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Carbon dioxide affinity (“carboxophilicity”) of trivalent light metal pyrazolates†

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Trivalent group 3 and 13 light metal pyrazolates were synthesised and their reactivity towards CO₂ was investigated. The homoleptic complex Al(pz^{tBu})₃ reversibly inserts two molecules of CO₂ to afford Al(CO₂·pz^{tBu})₂(pz^{tBu}), exhibiting CO₂ release only at elevated temperatures (>100 °C). In contrast, donor-stabilised Sc(pz^{tBu})₃(thf) forms mono-inserted species [Sc(μ-CO₂·pz^{tBu})(pz^{tBu})₂]₂, which already releases CO₂ at ambient temperature and pressure and hence is isolable only at low temperature. For the yttrium complex Y(pz^{tBu})₃(thf)₂, insertion of CO₂ is not observable at ambient temperature. The new homoleptic aluminium diisopropyl pyrazolate complex [Al(pz^{iPr})₃]₂ shows exhaustive CO₂ insertion, while dimethyl pyrazolate could be isolated as the separated ion pair [Al(N,N',N''-Al(pz^{Me})₃Me)₂][Al(pz^{Me})₃Me]. The scandium complex Sc(pz^{tBu})₃(thf) performed best in the catalytic cycloaddition reaction of CO₂ and epoxides, unveiling an inverse correlation of carboxophilicity (=CO₂ affinity) and catalytic activity. Carboxophilicity is assessed using CO₂-release temperature (via VT ¹H NMR spectroscopy and thermogravimetric analysis).

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Introduction

Anthropogenic greenhouse gases, in particular carbon dioxide, are the main reason for global climate change. Consequently, combating CO₂ build-up has developed into the most important and compelling research field in the chemical sciences.^{1–11} Carbon dioxide capture and storage (CCS) from flue gas or directly from air (DAC) are industrially realised with aqueous amine scrubbers; this technology, however, is affected by low capacities (<15 wt% CO₂), sensitivity to oxygen and high regeneration energies (high “energy penalty”).^{8,9} Academic research has focused on amino-functionalized porous materials such as mesoporous silica, zeolites or metal-organic frameworks, with the latter showing promising results under simulated flue gas.^{5,12–17} Moreover, a detailed molecular understanding of metal-ligand interactions with carbon dioxide seems crucial for developing efficient (catalytic) processes for its chemical valorization.¹⁸ Here, metal-N(ligand) cooperativity has proven particularly effective in CO₂ transformations together with a synergistic interplay to reversibly insert this heteroallene.¹⁸ Any reversible insertion/de-insertion process will rely on a fine balance of metal-centred oxophilicity

and ligand-nitrogen nucleophilicity, which we have termed carboxophilicity (Fig. 1, top).

Recently, we found that CO₂ reversibly inserts into metal-pyrazolato bonds involving oxophilic metal centres. It was revealed that tetravalent dimeric [Ce(pz^{Me})₄]₂ and the trivalent cluster [Ce(pz^{Me})₃]₄ can accommodate 25 wt% CO₂.¹⁹ Adapting this approach to the environmentally friendlier earth-abundant light metal magnesium, parent pyrazolate [Mg(pz)₂]_n achieved an exceptionally high reversible CO₂ uptake of up to 35.7 wt%.²⁰ Structurally authenticated complexes include tetravalent Ce(CO₂·pz^{Me})₄ (A)¹⁹ and divalent Mg(CO₂·pz^{tBu})₂(thf)₂ (B),²⁰ showing exclusive κ²(N,O) carbamate coordination (Fig. 1,

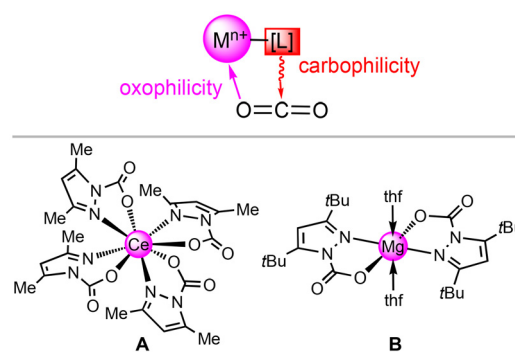


Fig. 1 Top: Carboxophilicity of metal–ligand entities as driven by the oxophilicity of the metal centre and nucleo(carbo)philicity of the ligand. Bottom: Examples of tetravalent (cerium, A)¹⁹ and divalent (magnesium, B) carbamate complexes,²⁰ which feature fully reversible CO₂ insertion.

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bottom). Moreover, all pyrazolate complexes displayed moderate catalytic activity in the conversion of CO₂ and epoxides to their corresponding cyclic carbonates. In this work, we report on the reactivity of trivalent pyrazolates of highly oxophilic group 3 and 13 light metals aluminium, scandium and yttrium towards CO₂. In addition, we discuss CO₂ release temperature as a quantifiable measure for assessing carboxophilicity.

The reactivity of organoaluminium complexes towards carbon dioxide was described by Ziegler in 1960 and expanded on later in 1970 by Weidlein.^{21,22} Accordingly, CO₂ inserts irreversibly into trialkyl aluminium compounds to afford tertiary alkoxides or carboxylates, which upon hydrolysis, produced their corresponding alcohols or carboxylic acids. Dimeric [Al(μ-CO₂-N(iPr)₂)(CO₂-N(iPr)₂)₂]₂ features the first structurally characterised aluminium carbamate complex, accessed from AlBr₃/HN(iPr)₂/CO₂.²³ Moreover, dimeric heteroleptic carbamate [Me₂Al(μ-CO₂-N(iPr)₂)₂]₂ was obtained (among others) *via* CO₂ insertion into [Me₂Al(μ-N(iPr)₂)₂Mg(μ-Me)]_n.²⁴ More recently, compound [Al(κ²-N,N-2-{methylamino}pyridine)₂R] (R = Et, iBu) was shown to insert CO₂ not only into the Al-C(alkyl) bond but also in one of the two Al-N bonds of each pyridine ligand.^{25,26} Furthermore, the frustrated Lewis acid pair 9,9-dimethylxanthene(PPh₂-AlMe₂Cl-AlMeCl) engaged in reversible CO₂ insertion.²⁷ In addition, aluminium compounds supported by a rigid ligand backbone, such as porphyrinato, salen or amino-tris(phenolato), are active in the cycloaddition of CO₂ with epoxides, with the latter displaying a promising performance with low catalyst loads.^{28–36} The porphyrinate complex (TPP)Al(OMe) showed reversible insertion behaviour towards CO₂ in the presence of 1-methylimidazole.²⁸

