Olefin Metathesis in Supercritical Carbon Dioxide

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Abstract: Liquid or supercritical carbon dioxide ($scCO_2$) is a versatile reaction medium for ring-opening metathesis polymerization (ROMP) and ring-closing olefin metathesis (RCM) reactions using well-defined metal catalysts. The molybdenum alkylidene complex **1** and ruthenium carbenes **2** and **3** bearing PCy_3 or N-heterocyclic carbene ligands, respectively, can be used and are found to exhibit efficiency similar to that in chlorinated organic solvents. While compound **1** is readily soluble in $scCO_2$, complexes **2** and **3** behave like heterogeneous catalysts in this reaction medium. Importantly, however, the unique properties of $scCO_2$ provide significant advantages beyond simple solvent replacement. This pertains to highly convenient workup procedures both for polymeric and low molecular weight products, to catalyst immobilization, to reaction tuning by density control (RCM versus acyclic diene metathesis polymerization), and to applications of $scCO_2$ as a protective medium for basic amine functions. The latter phenomenon is explained by the reversible formation of the corresponding carbamic acid as evidenced by ^1H NMR data obtained in compressed CO_2. Together with its environmentally and toxicologically benign character, these unique physicochemical features sum up to a very attractive solvent profile of carbon dioxide for sustainable synthesis and production.

Introduction

Numerous advantages are associated with the use of compressed and especially supercritical carbon dioxide ($scCO_2$; $T_c = 31.0$ °C, $p_c = 73.8$ bar, $d_c = 0.477$ g·mL^{-1}) as an ecologically benign and economically feasible reaction medium for metal-catalyzed reactions.[1,2] Technical aspects such as its nonflammability and the lack of virtually any toxicity and immediate ecological hazards make $scCO_2$ particularly attractive for sustainable chemical processes.[3] The high miscibility of $scCO_2$ with many reaction gases and the absence of a gas/liquid-phase boundary can lead to enhanced reaction rates.[4] The rich phase behavior of supercritical reaction media provides novel approaches to catalyst immobilization.[5] In addition to solubility control, other physiochemical properties of a supercritical fluid can also be tuned within a certain range by adjusting its density through small variations of pressure and temperature.[6,7] Chemical interactions of $scCO_2$ with substrates and/or catalysts offer an as yet largely unexplored potential for activity and selectivity control.[8] The utilization of $scCO_2$ as solvent *and* C1-building block opens further opportunities for homogeneous catalysis.[4,8,9]

Olefin metathesis refers to the mutual alkylidene exchange reaction of alkenes.[10] This type of reaction has become increasingly important as a synthetic tool during the last few years owing to the application of well-defined carbene complexes as catalysts or catalyst precursors.[11] Herein we report on transition-metal-catalyzed olefin metathesis in compressed (supercritical or liquid) CO_2.[12] As shown below, the reaction can be performed efficiently in this unconventional medium, and even more intriguingly, the properties of supercritical CO_2 remarkably increase the scope of this versatile transformation. Detailed investigations provide insights into mechanistic aspects and therefore help to rationalize the beneficial effects at the molecular level.

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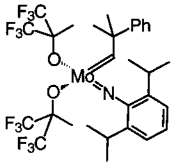
Table 1. ROMP in Compressed Carbon Dioxide

no.	monomer	cat.	n(mon.)/ n(cat.)	method (cf. the text)	t (h)	T (°C)	P (bar)	d (g·mL^{-1})	yield (%)	σ_{cis}[a] (%)	M_n	M_w	PDI[b]	T_g[c] (°C)
1	norbornene	**2a**	850	B	0.1	56	95	0.44	46	23	62 500[d]	1.6×10^6 [d]	26	42
2	norbornene	**2b**	575	A	1	23	58	Liq.	94	25	206 100[d]	655 300[d]	3.2	41
3	norbornene[f]	**2b**	625	C	1	46	92	0.54	97	22	464 800[e]	901 000[e]	2.0	41
4	norbornene	**2b**	645	B	14	45	93	0.58	84	25	75 200[d]	192 600[d]	2.6	41
5	norbornene	**2b**	5350	B	24	37	165	0.83	97	26		nd[g]		48
6	cyclooctene	**2b**	195	A	6	45	100	0.56	47	28	10 900[d]	22 300[d]	2.0	25
7	cyclooctene	**2**	5250	D	24	38	160	0.83	21	39		nd[g]		30
8	norbornene	**1**	425	A	1	25	58	Liq.	13	82		nd[g]		52
9	norbornene[f]	**1**	310	C	24	45	120	0.63	94	80		nd[g]		57

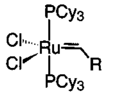
[a] Percentage of double bonds with *cis*-configuration from ^{1}H NMR analysis. [b] PDI (polydispersion index) = M_w/M_n, uncorrected. [c] Glass transition temperature from DSC analysis. [d] From GPC analysis in decaline at 150 °C using polystyrene as reference. [e] From GPC analysis in chlorobenzene at 25 °C using polystyrene as reference. [f] A saturated solution of norbornene in toluene (ca. 7.5 M) was used. [g] nd = not determined.

