
Scheme 3. Stereoselectivity model.



favored when R' = H



favored when R' ≠ H



phosphine ligand (**IA**). This approach selectively introduces a disubstituted *E*-olefin at the more substituted side of the product.

Extending this ROM model to our cyclobutadiene cycloadducts[13] indicated shortcomings in our analysis. Contrary to our expectations, cross-metathesis of cyclobutene **13** with various terminal olefins demonstrates little regiocontrol or stereocontrol (eq 6). An optimization study confirmed that terminal olefin electronics, reaction temperature and solvent properties had little influence over the regio- and stereoselectivity of the reaction (Table 5).

Taking a closer look at the interactions that may affect the cross-metathesis selectivity in cyclobutene **25** suggested that the conformational preference of the methoxy group might play a role in the reaction outcome. If this is the case, other substrates containing substituents that occupy the analogous region of space may provide a more regio- and stereoselective ROM. As illustrated in Table 6, cycloadducts with a methyl (**31**→**32**) or hydroxyl group (**34**→**35**) in the appropriate location about the cyclobutene moiety provide for a reasonably regio- and stereoselective ROM.[14] Interestingly while compounds **31** and **34** offer good control, **33** does not undergo metathesis even under forcing reaction conditions (220 °C, sealed tube). When **31** and **33** are

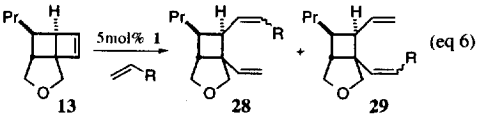
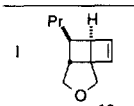
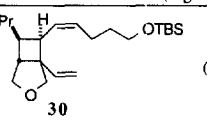
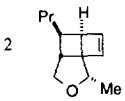
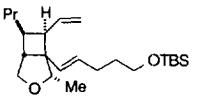
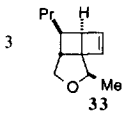
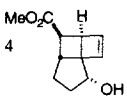
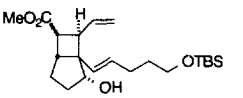
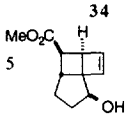
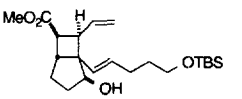


Table 5. ROM selectivity study.

entry	R	solvent	product ratio(28:29)	yield (%)
1	$(CH_2)_3OTBS$	CH_2Cl_2	1.4:1	76
2	$(CH_2)_3OTBS$	CCl_4	1.7:1	20
3	$(CH_2)_3OTBS$	THF	1.3:1	59
4	$(CH_2)_3OTBS$	$MeOH/CH_2Cl_2$	1.2:1	53
5	$(CH_2)_3OTBS$	t-$BuOH/CH_2Cl_2$	1.2:1	56
6	$(CH_2)_3OTBS$	CH_3CN	-	-
7	Ph	CH_2Cl_2	1.5:1	75
8	CH_2CN	CH_2Cl_2	-	-
9	CH_2OTBS	CH_2Cl_2	1.8:1	20
10	$C(CH_3)_2OTBS$	CH_2Cl_2	-	-
11	CH_2TMS	CH_2Cl_2	2.2:1	51
12	CH_2TMS	CCl_4	1.8:1	42
13	CH_2TMS	$CHCl_3$	2.4:1	53
14	CH_2TMS	C_6H_6	2.3:1	19

Table 6. Regio- and stereoselective ROM.

entry	olefin	product	yield[a] (regioisomer ratio)
1			76% (1.4 : 1)
2			72% (8 : 1)
3		—	0%
4			60% (10 : 1)
5			57% (1.9 : 1)