For rare-earth metals, a rich CO₂-insertion chemistry is already existent.^{19b} However, for most metal–ligand entities, CO₂ insertion turned out to be irreversible, forming carboxylates/formiate from alkyls/hydrides,^{37–42} carbonates from alkoxide/aryloxide^{43,44} or carbamates from amide complexes.^{45–48} Scandocene [(C₅Me₅)₂Sc(CO₂-*p*-tolyl)] features the first structurally characterised organoscandium CO₂ insertion complex.³⁷ Evans *et al.* described the first yttrium carbamate complex, [(C₅Me₅)₂Y(CO₂-ε-caprolactam)]₂, obtained by CO₂ insertion into the Y–N bond of (C₅Me₅)₂Y(O,N-ε-caprolactam).⁴⁷ Rare-earth-metal complexes also gained attention for their catalytic performance in the co-polymerisation of CO₂ and epoxides to polycarbonates,^{43,49–52} as well as the cycloaddition of both compounds to the cyclic carbonates with amino-tris(phenolates) as the most promising catalysts.^{52–59} Particularly thanks to the works of the groups of Deacon, Junk, and Winter, there exists a vast variety of rare-earth-metals pyrazolates, featuring distinct coordination modes.^{60–64} We were mostly interested in diamagnetic scandium and yttrium pyrazolates, such as Sc(pz^{tBu})₃,⁶¹ [Y(pz^{Me})₃(thf)]₂⁶² and Y(pz^{tBu})₃(do)₂.⁶⁰

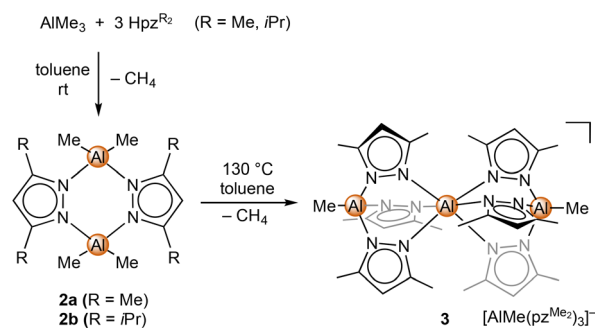
Results and discussion

Selection and CO₂ insertion of group 13 pyrazolates

Aluminium pyrazolates. Deacon *et al.* obtained discrete Al(pz^{tBu})₃ (**1**) *via* a salt-metathesis reaction of AlCl₃ and K(pz^{tBu})

in THF as the first and so far only known homoleptic aluminium pyrazolate complex.⁶⁵ In addition to *tert*-butyl-substituted pyrazolate complex **1**, we probed the feasibility of new derivatives bearing smaller, “lighter” methyl and isopropyl substituents. Since the salt-metathesis reactions of AlCl₃ and Kpz^{Me} led to no isolable product, a protonolysis protocol with AlMe₃ and Hpz^{Me} was applied. Even though a ratio of 1 : 3 of both compounds was used, only a single methane elimination occurred at ambient temperature, affording the well-known [Me₂Alpz^{Me}]₂ (**2a**) (Scheme 1).^{66,67}

Complex **2a** features a recurring structural motif,^{68–70} which was also observed for the new diisopropyl derivative [Me₂Alpz^{iPr}]₂ (**2b**). Refluxing a 1 : 3 mixture in toluene gave a more extensive but still incomplete ligand exchange. The crystalline material gained overnight revealed the solid-state structure of the separated ion pair [Al(N,N',N''-Al{pz^{Me}}₃Me)₂][MeAl(pz^{Me})₃] (**3**) (Fig. S102†). The mono-cationic fragment revealed an aluminium(III) centre coordinated by two mono-anionic [MeAl(pz^{Me})₃][−] ligands. The latter are reminiscent of the tris(pyrazolyl)hydroborato ligand Tp^{Me,Me}, while the Tp analogous aluminium ligand is accessed *via* a protonolysis reaction of LiAlH₄ with pyrazole.^{71–74} The separated anion in complex **3** is another [MeAl(pz^{Me})₃][−] entity. The central aluminium atom of the cationic fragment features a slightly distorted octahedral geometry (N–Al–N angles ±3° off). The aluminium centres of the tridentate “scorpionato”-type ligand adopt a slightly distorted tetrahedral geometry with N–Al–N angles around 100° and C–Al–N angles around 117°. The respective angles in the separated [MeAl(pz^{Me})₃][−] anion are 103° and 112° and hence are closer to tetrahedral. The three aluminium centres of the cationic fragment are almost linearly arranged (∠Al, Al, Al 1.5°), with the outer Al1/Al3–N (av. 1.874 Å and 1.893 Å) and inner Al2–N distances (av. 2.035 Å and 2.048 Å) reflecting the distinct coordination numbers. The trinuclear complex [AlMe({N,N'-3,3'-bipyrazolate}₂AlMe₂)₂], obtained from bispyrazole and AlMe₃ (1 : 1.5),⁷⁵ shows a similar structural motif. The ²⁷Al NMR spectrum of compound **3** revealed only two signals at δ = 75.7 ppm and 0.3 ppm, assignable to 4- and 6-coordinated aluminium centres, respectively.

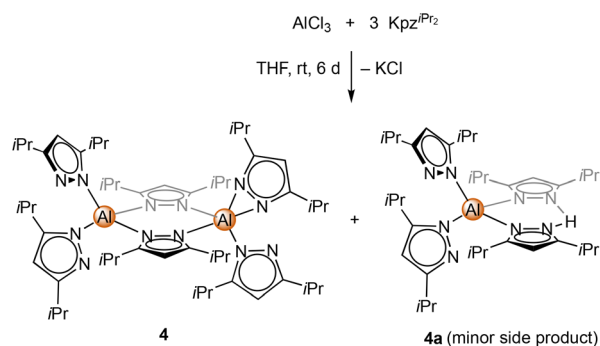


Scheme 1 Protonolysis reactions of AlMe₃ with three equivalents Hpz^R (R = Me and iPr), to form [Me₂Alpz^{Me}]₂ (**3**) at ambient temperature and separated ion pair [Al(N,N',N''-Al{pz^{Me}}₃Me)₂][MeAl(pz^{Me})₃] (**4**) by refluxing at 130 °C.



Further heating a 1 : 3 mixture of AlMe_3 and Hpz^{Me_2} in mesitylene to 180 °C, in order to achieve full methyl elimination, did not lead to any isolable product, and thus the homoleptic $[\text{Al}(\text{pz}^{\text{Me}_2})_3]$ remains elusive.