Results and Discussion

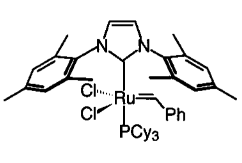
The development of well-accessible alkylidene complexes combining high activity with an excellent tolerance to a variety of functional groups has been key to the widespread application of olefin metathesis in organic synthesis and polymer chemistry. The most notable examples are the molybdenum alkylidene **1**[13] and ruthenium carbenes with bulky electron-rich phosphine (**2**)[14] or heterocyclic carbene (**3**)[15] ligands. No attempts, however, to exploit these versatile catalysts in scCO$_2$ have been reported.[16] In view of the potential advantages of scCO$_2$ for fine chemical synthesis and polymerization, a comprehensive investigation of ring-opening metathesis polymerization (ROMP) and ring-closing metathesis (RCM) appeared a rewarding endeavor (Scheme 1).



1

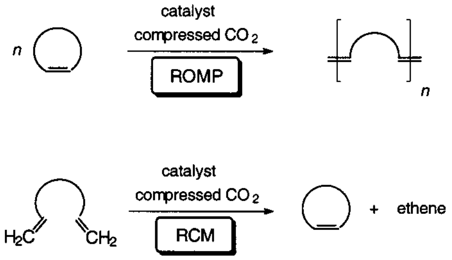


2a (R = CH=CPh$_2$)
2b (R = Ph)



3

Scheme 1



Polymerization. We found that catalysts of types **1** and **2** are highly active for ROMP of norbornene and cyclooctene in compressed carbon dioxide to form the technically important polymers Norsorex and Vestenamer (Table 1). The activities of these catalysts for ROMP of norbornene in compressed carbon dioxide are considerably higher than that observed with Ru(H$_2$O)$_6$(OTos)$_2$ in the same medium.[16d] The desired polymers are obtained in excellent yields after short reaction times, in both liquid and supercritical carbon dioxide. Complete conversion (yield 97%) is observed even at norbornene/**2b** ratios above 5000/1 under optimized conditions (Table 1, entry 5).

The catalysts and the substrate can be directly loaded into the reactor (method A) in cases where the polymerization occurs with a moderate rate. Preferentially, however, catalyst **2** is injected as a solid (method B) or in dissolved form (method D) into the homogeneous solution of the monomer in CO$_2$ to avoid broad molecular weight distributions resulting from uncontrolled initiation of the polymerization reaction. The injection of a monomer solution to the catalyst in CO$_2$ is also possible (method C) and may be interesting for larger scale operations. Representative procedures are described in the Experimental Section.

During the course of the reaction the polymers precipitate from the CO$_2$ phase and are readily isolated in solvent-free form by simply venting the reactor. The crude polymer produced with catalyst **1** has a pale gray-green color and must be purified following standard procedures. In contrast, the use of **2b** can result in formation of a bright colorless product in which any metal species are comparted in a very small highly colored portion that can be simply cut off. The loss of polymer is less than 1% in weight, which compares favorably to any other workup procedure. No ruthenium can be detected by EDX analysis in the remaining bulk material. Figure 1 illustrates this remarkable segregation phenomenon for the polymer sample obtained under the conditions of entry 5. The obvious partition of the ruthenium complex suggests that only a small fraction of **2b** has initiated polymer growth under these conditions. Consistent with this observation, analysis of the molecular weight M_n indicates a low initiation efficiency of 10−35% in entries 1−3.[17]

The *cis/trans* ratios of the polymers formed in CO$_2$ are largely identical to those obtained in CH$_2$Cl$_2$ by conventional means