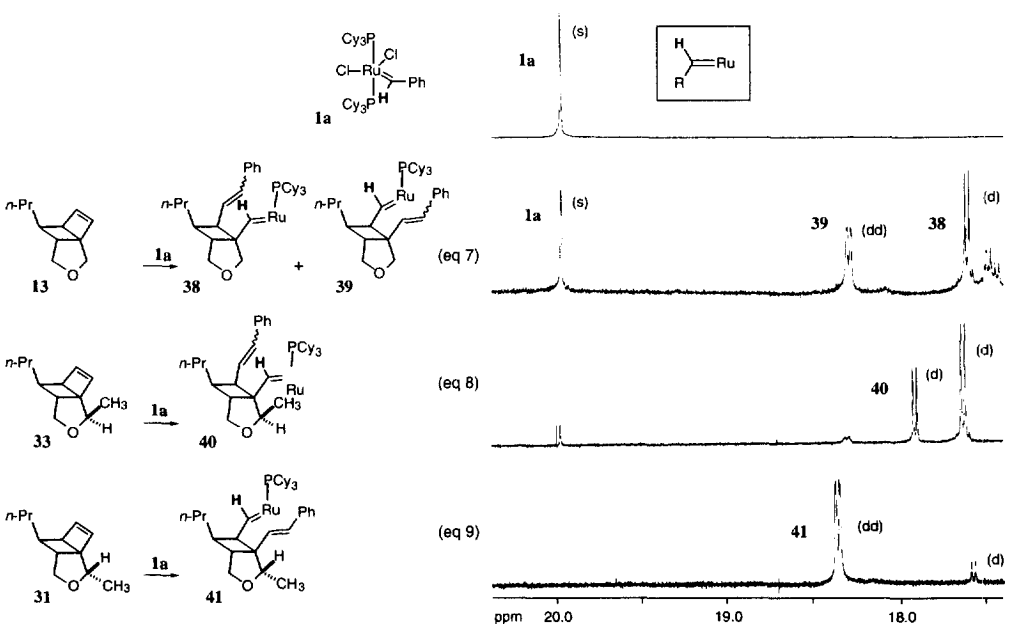
[a]The major regioisomer of each reaction is shown.

run as a 1:1 mixture in ROM, again no metathesis products are observed and only starting materials are recovered. These results suggest that cyclobutene **33** selectively "deactivates" the metathesis catalyst, a conclusion supported further by the evidence presented below.

Stoichiometric Ring Opening: To better understand the effects of local chirality on reactivity and selectivity, a stoichiometric ROM with cyclobutenes **13**, **31**, and **33** was pursued. These alkenes were reacted with one equivalent of ruthenium catalyst **1a** and the products were examined by ^{1}H (data shown below) and ^{31}P NMR. Cyclobutene **13** reacts with **1a** to provide several new ruthenium alkylidenes, represented by regioisomers **38** and **39**, each as a mixture of stereoisomers about the newly formed olefin (eq 7). The 1.7:1 ratio of regioisomers (**38**:**39**) obtained in this nonselective metathesis is similar to the 1.5:1 selectivity observed for product formation in the catalytic version of this reaction (Table 5, entry 7).

Likewise, when **31** is treated with **1a**, a 11:1 ratio of alkylidenes is formed with **41** as the major regio- and stereoisomer (eq 9). It is clear from decoupling experiments that one aliphatic proton and one phosphine ligand are coupled to the new alkylidene proton. This suggests that, unlike complex **1a**, the tricyclohexylphosphine ligand has an orientation relative to the alkylidene proton other than 90°. The ^{31}P NMR of the reaction mixture shows the presence of two major phosphine peaks (106 ppm and 36 ppm); the first signal indicates one equivalent of an unbound tricyclohexyl phosphine oxide and the second is consistent with a single ruthenium bound phosphine. Subsequent treatment of this new alkylidene (**41**) with excess styrene provides *trans*-stilbene and the same product (**42**, not shown) that is observed in a catalytic ROM.

Stoichiometric ring-opening of **33**, on the other hand, provides mainly alkylidene **40** as a 1.6:1 mixture of *Z*:*E* olefin isomers (eq 8). As expected, when styrene is added to the alkylidene **40**, no new ROM products or *trans*-stilbene are formed; further



ruthenium alkylidene ^{1}H NMR signals (coupling)

evidence that the ruthenium alkylidene **40** is not metathesis active. While it is speculative, a reason for the lack of reactivity for **33** could be that the newly formed ruthenium alkylidene is sandwiched between the adjacent olefin and the methyl group, not allowing other olefins to approach the reactive functionality. Experimental tests of this explanation will require the construction and evaluation of additional substrates.