Unlike the dimethyl derivative, potassium diisopropyl pyrazolate reacted smoothly with aluminium chloride *via* a salt-metathesis route (Scheme 2). The crystal structure revealed the homoleptic bimetallic complex $[\text{Al}(\text{pz}^{\text{iPr}_2})_3]_2$ (**4**) (Fig. 2), with two bridging pyrazolato ligands arranged in an approximate boat conformation with the aluminium atoms. Interestingly, the terminal pyrazolato ligands show different coordination modes. One aluminium centre features terminal pyrazolatos coordinated exclusively in a κ^1 coordination mode, while the other one accommodates the N-ligand in both κ^1 and κ^2 fashion. The ^1H and ^{13}C NMR spectra of **4** show the bridging and terminal pyrazolatos as two different signal sets in a ratio of 1 : 2. The ^{27}Al NMR resonance was detected at $\delta = 68.1$ ppm. Some reactions gave ^1H NMR spectra with an additional slightly shifted signal set. We were able to fractionally crystallize this side product, and the solid-state structure revealed the monomeric mixed pyrazole/pyrazolato complex $\text{Al}(\text{pz}^{\text{iPr}_2})_3(\text{Hpz}^{\text{iPr}_2})$ (**4a**) (Fig. S104†). The structure of **4a** is quite similar to that of **4** with one $\text{Al}(\text{pz}^{\text{iPr}_2})_2$ fragment replaced by a



Scheme 2 Synthesis of homoleptic $[\text{Al}(\text{pz}^{\text{iPr}_2})_3]_2$ (**4**) *via* salt metathesis of AlCl_3 and $\text{Kpz}^{\text{iPr}_2}$. The side product $\text{Al}(\text{pz}^{\text{iPr}_2})_3(\text{Hpz}^{\text{iPr}_2})$ (**4a**) is formed in the presence of residual moisture.

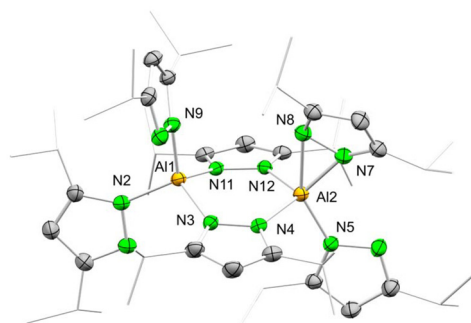


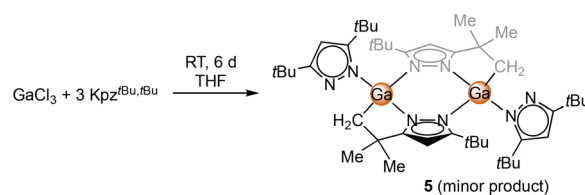
Fig. 2 Crystal structure of $[\text{Al}(\text{pz}^{\text{iPr}_2})_3]_2$ (**4**). Ellipsoids are set at the 50% probability level. Hydrogen atoms are omitted for clarity. See ESI† for selected interatomic distances and angles.

proton, which forms a hydrogen bond with the pyrazolyl moieties. Most likely, the pyrazole originated from partial hydrolysis caused by residual moisture in the solvent THF.

Attempts at homoleptic gallium pyrazolates. Since CO_2 insertion/de-insertion into metal–ligand bonds crucially depends on the bond polarization, we also aimed at employing gallium pyrazolates. Surprisingly, homoleptic gallium pyrazolates have not been reported yet.^{73,76–79} Given that $[\text{Al}(\text{pz}^{\text{R}2})_3]$ ($\text{R} = \text{iPr}, \text{tBu}$) could be readily obtained by salt metathesis, we used similar protocols to access putative gallium derivatives. However, the reactions of GaX_3 ($\text{X} = \text{Cl}, \text{Br}$) with $\text{Kpz}^{\text{R}2}$ ($\text{R} = \text{Me}, \text{tBu}$) turned out very unsatisfactorily, and only a small amount of crystalline material could be obtained (Scheme 3).

An X-ray structural analysis revealed the formation of the dimeric complex $[\text{Ga}(\text{pz}^{\text{tBu}_2})(\mu\text{-N,N,C-pz}^{\text{tBu,C}(\text{CH}_3)_2\text{CH}_2})_2]$ (**5**) (Fig. 3). C–H-bond activation at one *t*Bu moiety under release of pyrazole generated a dianionic pyrazolato ligand, bridging with both nitrogen atoms and one CH_2 group between the gallium atoms.

The molecular structure of complex **5** indicates a rather complex reactivity of gallium pyrazolates. Such distinct behaviour of aluminium and gallium in salt-metathesis reactions is not unknown, as previously shown for $\text{MCl}_3/\text{LiN}(\text{SiMe}_3)_2$ or $\text{MCl}_3/\text{LiN}(\text{SiHMe}_2)_2$ mixtures ($\text{M} = \text{Al}, \text{Ga}$). There, gallium also engaged in extensive Si–X-bond activation ($\text{X} = \text{C}, \text{H}$).⁸⁰ Application of a protonolysis protocol employing a 1 : 3 mixture of GaMe_3 and $\text{Hpz}^{\text{tBu}_2}$ led to the known $[\text{Me}_2\text{Ga}$



Scheme 3 Reaction of GaCl_3 with $\text{Kpz}^{\text{tBu}_2}$ to yield $[\text{Ga}(\text{pz}^{\text{tBu}_2})(\mu\text{-N,N,C-pz}^{\text{tBu,C}(\text{CH}_3)_2\text{CH}_2})_2]$ (**5**) as a side product.

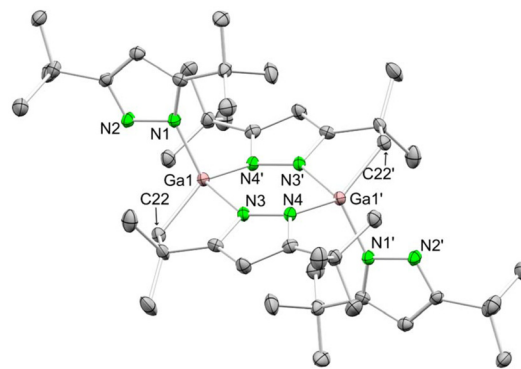


Fig. 3 Crystal structure of $[\text{Ga}(\text{pz}^{\text{tBu}_2})(\mu\text{-N,N,C-pz}^{\text{tBu,C}(\text{CH}_3)_2\text{CH}_2})_2]$ (**5**). Ellipsoids are set at the 50% probability level. Hydrogen atoms are omitted for clarity. See ESI† for selected interatomic distances and angles.



(pz^{tBu})₂,⁸¹ analogous to the aluminium-based reactions displayed in Scheme 1.