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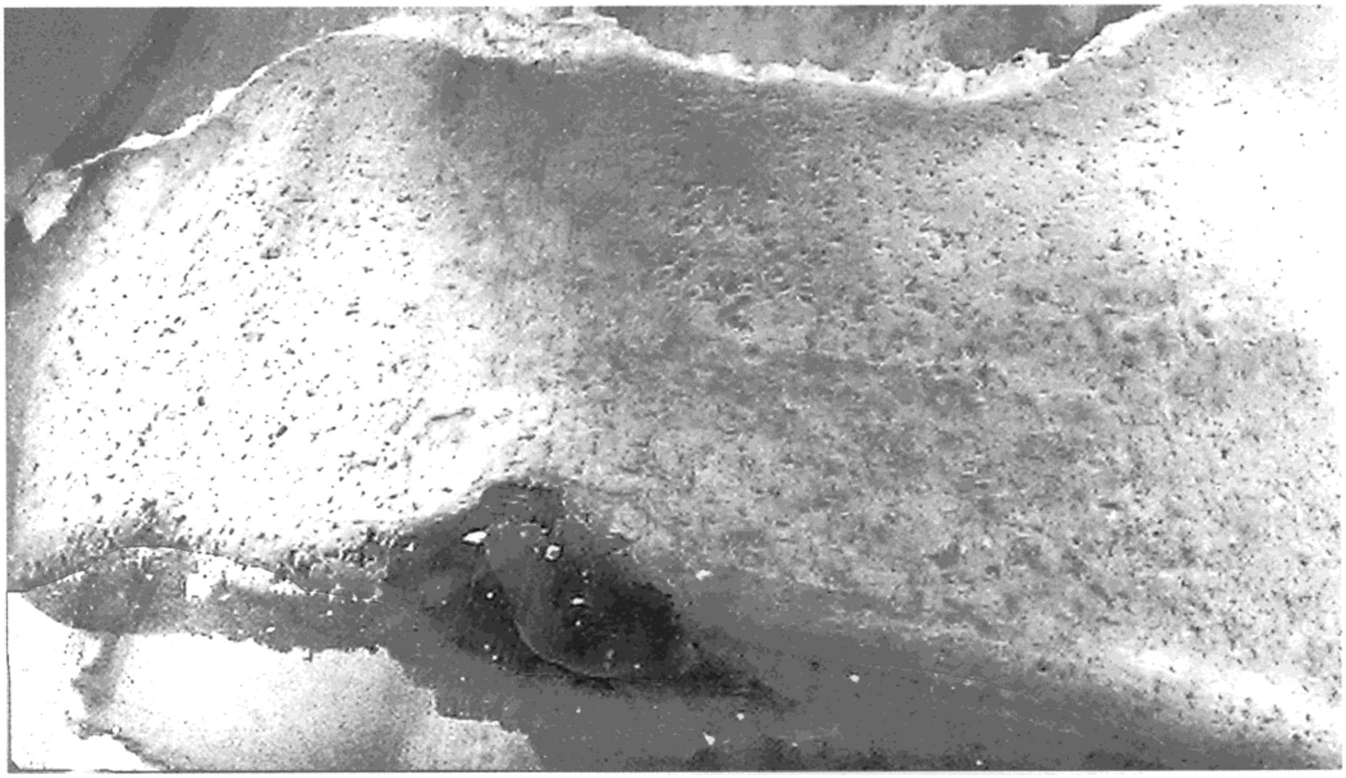

Figure 1. Image showing the polynorbornenamer obtained directly from ROMP in $scCO_2$ as described in entry 5 of Table 1. The dark spot containing the metal species is clearly visible within the white bulk polymer.

and reflect the characteristic stereoselectivity of the individual catalysts.[13,18] Likewise, the morphology of the polymeric material is also determined by the catalyst rather than the reaction medium as shown by SEM micrographs of various samples.[19]

Ring-Closing Metathesis. During the past decade, RCM has evolved as a powerful methodology for the synthesis of carbo- and heterocycles with ring sizes ≥ 5.[11] It has been successfully implemented into the total synthesis of complex natural products and bears considerable potential for the production of fine chemicals. This includes compounds used as fragrances and flavors by the cosmetic and food industries. Obviously, the replacement of organic solvents with innocuous carbon dioxide would manifest a major step toward sustainable or "green" manufacture of such high-value products.[20]

It may seem unfavorable at first sight to use high-pressure conditions for a reaction that releases stoichiometric amounts of ethene (cf. Scheme 1). However, the total pressure in the reaction vessel is almost exclusively determined by the amount of CO_2, which does not affect the release of ethene. Gratifyingly, prototype RCM reactions catalyzed by complex **2a** proceed smoothly in $scCO_2$ under mild conditions (Table 2). The five-membered ring **5** is obtained in almost quantitative yield from **4** in the form of colorless crystals after release of CO_2. Entry 2 shows that enyne metathesis reactions[21] can also be successfully performed in $scCO_2$. For diene metathesis, the remarkably simple syntheses of the macrocycles **9** and **11** are of special interest. These two compounds, which exhibit a strong musk-like odor on their own, can be converted into the commercial perfume ingredients Exaltolide and Arova 16 by hydrogenation of the C═C double bonds.[22,23] Another remarkable feature pertains to the synthesis of epilachnene **13**, an insect repellant alkaloid isolated from the pupae of the Mexican beetle *Epilachnar varivestis*,[24] by RCM of diene **12** without the need for N-protection.[25] This example illustrates the possibility to use compressed CO_2 as a "protective medium" in organic synthesis (vide infra).

The RCM of highly substituted or sterically more hindered double bonds is successfully achieved using the more reactive catalysts **1** and **3** in $scCO_2$ (Table 3). The synthesis of karahanaenone **23**, an olfactory substance contained in hops and cypress oil (*Cypressus sempervirens*),[26] may serve as an example for the formation of a trisubstituted cycloalkene using **1**.

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[17] At 100% initiation, M_n should ideally correspond to M_n(ideal) = n(monomer)/n(Ru) × conversion × molecular weight(monomer). The initiation efficiency can be estimated from 100 × M_n(ideal)/M_n(observed) using the data in Table 1.