Conclusions

Under appropriate conditions, a cyclic olefin will undergo ROM with a terminal olefin to provide unique diene-containing products. Additional efforts are required to fully evaluate the steric and electronic influences of the olefins; however, strain and substitution in the cyclic olefin appear to play a role in affecting cross-metathesis selectivity. Furthermore, with appropriate substrate functionality, a regio- and stereoselective ROM is possible. While the details of the ROM mechanism are still unclear, a first generation model is presented which predicts the outcome of ROM. As additional information and examples become available, modifications to the model will certainly be necessary. For example, key questions currently being addressed that could affect the model include: why does ruthenium **1** add to cyclobutene **33** with a different regioselectivity than **31**, and what does the crystal structure of ruthenium alkylidene **40** and **41** reveal about the complexes' environment. Addressing these issues, as well as others, will assure that the full scope and utility of ROM is realized in an efficient and effective manner.

Experimental Section

General methods. Starting materials and reagents were purchased from commercial suppliers and used without further purification except the following: Benzene and Et_2O were distilled from sodium/benzophenone ketyl under N_2 atmosphere. Similarly, acetone (HPLC grade) was distilled from fresh $CaSO_4$; CH_2Cl_2 and pentane were distilled from CaH_2 under N_2 atmosphere. Hexanes, 2-methylbutane, and ethyl acetate were distilled prior to use.

All oxygen- or moisture-sensitive reactions were carried out under N_2 or Ar atmosphere in oven-dried (140 °C, ≥ 4 h) glassware. Air- and/or moisture sensitive liquids were transferred by syringe or cannula and were introduced into the reaction flask through rubber septa or through a stopcock under N_2 or Ar positive pressure. Air- and/or moisture sensitive solids were transferred in a glove box. Unless otherwise stated, reactions were stirred with a Teflon™ covered stir bar and carried out at rt. Concentration refers to the removal of solvent using a Büchi rotary evaporator followed by the use of a vacuum pump at approximately 1 torr. Silica gel flash column chromatography was performed using Baxter brand silica gel 60Å (230-400 mesh ASTM). The use of brine refers to saturated (sat.) $NaCl_{(aq)}$.

Proton nuclear magnetic resonance (**^{1}H NMR**) spectra were measured on either a Varian Unity-300 spectrometer (300 MHz), a Varian Gemini-400 spectrometer (400 MHz), or a Varian Unity-500 spectrometer (500 MHz). **^{13}C NMR** spectra were recorded on either a Varian Unity-300 spectrometer (75 MHz), a Varian Gemini-400 spectrometer (100 MHz), or a Varian Unity-500 spectrometer (125 MHz) with complete proton decoupling. **^{31}P NMR** spectra were recorded on a Varian Unity-300 spectrometer (121 MHz) and referenced to an H_3PO_4 external standard with complete proton decoupling. All ^{1}H and ^{13}C NMR chemical shifts are reported in ppm downfield from tetramethylsilane. Infrared spectra (**IR**) were measured on either a Nicolet 510 FT-IR or a Perkin-Elmer 1310 Infrared Spectrometer, ν_{max} in cm^{-1}.

Elemental analyses (**Anal**) were performed by Robertson Microlit Laboratories, Inc., Madison, NJ and were reported in percent atomic abundance. High resolution mass spectral analyses (**HRMS**) were performed by the Mass Spectrometry Laboratory, University of Illinois at Urbana-Champaign.