Reactivity of aluminium pyrazolates towards CO₂. Reacting Deacon's Al(pz^{tBu})₃ (**1**) with an excess of CO₂ in THF led to heteroallene insertion into two of the three pyrazolato ligands forming the bis(carbamato) complex Al(CO₂·pz^{tBu})₂(pz^{tBu}) (**1-CO₂**) (Scheme 4). The CO₂ content in **1-CO₂** corresponds to 13.5 wt% CO₂ or 3.1 mmol CO₂ per gram. Performing an NMR-scale reaction revealed the formation of a mono-inserted intermediate prior to full conversion into **1-CO₂**. This contrasts with our observations with magnesium and cerium pyrazolates showing such an intermediate only in the CO₂-releasing steps.^{19,20}

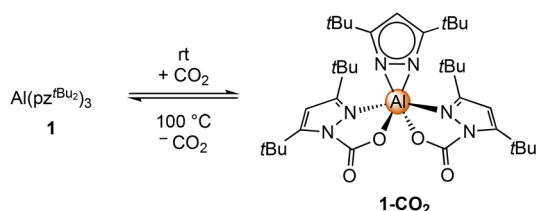
The crystal structure of **1-CO₂** revealed a strongly distorted octahedral geometry (see Fig. 4). The aluminium centre is coordinated with two carbamato moieties in the κ²(N,O) mode and one pyrazolato ligand in the terminal κ²(N,N) mode. Because of the sterically demanding *t*Bu moieties, all three ligands are twisted against each other, which gives the complex a propeller-like overall geometry. Both stereoisomers (Λ,Δ) can be found in the unit-cell which is further corroborated by the centrosymmetric space group *Pbca*. The solid-state structure might also explain the non-occurrence of an exhaustive CO₂ insertion, since the bulky *t*Bu moieties hinder a vital tilt of the third pyrazolato ligand. The inserted CO₂ moieties exhibit an angle around 127.5°, along with localized C–O double (1.199–1.203 Å) and single bonds (1.285–1.288 Å). Such

bond localization is also found in the pyrazolato rings. The 4C–3/5C and the 1/2N–3/5C distances of the non-inserted pyrazolato ring differ slightly by 0.005 Å, whereas, for the carbamate pyrazolato rings, the differences are significantly larger at 0.031–0.034 Å and 0.047 Å, respectively.

DRIFTS measurements further validate this behaviour, displaying strong absorption bands at $\tilde{\nu} = 1774/1763 \text{ cm}^{-1}$ and $\tilde{\nu} = 1328 \text{ cm}^{-1}$ for the C=O and C–O stretching vibrations, respectively. The ¹H NMR spectrum of **1-CO₂** shows two singlets for the pyrazolato backbone proton at $\delta = 6.32$ and 6.00 ppm in a 1:2 ratio. Additionally, three singlets with an integral of 18 protons each, one at $\delta = 1.50$ and two at $\delta = 1.05$ ppm, are detected, in accordance with three distinct *t*Bu moieties. Further, the ¹³C NMR spectrum of **1-CO₂** shows a signal at $\delta = 146.9$ ppm, assignable to inserted CO₂, while the ²⁷Al resonance at $\delta = 17.0$ ppm appears slightly shifted, broadened and less intense (due to loss of symmetry) compared to that of precursor **1** ($\delta = 23.3$ ppm).

Unlike the previously examined cerium and magnesium pyrazolates, solid **1-CO₂** does not show any CO₂ release at ambient temperature, not even under reduced pressure. This high carboxophilicity was further revealed by a variable-temperature (VT) NMR study in THF-*d*₈ (see S15), revealing prominent CO₂ release only at 90 °C. At this temperature, the formation of small amounts of the mono-inserted complex [Al(CO₂·pz^{tBu})(pz^{tBu})₂] can be detected, while increasing the temperature to 100 °C led to small amounts of **1**. This is in contrast to the CO₂-inserted magnesium pyrazolates which fully de-insert the heteroallene in this temperature range.¹⁹ Cooling the sample which was heated to 100 °C to ambient temperature shows the re-formation of **1-CO₂** as the predominant species, along with small amounts of the mono-inserted complex and **1**. Retreatment of this mixture with an excess of CO₂ fully restores compound **1-CO₂**. A thermogravimetric analysis (TGA) of **1-CO₂** revealed CO₂ release in the temperature range between 114 °C and 196 °C, with a mass loss of 15.8% which is in good agreement with the calculated 13.5%. A single CO₂-release step like in solution could not be observed.

Treatment of [Al(pz^{iPr})₃]₂ (**4**) with 1 bar CO₂ gave no crystalline material; however, the NMR data suggest an exhaustive insertion into every pyrazolato ligand (see S16–S18†). Three signals for the pyrazolato backbone protons appear in the ¹H NMR spectrum in a 1:1:1 integral ratio. Furthermore, four septets for the tertiary *i*Pr proton are detected in a 3:1:1:1 integral ratio. This indicates the expected asymmetry of the *i*Pr groups resulting from CO₂ insertion, in accordance with distinct signals for the *i*Pr moieties adjacent to the inserted CO₂ and one signal for *i*Pr distant to the inserted CO₂. This assignment is further strengthened by the ¹³C NMR spectrum, which shows three signals for inserted CO₂ ranging from $\delta = 147.0$ to 146.6 ppm. A ¹H–¹³C HMBIC experiment revealed that each of the three pyrazolato backbone proton signals couples with two carbon signals in the shift region for 3/5-pyrazolato carbon atoms, lending more evidence for the new asymmetry. The isopropyl CH₃ groups appear as one multiplet with 24 protons and four doublets with 3 protons. This suggests a hindered



Scheme 4 Reaction of Al(pz^{tBu})₃ (**1**) with excess CO₂ in toluene.

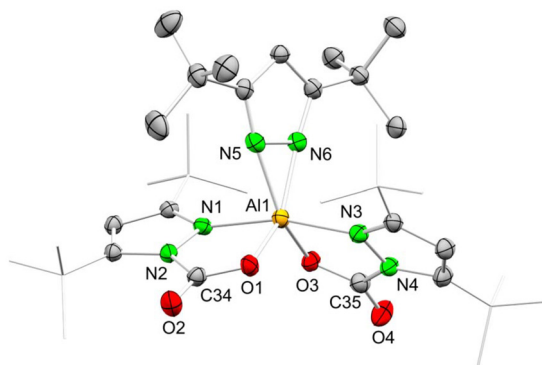


Fig. 4 Crystal structure of Al(CO₂·pz^{tBu})₂(pz^{tBu}) (**1-CO₂**). Ellipsoids are set at the 50% probability level. Hydrogen atoms and disorder in the *t*Bu moieties are omitted for clarity. See ESI† for selected interatomic distances and angles.



rotation of the *i*Pr moieties as a result of the three inserted CO₂. Upon CO₂ insertion, the ²⁷Al NMR signal shifted to higher field, from $\delta = 68.1$ ppm in **4** to $\delta = 12.1$ ppm. The putative [Al(CO₂·pz^{*i*Pr})₃] (**4**-CO₂) would infer a capacity of 21.6 wt% CO₂.

Reactivity of group 3 metal pyrazolates towards CO₂

The scandium pyrazolate Sc(pz^{*t*Bu})₃(thf) (**7**) was synthesized by applying the salt-metathesis protocol described by Deacon for aluminium pyrazolate Al(pz^{*t*Bu})₃ (**1**, *vide supra*). Accordingly, the mercury-free synthesis using THF-activated scandium chloride and Kpz^{*t*Bu} gave **7** in a good yield (see Scheme 5).