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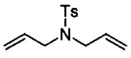
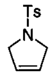
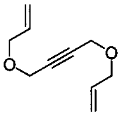
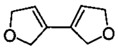
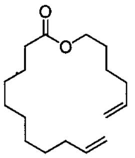
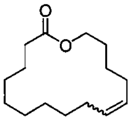
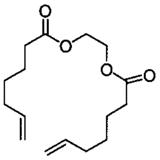
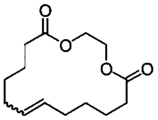
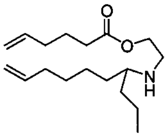
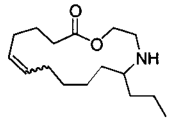
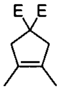
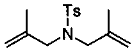
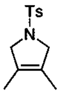
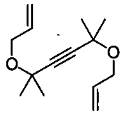
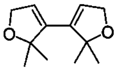
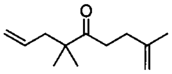
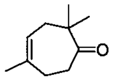
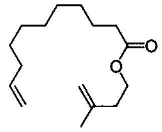
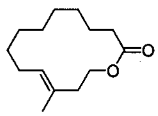
Table 2. Synthesis of Heterocyclic Products of Different Ring Sizes by RCM in $scCO_2$ Catalyzed by the Ruthenium Carbene Complex **2a**[a]

Entry	Substrate	Product	Yield
1	 **4**	 **5**	93%
2	 **6**	 **7**	62%
3	 **8**	 **9**	88%^{b,f}
4 5	 **10**	 **11**	30%^{c} 67%^{d}
6	 **12**	 **13**	74%^{e,f}

[a] Reaction conditions: catalyst **2a** (1 mol %), $T = 40$ °C, $d(CO_2) = 0.76$ g·mL^{-1}, $t = 72$ h unless stated otherwise. [b] $d(CO_2) = 0.83$ g·mL^{-1}. [c] $d(CO_2) = 0.62$ g·mL^{-1}, $t = 24$ h. [d] $d(CO_2) = 0.62$ g·mL^{-1}, $t = 170$ h; in this run, the catalyst from entry 4 remaining in the autoclave was used. [e] E:Z = 2.4:1. [f] GC yield.

Table 3. RCM in $scCO_2$ Catalyzed by the Molybdenum Alkylidene **1** (5 mol %) or the "Second-Generation" Ruthenium Carbene Complex **3** (2.5 mol %) (E = COOEt)[a]

Entry	Substrate	Catalyst	Product	Yield
1	 **14**	3	 **15**	85%
2	 **16**	3	 **17**	51%^{b,c,e}
3	 **18**	3	 **19**	83%
4	 **20**	3	 **21**	62%^{b}
5	 **22**	1	 **23**	62%
6	 **24**	3	 **25**	51%^{b,d,e}

[a] Reaction conditions: $T = 40$ °C, $d(CO_2) = 0.75$ g·mL^{-1}, $t = 24$ h unless stated otherwise. [b] Using 5 mol % catalyst. [c] $t = 120$ h. [d] $t = 72$ h. [e] GC yield.

Moreover, the high activity of "second-generation" ruthenium catalyst **3** is fully retained in $scCO_2$ as seen from the formation of the tetrasubstituted cycloalkenes **17** and **19**, the synthesis of a trisubstituted macrocycle **25,** and the successful enyne metathesis of the congested substrate **20**.

In all cases, the isolated yields and relative reactivities are comparable to those observed using the same catalysts in homogeneous CH_2Cl_2 solution.[15,27] Complex **1** gives rise to bright yellow solutions in $scCO_2$, and no solid particles can be detected by visual inspection of the reaction mixtures when using window-equipped high-pressure vessels. The high solubility of **1** in $scCO_2$ is ascribed to the presence of "CO_2-philic" fluorinated ligands,[28,29] leading to the typical characteristics of homogeneous catalysis. In contrast, the highly effective ruthenium precursors **2** and **3** show *no visible solubility* under the reaction conditions, and no UV/vis absorption bands could be detected in pure $scCO_2$.

To gain further insight into the nature of the active ruthenium species, the inorganic material remaining in the autoclave after RCM of **8** with precatalyst **2b** was purified and isolated by extraction of the organic products with CO_2. The color and morphology of the material were identical to those of fresh **2b**, and its ^{31}P NMR spectrum showed no significant difference from that of the original catalyst batch. This clearly indicates that only a minor fraction of the charged complex **2b** has exchanged its alkylidene unit to catalyze the RCM process.[30]

In an attempt to decide whether this highly reactive species operates in dissolved or undissolved form, an experiment was conducted where diene **4** and catalyst **2b** were introduced into the reactor in separate compartments. The autoclave was carefully pressurized with CO_2 at 40 °C to form a supercritical phase ($d(CO_2) = 0.62$ g·mL^{-1}). After a reaction time of 24 h, the reactor was cooled and vented very slowly to prevent extrusion of volatile organic materials. GC analysis of the organic material remaining in the reactor revealed 92% conversion to the five-membered heterocycle **5**. The small vial containing **2b** was then removed, new substrate **4** was added, and the reactor was pressurized and heated again to similar conditions for another 70 h. After the same workup, GC analysis revealed that no significant conversion occurred in the second run. Although this finding does not allow a final conclusion to be drawn as to the actual nature of the active species in $scCO_2$, it substantiates the notion that complexes **2** and **3** behave in practical terms just like ordinary heterogeneous catalysts in this particular medium. This property can be exploited for "im-

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(27) Fürstner, A.; Thiel, O. R.; Ackermann, L. *Org. Lett.* **2001**, *3*, 449–451.