Heats of formation (kcal/mol) were calculated at the AM1 level using Spartan software version 4.0 (Wavefunction, Inc., Irvine, CA 92715). For example: Table 3, entry 1: 2,2-dimethylcyclopropene (H_f = 62.49 kcal/mol) + 1-propene (H_f = 6.57 kcal/mol) → 3,3-dimethyl-1,4-hexadiene (H_f = 12.06 kcal/mol), ΔH_{calc} = -57 kcal/mol. ΔH_{calc} for entries 2 - 6 were calculated in a similar manner.

***Representative experimental for ROM of substrate and terminal olefin catalyzed by* 1.** To a stirring solution of **1** (7.4 mg, 0.009 mmol) in CH_2Cl_2 (0.6 mL), **31** (35.2 mg, 0.18 mmol), styrene (93.6 mg, 0.90 mmol) and dodecane (5 μL) dissolved in CH_2Cl_2 (1.2 mL) are added by syringe over 5 h. The reaction is monitored by GC. When consumption of **31** is complete, the reaction mixture is purified by silica gel chromatography (20:1 hexane:Et_2O, R_f=0.18) to produce **42** (49.0 mg, 0.17 mmol, 94% yield).

(±)-1α-Ethenyl-7α-[(*E*)-2'-pheneth-1'-enyl]-2β-methyl-6α-propyl-3-oxa-bicyclo[3.2.0]heptane (42). **^{1}H NMR** ($CDCl_3$, 400 MHz): δ 7.39 (2H, d, J = 7.2 Hz), 7.33 (2H, t, J = 7.2 Hz), 7.24 (1H, d, J = 6.8 Hz), 6.48 (1H, d, J = 16.0 Hz), 6.29 (1H, d, J = 16.4 Hz), 5.94 (1H, dt, J = 16.8, 10.4 Hz), 5.05 (1H, dd, J = 16.8, 2.4 Hz), 5.03 (1H, dd, J = 10.0, 2.4 Hz), 3.90 (1H, d, J = 9.6 Hz), 3.80 (1H, dd, J = 9.2, 5.6 Hz), 3.47 (1H, q, J = 6.0 Hz), 3.23 (1H, t, J = 10.0 Hz), 2.56 (1H, dd, J = 4.4, 4.0 Hz), 2.00 (1H, dtd, J = 12.8, 6.0, 3.6 Hz), 1.48-1.38 (4H, m), 1.28 (3H, d, J = 6.0 Hz), 0.87 (3H, t, J = 7.6 Hz). **^{13}C NMR** ($CDCl_3$, 100 MHz): δ 137.9, 137.6, 131.0, 129.9, 129.2, 128.0, 126.8, 117.4, 84.1, 74.3, 56.6, 48.1, 43.3, 41.1, 34.7, 21.1, 14.8, 13.4. **IR** (NaCl, thin film): 3073, 3024, 2959, 2848, 1633, 1601, 1497, 1454, 1383 cm^{-1}. **MS** (70 eV) *m/z* (rel int): 282(1, M^+), 251(1), 238(8), 186(36), 168(13), 143(100), 129(40), 115(24), 91(32), 77(14). **Anal** Calcd for $C_{20}H_{26}O$: C, 85.11; H, 9.22. Found: C, 84.94; H, 9.13.

(±)-1α-Ethenyl-3α-[(*E*)-oct-1'-enyl]-cyclopentane (16-*trans*). **^{1}H NMR** ($CDCl_3$, 400 MHz): δ 5.80 (1H, ddd, J = 17.2, 10.2, 7.5 Hz), 5.38 (2H, td, J = 3.6, 1.9 Hz), 4.97 (1H, ddd, J = 17.2, 2.0, 1.3 Hz), 4.87 (1H, ddd, J = 10.2, 2.0, 0.9 Hz), 2.56-2.41 (2H, m), 1.98-1.94 (2H, m), 1.91 (2H, dt, J = 12.5, 6.3 Hz), 1.85-1.75 (2H, m), 1.44-1.36 (2H, m), 1.36-1.22 (6H, m), 1.12 (2H, dt, J = 12.3, 10.6 Hz), 0.88 (3H, t, J = 6.9 Hz). **^{13}C NMR** ($CDCl_3$, 100 MHz): δ 144.2, 135.3, 129.4, 112.9, 45.0, 44.0, 41.4, 33.2, 32.9, 32.4, 32.4, 30.3, 29.5, 23.3, 14.8. **IR** (NaCl, thin film): 3081, 2981, 2957, 2929, 2872, 2857, 1643, 1466, 1448, 991, 965, 908, 727, 664 cm^{-1}. **MS** (70eV) *m/z*(rel int): 206(2, M^+), 191(1), 178(1), 177(3), 164(2), 163(2), 150(10), 149(4), 136(4), 135(7), 122(17), 121(26), 108(16), 107(27), 95(19),94(25), 93(100), 92(8), 91(23), 80(61), 79(82), 68(18), 67(70), 66(18), 55(35), 54(22), 43(33), 41(82), 39(33). **HRMS** *m/z* calcd for $C_{15}H_{26}$: 206.2035, found 206.2036.