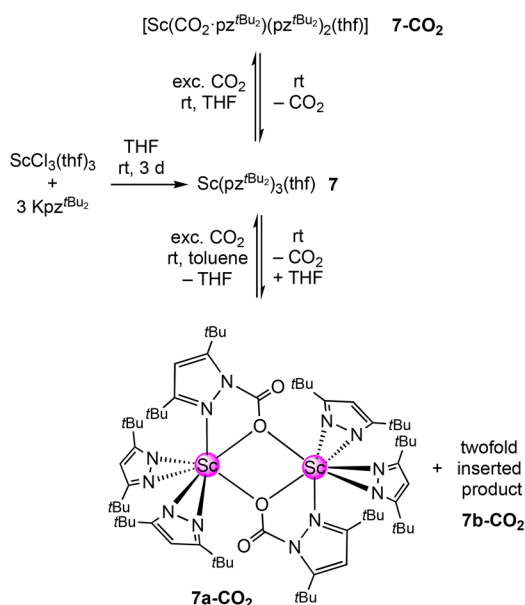
The crystal structure of **7** revealed one THF donor molecule bound to the scandium centre and three κ^2 (N,N)-coordinated pyrazolato ligands (see Fig. S107†). Unsurprisingly, the Sc–N distances are slightly longer than those in donor-free Sc(pz^{*t*Bu})₃.⁶¹ The scope of group 3 metal pyrazolates was extended to the literature known complex [Y(pz^{*Me*})₃(thf)]₂ (**9**) obtained *via* protonolysis of YCp₃ with Hpz^{*Me*}.⁶² Dimeric **9** contains two bridging and four terminal pyrazolato ligands which appear in solution ¹H and ¹³C NMR experiments as only one signal set due to fast ligand exchange. A ¹³C CP/MAS NMR experiment revealed separated signal sets for the terminal and bridging ligands (see S26†). The quaternary carbon atoms of the terminal pyrazolates even appear as four well separated signals. Applying the synthesis protocol as used for scandium complex **7**, monomeric [Y(pz^{*t*Bu})₃(thf)]₂ (**10**) was obtained. The solid-state structure of **10** revealed two THF donor molecules

bound to the metal centre, isostructural to the pyridine-stabilized derivative [Y(pz^{*t*Bu})₃(Py)]₂ (see S108†).⁶⁰

Treatment of Sc(pz^{*t*Bu})₃(thf) (**7**) with 1 bar CO₂ in THF-*d*₈ gave immediate CO₂ insertion, as evidenced by ¹H NMR spectroscopy. Three signals for *t*Bu moieties appeared at $\delta = 1.51$, 1.24 and 0.77 ppm, with an integral ratio of 9:36:9, respectively, as well as two signals for pyrazolato backbone protons at $\delta = 6.15$ ppm and $\delta = 6.04$ ppm with an integral ratio of 2:1, respectively. In addition, two signals of coordinated THF were observed. These signals can be assigned to the mono-inserted donor-stabilized complex [Sc(CO₂·pz^{*t*Bu})(pz^{*t*Bu})₂(thf)] (**7**-CO₂). The ¹³C NMR spectrum shows the resonance for the inserted CO₂ at $\delta = 149.7$ ppm. The CO₂ insertion can be also tracked by ⁴⁵Sc NMR spectroscopy, since the sharp resonance of **7** at $\delta = 41.6$ ppm shifts slightly towards lower field at $\delta = 69.1$ ppm for **7**-CO₂, also involving signal broadening. Unfortunately, we were not able to isolate any crystalline material of **7**-CO₂, due to immediate complete CO₂ release in the absence of solvent, already at ambient temperature and pressure. This effective and immediate reversibility of **7**/**7**-CO₂ is a stark contrast to the aluminium derivative **1**-CO₂, where CO₂ release only occurred at elevated temperature and was not observed at reduced pressure. To further confirm CO₂ insertion into scandium pyrazolate **7**, *in situ* DRIFTS experiments were pursued. At 1 bar CO₂ atmosphere, the immediate formation of a single strong band at $\tilde{\nu} = 1759$ was observed, indicative of a C=O bond stretching vibration (see S98 and S99†). Replacing the carbon dioxide atmosphere by argon resulted in complete CO₂ deinsertion and back-formation of **7**. A VT ¹H NMR experiment uncovered a fully dynamic equilibrium between **7** and **7**-CO₂ in solution inside a closed vessel (see S31†). Starting with **7**-CO₂, even at ambient temperature, traces of **7** were detected. By gradually increasing the temperature, the conversion of **7**-CO₂ into **7** became more and more prominent and *vice versa*. Cooling the mixture to ambient temperature resulted in an almost identical ¹H NMR spectrum as that at the outset of the VT NMR experiment.

Treatment of **7** with 1 bar CO₂ in toluene-*d*₈ instead of THF-*d*₈ resulted in immediate CO₂ insertion as well. However, this time, the ¹H NMR spectrum revealed the formation of two distinct insertion products, **7a**-CO₂ and **7b**-CO₂. One species shows three signals for *t*Bu moieties (9:36:9) with chemical shifts close to **7**-CO₂, while the second species gives four *t*Bu proton signals at $\delta = 1.69$, 1.49, 0.74 and 0.49 ppm with an integral ratio of 18:9:18:9. This second species appeared to be a product with a higher degree of inserted CO₂. Correspondingly, the pyrazolato backbone protons appeared as two sets of two singlets with an integral ratio of 2:1. Furthermore, the ⁴⁵Sc NMR spectrum showed two resonances at $\delta = 165.7$ ppm and $\delta = 39.1$ ppm.

This time, single-crystalline **7a**-CO₂ could be obtained from the solution; however, like observed for **7**-CO₂, solid **7a**-CO₂ showed immediate CO₂ release at ambient temperature. Therefore, permanent cooling at -40 °C was essential for setting up and performing a successful XRD measurement. The crystal structure revealed the dimeric donor-free mono-



Scheme 5 Salt-metathesis reaction of ScCl₃(thf)₃ and Kpz^{*t*Bu} to yield donor-stabilised Sc(pz^{*t*Bu})₃(thf) (**7**). Treatment with an excess of CO₂ produces the donor-stabilised mono-insertion product [Sc(CO₂·pz^{*t*Bu})(pz^{*t*Bu})₂(thf)] (**7**-CO₂) in THF and a mixture of the mono-inserted species [Sc(CO₂·pz^{*t*Bu})(pz^{*t*Bu})₂]₂ (**7a**-CO₂) and a higher inserted species **7b**-CO₂ in toluene.