(28) For a general discussion see: Leitner, W. *Nature (London)* **2000**, *405*, 129–130.

(29) The solubility of catalysts ensured by suitably designed ligands has been found to be a decisive factor in many other transformations performed in $scCO_2$; see: Kainz, S.; Koch, D.; Baumann, W.; Leitner, W. *Angew. Chem.* **1997**, *109*, 1699–1701; *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1628–1630 and references therein.

(30) This finding is consistent with the low initiation efficiency of the same catalyst for some of the ROMP experiments in $scCO_2$ as described above.

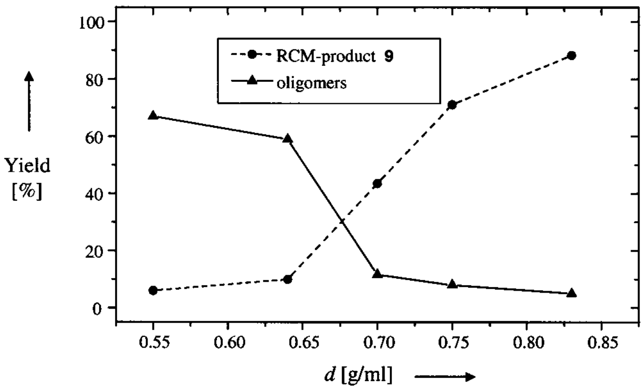

Figure 2. Product control by density variation during RCM of **8** with catalyst **2b** in $scCO_2$ at 40 °C. The highest and lowest densities correspond to approximately 200 and 130 bar, respectively.

mobilization" purposes without the need for chemical modification of the catalysts and/or fixation on organic or inorganic supports.[31]

Advantages of $scCO_2$ beyond Solvent Replacement. The applications in polymerization and fine chemical synthesis summarized above show that $scCO_2$ can be applied as an environmentally benign solvent for olefin metathesis in its broadest scope. At the same time, they illustrate nicely how to exploit the unique physicochemical properties of this particular medium in metal-catalyzed syntheses.

One major aspect pertains to the straightforward isolation of products and their effective separation from the catalyst. This is of particular interest in view of potential technical applications. The simple way to obtain pure and dry norbornenamer directly from ROMP in $scCO_2$ has already been discussed above. The isolation of the polymers is facilitated by the fact that $scCO_2$ is generally a poor solvent for hydrocarbons of moderate or high molecular weight.[32]

On the other extreme, the solubility properties of $scCO_2$ can be exploited in RCM to isolate the low molecular weight products via selective supercritical fluid extraction (SFE).[33] In this case the volatile organic materials can be collected directly from the gas stream in appropriate traps, leaving the ruthenium complex behind. The metal residues in the autoclave are still active for RCM (entries 4 and 5, Table 2). We refer to such combinations of organometallic catalysis and separation as "catalysis and extraction using supercritical solutions" (CESS process).[5] The absence of trace amounts of CH_2Cl_2 in the products is particularly relevant for the production of consumer goods such as the fragrances **9** and **11**.

The two separation principles discussed above can be fine-tuned for specific applications by variation of the solvent power of $scCO_2$ through density control. Even more intriguingly, density can also be used as an additional parameter to affect the course of the reaction dramatically as shown in Figure 2. The 16-membered cyclic compound **9** is formed with high selectively by RCM of diene **8** at $d(CO_2) > 0.65$ g·mL^{-1}, whereas the formation of oligomers by ADMET (acyclic diene metathesis polymerization)[34] prevails below this threshold. As the density is controlled with pressure at constant temperature, this translates into an increase of the intramolecular versus the intermolecular pathway with increasing system pressure. It is noteworthy that this trend is opposite the conventional pressure effects originating from different activation volumes for intermolecular and intramolecular transition states.[35]

The preference for cyclization over oligomerization at high density may result from either kinetic or thermodynamic control. Increasing the density at constant volume leads to an increasing number of inert solvent molecules and mimics the effect of dilution in conventional solvents ("Ziegler-Ruggli's dilution principle");[36] therefore, high density is expected to favor cyclizations. If the density of $scCO_2$ is low, solute/solute clustering[37] may result in considerably higher local concentrations of the diene **8** than those estimated from bulk values, increasing the probability of intermolecular reactions. Hence, the "effective molarity" [38] can be adjusted by density variation, allowing the competition between the intra- and the intermolecular reaction pathways to be controlled if the reaction is under kinetic control.