(±)-1α-Ethenyl-3α-[(*Z*)-oct-1'-enyl]-cyclopentane (16-*cis*). **^{1}H NMR** ($CDCl_3$, 400 MHz): δ 5.81 (1H, ddd, J = 17.1, 10.2, 7.5 Hz), 5.30-5.27 (2H, m), 4.98 (1H, ddd, J = 17.2, 1.9, 1.2 Hz), 4.88 (1H, ddd, J = 10.2, 2.0, 1.0 Hz), 2.80 (1H, tdd, 16.7, 8.4, 2.2 Hz), 2.58-2.48 (1H, m), 2.03 (2H, td, J = 7.0, 5.9 Hz), 1.91 (2H, dt, J = 12.3, 6.8 Hz), 1.87-1.77 (2H, m), 1.46-1.40 (2H, m), 1.40-1.20 (6H, m), 1.08 (2H, dt, J = 12.3, 10.6 Hz), 0.88 (3H, t, J = 6.8 Hz). **^{13}C NMR** ($CDCl_3$, 100 MHz): δ 144.1, 135.6, 129.5, 113.0, 45.2, 41.8, 38.7, 33.3, 32.5, 32.5, 30.6, 29.7, 28.2, 23.4, 14.8. **IR** (NaCl, thin film): 3081, 3000, 2954, 2927, 2857, 1641, 1466, 991, 908, 740, 664 cm^{-1}. **MS** (70eV) *m/z*(rel int): 206(2, M^+), 191(1), 178(1), 177(3), 164(2), 149(4), 135(8), 122(18), 121(26), 108(16), 107(28), 95(21), 94(27), 93(100), 91(25), 80(67), 79(90), 78(18), 77(27), 68(20), 67(77), 66(19), 55(39), 53(25), 43(35), 41(92), 39(39). **HRMS** *m/z* calcd for $C_{15}H_{26}$: 206.2035, found 206.2036.

(±)-(*Z*)-1,9-Hexadecadiene (18-*cis*). **^{1}H NMR** ($CDCl_3$, 400 MHz): δ 5.81 (1H, ddt, J = 17.0, 10.3, 6.8 Hz), 5.40-5.37 (2H, m), 4.99 (1H, ddt, J = 17.1, 2.2, 1.6 Hz), 4.93 (1H, ddt, J = 10.3, 2.2, 1.1 Hz), 2.04 (2H, dtt, J = 7.7, 6.8, 1.4 Hz), 1.99-1.94 (4H, m), 1.40-1.21 (16H, m), 0.88 (3H, t, J = 6.5 Hz). **^{13}C NMR** ($CDCl_3$, 100 MHz): δ 139.9, 131.1, 131.0, 114.8, 34.5. 33.32, 33.28, 32.5, 30.33, 30.28, 29.70, 29.68, 29.6, 29.5, 23.4, 14.8. **IR** (NaCl, thin film): 3081, 2956, 2925 (s), 2854, 1641, 1466, 1458, 1437, 992, 966, 909, 724 cm^{-1}. **MS** (70eV) *m/z*(rel int): 222(4, M^+), 207(1), 194(1), 180(1), 166(1), 152(1), 151(1), 138(3), 137(4), 124(8), 123(6), 110(18), 109(16), 97(11), 96(31), 95(35), 83(23), 82(44), 81(55), 69(44), 68(36), 67(65), 56(15), 55(94), 54(49), 53(15), 43(41), 41(100), 39(31). **HRMS** *m/z* calcd for $C_{16}H_{30}$: 222.2348, found 222.2347.