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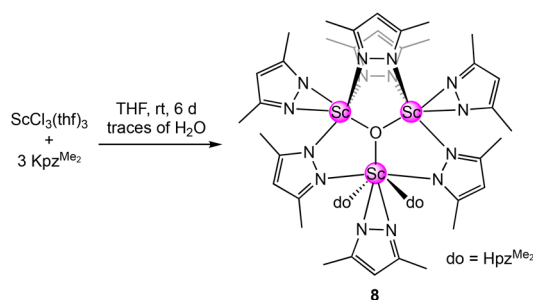
inserted species $[\text{Sc}(\text{CO}_2\text{-pz}^{t\text{Bu}_3})(\text{pz}^{t\text{Bu}_3})_2]_2$ (**7a-CO₂**) bearing the two carbamate ligands in a $[\mu\text{-}1\kappa^2(\text{N},\text{O}):2\kappa(\text{O})]$ bridging fashion (Fig. 5). Moreover, the scandium centres accommodate two terminal $\kappa^2(\text{N},\text{N}')$ pyrazolatos. As indicated by the ^1H NMR spectrum, coordinated THF from the starting material was displaced.

The overall reversibility of the CO_2 insertion of **7a-CO₂** is akin to that of **7-CO₂**. The original NMR solution as well as isolated **7a-CO₂** redissolved in toluene- d_8 , giving similar ^1H NMR spectra, both showing small amounts of the second species **7b-CO₂**. In the absence of a CO_2 atmosphere, **7b-CO₂** seems to be unstable in solution at ambient pressure, which is why no crystalline **7b-CO₂** could be isolated. Given the *t*Bu proton signal set (integral ratio of 18 : 9 : 18 : 9), representing two carbamate ligands and one pyrazolato ligand, species **7b-CO₂** likely features the twofold CO_2 -inserted compound $[\text{Sc}(\text{CO}_2\text{-pz}^{t\text{Bu}_3})_2(\text{pz}^{t\text{Bu}_3})]$.

Our attempts to synthesize the homoleptic scandium dimethyl pyrazolate *via* a salt-metathesis protocol $[\text{ScCl}_3(\text{thf})_3 + 3\text{Kpz}^{\text{Me}_3}]$ were unsuccessful. However, on one occasion, the trimetallic oxo-centred cluster $[\text{Sc}_3\text{O}(\text{pz}^{\text{Me}_3})_7(\text{Hpz}^{\text{Me}_3})_2]$ (**8**) was obtained as the main product in a crystalline yield of 74% (see Scheme 6, Fig. 6).⁸²

Two scandium centres in **8** are coordinated by four pyrazolato ligands each, and one is coordinated by three pyrazolatos and two donor pyrazoles. Each scandium centre bears one terminal $\kappa^2(\text{N},\text{N}')$ pyrazolato ligand, while two scandium centres are bridged twice by $\mu\text{-}1\kappa(\text{N}):2\kappa(\text{N}')$ pyrazolatos. The scandium centre being single-bridged to the other two accommodates the two pyrazole donors. Overall, a total of one equivalent H_2O is formally required to yield complex **8**, which most likely originated from residual water in the solvent THF.

The ^1H NMR spectrum of compound **8** displays the methyl groups and the backbone protons of the pyrazolato and pyrazole ligands as one signal each, at $\delta = 2.13$ ppm and $\delta = 5.73$ ppm, respectively, which indicates rapid exchange of the ligands in solution. The two NH-protons appear as one broad



Scheme 6 Synthesis of the oxo-centred cluster $[\text{Sc}_3\text{O}(\text{pz}^{\text{Me}_3})_7(\text{Hpz}^{\text{Me}_3})_2]$ (**8**).

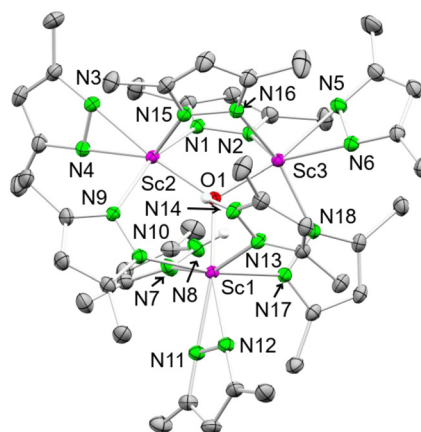


Fig. 6 Crystal structure of $[\text{Sc}_3\text{O}(\text{pz}^{\text{Me}_3})_7(\text{Hpz}^{\text{Me}_3})_2]$ (**8**). Ellipsoids are set at the 50% probability level. Hydrogen atoms are omitted for clarity. See ESI† for selected interatomic distances and angles.

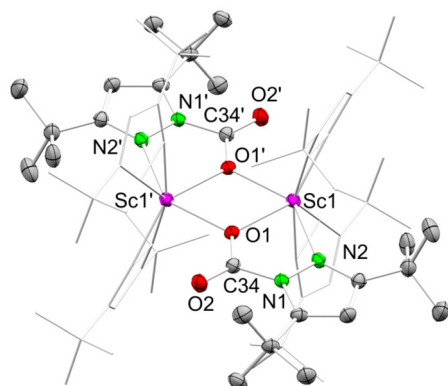


Fig. 5 Crystal structure of $[\text{Sc}(\text{CO}_2\text{-pz}^{t\text{Bu}_3})(\text{pz}^{t\text{Bu}_3})_2]_2$ (**7a-CO₂**). Ellipsoids are set at the 50% probability level. Hydrogen atoms and disorder in the *t*Bu moieties are omitted for clarity. See ESI† for selected interatomic distances and angles.

signal at $\delta = 11.82$ ppm. As expected, the ^{45}Sc NMR spectrum features two resonances at $\delta = 153.2$ ppm and $\delta = 45.1$ ppm in a ratio of 1 : 2. More surprisingly, treatment of **8** with 1 bar CO_2 led to two well-defined products as suggested by NMR spectroscopy. One product presents the carbamic acid $\text{HO}_2\text{Cpz}^{\text{Me}_3}$ with typically broad proton and carbon signals, which we reported lately as a co-product of the reaction of mixed pyrazolato/pyrazole magnesium complexes with CO_2 or as a hydrolysis product of the carbamate complexes.²⁰ The second product **8-CO₂** appeared as three sharp signals in the ^1H NMR spectrum at $\delta = 5.95$, 2.26 and 2.18 ppm. This pattern indicates exhaustive CO_2 insertion into the oxo-cluster. This is further implied by the ^{45}Sc NMR spectrum, featuring only one signal at $\delta = 53.6$ ppm. The ^{13}C NMR spectrum revealed two signals for inserted CO_2 at $\delta = 151.2$ ppm and $\delta = 150.2$ ppm, assignable to the carbamic acid and the CO_2 -functionalized oxo cluster, respectively. However, no crystalline material of **8-CO₂** could be obtained yet, and attempts to reproduce **8** by using an equimolar amount of water in the reaction depicted in Scheme 5 were unsuccessful.