If thermodynamic control is operative, high activities (*a*) of substrate in $scCO_2$ (i.e., high mole fractions) favor linear oligomers over cyclization products as can be seen from eqs 1 and 2.[39]

$$K_{\text{inter}} = \frac{a(\text{oligo})a(\text{ethene})^{n-1}}{a(\text{substrate})^{n}} \tag{1}$$

$$K_{\text{intra}} = \frac{a(\text{macrolide})a(\text{ethene})}{a(\text{substrate})} \tag{2}$$

Since a thermodynamic contribution to the density effect, however, requires full reversibility of the metathesis process, we probed whether ring opening of **9** occurs in the presence of ethylene under the unusual reaction conditions in $scCO_2$.[40] Specifically, addition of 1 equiv of ethylene-d_4 to a mixture of macrocycle **9** and catalyst **2a** in $scCO_2$ ($d(CO_2) = 0.69$ g·mL^{-1}) leads indeed to the formation of small amounts (6%) of diene **26** with four terminal deuterium atoms (Scheme 2). The number

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[31] Attempts to immobilize ruthenium carbene complexes on solid supports have met with different successes; see the following for leading references: (a) Nguyen, S. T.; Grubbs, R. H. *J. Organomet. Chem.* **1995**, *497*, 195–200. (b) Schürer, S. C.; Gessler, S.; Buschmann, N.; Blechert, S. *Angew. Chem.* **2000**, *112*, 4062–4065; *Angew. Chem., Int. Ed.* **2000**, *39*, 3898–3901. (c) Yao, Q. *Angew. Chem.* **2000**, *112*, 4060–4062; *Angew. Chem., Int. Ed.* **2000**, *39*, 3896–3898. (d) Ahmed, M.; Barrett, A. G. M.; Braddock, D. C.; Cramp, S. M.; Procopiou, P. A. *Tetrahedron Lett.* **1999**, *40*, 8657–8662.

[32] (a) DeSimone, J. M.; Maury, E. E.; Menceloglu, Y. Z.; McClain, J. B.; Romack, T. J.; Combes, J. R. *Science (Washington, D.C.)* **1994**, *265*, 356–359. (b) Sarbu, T.; Styranec, T.; Beckman, E. J. *Nature (London)* **2000**, *405*, 165–168.

[33] Zosel, K. *Angew. Chem.* **1978**, *90*, 748–755; *Angew. Chem., Int. Ed. Engl.* **1978**, *17*, 702–709.

[34] Review: Tindall, D.; Pawlow, J. H.; Wagener, K. B. *Top. Organomet. Chem.* **1998**, *1*, 183–198.

[35] Reiser, O. *Top. Catal.* **1998**, *5*, 105–112.

[36] For a pertinent discussion see: Ziegler, K. *Methoden der Organischen Chemie (Houben-Weyl)*, 4th ed.; Thieme: Stuttgart, 1955; Vol. 4/II, pp 729–822.

[37] (a) Combes, J. R.; Johnston, K. P.; O'Shea, K. E.; Fox, M. A. In *Supercritical Fluid Technology*; Bright, F. V., McNally, M. E. P., Eds.; ACS Symposium Series, Vol. 488; American Chemical Society: Washington, DC, 1992; pp 31–47. (b) Spectroscopic evidence for solute/solute clustering with compounds of type **8**: Pandey, S.; Kane, M. A.; Baker, G. A.; Bright, F. V.; Fürstner, A.; Seidel, G.; Leitner, W. *J. Phys. Chem. B* **2001**, in press.

[38] Mandolini, L. *Adv. Phys. Org. Chem.* **1986**, *22*, 1–111.

[39] If solute/solute clustering were operative, K_{inter} would also increase more strongly than K_{intra} as the pressure (density) is lowered; for a pertinent discussion see: Kazarian, S. G.; Gupta, R. B.; Clarke, M. J.; Johnston, K. P.; Poliakoff, M. *J. Am. Chem. Soc.* **1993**, *115*, 11099–11109. We thank one of the reviewers for bringing this aspect to our attention.

[40] There is general consensus that RCM is in principle reversible but the retroreaction is kinetically hindered in many cases and does not come into play. Only recently it has been shown that the outcome of macrocyclizations in conventional sovents can be affected by the reversibility of the reaction; cf: (a) Reference 27. (b) Smith, A. B.; Adams, C. M.; Kozmin, S. A. *J. Am. Chem. Soc.* **2001**, *123*, 990–991. (c) Lee, C. W.; Grubbs, R. H. *Org. Lett.* **2000**, *2*, 2145–2147. (d) Fürstner, A.; Thiel, O. R.; Kindler, N.; Bartkowska, B. *J. Org. Chem.* **2000**, *65*, 7990–7995.