(±)-(*E*)-1,9-Hexadecadiene (18-*trans*). **^{1}H NMR** ($CDCl_3$, 300 MHz): δ 5.81 (1H, ddt, J = 17.1, 10.3, 6.7 Hz), 5.38 (2H, m), 4.99 (1H, ddt, J = 17.1, 2.2, 1.6 Hz), 4.93 (1H, ddt, J = 10.3, 2.2, 1.1 Hz), 2.09-1.90 (6H, m), 1.36-1.21 (16H, m), 0.88 (3H, t, J = 6.8 Hz). **IR** (NaCl, thin film): 3079, 3005, 2958, 2926 (s), 2855, 1466, 1457, 1437, 1380, 1260, 1094, 1017, 993, 967, 909, 805, 724, 698, 669, 638 cm^{-1}. **MS** (70eV) *m/z*(rel int): 222(4, M^+), 207(1), 194(1), 180(1), 152(1), 151(1), 138(3), 137(4), 124(8), 123(7), 110(17), 109(16), 97(12), 96(33), 95(35), 83(22), 82(47), 81(56), 69(42), 68(36), 67(66), 56(15), 55(95), 54(49), 53(15), 43(40), 41(100), 39(29). **HRMS** *m/z* calcd for $C_{16}H_{30}$: 222.2348, found 222.2347.

(±)-3α-[(*Z*)-Dec-1'-enyl]-2β-ethyl-4α-ethenylcyclopentan-1β-ol (23-*cis*). **^{1}H NMR** ($CDCl_3$, 300 MHz): δ 5.74 (1H, ddd, J=16.9, 10.4, 8.2 Hz), 5.44 (1H, dtd, J=10.9, 7.2, 0.7 Hz), 5.14 (1H, tt, J=10.4, 1.4 Hz), 4.91 (1H, ddd, J = 10.4, 2.0, 0.7 Hz), 4.89 (1H, ddd, J = 16.9, 2.0, 1.0 Hz), 4.31 (1H, t, 3.8 Hz), 2.95 (1H, app tt, J = 8.5, 8.1 Hz), 2.84 (1H, q, J = 9.9 Hz), 2.03-1.99 (2H, m), 1.94 (1H, ddd, J =14.2, 7.6, 1.3 Hz), 1.80 (1H, ddd, J = 14.1, 7.6, 4.8 Hz), 1.58-1.20 (15H, m), 0.95 (3H, t, J = 7.3 Hz), 0.88 (3H, t, J = 6.7 Hz). **^{13}C NMR** ($CDCl_3$, 125 MHz): δ 141.5, 132.0, 131.7, 114.0, 73.9, 54.0, 45.4, 44.8, 41.8, 32.6, 30.6, 30.3, 30.1, 30.0, 28.4, 23.4, 21.5, 14.6, 13.4. **IR** (NaCl, thin film): 3374(b), 3080, 3004, 2957(s), 2926(s), 2855(s), 1676, 1461, 1005, 908 cm^{-1}. **MS** (70eV) *m/z*(rel int): 278(6, M^+), 249(6), 231(6), 161(4), 147(14), 123(14), 119(5), 111(24), 105(9), 97(32), 83(67), 79(33), 69(61), 55(100), 41(91). **HRMS** *m/z* calcd for $C_{19}H_{34}O$: 278.2610, found 278.2610.