The CO_2 -inserted product of $[\text{Y}(\text{pz}^{\text{Me}_3})_3(\text{thf})_2]$ (**9**) shows the typical splitting of the methyl groups in the ^1H NMR spectrum (THF- d_8), resonating at $\delta = 2.18$ ppm and $\delta = 2.09$ ppm, indica-



tive of the formation of $Y(\text{CO}_2\text{pz}^{\text{Me}_e})_3(\text{thf})$ (**9-CO₂**). However, several other non-assignable signals were detected along with that of putative **9-CO₂** (see Fig. S45†), most likely representing a rather complex cluster species. A VT ¹H NMR study revealed that **9-CO₂** fully back-converts into **9** at 70 °C, while the unknown species remains unchanged (see Fig. S48†). Recently, we introduced a solvent-free procedure, in which the pyrazolate compound is reacted with CO₂ neat as a solid.²⁰ By using this procedure for **9**, the resulting **9-CO₂** exhibited a mass gain of 15.6 wt%. This is slightly higher than the expected value for a two-fold insertion (14.5 wt%) and lower than that for a complete insertion (20.3 wt%). Correspondingly, the ¹³C CP/MAS spectrum of **9-CO₂** revealed two signal sets. One can be assigned to unreacted **9** and the other to putative **9-CO₂**. The chemical shifts are comparable to those observed for $[\text{Mg}(\text{CO}_2\text{pz}^{\text{Me}_e})_2]_n$ with a resolved signal for inserted CO₂ at 152.1 ppm. A final statement on the amount of inserted CO₂ in **9-CO₂** cannot be made. In contrast, $Y(\text{pz}^{\text{tBu}_i})_3(\text{thf})_2$ (**10**) did not show any traceable CO₂ insertion into the Y–N bond at ambient temperature. Only traces of the carbamic acid HO₂Cpz^{tBu_i} could be detected in the ¹H NMR spectrum, pointing to some Hpz^{tBu_i} impurities in **10** (see Fig. S51†). Overall, this indicates that yttrium complex **10** has an even less pronounced capability to bind CO₂ than the scandium congener **7**. This is also in agreement with the CO₂-insertion capability of homoleptic ceric pyrazolates Ce(pz^{RR'})₄ which was found to decrease in the order of pz^{Me₂} > pz^{tBu_i,Me} > pz^{Ph_i} > pz^{tBu_i}.^{8,3}

Synthesis and reactivity of unsubstituted “parent” pyrazolates of aluminium and scandium

Since the parent pyrazolate $[\text{Mg}(\text{pz})_2]_n$ displayed an exceptionally high reversible CO₂ uptake of up to 35.7 wt%,²⁰ it was of interest to examine such reaction behaviour for the trivalent light metals. The trivalent parent pyrazolates $[\text{Al}(\text{pz})_3]_n$ (**11**) and $[\text{Sc}(\text{pz})_3]_n$ (**12**) were accessed *via* transamination of Al(pz^{tBu_i})₃ (**1**) and Sc(pz^{tBu_i})₃(thf) (**7**) with Hpz in toluene, as indicated by the instant formation of a white precipitate. The ¹³C CP/MAS spectra of amorphous **11** and **12** showed the expected signal sets (Fig. S52/S54†). The ²⁷Al CP/MAS experiment revealed a signal at 5.2 ppm (Fig. S53†) featuring the most high-field shifted signal observed for a homoleptic aluminium pyrazolate. For polymeric **12**, the ⁴⁵Sc resonance was resolved at 156.0 ppm (Fig. S55†). Not unexpectedly, the CO₂-uptake behaviours of **11** and **12** were in line with those of the discrete substituted pyrazolates (*vide supra*). When exposing the solids in a very simple manner to an atmosphere of 1 bar CO₂ for three hours, mass gains of 8.2 wt% for **11** and 6.9 wt% for **12** were found. However, these materials rapidly release CO₂ at atmospheric pressure, as indicated by FTIR spectroscopy.

Catalytic cycloaddition of epoxides and CO₂

Given our previous works on metal pyrazolates, we were interested in the behaviour of trivalent metal pyrazolates as catalysts in the cycloaddition of epoxides and CO₂ (Table 1). Applying the standard protocol (0.5 mol% catalyst, 1 mol% cocatalyst tetra-*n*-butylammonium bromide (TBAB), epoxide as

Table 1 Catalytic activities of trivalent metal pyrazolates in the conversion of epoxides to cyclic carbonates^{a,b}

Entry	Catalyst	R = Me	R = Ph	R = <i>t</i> Bu	R = <i>n</i> Bu
1	1-Al	65%	5%	2%	7%
2	4-Al	43%	8%	3%	11%
3	7-Sc	>99%	27%	24%	29%
4	9-Y	84%	20%	5%	22%
5	10-Y	97%	22%	8%	18%
6	13-Ce^{III}	96%	13%	5%	9%
7	14-Ce^{IV}	88%	23%	13%	25%

^a Reaction conditions: 1 bar CO₂, 0.5 mol% metal centre of the catalyst, 1 mol% TBAB at ambient temperature for 24 h. ^b Conversion determined by comparison of the integral protons at the α-position of the epoxide and the corresponding cyclic carbonate (expect for 3,3-dimethyl-1,2-butene carbonate where the integral of the *t*Bu moieties was used).

solvent), the catalysis was performed under 1 bar CO₂ at ambient temperature. After 24 h, the conversion was determined from the ¹H NMR spectra. Pyrazolates Al(pz^{tBu_i})₃ (**1**) [Al(pz^{iPr_i})₃]₂ (**4**), Sc(pz^{tBu_i})₃(thf) (**7**), [Y(pz^{Me_e})₃(thf)]₂ (**9**) and Y(pz^{tBu_i})₃(thf)₂ (**10**) were employed as catalysts in addition to tetrametallic cluster [Ce(pz^{Me_e})₃]₄ (**13**) and the tetravalent [Ce(pz^{Me_e})₄]₂ (**14**) for comparison. Propylene oxide, styrene oxide, 2-*tert*-butyloxirane and 1,2-epoxyhexane were employed as substrates. Aluminium complex **1** showed only moderate catalytic activity, converting 65% of propylene oxide to the cyclic carbonate (entry 1). The sterically more demanding epoxides were only minimally converted by complex **1**, which achieved the highest conversion for 1,2-epoxyhexane (7%).