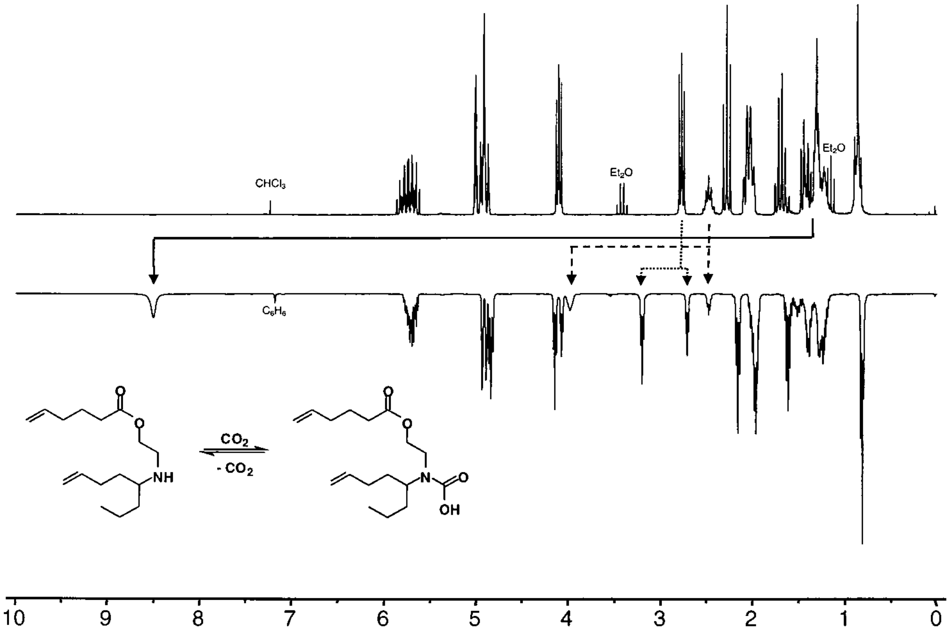
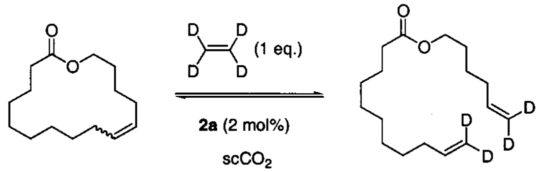


Figure 3. ^{1}H NMR spectra (400 MHz) of compound **12** in $CDCl_3$ at 27 °C (top trace) and in liquid CO_2 at 27 °C and 82 bar. The most significant shifts indicating the formation of the carbamic acid are highlighted by arrows.

Scheme 2



9 **26**

and positions of the deuterium labels in **26**-d_4 were unambiguously identified by GC/MS analysis. This indicates that thermodynamic effects may play a role in the remarkable selectivity influence described above.

Regardless of their individual contributions, the kinetic and/or the thermodynamic control mechanisms work in favor of RCM at high CO_2 density. This tuning of the product distribution nicely features the unique advantages offered from the compressibility of the supercritical phase in catalytic chemical synthesis.

In addition to the beneficial physical properties of the supercritical state, the successful use of $scCO_2$ as a protective medium highlights how to exploit the chemical reactivity of the CO_2 molecule in this medium (Table 2, entry 6). Figure 3 shows the ^{1}H NMR spectra of **12** in $CDCl_3$ and in compressed CO_2 for comparison. The significant low-field shift of the resonance of the N−H proton ($\Delta\delta = +7$ ppm) is consistent with the formation of the corresponding carbamic acid. As expected, the signals of the neighboring CH groups are also shifted to lower field. Their split into two sets of signals is attributed to hindered rotation around the N−C(O)OH bond as found also in the corresponding alkyl carbamates.[23b] The change of their relative intensities from 60:40 to 40:60 upon raising the temperature from 27 to 40 °C further supports this assignment.

Conclusions. Compressed carbon dioxide is shown to be a versatile reaction medium for olefin metathesis using well-defined metal alkylidene catalysts. Ruthenium and molybdenum catalysts were found to effect ROMP and RCM processes in $scCO_2$ with efficiency similar to that in chlorinated organic solvents. Particular advantages can be taken, however, by exploiting the unique properties of $scCO_2$. This pertains to simplified and highly convenient workup procedures for both polymeric and low molecular weight products, to catalyst immobilization, to reaction tuning by density control, and to applications of $scCO_2$ as a protective medium. Together with its environmentally and toxicologically benign character, these unique physicochemical features sum up to a very attractive solvent profile of carbon dioxide for sustainable synthesis and production.

Experimental Section

General Procedures. Complexes **1** and **2b** were purchased (Strem) and used as received. Complexes **2a**[14] and **3**[15] were prepared according to literature procedures. All experiments involving the organometallic catalysts **1**−**3** were carried out under an inert atmosphere using a combination of Schlenk line and high-pressure techniques. For a compilation of the instrumentation used, see refs 2e, 15f, and 24b. *Caution! The use of highly compressed liquified or supercritical gases must be conducted only with suitable high-pressure equipment and under appropriate safety conditions.*

Polymer Characterization. The glass transition temperatures of the polymers were determined by reheat-DSC measurements (0 to 250 to −30 to 250 °C). The presence of *cis* and *trans* C=C bonds was confirmed by the corresponding bands in the FT-IR spectra and quantitatively determined from ^{1}H NMR spectra (300 or 400 MHz, rt, $CDCl_3$, 5 mg in 0.5 mL, number of scans 128) by integration of the signals of the olefinic protons. GPC analyses were carried out on PSS columns with refraction index detection using polystyrene as standard. High-temperature GPC measurements were carried out at 150 °C using 10 mg of polymer in 10 mL of decaline and β-ionole as tracer. Low-temperature GPC was carried out at 25 °C in chlorobenzene as solvent.