(±)-4α-[(*Z*)-Dec-1'-enyl]-2β-ethyl-4α-ethenylcyclopentan-1β-ol (24-*cis*). **^{1}H NMR** ($CDCl_3$, 300 MHz): δ 5.65 (1H, dt, J = 16.4, 9.9 Hz), 5.35 (1H, dt, J = 10.7, 7.1 Hz), 5.24 (1H, tt, J = 10.5, 1.3 Hz), 4.96 (1H, ddd, J = 10.2, 2.2, 0.5 Hz), 4.92 (1H, ddd, J = 16.8, 2.0, 0.7 Hz), 4.31 (1H, t, J = 4.0 Hz), 3.30 (1H, dtd, J = 9.5, 8.8, 8.1 Hz), 2.46 (1H, q, J = 9.8 Hz), 2.01-1.94 (2H, m), 1.95 (1H, ddd, J = 14.2, 7.8, 1.2 Hz), 1.64 (1H, ddd, J = 14.0, 8.0, 4.6 Hz), 1.57-1.34 (4H, m), 1.34-1.20 (11H, m), 0.96 (3H, t, J = 7.3 Hz), 0.88 (3H, t, J = 6.7 Hz). **^{13}C NMR** ($CDCl_3$, 125 MHz): δ 140.9, 132.5, 130.6, 115.3, 74.1, 52.6, 51.9, 43.6, 39.3, 32.6, 30.5, 30.3, 30.1, 30.0, 28.2, 23.3, 21.4, 14.6, 13.4. **IR** (NaCl, thin film): 3374(b), 3076, 3004, 2958(s), 2925(s), 2874, 2856(s), 1655, 1639, 1462, 1379, 1182, 1146, 1004(s), 909 (s) cm^{-1}. **MS** (70eV) *m/z*(rel int): 278(8, M^+), 263(1), 260(4), 249(8), 234(2), 231(8), 223(3), 195(5), 189(4), 162(5), 161(5), 148(5), 147(17), 137(8), 133(6), 125(9), 123(16), 111(26), 97(33), 95(30), 83(68), 81(31), 79(35), 77(22), 69(61), 67(54), 57(61), 55(100), 43(65), 41(91), 39(22). **HRMS** *m/z* calcd for $C_{19}H_{34}O$: 278.2610, found 278.2610.

(±)-4α-[(*E*)-Dec-1'-enyl]-2β-ethyl-4α-ethenylcyclopentan-1β-ol (24-*trans*). **^{1}H NMR** ($CDCl_3$, 300 MHz): δ 5.60 (1H, dt, J = 16.8, 9.9 Hz), 5.33-5.29 (2H, m), 4.96 (1H, ddd, J = 10.3, 2.2, 0.5 Hz), 4.93 (1H, ddd, J = 16.8, 2.2, 0.7 Hz), 4.30 (1H, t, J = 3.9 Hz), 3.00-2.88 (1H, m), 2.43 (1H, q, J = 9.8 Hz), 2.00-1.93 (2H, m), 1.91 (1H, ddd, J = 14.0, 7.8, 1.3 Hz), 1.74 (1H, ddd, J = 14.1, 8.0, 4.7 Hz), 1.60-1.20 (15H, m), 0.96 (3H, t, J = 7.3 Hz), 0.88 (3H, t, J = 6.7 Hz). **^{13}C NMR** ($CDCl_3$, 125 MHz): δ 141.1, 132.6, 130.8, 115.5, 73.7, 52.2, 51.9, 44.4, 42.4, 42.1, 33.2, 32.6, 30.2, 30.1, 29.8, 23.4, 21.1, 14.8, 13.5. **IR** (NaCl, thin film): 3372(b), 3079, 2966, 2924(s), 2873, 2854, 1641, 1464, 1260, 1095, 1076, 1009(s), 967, 911 (s), 801, 722, 790 cm^{-1}. **MS** (70eV) *m/z*(rel int): 278(4, M^+), 263(1), 261(1), 260(1), 249(8), 234(3), 231(12), 195(5), 179(1), 166(2), 165(3), 161(4), 151(3), 147(24), 124(5), 123(17),121(10), 111(9), 110(7), 109(12), 105(11), 95(18), 91(27), 84(20), 83(58), 81(25), 79(38), 77(23), 69(20), 68(14), 67(58), 57(44), 55(80), 53(19), 43(57), 41(100), 39(24).