Dimeric complex **4** displayed an even lower conversion of 43% for propylene oxide, but performed slightly better in the cases of styrene oxide (8%) and 1,2-epoxyhexane (11%) (entry 2). This can be ascribed to the smaller *i*Pr groups of **4** (versus *t*Bu of **1**) in agreement with the observations made for magnesium pyrazolates.²⁰

Scandium complex **7** performed best in this cycloaddition reaction, affording 99% conversion of propylene oxide with only traces of the starting material left (entry 3). Complex **7** also exhibited the highest catalytic activity of the metal pyrazolates under study for the three other epoxides, ranging from 24 to 29%. The yttrium-based catalysts **9** and **10** provided similar results, with monomeric **10** achieving slightly higher conversions than dimeric **9**, except for 1,2-epoxyhexane (entry 4 and 5). The results obtained for the cerium-based catalysts were in line with our earlier report, showing only slight deviations.¹⁹ Strikingly, there seems to be a negative correlation between the carboxophilicity of the metal pyrazolate and its catalytic activity (Table 2). As described above, scandium carbamate **7-CO₂** releases CO₂ readily in the absence of a solvent or when placed in an open vessel. Also, under the applied conditions, mono-



Table 2 Correlation of catalytic conversion and CO₂ release temperatures (from VT ¹H NMR studies and TG measurements)

Catalyst	CO ₂ -release temperature [°C]			Oxophilicity M [Θ] ^b
	¹ H NMR start → end	TGA start → end	Catalytic convers. [%]	
15-Mg ^a	70–105	134–233	56	0.6
1-Al	100–120 ^c	114–196	65	0.8
9-Y	rt–70	60–154	84	0.8
14-Ce ^{IV}	10–60 ^a	55–95 ^a	88	0.9
13-Ce ^{III}		52–90 ^a	96	0.9
10-Y		—	97	0.8
7-Sc	rt	rt	>99	0.8

^a Previous work Mg,²⁰ Ce.¹⁹ ^b Ref. 84. ^c De-insertion not complete at this temperature, which is the upper limit of the VT NMR setup.

meric yttrium pyrazolate **10** did not insert any significant amount of CO₂, while dimeric yttrium pyrazolate **9** did insert CO₂ and displayed a CO₂-releasing step at 70 °C. Since the CO₂-release temperature range of complexes that reversibly insert CO₂ is an approximate measure of their carboxophilicity, comparison with the respective catalytic conversions clearly show that the lower the carboxophilicity, the higher the catalytic activity (Table 2). On the other hand, the carboxophilicity does not reflect the trends in the extent of the (calculated) oxophilicity (Table 2)⁸⁴ and electronegativity (Pauling scale)⁸⁵ and might be affected further by the Lewis acidity of the metal centre (Al³⁺ > Sc³⁺ > Y³⁺), as well as the carbophilicity,⁸⁶ sterics and coordination mode (terminal *versus* bridging) of the carbamate ligand. For further comparison, the average N–C(CO₂) distance in complexes **1-Al-CO₂** (1.444(3) Å), **7-Sc-CO₂** (1.436(2) Å), [Ce(CO₂·pz^{Me})₃]₄ (**13-CO₂**) (1.432(12) Å), [Ce(CO₂·pz^{Me})₄] (**14-CO₂ = A**, Fig. 1 bottom) (1.436(3) Å) and [Mg(CO₂·pz^{tBu})₂(thf)₂] (**B**, Fig. 1 bottom) (1.477(1) Å) were detected in a close range.

Finally, the best-performing scandium complex **7** was examined for the cycloaddition of propylene oxide and CO₂ under varying conditions (Table 3). The aforementioned performance using the standard procedure (conversion of >99%) corresponds to a TON of >199 (entry 1). Decreasing the catalyst concentration to 0.25 mol% lowered the overall catalytic conversion to 71, but increased the TON to 284 (entry 2). Employing only 0.01 mol% of **7** at harsher reaction conditions (10 bar CO₂ and 90 °C), further increased the TON to 4600 (entry 3).

Table 3 Catalytic activity of **7** in the conversion of propylene oxide and CO₂ to cyclic carbonate under different conditions^a

Entry	T [°C]/p[bar]	C (Cat.) [mol%]	Conversion ^b [%]	TON ^c
1	24/1	0.5	>99%	199
2	24/1	0.25	71%	284
3	90/10	0.01	45%	4600

^a 24 h in neat epoxide. ^b Conversion determined by comparison of the integrals protons at the α-position of the epoxide and the corresponding cyclic carbonate. ^c ((epoxide/Mg) × conversion)/100.

The TOF of **7** was determined at 120 h⁻¹ over the progress of the reaction applying our standard procedure (Fig. S86 and Table S1†).

Accordingly, complete conversion (>99%) was already detected after 12 h, but already after 6 h, the conversion was noted at 96%. Using half the amount of catalyst (entry 2) did not give similarly high conversions after 6 or 10 h, pointing to the catalyst load as the determining factor. Overall, a mechanism/catalytic cycle as described for the cerium and magnesium congeners is proposed.^{19,20} To put the present catalytic results into a proper perspective, even the most active catalysts under study show only moderate catalytic activity in comparison to systems described in literature. For example, the chlorinated tetraphenyl porphyrin aluminium complex (tetra(2,4-chloro)phenylporphyrin)AlCl reaches TOFs of up to 185 200 h⁻¹.³⁶ For the rare-earth metals, the scorpionate complex [La{N(SiHMe₂)₂]₂{κ³-(1-[2,2-bis(pz^{Me})-1,1-Ph₂Et]-1,3-Cp)}] was noted at TOFs of 15 000 h⁻¹ and TONs of up to 306 667.⁵⁷

Conclusions

The scope and feasibility of reversible metal-pyrazolate CO₂-insertion chemistry is expandable to the trivalent light metals of groups 3 and 13. The reaction behaviors of monomeric aluminium(III) and scandium(III) pyrazolates are strikingly distinct under identical conditions. While homoleptic Al(pz^{tBu})₃, bearing the comparatively small metal centre, inserts two CO₂ molecules to form Al(CO₂·pz^{tBu})₂(pz^{tBu}), Sc(pz^{tBu})₃(thf) accommodates only one molecule CO₂ per scandium, affording the dimeric complex [Sc(μ-CO₂·pz^{tBu})(pz^{tBu})₂]₂. Both complexes feature completely reversible heteroallene insertion, as revealed by FTIR and VT ¹H NMR spectroscopy and thermogravimetric analysis (TGA). Again, strikingly, the aluminium complex releases the CO₂ only at temperatures >100 °C, while the scandium complex undergoes CO₂ de-insertion at ambient temperature and pressure. The implications of the pyrazolato substituents for the extent of CO₂ insertion was demonstrated for the new homoleptic complex [Al(pz^{iPr})₃]₂, which gave exhaustive CO₂ insertion, marking a capacity of 21.6 wt% CO₂. Applying the metal pyrazolates under study as catalysts in the cycloaddition of CO₂ and epoxides to cyclic carbonates revealed an inverse correlation of the catalytic activity and carboxophilicity (=CO₂ affinity): the higher the carboxophilicity, the lower the catalytic activity. Given the reversible CO₂ insertion into metal pyrazolates, the carboxophilicity can be assessed by the CO₂-release temperature (*via* VT ¹H NMR spectroscopy and TGA). The scandium complex Sc(pz^{tBu})₃(thf) performed best, with a maximum TOF of 120 h⁻¹ and a TON of 284 at ambient conditions.

Data availability

The data that support the findings of this study are available in the ESI† of this article.



Conflicts of interest

There are no conflicts of interest.

Acknowledgements

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