General Procedures for ROMP in Compressed Carbon Dioxide. Method A. A stainless steel high-pressure vessel ($V = 27$ mL) equipped with thick-wall glass windows, a PTFE stirring bar, a bore hole for a thermocouple, a needle, and ball valves was charged with monomer (4 mmol) and catalyst (0.005−0.01 mmol) under Ar. By means of a compressor, the reactor was filled through the needle valve with a weighed amount of CO_2 (ca. 15 g) to reach the desired density. The resulting mixture was stirred at the given reaction temperature until a solid material started to precipitate in the reactor. Stirring was continued until no further change of the mixture was visible. After the mixture was cooled to room temperature, the volatiles were vented and the polymer was isolated from the vessel. If necessary, purification of the polymer was achieved by dissolving in $CHCl_3$, quenching with ethyl vinyl ether, and precipitation with MeOH. In most cases the crude polymer, however, was directly subjected to analysis.

Method B. A solution of monomer in CO_2 was prepared as in method A. A dosing unit containing the solid catalyst was connected to the reactor through the ball valve and pressurized with argon to 20 bar above the CO_2 pressure. By opening the ball valve, the solid catalyst was introduced into the reaction vessel. Workup and purification were achieved as in method A.

Method C. A mixture of catalyst and CO_2 was prepared as in method A. A dosing unit containing the monomer in toluene solution was connected to the reactor through the ball valve and pressurized with argon to 20 bar above the CO_2 pressure. By opening the ball valve, the substrate solution was introduced into the reaction vessel. Workup and purification were achieved as in method A.

Method D. The procedure was essentially identical to that of method B, but the catalyst was injected in the form of a CH_2Cl_2 solution (0.8 mL).

Representative Procedure for RCM in Compressed Carbon Dioxide. Synthesis of 1,14-Dioxacyclohexadec-7-ene-2,13-dione (11). The unsaturated ester **10** (170 mg, 0.60 mmol) and the catalyst **2a** (9 mg, 0.01 mmol) were filled into separate compartments in a high-pressure vessel ($V = 225$ mL) under Ar. The reactor was pressurized with CO_2 (140 g, $p = 103$ bar, $d(CO_2) = 0.62$ g/mL) using a compressor. The resulting reaction mixture was stirred for 170 h at 40 °C. The volatiles were then passed through a cooled trap at −60 °C in which the crude product was collected. Subsequent flash chromatography (hexane/ethyl acetate, 4/1) provided product **11** as colorless crystals (102 mg, 67%). The analytical data are in full agreement with those reported in the literature.[23b]

Compounds **5**,[41] **7**,[21] **9**,[23b] **13**,[23b] **15**,[14] **17**,[42] **19**,[15c,f] and **25**[27] have been obtained analogously. The analytical and spectroscopic data are in full agreement with those reported in the literature cited. The data of the new compounds are compiled below.

2,2,2′,2′-Tetramethyl-2,5,2′,5′-tetrahydro-[3,3′]bifuranyl (21): ^{1}H NMR (CD_2Cl_2, 300 MHz) δ 5.76 (s, 2H), 4.57 (s, 4H), 1.39 (s, 12H); ^{13}C NMR (CD_2Cl_2, 75 MHz) δ 139.3, 122.6, 88.8, 72.3, 27.4; IR (KBr) 3091, 1638, 1459, 1364, 1272, 1195, 1145, 1074, 806, 761 cm^{-1}; MS (EI) m/z (rel intens) 194 ([M$^+$], 27), 179 (100), 135 (31), 121 (26), 109 (11), 107 (13), 93 (26), 91 (20), 78 (29), 55 (11), 43 (84); HR-MS calcd 194.1307, found 194.1308.

2,2,5-Trimethylcyclohept-4-en-1-one (23): ^{1}H NMR ($CDCl_3$, 200 MHz) δ 5.48 (tq, 1H, $J = 6.7$, 1.5 Hz), 2.76 (t, 2H, $J = 6.6$ Hz), 2.32−2.22 (m, 4H), 1.68 (m, 3H), 1.09 (s, 6H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 217.2, 136.7, 121.8, 50.4, 37.3, 36.9, 31.9, 25.2, 25.1; IR (film) 3080, 2968, 2929, 2868, 1706, 1469, 1448, 1437, 1381, 1360, 1225, 1066, 829, 815 cm^{-1}; MS (EI) m/z (rel intens) 152 ([M$^+$], 58), 137 (10), 109 (19), 95 (31), 84 (100), 67 (29).

High-Pressure NMR Spectroscopy. Measurements were carried out using a 5 mm sapphire NMR tube with a titanium pressure head.[43] The tubes were always kept behind a protective shield and/or inside a cylinder made from polymethacrylate during handling, filling, transport, and insertion into the magnet of the spectrometer. The diene **12** (60 mg) and a small amount of the lock solvent benzene-d_6 (50 mg) were placed into the tube, which was pressurized with CO_2 (660 mg) at room temperature. ^{1}H NMR spectra were recorded on a Bruker AMX 400 spectrometer.

Acknowledgment. This work was supported by the Max-Planck-Gesellschaft, by the Deutsche Forschungsgemeinschaft within the Leibniz program (A.F.) and the Gerhard-Hess program (W.L.), by the Fonds der Chemischen Industrie (Kekulé stipends to L.A. and K.L.), and by Dragoco AG. We thank Prof. G. Fink, MPI Mülheim, and Dr. W. Risse, UCD Dublin, for their support with the GPC measurements.

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