(±)-1α-Ethenyl-7α-[(*Z*)-2'-pheneth-1'-enyl]-6α-propyl-3-oxabicyclo[3.2.0]heptane (28-*cis*) Table 5, entry 7. **^{1}H NMR** ($CDCl_3$, 400 MHz): δ 7.32 (2H, t, J = 7.2 Hz), 7.22 (1H, t, J = 7.2 Hz), 7.12 (2H, d, J = 7.2 Hz), 6.52 (1H, d, J = 11.6 Hz), 6.01 (1H, dd, J = 17.6, 10.8 Hz), 5.85 (1H, dd, J = 11.6, 11.2 Hz), 5.21 (1H, dd, J = 10.8, 1.2 Hz), 5.12 (1H, dd, J = 8.8, 4.8 Hz), 3.91 (1H, d, J = 9.2 Hz), 3.89 (1H, d, J = 8.8 Hz), 3.67 (1H, dd, J = 8.8, 4.8 Hz), 3.43 (1H, app t, J = 10.4 Hz), 3.29 (1H, d, J = 8.8 Hz), 2.51 (1H, app t, J = 4.4 Hz), 2.16 (1H, dtd, J = 10.0, 7.4, 5.2 Hz), 1.49-1.21 (4H, m), 0.88 (3H, t, J = 7.2 Hz). **^{13}C NMR** ($CDCl_3$, 100 MHz): δ 139.0, 131.1, 130.7, 129.2, 128.9, 127.4, 126.8, 115.1, 79.7, 75.4, 47.4, 42.7, 40.8, 34.7, 21.1, 20.8, 14.9. **IR** (NaCl, thin film): 3079, 3060, 3025, 2954, 2922, 2846, 1634, 1494, 1465, 1448, 1081, 1039 cm^{-1}. **MS** (70 eV) *m/z* (rel int): 268(1, M^+), 237(1), 225(1), 172(23), 154(46), 143(24), 129(100), 115(28), 91(29), 77(15), 65(10). **Anal** Calcd for $C_{19}H_{24}O$: C, 85.07; H, 8.96. Found: C, 84.86; H, 8.97.

Representative experimental for stoichiometric metathesis. In a glove box, **1a** (41.2 mg, 0.050 mmol) is added to a 5 mm borosilicate NMR tube and sealed under an Ar atmosphere with a septa. To the NMR tube, $CDCl_3$ (0.15 mL) is added by syringe and the mixture is agitated for 15 min. The appropriate amount of **19** (8.2 mg, 0.05 mmol) in $CDCl_3$ (0.15 mL) is then introduced. The NMR tube is agitated for 10 min and allowed to sit for 1 h. The reaction is then monitored by NMR. Ruthenium alkylidene **41** was purified by silica gel chromatography (12:1 hexane:Et_2O, R_f=0.20).

Ruthenium alkylidene 41. **^{1}H NMR** ($CDCl_3$, 400 MHz): δ 18.43 (1H, dd, J = 9.2, 2.8 Hz), 7.75 (2H, dd, J = 7.2, 2.0 Hz), 7.31 (3H, m), 6.83 (1H, d, J = 14.8 Hz), 6.42 (1H, dd, J = 14.8, 2.0 Hz), 4.03 (1H, q, J = 6.4 Hz), 3.79 (1H, d, J = 9.2 Hz), 3.65 (1H, dd, J = 9.6, 3.6 Hz), 2.74 (1H, dd, J = 6.0, 4.0 Hz), 2.62 (1H, tt, J = 8.8, 6.4 Hz), 2.40 (3H, app q, J = 12.0 Hz), 1.85-1.12 (35H, complex), 1.53 (3H, d, J = 6.4 Hz), 0.87 (3H, t, J = 6.8 Hz). **^{31}P NMR** ($CDCl_3$, 121 MHz): δ 36.06.

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